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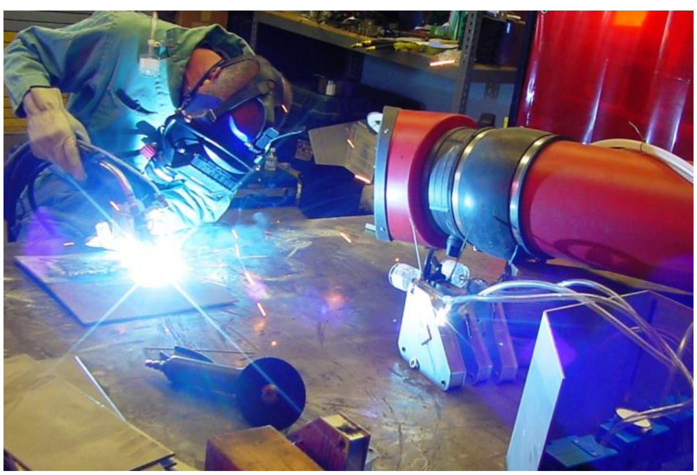
FINAL REPORT:

INTRODUCTION AND VALIDATION OF CHROMIUM-FREE CONSUMABLES FOR WELDING STAINLESS STEELS



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14. ABSTRACT

Fusion welding of stainless steels results in the formation of Cr (VI) in the welding fume. The Cr (VI) is a carcinogen and is considered a significant health hazard for the welding personnel. In 2006, OSHA reduced the Permissible Exposure Limit (PEL) for Cr (VI) in welding fume from 52 to 5 micrograms per cubic meter 8-hour time weighted average. This regulatory change has imposed stringent requirements for reduction of Cr (VI) exposure during welding of stainless steel that necessitate considerable expense for ventilation systems and/or personal protective equipment.

The objective of this project was to demonstrate and validate two new chromium (Cr)-free welding consumables for application at the Department of Defense (DOD). These consumables have been developed as a replacement for the conventional consumables used to weld austenitic stainless steel and provide almost a 100-fold reduction of the carcinogenic hexavalent chromium in the welding fume of stainless steel. Welds of both Cr-free consumables met the performance objectives of 70,000 pounds per square inch tensile strength and successfully passed the bend test. During the Field Demonstration, some of the ENiCuRu welds contained lack of fusion defects and did not pass the X-ray test. Lack of fusion, lack of penetration, and undercut defects were found in welds made with the ERNiCuRu electrode.

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FINAL REPORT

Introduction and Validation of Chromium-Free Consumables for Welding Stainless Steels

ESTCP Project WP-200903

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List of Acronyms

AC	alternative current
AED	Ammunition Equipment Division
Al	aluminum
ANSI	American National Standards Institute
APE	ammunition peculiar equipment
AS	aerosol spectrometer
As	arsenic
ASTM	American Society for Testing and Materials
AWS	American Welding Society
Cd	cadmium
CFM	cubic feet per minute
Co	cobalt
Cr	chromium
Cr (VI)	hexavalent chromium
Cu	copper
DAC	derived air concentration
DC	direct current
DCP	direct coupled plasma
DoD	Department of Defense
ECM	Environmental Cost Management
ELPI	Electric Low Pressure Impactor
ENiCuRu	Shielded metal arc welding electrode alloyed with Ni, Cu, and Ru
E308L-16	Shielded metal arc welding electrode alloyed with Cr, Ni, and with low C content
ER308LSi	Solid wire gas-metal arc electrode alloyed with Cr, Ni, Si, and with low C content
ERNiCuRu	Solid wire gas-metal arc welding electrode alloyed with Ni, Cu, and Ru
ESTCP	Environmental Security Technology Certification Program
Fe	iron
FGR	fume generation rate
GMAW	gas metal arc welding
GTAW	gas tungsten arc welding
HAP	Hazardous Air Pollutant
ICP	inductively coupled plasma
IH	industrial hygiene
ISO	International Standardization Organization
K	potassium
K_2CrO_4	potassium chromate

ksi	kilopounds per square inch
lb	pound
lbs	pounds
MCE	mixed cellulose ester
µg	micrograms
$\mu g/m^3$	micrograms per cubic meter of air
mg/m^3	milligrams per cubic meters
Mg	magnesium
Mn	manganese
Mo	molybdenum
Na	sodium
NaF	sodium fluoride
NDE	Nondestructive evaluation
Ni	nickel
NIOSH	National Institute of Occupational Safety and Health
NSWCCD	Naval War Surface Center Carderock Division
O	oxygen
OSHA	Occupational Safety and Health Administration
OSU	Ohio State University
Pb	lead
Pd	palladium
PEL	permissible exposure limit
PI	Principle Investigator
PVC	polyvinyl chloride
Ru	ruthenium
SEM	scanning electron microscope
SERDP	Strategic Environmental Research and Development Program
Si	silicone
SMA	shielded metal arc
SMAW	shielded arc welding
Sr	strontium
TEAD	Army Depot, Ammunition Equipment Division
Ti	titanium
TWA	time weighted average
UHR	ultra-high resolution
UTS	ultimate tensile strength
V	vanadium
wt %	weight percent

XEDS	x-ray energy dispersive spectroscopy
XRD	x-ray diffraction
XRF	x-ray fluorescence
YS	yield strength
Zn	zinc

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Executive Summary

Background

Fusion welding of stainless steels results in the formation of hexavalent chromium (Cr(VI)) in the welding fume. Cr(VI) is mostly generated during the arc melting of stainless steel consumables that typically contain 18 to 20 weight percent (wt %) Cr(VI). Cr(VI) is a carcinogen and is considered a significant health hazard for the welding personnel. In 2006, the Occupational Safety and Health Administration (OSHA) reduced the permissible exposure limit (PEL) for Cr(VI) in welding fume from 52 to 5 $\mu g/m^3$ (micrograms per cubic meter of air) 8-hour time-weighted average (TWA). This regulatory change has imposed stringent requirements for reduction of Cr(VI) exposure during welding of stainless steel that necessitate considerable expense for ventilation systems and/or personnel protection equipment.

New Cr-free shielded metal arc welding (SMAW) and gas metal arc welding (GMAW) consumables have been developed as a replacement for the conventional Types 308 and 316 welding consumables for austenitic stainless steel. These new Cr-free consumables provide almost a 100-fold reduction of Cr(VI) in the welding fume and produce welds with comparable corrosion resistance and mechanical properties relative to the conventional stainless steel consumables. In some conditions relevant to the Department of Defense (DoD) interests, such as cramped ship interiors, it is extremely difficult or/and cost prohibitive to ventilate effectively or to perform welding operations using personnel protection equipment. For such conditions, the newly developed Cr-free welding consumables provide a feasible alternative for meeting the OSHA PEL for Cr(VI) in the welding fume.

Objective of the Demonstration

This project was developed in two stages: Laboratory Demonstration and Field Demonstration. The objective of the Laboratory Demonstration was further optimization of the Cr-free SMAW and GMAW consumables aiming to ensure full compliance with the relevant American Welding Society (AWS), American Society for Testing and Materials (ASTM), International Standardization Organization (ISO), and OSHA codes and regulations.

The objective of the Field Demonstration was to conduct on-site demonstration and validation of the optimized Cr-free welding consumables during typical welding operations in fabrication of stainless steel. The performance objectives included: 1) 90% reduction in exposure to Cr(VI) and in hazardous air emissions, 2) production of welds with mechanical properties that meet relevant AWS specifications and are free of defects, and 3) demonstration of acceptable welding operability. These performance objectives were successfully met during the Field Demonstration and validation.

Demonstration Results

The main objective of this project of a 90% reduction in Cr(VI) and hazardous air emission during welding with the newly developed Cr-free SMAW (ENiCuRu) and GMAW (ERNiCuRu) electrodes has been successfully achieved. The ENiCuRu electrode provided reduction in Cr(VI) exposure of more than 92% compared to the OSHA PEL and more than 94% compared to the conventional E308L-16 electrode. The emission of metallic chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni) (alloying elements), arsenic (As), cadmium (Cd), cobalt (Co), molybdenum (Mo), lead (Pb), vanadium (V), and zinc (Zn) in the fume of ENiCuRu was between two and four orders of magnitude lower than the corresponding OSHA PELs. Emission of strontium (Sr) in the order of 0.002 to 0.02 mg/m^3 was measured in the fume of ENiCuRu, which can be related to the presence of 19 wt % $SrCO_3$ in the coating of this electrode. There is currently no OSHA PEL for Sr and it is regulated as a compounded chromate.

The ERNiCuRu electrode provided reduction in Cr(VI) exposure of more than 92% compared to the OSHA PEL and more than 71% compared to the conventional E308L-16 electrode. The emission of metallic Cr, Fe, Mn (alloying elements), As, Cd, Co, Mo, Pb, Sr, V, and Zn in the fume of ENiCuRu was between one and four orders of magnitude lower than the corresponding OSHA PELs. The content of Cu and Ni in the fume of ERNiCuRu was up to two orders of magnitude higher than in the conventional ER308LSi and in single measurements exceeded the corresponding OSHA PELs. Such behavior is expected since ERNiCuRu is a Ni-base welding consumable with high alloying content of Cu. Possible solution for reduction of the Ni and Cu emission in the welding fume of this electrode is using a low heat input GMA welding process such as cold metal transfer.

The emission of ruthenium (Ru) in the fume of Cr-free SMAW and GMAW electrodes was extremely low (0.0003 to 0.0044 mg/m^3), in most measurements below the limit of quantitation, and similar to the corresponding conventional electrodes. There is currently no OSHA PEL for Ru. A point of concern related to the presence of Ru in the Cr-free electrodes was possible exposure to radiation generated by Ru isotopes. The field screening for alpha, beta, and gamma radiation showed peak counts that were in the order of the background. The exposure to radiation of the welding personnel was two orders of magnitude lower than the derived air concentration (DAC) for ruthenium isotopes (DAC for ^{106}Ru 5×10^{-9} μCi/ml).

Welds of both Cr-free consumables met the performance objectives of 70 kilopounds per square inch (ksi) tensile strength and successfully passed the bend test. During the Laboratory Demonstration, the ENiCuRu electrodes produced high quality welds that were free of defects in all welding positions. Some of the ENiCuRu welds produced during the Field Demonstration lacked fusion defects and did not pass the X-ray test. Similarly, during the Laboratory Demonstration the ERNiCuRu electrode produced welds that were free of defects. Lack of fusion, lack of penetration, and undercut defects were found in welds made with this electrode during the Field Demonstration. Similar defects were found in welds of conventional E308L-16 and ER308LSi made during the Field Demonstration. Particular defect-free welds of both the ENiCuRu and ERNiCuRu consumables met the performance objective of a minimum 30% elongation. Welds with lack of fusion and lack of penetration defects of both the Cr-free consumables and the conventional reference electrodes had elongation less than 30%. The weld quality achieved during the Laboratory and Field Demonstration reflected welders' experience with Ni-based welding consumables. Both Cr-free welding consumables demonstrated good welding operability and arc stability that are comparable to conventional Ni-based welding consumables.

Implementation Issues

Possible issues related to the implementation of the Cr-free ENiCuRu and ERNiCuRu welding consumables may be the absence of OSHA PELs for Ru in welding fume. This issue can be addressed by conducting related studies at particular National Institute of Occupational Safety and Health (NIOSH) or DoD laboratories. Another possible implementation issue could be the need for additional training of welders who have no experience in working with Ni-based welding consumables.

1. Introduction

1.1 Background

Stainless steels are usually selected as a material of construction for their corrosion resistance. When they are fabricated into structures, stainless steel components are often joined by welding. To ensure that the welds exhibit sufficient corrosion resistance, filler metals matching or exceeding the chromium (Cr) content of the base metal must be used. The Cr content of Types 304 and 308 stainless steels, the most commonly used stainless steel base metal and the filler metal used to weld it, respectively, is 18 to 20 weight percent (wt %). Fusion welding of these steels results in the formation of carcinogenic hexavalent chromium Cr(VI) in the fumes. This is a significant health hazard for the welders and necessitates considerable expense for ventilation systems, and potential longer term expense dealing with litigation. In some conditions relevant to the Department of Defense (DoD) interests, such as cramped ship interiors, it is extremely difficult to ventilate effectively. DoD facilities are required to estimate the residual risk to public health and, in certain states, must report the findings to the public when cancer risk exceeds a threshold of one in one million. When the threshold is exceeded, the facility is also expected to initiate measures to reduce the fugitive emissions.

New Cr-free shielded metal arc welding (SMAW) and gas metal arc welding (GMAW) consumables have been developed as a replacement for the conventional Types 308, 309, and 316 welding consumables for austenitic stainless steel base metal. These new consumables have comparable corrosion resistance and mechanical properties relative to the consumables they are designed to replace. The measured Cr(VI) in the fume of the Cr-free SMAW electrode when welding Type 304 stainless steel is virtually zero (0.02 wt %) and represents a 100-fold reduction in Cr(VI) relative to a conventional Type 308 consumable.

Using the newly developed Cr-free welding consumables, DoD can reduce the fugitive emissions of carcinogenic Cr(VI) generated during welding operations. The Cr-free consumables can be used to replace the conventional stainless steel welding consumables in specific welding operations where meeting the Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) for Cr(VI) in the welding fume using ventilation and/or personal protection equipment is impossible or/and cost prohibitive.

1.2 Objective of the Demonstration

This project included Laboratory Demonstration and Field Demonstration stages. Under the Laboratory Demonstration stage of this project, further optimization of the Cr-free SMAW and GMAW consumables were conducted to improve their operability characteristics during welding. The objective of the Laboratory Demonstration was to establish performance objectives and acceptance criteria, and apply these during laboratory testing of the optimized Cr-free ENiCuRu and ERNiCuRu consumables to ensure full compliance of the latter with the relevant American Welding Society (AWS), American Society for Testing and Materials (ASTM), International Standardization Organization (ISO), and OSHA codes and regulations.

The objective of the Field Demonstration was to conduct on-site demonstration and validation of the optimized heats of the Cr-free SMAW (ENiCuRu) and GMAW (ERNiCuRu) consumables during typical welding operations in the fabrication of stainless steel. This demonstration was performed at the Army Depot, Ammunition Equipment Division (TEAD), Tooele, UT.

The performance objectives for the Field Demonstration of the Cr-free SMAW and GMAW consumables included:

- Meeting the OSHA PEL of 5 μg/m^3 time weighted average (TWA) for Cr (VI);
- Providing comparable welding operability and welder's satisfaction to the conventional E308L and ER308L welding consumables;
- Weld mechanical properties exceeding the minimum requirements for Type 304L stainless steel and comparable to welds of conventional E308L and ER308L consumables.

All of these performance objectives were successfully met during the Field Demonstration and validation. The targeted hazardous materials, the current processes, applications, and specifications, and the affected programs and potential applications of the new Cr-free welding consumables are listed in Table 1.1.

Table 1.1 Target Hazardous Material (HazMat) Summary

Target HazMat	Current Process	Applications	Current Specifications	Affected Programs	Candidate Parts and Substrates
E308L, E309, E316 ER308, ER309, ER316	SMAW GMAW GTAW	Welding of type 304, 309 and 316 stainless steels	AWS A5.4 AWS A5.9	Repair welding of stainless steel in confined spaces	Navy ships and DoD facilities where effective welding fume ventilation is impossible or impractical

1.3 Regulatory Drives

The main regulatory driver for the development of this project is the recent reduction in the PEL for Cr(VI) in welding fumes from 52 to 5 μg/m^3 (micrograms per cubic meter of air) 8-hour TWA introduced by OSHA [1, 2].

2. Demonstration Technology

2.1 Technology Description

The welding consumables tested under this Laboratory Demonstration plan were developed in a Strategic Environmental Research and Development Program (SERDP) Project PP-1415 “Development of Cr-Free Welding Consumables for Stainless Steels” [3].

The consumable with nominal composition Ni-7.5Cu-1Ru was developed as SMAW and GMAW electrodes to serve as a replacement for conventional stainless steel consumables such as Types 308, 309 and 316 for welding austenitic stainless steel base metal. The new consumable has shown to have comparable corrosion resistance and mechanical properties relative to the consumables it is designed to replace. The measured Cr(VI) in the fume of this electrode when welding Type 304 stainless steel is virtually zero (0.02 wt %) and represents a 100-fold reduction in Cr(VI) relative to a conventional Type 308 consumable. Use of this electrode will allow the new OSHA PEL for Cr(VI) to be routinely met in the welding of austenitic stainless steels.

Figure 2.1 shows the welding process with a Cr-free ENiCuRu electrode. Cross sections of SMA and GMA welds produced with the ENiCuRu and ERNiCuRu electrodes are shown in Figure 2.2. Both consumables produce welds that are free of porosity, cracks and other welding defects.

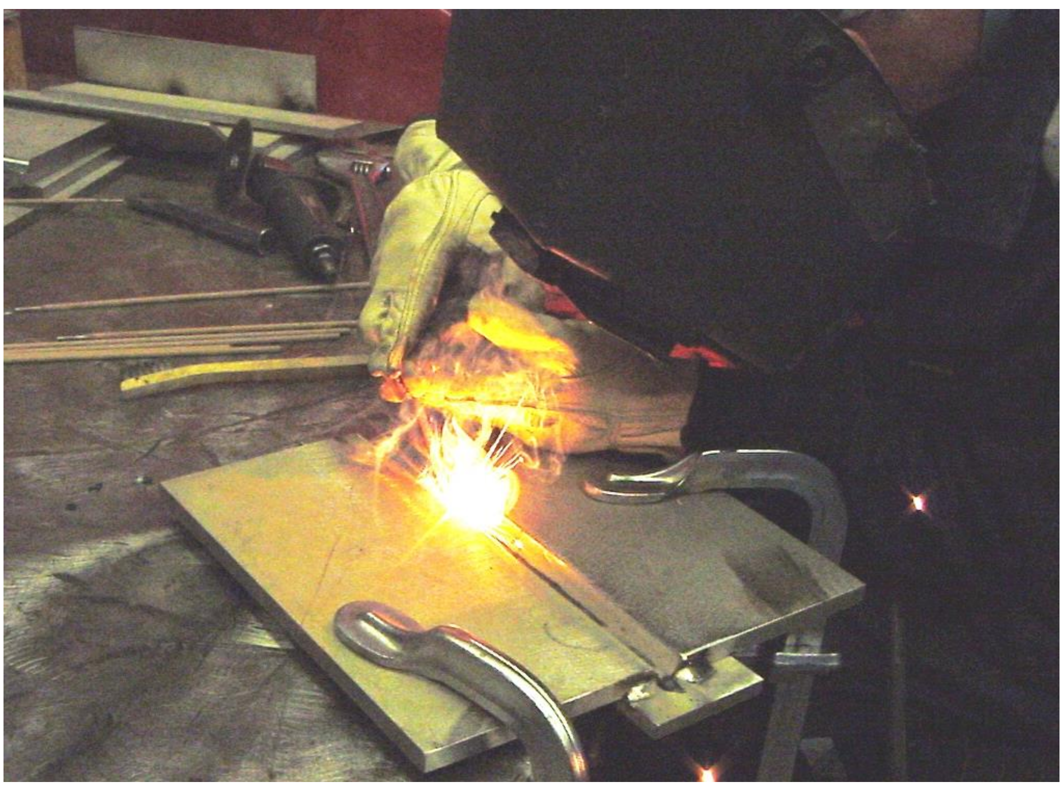
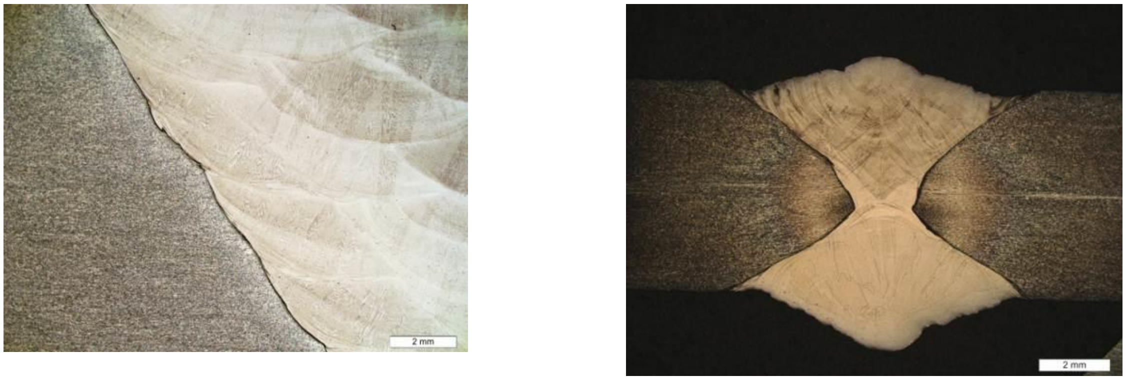


Figure 2.1 Shielded Arc Metal Welding with Cr-free ENiCuRu Electrode



a) b)

Figure 2.2 Cross Sections of: a) 0.75-inch Thick SMA Weld Test Assembly Produced with the ENiCuRu Electrode; b) 0.25-inch Thick GMA Weld Test Assembly Produced with the ERNiCuRu Electrode

Figure 2.3 shows an example of the magnitude of Cr(VI) reduction in the Cr-free consumable as compared to E308-16 electrodes. The example assumes that no ventilation is used and that the fume is dispersed uniformly throughout the enclosed space. Using the Cr(VI) PEL value of 5 μg/m^3, a welder exposed to a fume of E308-16 would be within the PEL as long they were in a room of approximately 12.5 × 12.5 × 3 meters. By switching to the Cr-free consumable and making a similar weld, the allowable size of the room is decreased to 2.3 × 2.3 × 3 meters. The reduction in room size allows welding related personnel to be within exposure limits during fabrication and production situations within enclosed spaces by using a Cr-free consumable.

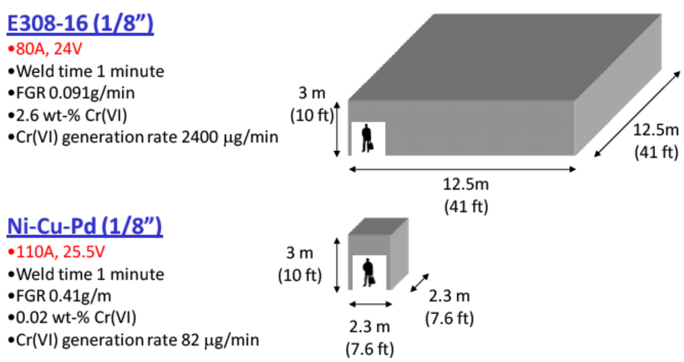


Figure 2.3 Comparison of Cr(VI) Generation Characteristics of E308-16 and Generation II of the Cr-free Welding Consumable for One Minute Welding in an Enclosed Space

The main application of the Cr-free welding consumable is for welding stainless steel in confined spaces where providing efficient ventilation is impossible and/or is not feasible and the OSHA PEL of 5 μg/m^3 8-hour-TWA cannot be met by the standard stainless steel welding consumables.

2.2 Technology Development

The main objectives in the development of Cr-free consumables were to achieve elimination of the carcinogenic Cr(VI) in the welding fume during stainless steel welding and to provide a compatible replacement of the standard stainless steel welding consumables in terms of weld corrosion resistance and mechanical properties, and consumable welding operability and weldability. In order to achieve these objectives the following design criteria were imposed:

- The breakdown and repassivation potentials of the weld metal should be higher than the corrosion potential of the stainless steel substrate to prevent localized attack of the weld metal.

- If possible, the corrosion potential of the weld metal should be slightly higher than that of the stainless steel substrate so that the weld metal is cathodically protected.

- The strength and ductility of the welds must meet or exceed minimum requirements for the base metals they join.

- Weldability, including susceptibility to various forms of cracking during welding, should be within the range of comparable consumables.

- The operating characteristics of the consumable should be such that it can be readily used in applications requiring manual, semi-automatic, and fully automated welding processes.

Four generations of Cr-free consumables were developed to meet the design requirements listed above. These can be summarized as follows:

Generation I – A nominal Ni-8.0Cu-0.2Pd bare wire consumable that was designed based on the results of corrosion tests on small button melts.

Generation II – Nominal Ni-7.5Cu and Ni-7.5Cu-1Pd coated electrodes that were produced by Special Metals Welding Products Company. The Cu and Pd were added to the coating rather than the core wire. It was found that the transfer of substantial Pd across the arc was difficult with these electrodes.

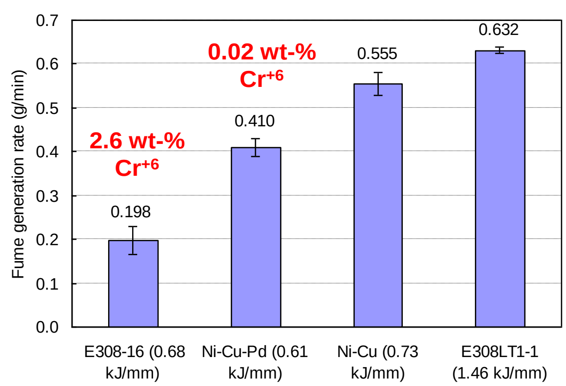
Generation III – Nominal Ni-7.5Cu-1Ru-0.5Ti bare wire that was melted by Haynes International. Ru replaced Pd as a lower cost alternative. Attempts to use this composition as a core wire for coated electrodes were unsuccessful due to porosity and operability problems. This wire worked very well for GTAW and GMAW applications.

Generation IV – A nominal Ni-7.5Cu-4Ti-1Ru composition that was developed as a core wire for the coated electrodes (SMAW). The higher Ti relative to Generation III effectively eliminated the porosity and operability problems.

Thus, the final target weld metal composition that meets the design requirements for strength and corrosion resistance is nominally Ni-7.5Cu-1Ru-0.5Ti. As noted above this composition is achieved in the coated electrode by over-alloying the core wire with Ti; the core wire has 4% Ti, whereas the deposited metal has only 0.5% Ti as most of the Ti is lost in the arc.

The four generations of the Cr-free welding consumable were subjected to extensive corrosion, mechanical, and weldability testing, and fume characterization in the frame work of SERDP Project P-1415 [3]. The test results have confirmed that the main design criteria of this consumable have been successfully met.

Figure 2.4 provides a comparison of the fume characteristics in Ni-Cu, Ni-Cu-Pd, and E308-16 SMAW electrodes and in a flux cored E308LT1-1 electrode. The Cr-free electrodes had higher fume generation rate (FGR) than E308-16, but the content of Cr(VI) in the Ni-Cu-Pd fume was more than two orders of magnitude lower than in E308-16. Based on these measurements, the Cr(VI) generation rate of the E308-16 was calculated approximately 60 times higher than that of the Ni-Cu-Pd consumable for similar welding conditions.



Average Welding Fume Composition**

Element	Ni-Cu (Wt-%)	E308-16 (Wt-%)
F	17.5	-
Na	38.8	0.8
Mg	0.2	0.0
Si	3.0	8.7
Cl	0.3	1.0
K	2.3	45.8
Ca	5.0	3.1
Ti	5.1	5.1
Cr	0.5	9.7
Mn	0.6	7.0
Fe	1.1	9.0
Ni	15.6	-
Cu	9.9	-

**Note that Oxygen was also present in fume from both electrodes.

Figure 2.4 Comparison of the Fume Generation Rates, Fume Cr(VI) Content, and Bulk Fume Composition of Cr-free and Standard Stainless Steel SMAW Electrodes

The mechanical properties of the Cr-free consumable exceeded the minimum strength, elongation, and reduction in area of Type 304L stainless steel and E308L weld metal (Table 2.1 and Figure 2.5).

Table 2.1 Mechanical Properties of Ni-Cu, Ni-Cu-Pd and Ni-Cu-Ru Weld Metals

Weld Metal	Base Metal	Failure Location	Tensile Strength, MPa	Elongation, %	Reduction in Area, %
Ni-Cu	304L	Weld metal	597	33.2	43.0
Ni-Cu-Pd	304L	Weld metal	531	31.7	52.9
Ni-Cu-Ru	304L	Weld Metal	540	52.0	54.0
304L Minimum Values			480	40	50
E308L-16 Typical Values			517	35	-

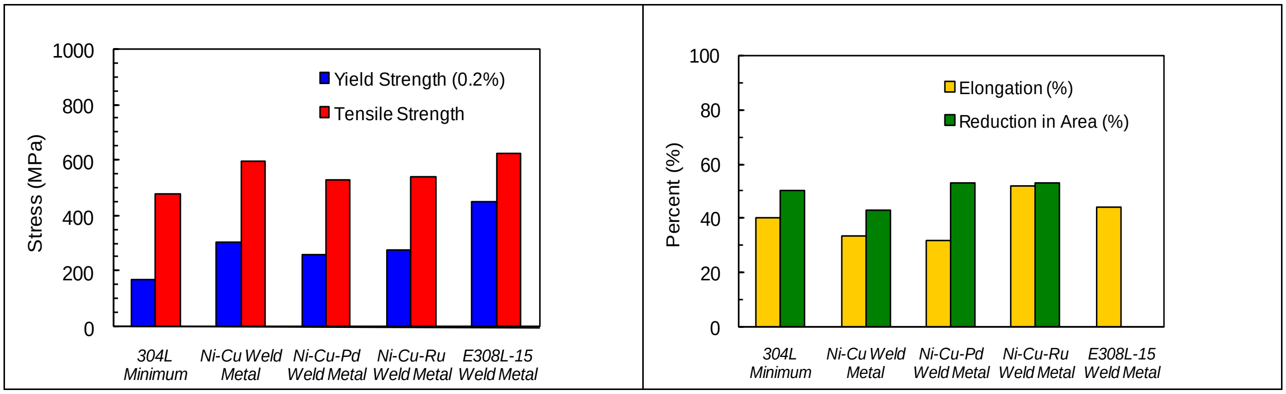


Figure 2.5 Mechanical Properties of the Ni-Cu, Ni-Cu-Pd, and Ni-Cu-Ru Welds

2.3 Advantages and Limitations of the Technology

The new Cr-free welding consumable produces welds with mechanical properties that fulfill the requirements for Type 304 stainless steel and are comparable to the mechanical properties of the standard type E308 electrodes for welding of stainless steel. This new consumable has welding operability, weldability, and FGRs that are similar to the standard stainless steel electrodes.

The main advantage of the new Cr-free welding consumable over the conventional E308 welding electrodes is that it nearly completely eliminates the carcinogenic Cr(VI) in the welding fume generated during welding of austenitic stainless steel. Use of this electrode allows the new OSHA PEL for Cr(VI) to be routinely met in shop and field welding applications. There are no other available stainless steel consumables for welding the 300-series stainless steels that will meet the OSHA PEL.

The disadvantage of the new Cr-free welding consumable is its high price. The cost analysis of the older version of this consumable that was alloyed with 1 wt % palladium had predicted an increase in the welding cost at Navy shipyard applications between 75 and 200% [4]. This cost analysis was based on the price of palladium at $4,500/lb. In the last formulation of this consumable for this project, the palladium was substituted with ruthenium. Due to the lower price of ruthenium, this substitution will significantly reduce the costs of welding operations with the new consumable. Detailed cost analysis for the application of the new Cr-free consumable at DoD facilities is presented in Section 7.0 of this report.

Important advantages and cost savings of the new technology that cannot be quantified and have not been accounted for in the cost analysis are:

- Potential litigation cost for Cr(VI) related illness in workers related to welding of stainless steel;
- Efficiency of welding fume/Cr(VI) ventilation;
- Control and disposal of welding fume containing Cr(VI) that is not extracted by ventilation and accumulates in welding facilities;
- Control and disposal of ventilation filters containing welding fume with Cr(VI).

3. Performance Objectives

Separate performance objectives were developed for the Laboratory and Field Demonstration stages of this project. These are addressed separately in Sections 3.1 and 3.2 below.

3.1 Performance Objectives of the Laboratory Demonstration

The main objective of the Laboratory Demonstration was to optimize the welding operability of the Cr-free ENiCuRu electrode and to produce high quality ENiCuRu and ERNiCuRu consumables to be used in the Field Demonstration stage of this project. The performance objectives and acceptance criteria established for the Laboratory Demonstration aimed to ensure that the optimized ENiCuRu and ERNiCuRu consumables are in full compliance with the relevant AWS, ASTM, ISO, and OSHA codes and regulations. These performance objectives are listed below and are summarized in Table 3.2:

1. To ensure extremely low emission of Cr(VI) in the welding fume and to allow the OSHA PEL of 5 $\mu g/m^3$ 8-hour-TWA for Cr(VI) to be routinely met in DoD shop and field stainless steel welding applications.
2. The weld metal mechanical properties of the new Cr-free consumables to exceed the minimum requirements for Type 304 stainless steel base metal and be comparable to the mechanical properties of the conventional consumables for welding of stainless steel (E308L-15 and E308L-16).
3. To provide acceptable weldability (sound welds that are free of cracks, porosity, and other discontinuities) that is comparable to typical Ni-based welding consumables and to conventional consumables for welding of stainless steel.
4. To provide good welding operability that is comparable to the conventional consumables for welding of stainless steel.

The weld deposit composition targeted during the consumable optimization stage is shown in Table 3.1.

Table 3.1 Target Compositions of ERNiCuRu Wire and of ENiCuRu Weld Deposit (wt %)

C	Mn	P	S	Si	Cu	Ni	Ru	Al	Ti	Other elements total
0.1	0.5	0.02	0.02	0.5	5-10	Rem	1.5	1.0	1.0	0.5

Table 3.2 Performance Objectives and Acceptance Criteria of the Laboratory Demonstration

Performance Objective	Standard, Code, or Specification	Acceptance Criterion	Result
1. Emission of Cr(VI) in Welding Fume			
Welding fume generation rate	ANSI/AWS F1.2:2006 [4]	Not more than 50% higher than E308L and E308LT1-1	Objective met
Content of Cr(VI) in the welding fume		Not exceeding 0.25 wt %	Objective met
Extremely low Cr(VI) emission	OSHA 1910.1026 [1]	5 $\mu g/m^3$ 8-hour TWA	NA
2. Weld Metal Mechanical Properties			
Ultimate tensile strength	ANSI/AWS A5.4-92 [5]	Min 70 ksi	Objective met
Elongation	ASTM A 666-03 [6]	Min 30%	Overall objective met, some failures (see Sections 6.2.1 and 6.2.2)
Bend test	ANSI/AWS A5.11-97 [7]	Max three fissures; max. length 3/32"	Objective met
3. Weldability Characteristics			
Weld radiography soundness	ANSI/AWS B2.1-2000 [8] ANSI/AWS A5.11-97 [7]	No cracks, incomplete fusion, and incomplete penetration, slag inclusions and rounded indication in excess of permitted	Overall objective met, some failures (see Section 6.3.2)
4. Welding Operability			
Arc stability, slag detachment, welders satisfaction	Qualitative comparison to E308L-15 and E308L-16	Comparable to E308L-15 and E308L-16	Objective met

3.2 Performance Objectives of the Field Demonstration

The performance objectives of this Field Demonstration have been selected to provide reliable validation of the Cr-free SMAW and GMAW consumables during stainless steel welding that most closely replicate the welding operations in fabrication of stainless steel at DoD facilities. Parallel testing of the new technology (Cr-free consumables) versus the conventional technology (stainless steel consumables) was performed during the Field Demonstration to ensure that all performance objectives were met. The performance objectives are summarized in Table 3.3.

The first performance objective addresses the weldability evaluation, and the mechanical properties of stainless steel welds produced with the Cr-free consumables. This objective ensures that the innovative consumables have at least equivalent performance to the existing welding technology. Nondestructive evaluation (radiography) reveals presence of cracks and other defects in the test welds. The destructive testing characterizes the mechanical strength, weld geometry, welding defects, and microstructure of the test welds. The laboratory and field test results show that this performance objective has been met and the demonstrated Cr-free consumables have equivalent performance to the existing technology.

The second and third performance objectives address the criteria verifying that hazardous air emissions and occupational exposures will be reduced with the application of the innovative Cr-free welding consumables. The success criteria is a Cr(VI) reduction of greater than 90% for the Cr-free consumables versus the conventional technology. Test methods used for the area sampling are typical industrial hygiene engineering sampling methodologies. The field test results show that this performance objective has been met and the demonstrated Cr-free consumables provide greater than 90% Cr(VI) reduction compared to the existing technology.

There is currently no published occupational exposure limit for ruthenium and the field test results could not be compared to established guidelines or standards. It was expected that the Navy Toxicology Department would recommend limits based on similar materials and these findings.

The fourth performance objective addresses the ease of use of the Cr-free welding consumables and ensures that these consumables have similar welding operability as the conventional stainless steel electrodes. The welders report on this objective shows that the Cr-free consumables require that the welders be trained and have acceptable welding operability.

Table 3.3 Performance Objectives.

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Weldability, Welding Operability, and Mechanical Properties	**Nondestructive Testing -** *e.g., Radiography, ultrasonic, magnetic particles, liquid penetrate, eddy current* **Chemical –** *composition and corrosion* **Metallography –** *Light optical microscopy etc.* **Mechanical** – *e.g., hardness, tensile strength, yield strength, and ductility,* **Joints –** *bend, tensile strength, fillet weld, fracture toughness*	Equivalent to existing welding performance tests for the specific activity Comply with: • AWS D1.6/D1.6M:2007 Structural Welding Code [9] • AWS 5.11[7]: Mechanical - ultimate tensile strength 70 ksi, 30% elongation, Weldability - Acceptable defect level	Overall objective met, some failures (see Section 6.3.2) Objective met Overall objective met, some failures (see Sections 6.2.1, 6.2.2, and 6.3.2)
Reduction of Hazardous Air Emissions	Hazardous Air Pollutant (HAPs) emissions evaluations including heavy metals: Cr(VI), total Cr, Ni, Cu, Mn, Ru, Ti, etc.	90% reduction of HAP metals from current process vs. for Cr-free consumable process, Ru exposures below TBD level recommended by Navy Toxicology Department	Overall objective met, some failures (see section 6.1.2.4 and Table 6.12) Objective met
Reduction in Occupational Exposure	*Navy Marine Corps Public Health Center Field Operations Manual for Sampling Procedures* **NIOSH 7303** Metal Elements by Inductively Coupled Plasma (Nitric/Perchloric Acid Ashing) - total Cr, Mn, Ni, Cu, Ru, Ti, Pl, etc. **OSHA 215** - Hexavalent Chromium	**Cr free Consumables** >90% reduction in Cr(VI) OSHA exposures. Other metals below the OSHA PEL action level (where available). Provide emissions data for Ru since there is no PEL.	Overall objective met, some failures (see Sections 6.1.2.4 and Table 6.12) 0.0002 to 0.0044 mg/m^3
3.2.1 Qualitative Performance Objectives			
Ease of use (welder's appeal)	Feedback from field technician on stability of technology. Tracking time to weld (inches per minute)	Welder Acceptance. Reduction or equivalent time to weld.	Overall objective met, for welder's comment see Table 6.28

4. Site/Platform Description

4.1 Test Platforms/Facilities

The Army Depot, Ammunition Equipment Division in Tooele, UT was selected as the test site for the Field Demonstration. The Field Demonstration was conducted in August 2011.

The Tooele Army Depot (TEAD), a government-owned/government-operated facility, offers both engineering and ammunition expertise through a wide variety of applications, including design and manufacturing of ammunition peculiar equipment (APE) used in the maintenance and demilitarization for DoD. Tooele's products and services are available to other government agencies, contractors, and foreign allies. TEAD is ISO 9001:2000 certified. The 23,732-acre site is located in northeastern Tooele County, UT, about 35 miles southwest of Salt Lake City.

TEAD is the Center of Industrial and Technical Excellence for the depot-level activities in support of APE. Since 1955, TEAD has been designing, prototyping, fielding and providing maintenance/training of the ammunition equipment installed in Continental United States and Outside the United States installations. TEAD played a role in the engineering and manufacturing support of chemical demilitarization equipment. The special metal and welding requirements were a challenge that Army Depot, Ammunition Equipment Division was able to meet as its welders are used to fabricating conventional furnaces/chemical equipment from stainless steel material/special welding requirements and also in fabricating explosive barricades and ammunition storage containers.

4.2 Present Operations

TEAD utilizes welding operations for joining Type 304 stainless steel in the fabrication of APE. The welding operations in Type 304 steel are performed using SMAW, GMAW, and GTAW processes with conventional welding consumables E308L (SMAW) and ER308L (GMAW and GTAW). TEAD designs and builds unique equipment specific to a particular ammunition maintenance, surveillance or demolition need. Some years, TEAD may use up to 500 lb of consumables for 304 base metals; other years the usage may be minimal. Some examples of parts fabricated of Type 304, 310 and 316 stainless steel using welding operations with conventional consumables are summarized in Table 4.1.

The two Cr-free welding consumables that are demonstrated in this project are intended to replace the conventional stainless steel welding electrodes that generate significant amounts of Cr(VI) in welding fume. Type 304 steel plates with thicknesses of 0.25 inch and 0.5 inch were welded with the Cr-free SMAW and GMAW consumables to demonstrate and validate their application as a replacement of the conventional stainless consumables in typical operational conditions at TEAD.

Table 4.1 Summary of Type 304 Stainless Steel Welding at TEAD

Product	Base Material	Thickness	Welding process	Welding consumable	Shielding gas	Welding position
Replacement Baghouse Tube Sheet	304	3/8 in., 5/16 in., 1/4 in., 10 GA	GMAW, SMAW	ER308L	90/5/5, 98/2	Multiple
Heating Chamber Cover	304	11 GA	GTAW	"	"	Multiple
Autoclaves	304	Up to 1 in.	GMAW, GTAW	"	"	Multiple
Ventilation Piping	304	SCH 10	GMAW, GTAW	"	"	Multiple
Wet Scrubber Piping	304	Up to 1/4 in.	GMAW, GTAW	"	"	Multiple
Furnace Ducting	310	3/16 in.	GMAW	"	"	Multiple
Furnace Ducting	316L	10 GA	GMAW	"	"	Multiple

4.3 Site-related Permits and Regulations

No site permits are required to conduct these tests. The operations were direct duplicates of the current work practices except for consumable materials and shield gas. All personnel were required to abide by the installation contractor clauses and were provided with those clauses.

5. Test Design

This project was executed in two stages: 1) Laboratory Demonstration, and 2) Field Demonstration. A separate demonstration plan was developed for each of these stages that contained specifically designed tests. These are discussed separately in Sections 5.1 and 5.2 below.

5.1 Laboratory Testing

The test plan of the Laboratory Demonstration was designed to ensure that the optimized consumables met the performance objectives and the corresponding acceptance criteria specified in Table 3.2. The tests used in the Laboratory Demonstration are described below.

5.1.1 Mechanical Testing

The mechanical testing included tensile and bend tests of welds in Type 304L stainless steel produced with the Cr-free ENiCuRu and ERNiCuRu consumables. The test weld assemblies corresponded to ANSI/AWS B4.0-98, ANSI/AWS A5.11-97, and ANSI/AWS A5.4-92 [5, 7, 10].

A 0.75 in. thick test weld assembly with a 75 degree angle and 0.25 in. root opening was produced by Energy Solution Group using multipass welding with the ENiCuRu electrode. The welding procedure of this weld test assembly is presented in Appendix B.

Three 0.25 in. thick test weld assemblies with double-V groove, 60 degree angles and 0.05 in. root openings were produced by the Ohio State University using a pulsed GMAW process with the ERNiCuRu electrode. The welding procedure of this weld test assembly is presented in Appendix C. The welding setup and a completed weld test assembly of the ERNiCuRu electrode are shown in Figure 5.1 and Figure 5.2.

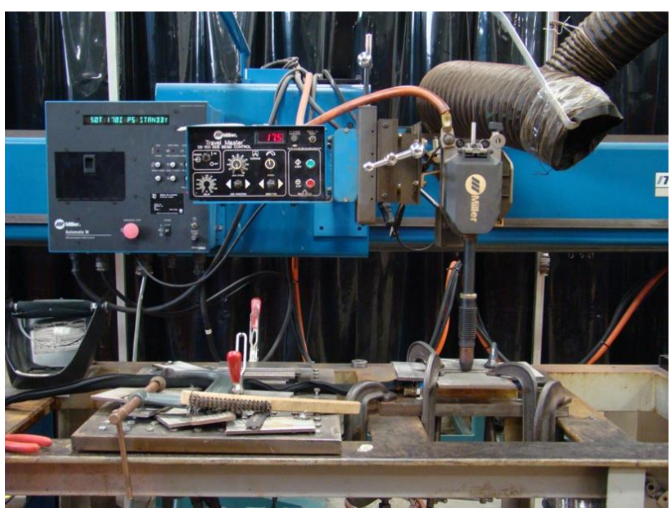


Figure 5.1 GMAW Equipment and Welding Setup for Production of ERNiCuRu Weld Test Assemblies at the Ohio State University

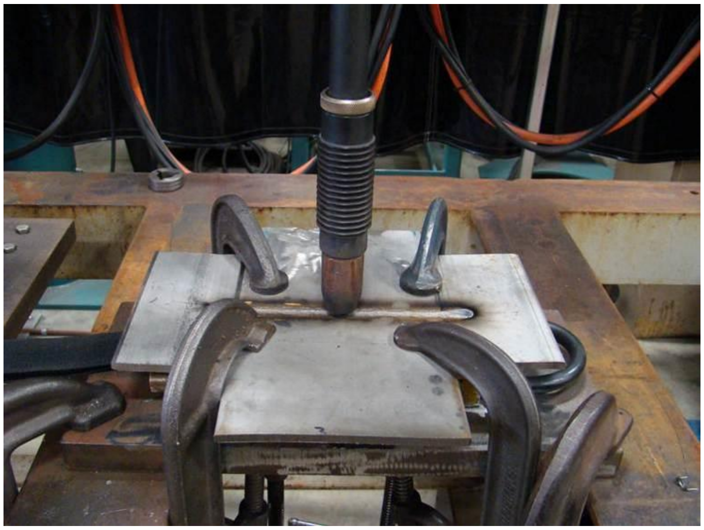


Figure 5.2 Completed Weld Test Assembly of ERNiCuRu

One ENiCuRu all-weld metal tensile test sample was machined out of a 0.75 in. thick test weld assembly that had 0.5 in. diameter and 2 in. gauge length. Three ERNiCuRu cross weld tensile test samples (Figure 5.3) were machined out of 0.25 in. thick weld test assembly. The geometry of the tensile test samples corresponded to ANSI/AWS B4.0-98, ANSI/AWS A5.11-97, and ANSI/AWS A5.4-92. The tensile testing was performed in accordance with ASTM E8 [11].

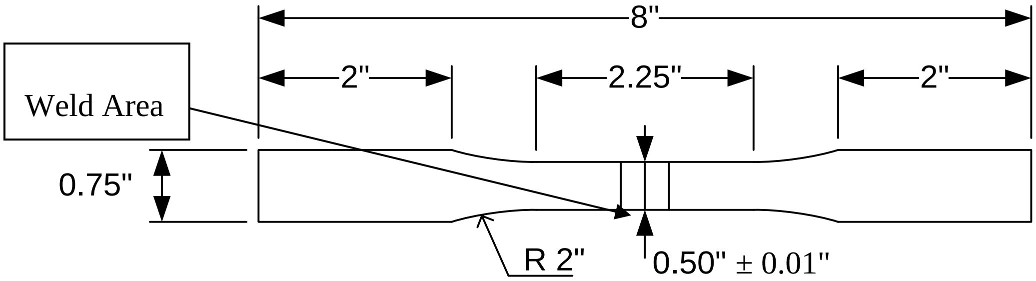


Figure 5.3 Cross Weld Tensile Test Sample of ERNiCuRu Weld

Three side bent samples with 0.375 in. thickness and 0.75 in. width were machined out of the ENiCuRu weld test assembly and three face bend samples (Figure 5.4) were machined out of the ERNiCuRu test weld assembly. The test-weld assemblies and sample geometries corresponded to ANSI/AWS B4.0-98. The bend testing was performed in accordance with ANSI/AWS B4.0-98 and ASTM E190 [12].

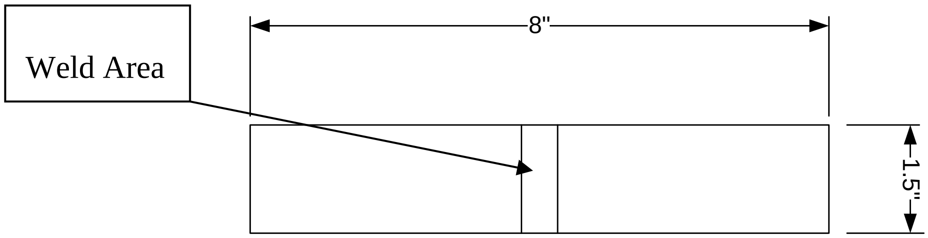


Figure 5.4 Face Bend Sample of ERNiCuRu Weld

5.1.2 Radiography

The 0.75 in. ENiCuRu weld test assembly and the 0.25 in. thick ERNiCuRu test assembly were subjected to radiographic testing. The testing was performed in accordance with the radiographic procedures specified in ANSI/AWS B4.0-98 and ASTM E142 [13]. The radiography of the ENiCuRu and ERNiCuRu weld test assemblies was performed by InspecTechCorp and by Edison Welding Institute, respectively.

5.1.3 Welding Operability

The welding operability of the ENiCuRu electrode was qualitatively evaluated and compared to conventional Ni-based welding consumables by two highly experienced welders at Energy Solution Group. The 15 criteria and the rating schedule used in this evaluation are provided in Appendix D. The welding operability was assessed for the 0.75 in. thick test weld assembly and for a series of fillet welds in 0.25 in. thick type 304L stainless steel in flat, vertical down, and overhead positions. The welding parameters for the 0.75 in. weld test assembly are provided in Appendix B. The welding parameters for the 0.25 in. fillet welds in vertical down and overhead positions are shown in Table 5.1.

Table 5.1 Welding Operability Evaluation of ENiCuRu in Fillet Welds

Parameter	Fillet Welds		
Welding Position	Flat	Vertical	Overhead
Electrode diameter, in.	0.125	0.125	0.125
Welding current, A	108	97	102
Voltage, V	23.5-24.6	23-25	23-25
Travel speed, in/min	8-10	3-4	4-6

Additional evaluation of the arc stability was performed using simultaneous recording of the arc current and voltage of the ENiCuRu electrode during fully mechanized SMAW. Figure 2.1shows the testing setup developed by Energy Solution Group. The electrode is moved along the weld bead with a pre-determined constant travel speed. The electrode feeding rate is controlled by an audio/visual device to maintain a constant arc length. The arc voltage and current are measured and recorded using a fast sampling rate data acquisition system.

Semiquantitative evaluation of the arc stability of the ENiCuRu electrode was performed by comparison to a conventional Ni-based SMA electrode using three-dimensional plots of current voltage, time and current voltage % occurrence.

Figure 5.5 Experimental Setup for Testing the Arc Stability in Shielded Metal Arc Electrodes

5.1.4 Macro- and Microstructure Examination

Weld test assemblies used for mechanical testing and welding operability evaluation were cross sectioned to extract samples for metallurgical evaluation. The sample preparation, including sectioning, mounting, and polishing, was conducted using standard metallography practices. All samples were electrolytically etched in 10% oxalic acid at 6V 1A current for 2 minutes. The characterization was performed using optical microscopy at magnification of 5x to 1000x.

5.1.5 Composition Analyses

Chemical analyses of all weld metal deposits from the ENiCuRu consumable and of the ERNiCuRu filler wire were performed at Sherry Laboratories using standardized analysis techniques as follows:

- Direct Coupled Plasma (DCP): ASTM E1097-07/CTP 3005/DCP [14];
- X-ray Fluorescence (XRF): ASTM E1621-09/CTP 3093/XRF [15];
- Detector for Oxygen and Nitrogen: ASTM E1019-08/CTP 3097/IG [16];
- Detector for Carbon and Sulfur: ASTM E1019-08/CO [16].

5.1.6 Fume Analyses

A total of three welding consumables were tested:

- The optimized Cr-free SMAW ENiCuRu electrode of 1/8 inch diameter;
- The Cr-free GMAW ERNiCuRu filler wire of 0.045 inch diameter;
- A conventional GMAW ER308LSi filler wire of 0.045 inch diameter, to be used as a baseline for comparison to the Cr-free ERNiCuRu filler wire.

Previous results from a conventional SMAW E308L-16 electrode were used as a baseline for comparison to the Cr-free ENiCuRu electrode. Welds of the three tested consumables were deposited on a 3/8-inch thickness plate of type 304L stainless steel. The welding parameters are shown in Table 5.2. SMAW was carried out using a Miller Aerowave CC AC/DC hybrid arc welding power source. A Miller PS Invision 456P DC Inverter Arc Welder equipped with a Miller 60M Series 24V wire feeder was used with the GMAW consumables.

Table 5.2 Welding Parameters Used in the Fume Testing Experiments

Parameter	SMAW		GMAW	
	ENiCuRu	E308-16	ERNiCuRu	ER308LSi
Welding current / Peak current, A	110	115	352	352
Background current, A	-	-	66	66
Frequency, Hz	-	-	115	115
Pulse width, ms	-	-	3.2	3.2
Voltage, V	26	28	27.5	27.5
Wire feed rate, in/min	-	-	174	174
Travel speed, in/min	10	10.75	17.5	17.5
Calculated heat Input, kJ/in	17.2	17.3	33.2	33.2
Electrode diameter, in	1/8	1/8	0.045	0.045
Contact tip to work distance, in	-	-	0.3125	0.3125
Gas flow rate ($Ar/38He/2CO_2$), ft^3/hr	-	-	40	40
Inductance	-	-	50	50
Trim	-	-	50	52

The welding fume for determination of FGR and the Cr(VI) content in the fume, and for x-ray diffraction (XRD) analyses was collected using a modified AWS F1.2:2006 type fume hood. The fume hood and the experimental setup are show in Figure 5.6 and Figure 5.7. The fume generated by the tested electrodes was drawn in with a 40 cubic feet per minute (cfm) flow rate and collected onto 0.3 µm Staplex glass fiber filters until the flow rate dropped to approximately 10 to 15 cfm. Fume filters were weighed before and after testing and then averaged to determine fume generation rate. The formula for FGR is shown below:

$$FGR = (W_f - W_i)/t,$$

where $\boldsymbol{W_f}$ is the final weight of the filter, $\boldsymbol{W_i}$ is the initial weight of the filter, and $\boldsymbol{t}$ is the collection time.

The Cr(VI) content in the fume of the ENiCuRu electrode was analyzed at NSL Analytical using a colorimetric method with diphenyl carbazide in accordance with ISO 3613:2000. Not enough fume was collected during the FGR testing of the ERNiCuRu filler wire to analyze the Cr(VI) content in the fume of this electrode.

The Ru content in the welding fume was also analyzed. The analyses were conducted with inductively coupled plasma (ICP) spectrometry using a Perkin-Elmer Elan instrument at the

Trace Element Research Laboratory of the Ohio State University. For the XRD analyses, the welding fume of the ENiCuRu and ERNiCuRu consumables was transferred from the 0.3 µm glass fiber filter on a “zero-background” piece of silicon dioxide (SiO_2). The fume was then analyzed using a Scintag XDS-2000 diffractometer equipped with a copper x-ray tube.

Figure 5.6 Chamber for Fume Collection with Plate Movement Device and Automatic Feeding of SMA Electrode

Figure 5.7 Entire Fume Collection System with Power Supply, Controller, and Air Pump (left) and Electric Low Pressure Impactor Unit (right)

The mass distribution of fume particles in the welding fume of ENiCuRu and ERNiCuRu consumables was studied using a Decati 10 lpm Electrical Low Pressure Impactor (ELPI; Figure 5.7). Welding fume from the weld area was drawn through a glass funnel connected to a 32 inch length of Tygon® tubing at a pressure of 100 mbar. The fume was collected for a total of 30 seconds on aluminum substrates. The filters were weighed using a high precision balance with an accuracy of 0.0001 g. The fume was separated in particle size ranges using 13 stages in the ELPI column (Table 5.3). Following testing, the filters were weighed with the high precision balance. The mass fraction was plotted as a function of particle size or aerodynamic diameter.

A scanning electron microscope (SEM) with ultra-high resolution (UHR) was used to analyze representative fume particles and agglomerates from stages 2, 4, 8, and 10 of the ELPI impactor. These size ranges correspond to 0.06, 0.16, 0.96, and 2.4 µm, respectively. X-ray energy dispersive spectroscopy (XEDS) was performed with an accelerating voltage between 15 and 20 kV in spot mode with a spot size of 3 to 4 depending on the particles size. Spectra were also collected in area mode for the fume piles from each stage. The purpose of this study was to analyze the morphology, size, distribution, and composition of the particles in the welding fume of Cr-free and conventional welding consumables.

Table 5.3 Fume Particle Size Ranges Collected in the Stages of ELPI Column

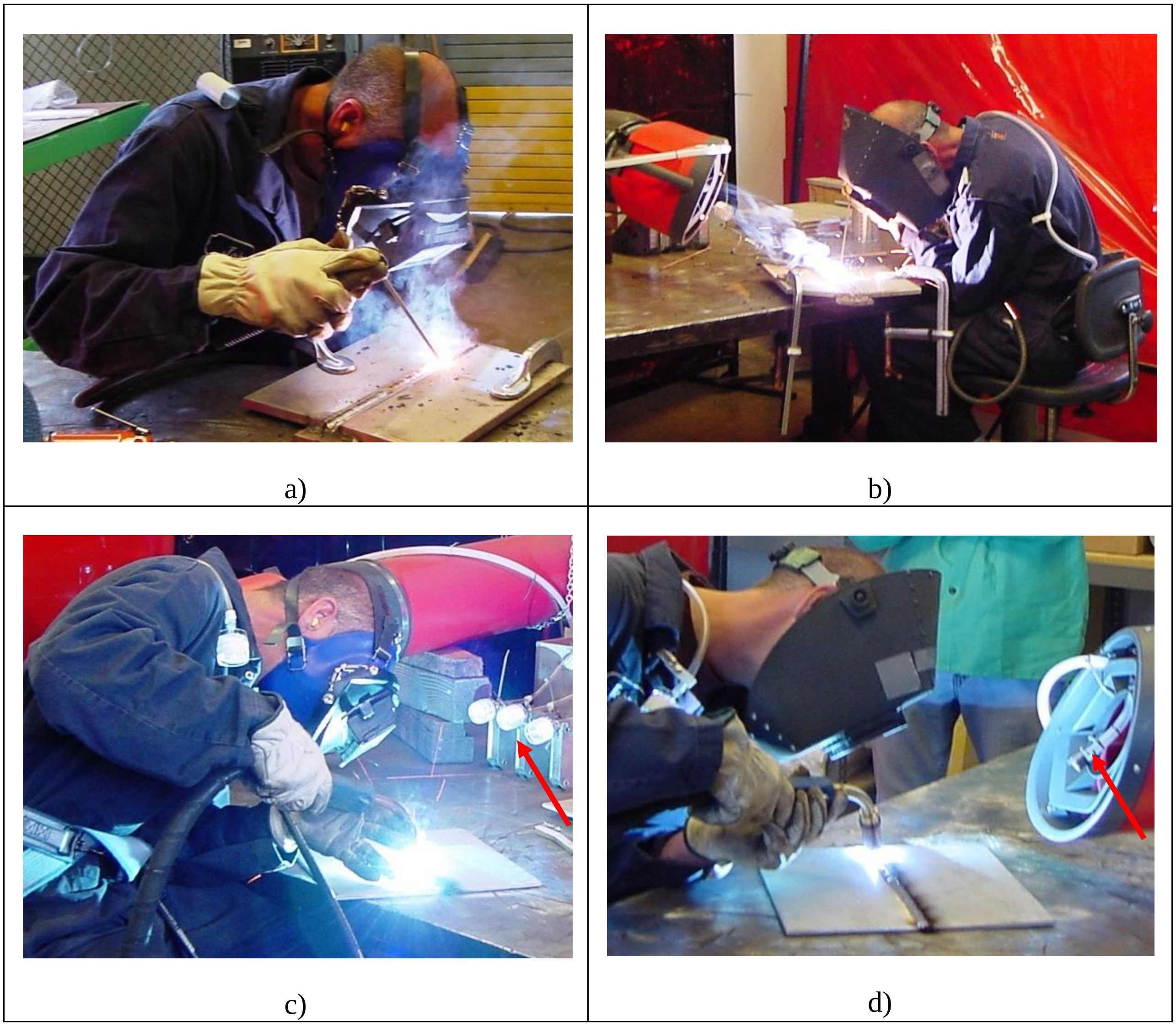
Impactor Stage	Particle size, µm
13	10.5
12	6.7
11	4
10	2.4
9	1.6
8	0.96
7	0.62
6	0.39
5	0.27
4	0.16
3	0.1
2	0.06
1	0.03

5.2 Field Testing

The Field Demonstration was conducted at TEAD, Tooele, Utah. The test plan of this Field Demonstration was designed to provide reliable validation of the Cr-free SMAW and GMAW consumables during stainless steel welding that most closely replicates the welding operations in fabrication of stainless steel at DoD facilities. To achieve that goal, the test plan included parallel testing and direct comparison of the Cr-free SMAW electrode (ENiCuRu) to a conventional stainless steel SMAW electrode (E308L-16) and of the Cr-free GMAW electrode (ERNiCuRu) to a conventional stainless steel GMAW electrode (ER308LSi).

5.2.1 Production of Weld Test Assemblies

The weld test assemblies were produced by a DoD welder during the Field Demonstration at TEAD. Six weld test assemblies were produced with each of the tested Cr-free ENiCuRu and ERNiCuRu consumables and baseline E308L-16 and ER308LSi consumables. The corresponding welding procedures are provided in Appendix E. Figure 5.8 shows the welding process involved in the production of each type weld test assembly.



a) b) c) d)

Figure 5.8 Field Demonstration Welding Processes: a) SMAW with Cr-free ENiCuRu Electrode, b) SMAW with Baseline E308L-16 Electrode; c) GMAW with Cr-free ERNiCuRu Filler Wire (IH pumps pointed by a red arrow); d) GMAW with Baseline ER308LSi Filler Wire (AS and ELPI sampling tubes pointed by a red arrow)

5.2.2 Field Welding Fume Collection and Occupational Safety, Health, and Environment (OSH&E) Testing

The welding fume collection and occupational safety hygiene and environmental testing during the Field Demonstration at TEAD were conducted by the Environmental Cost Management, Inc., Mesa, AZ. The testing procedures presented below have been developed and written by Environmental Cost Management, Inc.

The field welding occurred over 12 days during 3 weeks in August 2011. During the first 1.5 days, equipment was unpacked, setup and calibrated. The equipment used for air monitoring during these field tests included:

- Six industrial hygiene (IH) air pumps, with calibrated airflow rates
- GRIMM Technologies, Inc. Model Number 1.109 aerosol spectrometer (AS) for collection of airborne particles
- Dekati Ltd. ELPI – airborne particle collection and separation by size
- Ludlum Model 44-9 Pancake probe for beta and gamma detection for field screening of personnel and work areas
- Ludlum 2929 for measuring beta and gamma radiation of spent filtration media
- CES Landtec GEM 2000 for combustible gas, oxygen and carbon dioxide monitoring

Following equipment setup, welding was done during the first week as a pretest and initial baseline. During the second week, baseline and testing were done for the Ohio State University welding technology methods, using SMAW and GMAW. The Ohio State University was demonstrating Cr-free welding consumables (a shielded metal arc welding electrode and a GMAW/GTAW wire) that reduces the amount of Cr(VI).

Field Welding Air Monitoring Setup

The area used for welding was a room at the one end of a maintenance building that had two man doors, a double door on an inside wall, a large roll-up door on an exterior wall, and two windows. The exterior doors and windows were closed during testing. The interior doors were sealed off using duct tape and plastic sheeting. All doors were closed, openings taped shut and no one was allowed to go in and out of the room during welding.

The AS and ELPI were set up in a small room adjacent to the welding area (Figure 5.9). The air sampling tubes attached to each of the machines led out through the plastic sheeting and were attached to the Lincoln Collector duct located above the welding work table (Figure 5.8d and Figure 5.10). The intake end for the two tubes was positioned just above the welding activity on the table.

a)

b)

Figure 5.9 a) AS; b) ELPI Apparatus

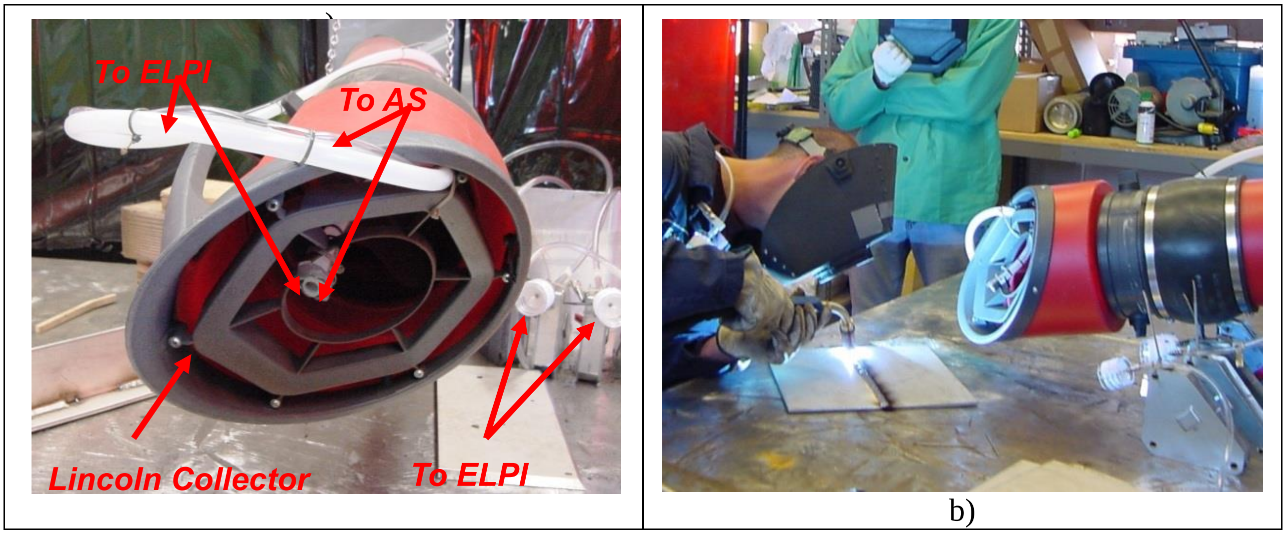


Figure 5.10 Near Fields Sampling during Field Welding and the Lincoln Collector

Four to six IH pumps were positioned in the welding room, fitted with filter cartridges on the intake tubing. The cartridges had polyvinyl chloride (PVC) or mixed cellulose ester (MCE) filters, depending on the analyte being tested. Each pump usually ran half of the workday before filters were changed out. The filters were replaced, labeled and bagged for transport to the laboratory. Each evening the pumps were recharged and flow rates were recalibrated. For each test, there was a set of pumps positioned on the work table (near field, Figure 5.8c and Figure 5.11a) and another set positioned approximately 10 feet away from the work table (far field, Figure 5.11b).

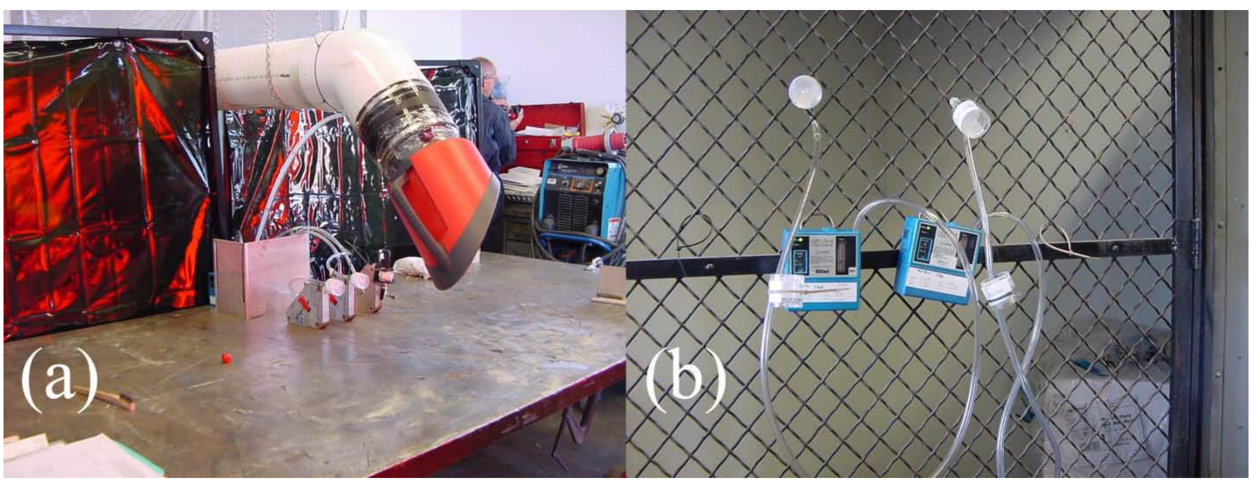


Figure 5.11 a) Location of IH Pumps for near Field Sampling; b) Location of IH Pumps for Far Field Sampling

The pumps were positioned and fitted with the following filters. Also listed is the analytical test method that was done on each of the filters:

- Pump 1 – NIOSH 7303 – 37 mm MCE filter, all metals near field

- Pump 2 – NIOSH 7303 - 37 mm MCE filter, all metals far field
- Pump 3 – OSHA ID-215 revision 2: 37 mm PVC filter, Cr(VI) near field
- Pump 4 – OSHA ID-215 revision 2: 37 mm PVC filter, Cr(VI) far field
- Pump 5 – NIOSH 7501: 37 mm PVC filter, Amorphous Silica – near field
- Pump 6 – NIOSH 7501: 37 mm PVC filter, Amorphous Silica – far field
- NIOSH 7600 Ruthenium: far field (Lab indicates Pump 2 – 7303 diluents can be used)
- NIOSH 7600 Ruthenium – near field (Lab indicates Pump 1 – 7303 diluents can be used)

The AS 1.109 used 47-mm PVC filters, which were analyzed for metals, ruthenium, and Cr(VI). This instrument was run during a single test or for multiple tests as needed. Following a run, the filter was removed, bagged and labeled. Flow rates and run times for each instrument were noted on the field sheet and on the chain of custody that accompanied the sample to the lab. The filter mount was cleaned with pressurized air and then a new filter placed in the mount. The machine was re-zeroed and run through self-tests prior to each run. This instrument is factory calibrated; therefore no field calibrations were required. The filters were sent to the lab for analysis for metals and ruthenium by NIOSH 7303 and Cr(VI) by OSHA ID 215.

The ELPI instrument was provided by the Ohio State University and required a set of 13 PVC filters during each run. The filters were placed on 13 individual metal screens (stages) that sieved the particles in the air stream as it was pumped across each filter, with particles separated from largest to smallest. This instrument was run during a single test or a group of tests. Following a run, the filters were removed from the 13 metal screens, individually bagged and labeled and analyzed separately for metals, ruthenium, and Cr(VI). The 13 metal screens and housing were decontaminated through an alcohol bath and dried with pressurized air. The screens were reassembled using new filters and the instrument was flushed with clean air, checked for leaks and re-zeroed prior to each run. This instrument is factory calibrated, so no field calibrations were required. Filters were analyzed for metals and ruthenium by NIOSH 7303 and for Cr(VI) by OSHA ID 215.

NAVFAC EXWC provided large filters for the Lincoln collector (Figure 5.10) but the holder for the filters did not function correctly. As an alternative, a PVC filter cartridge was taped to the top of the Lincoln collector exhaust and analyzed for total Cr(VI). This filter was changed out at the same frequency as the IH filters in the room. This information was used to determine the effectiveness of the Lincoln collector qualitatively rather than quantitatively.

Health and Safety Monitoring

Health and safety issues were addressed and procedures for monitoring test participants (welder, observer) and Enterprise Content Management personnel were followed as outlined in the Safety Program Plan for HAP Emissions Sampling ESTCP Innovative Welding Technology. The welding room was sealed during all welding tests as described above. The welding method being demonstrated by the Ohio State University was a Cr-free method that does involve possible exposure to Ru. This was monitored in two ways. Field screening was done using the Ludlum Model 44-9 Pancake probe in conjunction with the Ludlum Model 3-97 Survey Radiation NORM Meter. The welding table, welding rod, and welding plates were monitored daily. People working in the welding room were typically monitored in the morning, before leaving for a lunch break, before entering the room after lunch and then at the end of the day.

Beta radiation is primarily emitted by ruthenium isotopes; however, gamma radiation may be detected from some unstable isotopes such as ^{97}Ru and ^{103}Ru. The Ludlum Model 44-9 probe collectively detects alpha, beta, and gamma radiation. This instrument was calibrated daily during the times when it was in use.

The Ludlum 2929 was used to measure quantitatively the amount of radiation each person received daily while in the room during welding. A piece of duct tape, with the sticky side out, was attached to each person that was in the room during welding to collect the airborne particles in the breathing space. This tape was removed when the person left the room. At the end of each day, radiation of the piece of tape was measured and, along with the exposure time, was used to calculate the DAC for each person to determine if there was radiation exposure. The equation used to calculate the DAC is presented in the safety program plan. The results indicated mostly beta radiation, and the DAC never exceeded the project action levels. This instrument was checked daily during times when it was in use. The check source, technetium 99, was measured each day, preceded and followed by a measurement with just an empty tray to record "background" when no source was in the instrument.

Quality Assurance/Quality Control

The following quality control samples were collected during the course of field testing:

- One blank filter from each lot of filters. This filter was untouched and sent directly to the lab for analysis.
- Field blanks: filters with seals broken and packaged similar to other samples. No air was drawn through these filters but they were handled similarly to other samples. Typically, ECM prepared one field blank sample per day for:
    - OSHA ID-215 revision 2 (Cr(VI)): Include at least one field blank per day (typically at least one blank per 25 samples).
    - NIOSH 7303 (All Metals): Include one field blank per day for every set of samples.
    - NIOSH 7600 (Ruthenium): Include one field blank per day. Filter media is combined with sampling for NIOSH 7303 (All Metals)

In addition, a sample was run on the ELPI for 15 minutes to measure the ambient air within the instrument room adjacent to the welding room. This sample was collected during the third week, in between welding activities. The purpose was to test the ambient air to see if the particles from the welding area were coming into the neighboring space. The filters were analyzed for metals, ruthenium and Cr(VI).

5.2.3 Analysis of Welding Fume Collected during Field Demonstration

The analyses of all fume samples collected during the field testing were performed at the Navy and Marine Corps Public Health Center Comprehensive Industrial Hygiene Laboratory in San Diego, CA. The following analysis procedures were utilized:

- For Cr(VI): OSHA 215 and NIOSH 7600 using ion chromatography

- For ruthenium and other metals: NIOSH 7300 using ICP with an Aglient ICP-MS 7700 instrument

5.2.4 Mechanical and Quality Testing of Welds Produced during Field Demonstration

Weld test assemblies produced with the Cr-free consumables and with the baseline consumables were subjected to mechanical testing, metallographic characterization, chemical analysis, and radiographic examination at the Naval Surface Warfare Center Carderock Division. The test plan for these tests is shown in Table 5.4.

The tensile testing was conducted in accordance with ASTM E8. Standard metallographic techniques were used for sample extraction, mounting, polishing and etching in accordance with ASTM E 407. The etching of the baseline welds was performed with oxalic acid based etchant and of the test welds with oxalic acid/HNO_3 based etchant. The metallography samples were subjected to macro- and microstructural analyses using a light optical microscope at magnifications of 5x and 20x. The chemical analyses were conducted in accordance with ASTM E1019 (combustion infrared detection); carbon and sulfur, ASTM E1019 (inert gas fusion) for nitrogen, and ASTM E1097 (direct current plasma emission spectroscopy) for all other all other elements. The radiography testing was conducted in accordance with ASTM E 1032.

The location of the samples for tensile testing, microstructural characterization, and chemical analysis on the SMAW and GMAW test assemblies is shown in Figure 5.12 and Figure 5.13. The radiographic testing of the weld assemblies was conducted before cutting for sample extraction.

The GMA welds were subjected to transverse tensile testing in accordance with ANSI/AWS B 4.0 and ANSI/AWS A5.4-9. All weld metal tensile test samples with diameters of 0.35 in. were extracted from the SMA welds and subjected to tensile testing according to ANSI/AWS B 4.0 and ANSI/AWS A5.11-97. The tensile test sample design is shown in Appendix F.

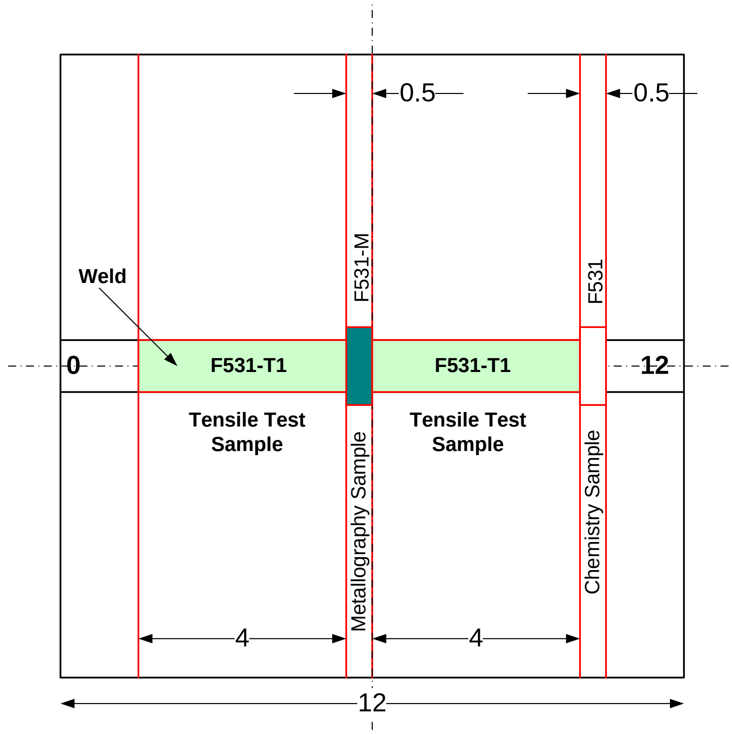


Figure 5.12 Schematic of Sample Extraction from the SMAW Test Assemblies (the weld is located along the central line 0 - 12)

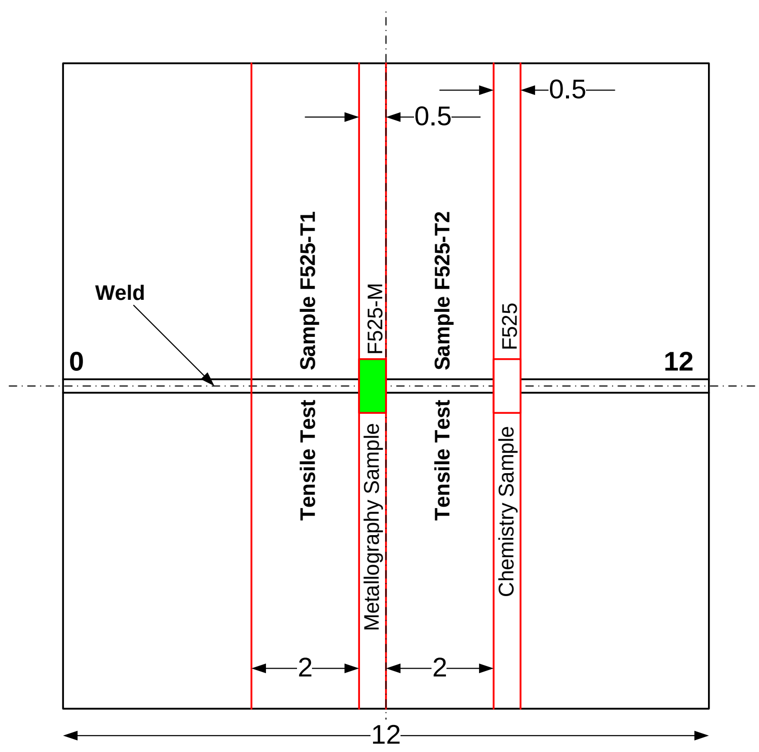


Figure 5.13 Schematic of Sample Extraction from the SMAW Test Assemblies

Table 5.4 Naval War Surface Center Carderock Division Testing Plan

Sample	Process	Test 1 Radiography	Test 2 Macro	Test 3 Tensile Test	Test 4 Micro	Test 6 WM Chemistry	Notes	Test Plate ID	NSWCCD ID	Date Welded
OSU/Base/ SMAW electrode	SMAW ½ in. Plate 304L SS E308L-16	3	3	6 transverse tensile samples (3 @ 2 /plate)	1 plate if tests 1,2 & 3 good; if problem in any, all 3 plates	1 if all is well; all 3 if problems	Analyze Cr, Ru, Ni Cu, Al, Ti	BOO3 BOO4 BOO5	F531 F532 F533	8/15/2011 8/16/2011* 8/16/2011
OSU /Test/ SMAW electrode		3	3					TOO3 TOO4 TOO5	F534 F535 F536	8/17/2011 8/17/2011 8/17/2011
OSU/ Base/ GMAW wire	GMAW ¼ in. plate 304L-SS ER308LSi	3	3	6 all weld metal samples (3@ 2 /plate)				BO1E1 BOO2 BOE3	F527 F525 F526	8/10/2011 8/10/2011 8/10/2011
OSU/ Test/ GMAW wire		3	3					TOO8G TOO9G TOO10G	F537 F538 F539	8/18/2011 8/18/2011 8/18/2011

*This plate was done over the course of two days.

6. Performance Assessment

The performance assessment was structured based on the performance objectives of the Laboratory Demonstration and Field Demonstration as defined in Section 3 of this report.

6.1 Reduction in Hazardous Air Emissions and Occupational Exposures

Fume studies to assess the hazardous air emissions and occupational exposures generated by the Cr-free ENiCuRu and ERNiCuRu consumables versus those generated by conventional E308L and ER308LSi consumables for welding stainless steel were conducted both during the Laboratory and the Field Demonstrations in this project. The results of these studies are discussed separately in the next subsections.

6.1.1 Laboratory Demonstration Fume Studies

Fume Generation Rate

The results of the fume generation rate study are summarized in Table 6.1 and Figure 6.1. It includes a conventional E308L-16 and ERNiCuRu G-IV consumable that was tested outside this project for reference purposes [17]. The ERNiCuRu G-IV was developed as the last generation of Cr-free SMAW consumable in the preceding SERDP project. Its coating has been optimized in the current ESTCP project to improve its welding operability. Thus, both ERNiCuRu G-IV and the optimized ERNiCuRu have the same composition electrode rods, but the latter has an optimized coating.

Table 6.1 Fume Generation Rates in Cr-free ENiCuRu and ERNiCuRu and in Conventional ER308LSi and E308L-16 Consumables

Process	GMAW		SMAW		
Consumable	ERNiCuRu	E308LSi	ENiCuRu	ENiCuRu G-IV	E308L-16
Fume Generation Rate, g/min	0.085	0.089	0.355	0.580	0.198

The two GMAW consumables have equal fume generation rate, which is very low. The fume in the GMAW process is generated by filler metal vaporization, mostly during transfer of molten metal droplets through the welding arc. The significantly higher fume generation rate in the SMAW process is related to decomposition/vaporization of the coating flux in the welding arc. The Cr-free ENiCuRu electrode had a 44% higher fume generation rate than the conventional E308L-15 electrode and met the performance objective stated in Table 3.2. The coating optimization of ERNiCuRu conducted during the Laboratory Demonstration of this project resulted in a 39% reduction in the FGR as compared to the ERNiCuRu G-IV (Table 6.1).

It should be noted that the FGR characterizes the intensity of particulate emission during welding and does not reflect the emission of Cr(VI) in the welding fume.

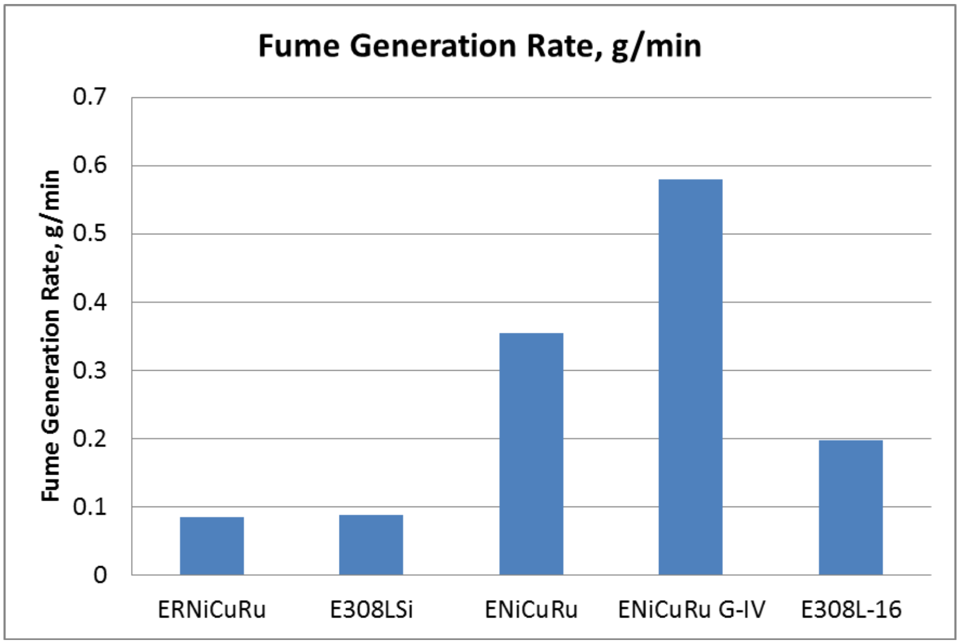


Figure 6.1 Fume Generation Rates in the Cr-free ERNiCuRu, ENiCuRu and ENiCuRu G-IV Consumables and in Conventional ER308LSi and E308L-16 Consumables

Cr(VI) Content in Welding Fume

The results of the study on Cr(VI) content in the welding fume of the tested Cr-free and conventional stainless steel consumables are summarized in Table 6.2. The ENiCuRu consumable provided 98.6% (factor of 71) reduction of the Cr(VI) content in the welding fume as compared with the conventional E308L-16 SMAW electrode and met the performance objective stated in Table 3.2. The extremely low amount of Cr(VI) found in the fume of Cr- free ENiCuRu consumable is generated by vaporization from the molten welding pool that is diluted with type 304L stainless steel. The latter typically contains about 20 to 28 wt % Cr(VI). The optimized coating of the ENiCuRu provided less Cr(VI) in the welding fume as compared to its older version (ENiCuRu G-IV).

Not enough fume was generated from the ER308LSi and ERNiCuRu GMAW electrodes to determine the Cr(VI) concentration in their fume. Since the valence state of Cr is dependent on what elements are present in the welding consumable, solid electrode wires do not generate a significant amount of Cr(VI). Due to the lack of alkaline elements in the welding consumable, they mostly generate Cr(III) or trivalent Cr (see Section 6.1.2).

Table 6.2 Cr(VI) Content in Welding Fume of Cr-free ENiCuRu and ERNiCuRu and in Conventional ER308LSi and E308L-16 Consumables

Process	GMAW		SMAW		
Consumable	**ERNiCuRu**	**E308LSi**	**ENiCuRu**	**ENiCuRu G-IV**	**E308L-16**
Cr(VI), wt %	**N/A**	**N/A**	**0.037**	**0.097**	**2.62**
% Reduction (Cr-free vs. conventional)	N/A		98.6%	96.3%	N/A

Ruthenium Content in the Welding Fume

The Ru content found using ICP spectrometry in two samples of the ENiCuRu welding fume is compared in Table 6.3 with the Ni content and the total Cr content in the fume. The Ru content in the welding fume is extremely low (0.003 wt %), more than one order of magnitude lower than the Cr(VI) content in the fume, Table 6.2.

Table 6.3 Content of Ru, Ni, and Total Cr in Welding Fume of ENiCuRu

Sample	Ni		Total Cr		Ru	
	ppm	Wt %	ppm	Wt %	ppm	Wt %
1	46557	4.7%	1010	0.10%	29	0.003%
2	45236	4.5%	1073	0.11%	27	0.003%

Mass Distribution

The results for mass percentage distribution of fume particles in the Cr-free ERNiCuRu and ENiCuRu electrodes are shown in Figure 6.2 and Figure 6.3, respectively. The majority of the fume mass for both consumables was in the fine range (0.1 to 1.0 µm). The peak mass percentage in the ENiCuRu fume was close to 0.62 µm diameter particles and in ERNiCuRu was close to 0.16 µm diameter particles. The mass distribution in the fume of ENiCuRu was similar to that of the E308L-16 consumable, where the peak mass percentage was near the 0.62 µm diameter size range. The mass distribution in the fume of ERNiCuRu was similar to that of a low carbon steel GMAW filler wire.

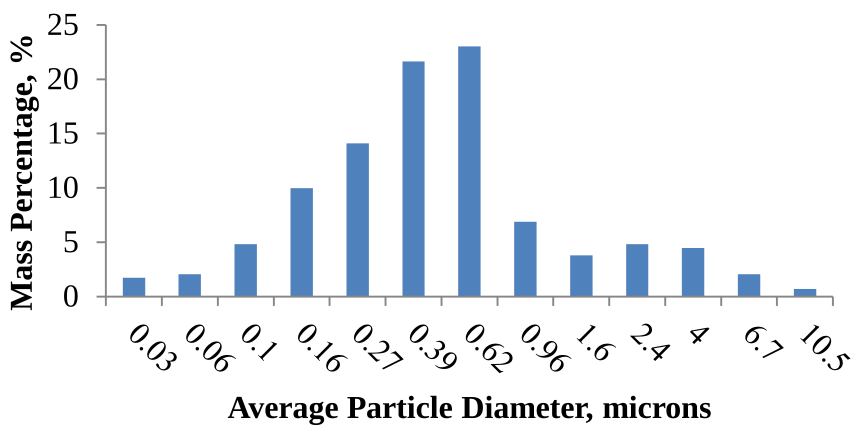


Figure 6.2 Mass Distribution of Fume Particles in Welding Fume of ENiCuRu SMAW Electrode

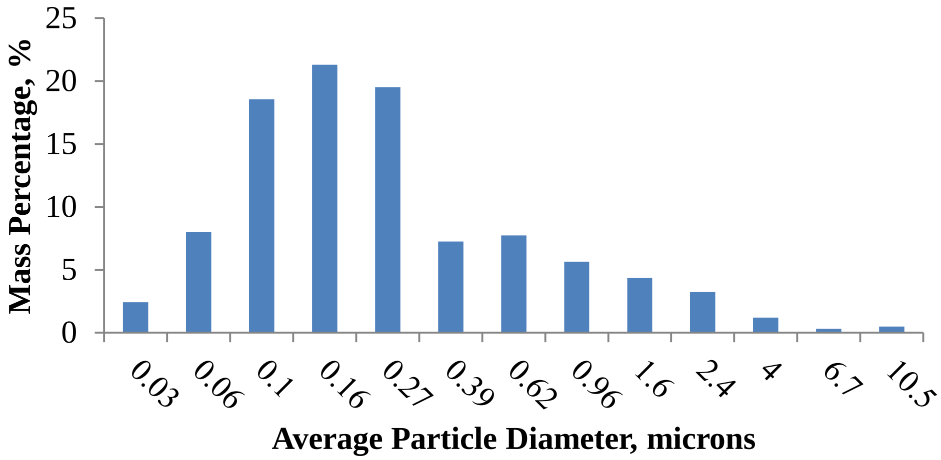


Figure 6.3 Mass Distribution of Fume Particles in Welding Fume of ERNiCuRu GMAW Electrode

X-Ray Diffraction Study on Welding Fume

The results from the XRD study in the fume of the tested electrodes are summarized in Table 6.4. The XRD spectra are shown in Figure 6.4 through Figure 6.7. The fume of the ENiCuRu electrode indicate the presence of nickel oxide (NiO) and nickel-copper oxide, while the ERNiCuRu fume contained nickel-copper oxide and nickel-titanium oxide. The presence of nickel-titanium oxide in the welding fume of ENiCuRu can be related to the higher titanium content, which was introduced into the electrode rode of this consumable to improve the weld metal deoxidation. Both the stainless steel consumables contained magnetite compounds, with the ER308LSi also containing nickel manganese oxide. The alkali components in the coating of the SMAW E308L-16 consumable resulted in the formation of NaF and K_2CrO_4. It was shown that Cr(VI) in the welding fume of SMAW electrodes is present in alkali oxides as K_2CrO_4 and Na_2CrO_4 [18]. No Cr(VI) containing compounds were found in the fume of ENiCuRu.

Table 6.4 Compounds Present in Welding Fume of Cr-free ENiCuRu and ERNiCuRu and in Conventional ER308LSi and E308L-16 Consumables

Process	GMAW		SMAW	
Consumable	ERNiCuRu	ER308LSi	ENiCuRu	E308-16
Compounds	$Ni_{.95}Cu_{.05}O$, $Ni_{2.44}Ti_{.77}O4$	Fe_3O_4, $NiMn_2O_4$	NiO, $Ni_{.90}Cu_{.10}O$	Fe_3O_4, $K_2(Fe,Mn,Cr)O_4$, NaF

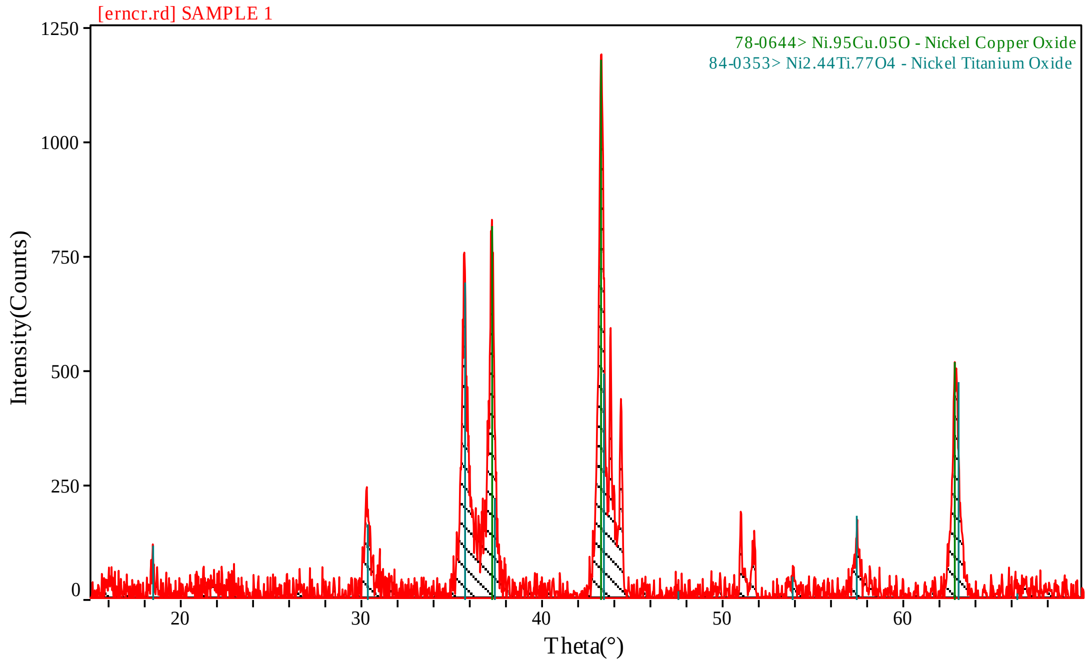


Figure 6.4 XRD Spectrum of Fume Generated by Cr-free ERNiCuRu Wire Electrode

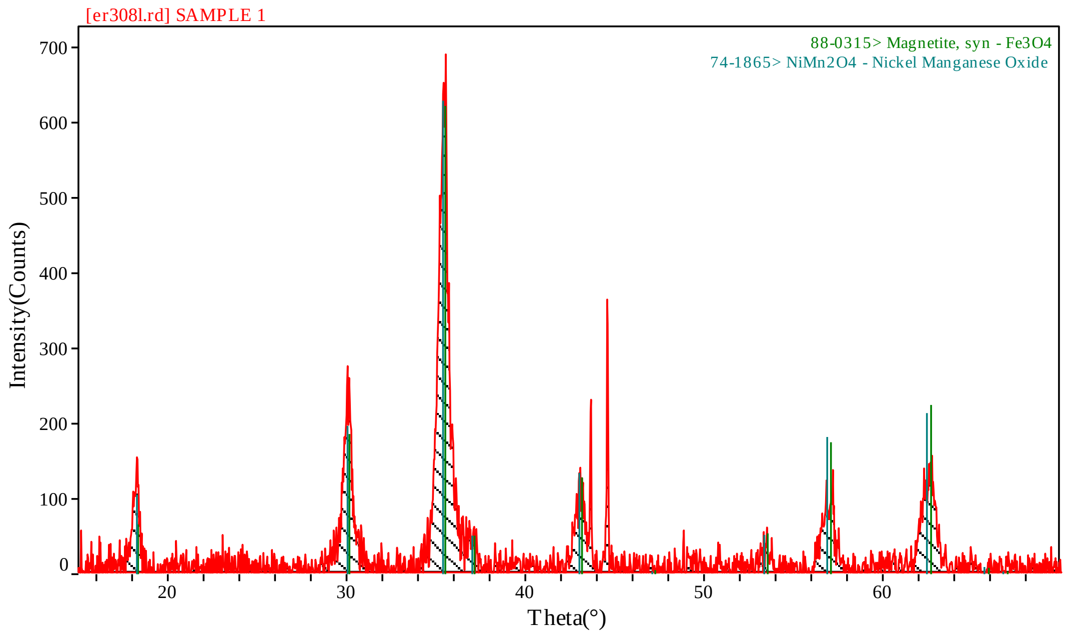


Figure 6.5 XRD Spectrum of Fume Generated by Conventional ER308LSi Wire Electrode

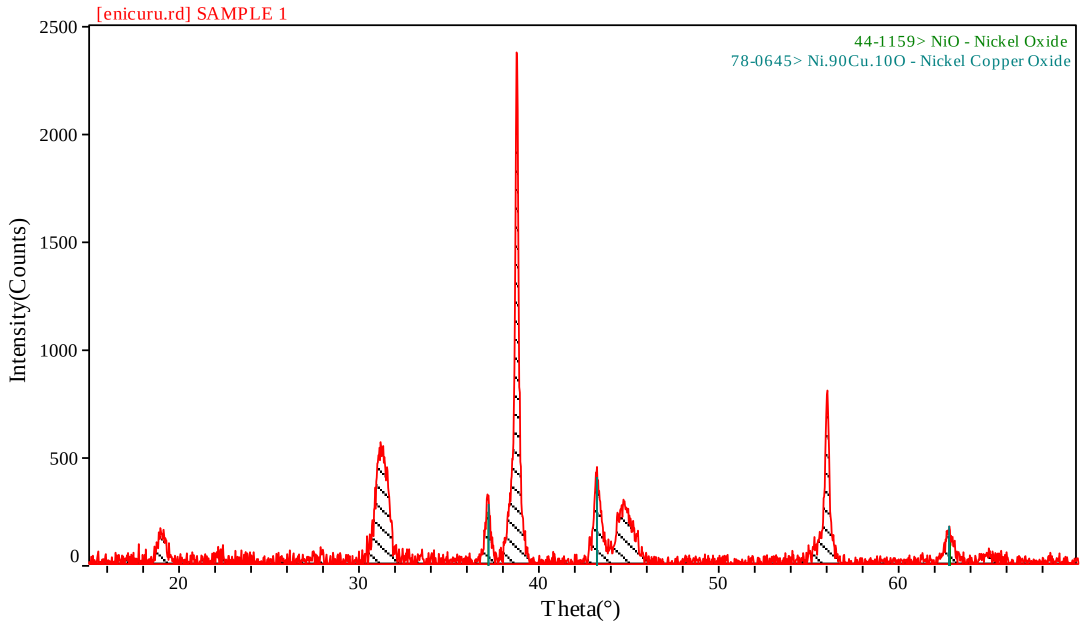


Figure 6.6 XRD Spectrum of Fume Generated by Cr-free ENiCuRu Electrode

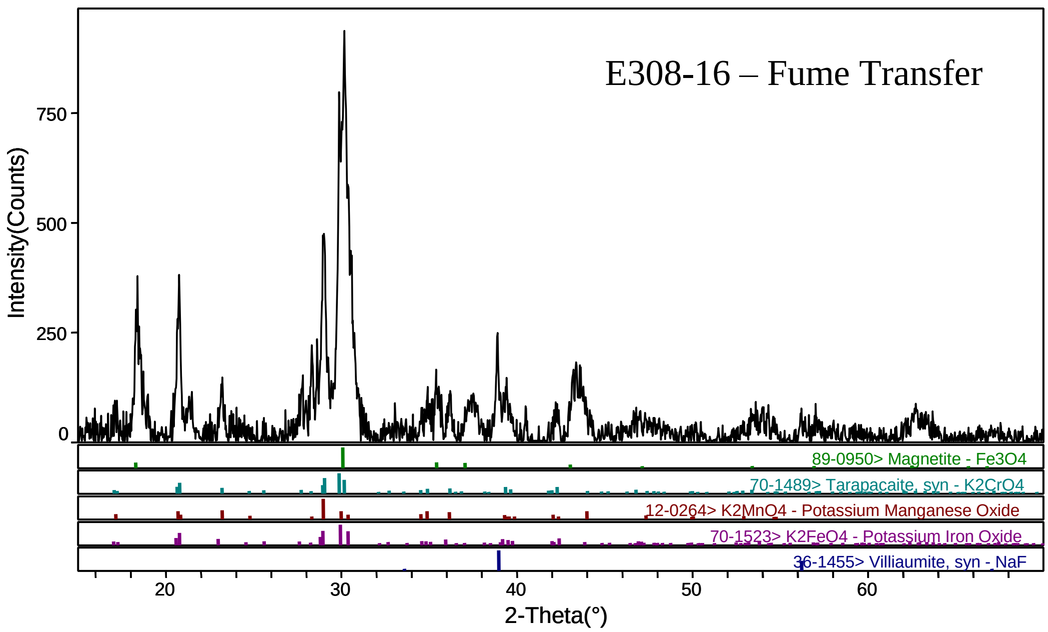
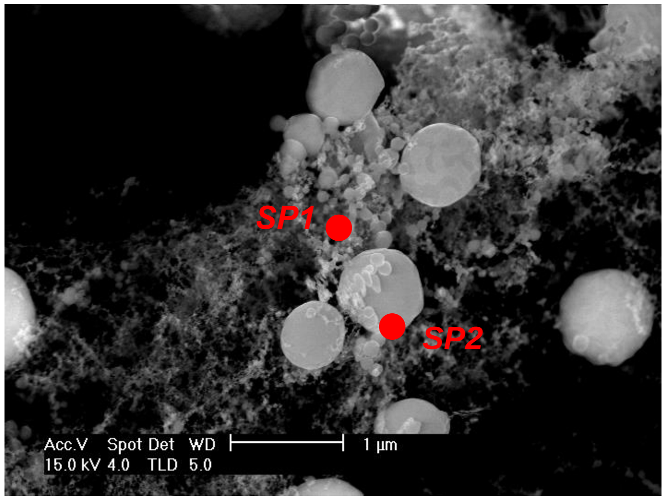


Figure 6.7 XRD Spectrum of Fume Generated by Conventional E308L-16 Electrode [17]

SEM Analyses on Welding Fume

Figure 6.8 and Figure 6.9 show UHR SEM images of fume particles collected on stage 8 in the ELPI from the welding fume of the ER308LSi and ERNiCuRu consumables. The composition of the tested species reflects the chemical composition of the corresponding welding filler wires: higher Cr and Fe content in ER308LSi and higher Ni and Cu content in ERNiCuRu. The Fe and Cr detected in the fume species of ERNiCuRu are a result of vaporization from the weld pool that is diluted with type 304L steel based metal.

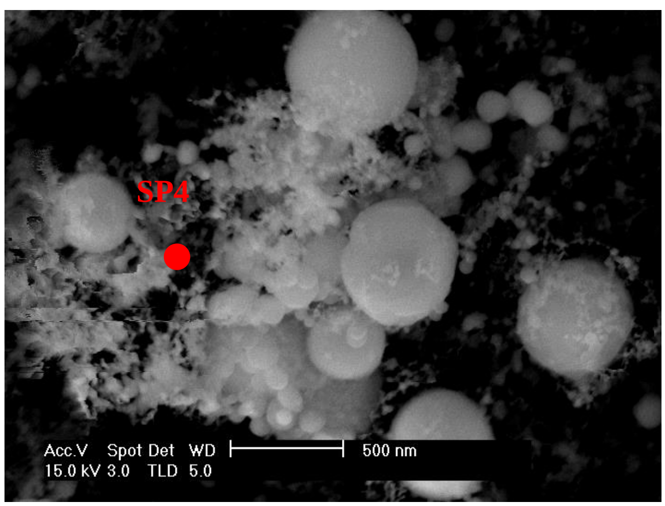
Elem, wt%	SP1
Si-K[1]	4.1
Cr-K[1]	29.3
Fe-K[1]	59.4
Ni-K[1]	7.1
Total	100



Elem, wt%	SP2
Si-K[1]	6.7
Cr-K[1]	27.3
Fe-K[1]	60.4
Ni-K[1]	5.5
Total	100

Figure 6.8 UHR SEM Image and XEDS of ER308LSi Fume Particles Collected on Stage 8

Footnotes specific to this table:
[1] The letter K after the element denotes the electronic shell detected by the EDS analyzer.



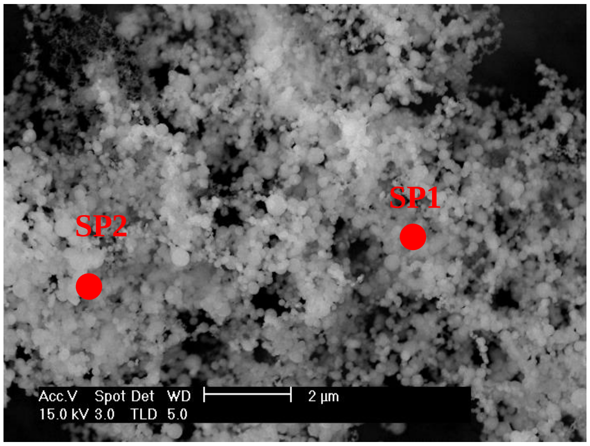
Elem, wt%	SP4
Ti-K[1]	0.7
Cr-K[1]	0.9
Fe-K[1]	4.6
Ni-K[1]	77.3
Cu-K[1]	16.5
Total	100

Figure 6.9 UHR SEM Image and XEDS of ERNiCuRu Fume Particles Collected on Stage 8

Footnotes specific to this table:
[1] The letter K after the element denotes the electronic shell detected by the EDS analyzer.

Figure 6.10 and Figure 6.11 show UHR SEM images of fume particles of the ENiCuRu electrode collected on stages 8 and 10 in the ELPI. The fume contains mostly Na and K from the electrode and Ti, Ni, and Cu from the electrode core wire. The Sr present in SP2 on Figure 6.10 is a result of the $SrCO_3$ present in the flux mixture. Compared to stage 8, stage 10 of the ELPI contained decreased amounts of Na, K, Ni, and Cu and increased amounts of Ti and Sr.

Elem, wt%	SP2
Na-K[1]	41.0
Mg-K[1]	1.5
Si-K[1]	1.0
K-K[1]	19.7
Ti-K[1]	5.5
Cr-K[1]	1.6
Fe-K[1]	3.1
Ni-K[1]	16.9
Cu-K[1]	9.7
Total	100

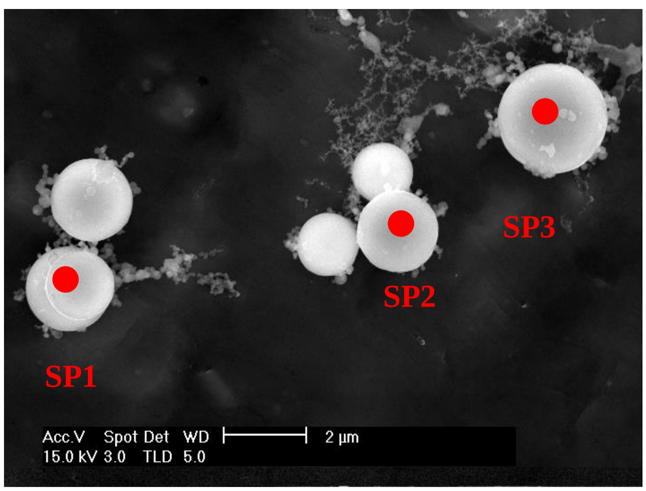


Elem, wt%	SP1
Na-K[1]	45.3
Mg-K[1]	1.2
Si-K[1]	0.7
Sr-L[1]	1.4
K-K[1]	16.1
Ti-K[1]	5.5
Fe-K[1]	0.4
Ni-K[1]	19.1
Cu-K[1]	10.3
Total	100

Figure 6.10 UHR SEM Images and XEDS of ENiCuRu Fume Particles Collected on Stage 8

Footnotes specific to this table:
[1] The letters K and L after the element denotes the electronic shell detected by the EDS analyzer.

Elem, wt%	SP1	SP2
Na-K[1]	28.6	29.5
Mg-K[1]	1.4	1.1
Si-K[1]	2.5	2.9
Sr-L[1]	12.8	16.7
K-K[1]	7.5	8.4
Ca-K[1]	4.3	5.5
Ti-K[1]	30.6	30.7
Ni-K[1]	16.9	2.2
Cu-K[1]	9.7	2.7
Total	100	100



Elem, wt%	SP3
Na-K[1]	25.7
Mg-K[1]	0.9
Si-K[1]	3.4
Sr-L[1]	14.7
K-K[1]	12.7
Ca-K[1]	4.7
Ti-K[1]	34.8
Ni-K[1]	1.1
Cu-K[1]	2.1
Total	100

Figure 6.11 UHR SEM Image and XEDS of ENiCuRu Fume Particles Collected on Stage 10

Footnotes specific to this table:
[1] The letter K after the element denotes the electronic shell detected by the EDS analyzer.

XEDS spectrum from the ENiCuRu fume collected on Stage 8 is shown in Figure 6.12. It indicates alloying elements originating from the core wire of ENiCuRu (Ni, Ti, Al, Ru), from the electrode coating (Na, Mg, Sr, K), and from the base metal that vaporized from the welding pool (Fe and Cr).

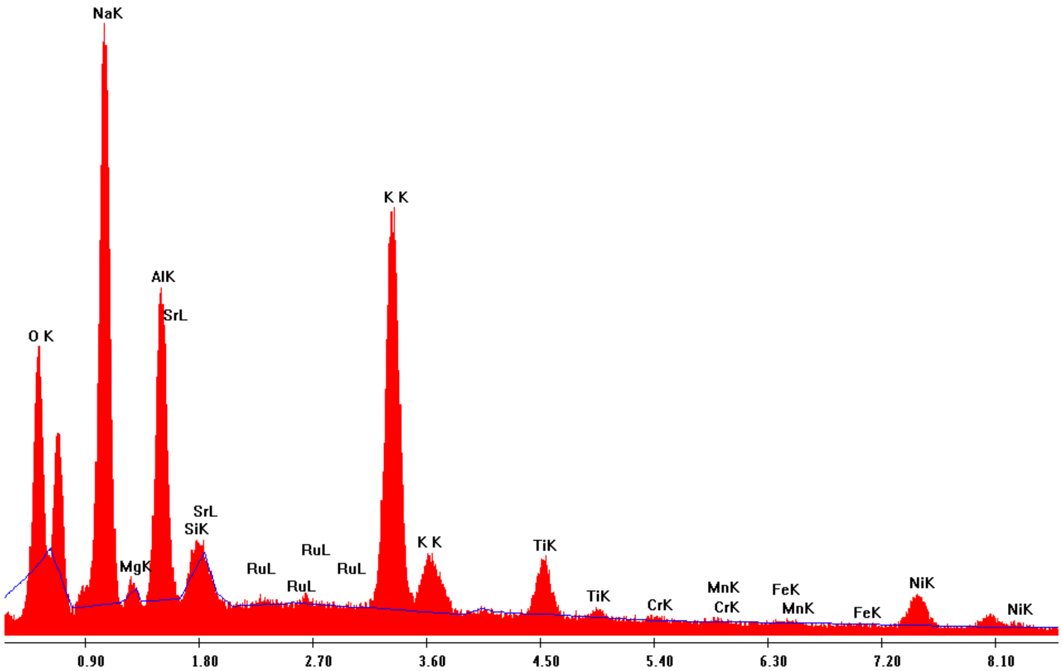


Figure 6.12 XEDS Spectrum from ENiCuRu Fume Collected on Stage 8
(Sr and Ru were detected.)

6.1.2 Field Demonstration Fume Studies

The analyses of fume samples collected by ECM during the field testing were conducted at the Navy and Marine Corps Public Health Center Comprehensive Industrial Hygiene Laboratory in San Diego, CA, using the analyses procedures specified in Section 5.2.3.

Cr(VI) Content in Welding Fume of Shielded Metal Arc Electrodes

The results of Cr(VI) analyses in the welding fume generated by the E308L-16 baseline electrode and by the ENiCuRu test electrode and collected using the ELPI, the AS, and the near and far location IH pumps are provided in Appendix G. A summary of the test results of the two electrodes is presented in Table 6.5. This table also includes the maximum, minimum, and average values of the Cr(VI) content in each set of tests, and the corresponding standard deviations. Information on the test sequence (test days) is also provided.

Significant sample-to-sample variations in the Cr(VI) content of welding fume collected with the same equipment were observed for each tested electrode. Variations between fume samples of each electrode resulted from using different equipment (ELPI, AS, and IH). No obvious relation between these variations and the sequence of testing (test day) can be found in Table 6.5.

Table 6.5 Cr(VI) Content in Welding Fume of ENiCuRu and E308L-16 Electrodes in μg/m^3

Collection	ELPI		AS		IH near field		IH far field	
Sample No.	E308L-16	ENiCuRu	E308L-16	ENiCuRu	E308L-16	ENiCuRu	E308L-16	ENiCuRu
1	9.21*	0.801	28.00	0.073	3.920	0.055	1.930	0.0514
2	7.88	0.135	8.96	0.270	2.690	0.197	1.220	0.1510
3	7.92	0.839	24.30	0.240	8.490	0.163	2.090	BDL**
4	15.60	0.209	19.70	0.066				
5	33.60	0.542	8.50	0.170				
6	9.54	0.520						
7	9.10	0.384						
8	11.30	0.150						
9		0.059						
Max	**33.60**	**0.839**	**28.00**	**0.270**	**8.49**	**0.197**	**2.09**	**0.1510**
Min	**7.88**	**0.059**	**8.50**	**0.066**	**2.69**	**0.055**	**1.22**	**0.0514**
Average	**13.02**	**0.4043**	**17.892**	**0.164**	**5.033**	**0.138**	**1.747**	**0.1012**
St. deviation	**8.6815**	**0.2902**	**8.867**	**0.093**	**3.056**	**0.074**	**0.463**	**0.0704**
*Fume collection day:		one	two	three		**BDL: below detection limit		

Possible sources of these variations in the test results could be the fume collection and fume analysis procedures. However, these test results still allow evaluation of the performance of the Cr-free ENiCuRu electrode in terms of reduction of Cr(VI) emission compared to the OSHA PEL of 0.5 μg/m^3 and compared to the Cr(VI) emission of the baseline E308L-16 electrode. Such comparison is provided in **Error! Not a valid bookmark self-reference.**.

The reduction in Cr(VI) emission of the test ENiCuRu electrode versus the OSHA PEL was calculated using the following equations:

Average Cr(VI) reduction = [1 –aver $Cr(VI)_{ENiCuRu}$/5] x100, % (1)

Max Cr(VI) reduction = [1 –min $Cr(VI)_{ENiCuRu}$/5] x100, % (2)

Min Cr(VI) reduction = [1 –max $Cr(VI)_{ENiCuRu}$/5] x100, % (2)

A similar approach was used to calculate the reduction in Cr(VI) emission of ENiCuRu versus the baseline E308L-16 electrode:

Average Cr(VI) reduction = [1 –aver $Cr(VI)_{ENiCuRu}$/aver $Cr(VI)_{E308L}$] x100, % (4)

Max Cr(VI) reduction = [1 –min $Cr(VI)_{ENiCuRu}$/max $Cr(VI)_{E308L}$] x100, % (5)

Min Cr(VI) reduction = [1 –max $Cr(VI)_{ENiCuRu}$/min $Cr(VI)_{E308L}$]x100, % (6)

$Cr(VI)_{ENiCuRu}$ and $Cr(VI)_{E308L}$ in Equations 1 through 6 are correspondingly the average, maximum, and minimum Cr(VI) contents in the welding fume of ENiCuRu and E308L-16 electrodes determined in this study (**Error! Not a valid bookmark self-reference.**). This calculation approach allowed the quantification of the reduction in Cr(VI) exposure provided by the ENiCuRu electrode based on the whole range of variations in the test results.

The ELPI measured Cr(VI) concentrations in the welding fume of E308L-16 and ENiCuRu electrodes are summarized in Figure 6.13 and Table 6.5 and **Error! Not a valid bookmark self-reference.**. It should be noted that the main application of the ELPI apparatus is quantification of the fume particle size and mass distribution. The ELPI separates the fume in 13 different filters/stages. In this study, the fume collected in all filters was analyzed to determine the cumulative Cr(VI) content in the welding fume. This could have introduced some of the variations in the Cr(VI) content in the welding fume collected with ELPI (Table 6.5).

In eight fume samples of E308L-16, the Cr(VI) concentration varied between 7.88 and 33.6 μg/m^3, thus exceeding between 1.6 and 6.7 times the OSHA PEL of 5 μg/m^3. In nine fume samples of the ENiCuRu electrode the Cr(VI) concentration varied between 0.059 and 0.839 μg/m^3, which is six to 85 times below the OSHA PEL. Compared to the OSHA PEL, the Cr-free electrode provided 83.2 to 98.8% reduction in Cr(VI) exposure. Compared to the baseline E308L-16 electrode, ENiCuRu provided 89.4 to 99.8% exposure reduction, which corresponds to a reduction factor of nine to 569.

A comparison of the Cr(VI) concentration in the welding fume of the tested electrodes measured using the AS is shown in Figure 6.14. The Cr(VI) values measured using the AS were lower than those measured with the ELPI, but showed the same trends.

Table 6.6 Reduction in Percent Cr(VI) Content in Welding Fume of ENiCuRu versus the OSHA PEL and E308L-16 Electrode

Collection	ELPI		AS		IH near field		IH far field	
Comparison	vs. OSHA PEL	vs. E308L-16	vs. OSHA PEL	vs. E308L-16	vs. OSHA PEL	vs. E308L-16	vs. OSHA PEL	vs. E308L-16
Max, %	98.82	99.82	98.68	99.76	98.89	99.35	98.97	97.54
Min, %	83.22	89.35	94.60	96.82	96.06	92.68	96.98	87.62
Average, %	91.91	96.89	96.72	98.95	97.23	97.58	97.98	94.21

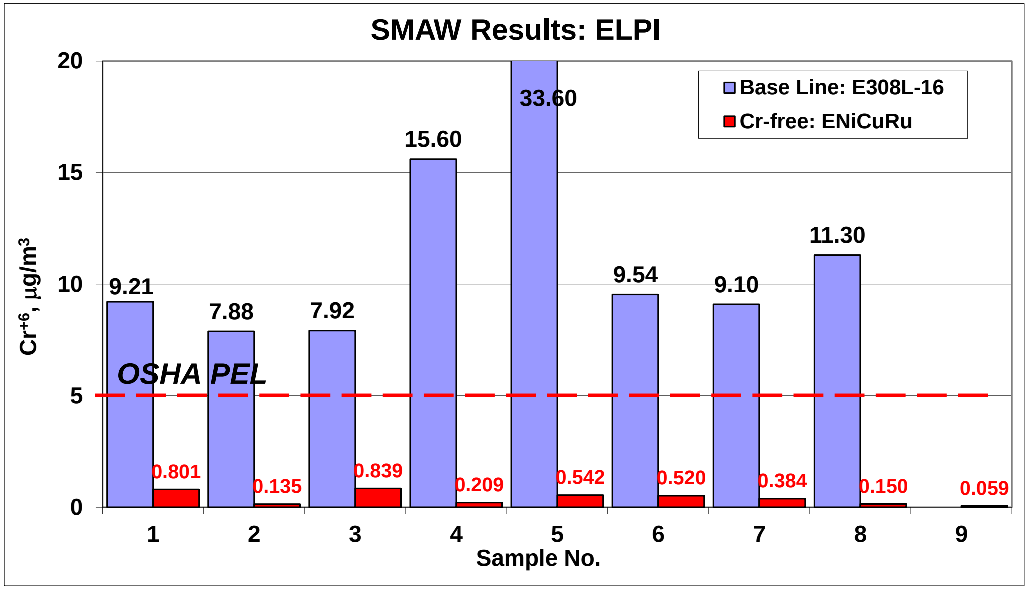
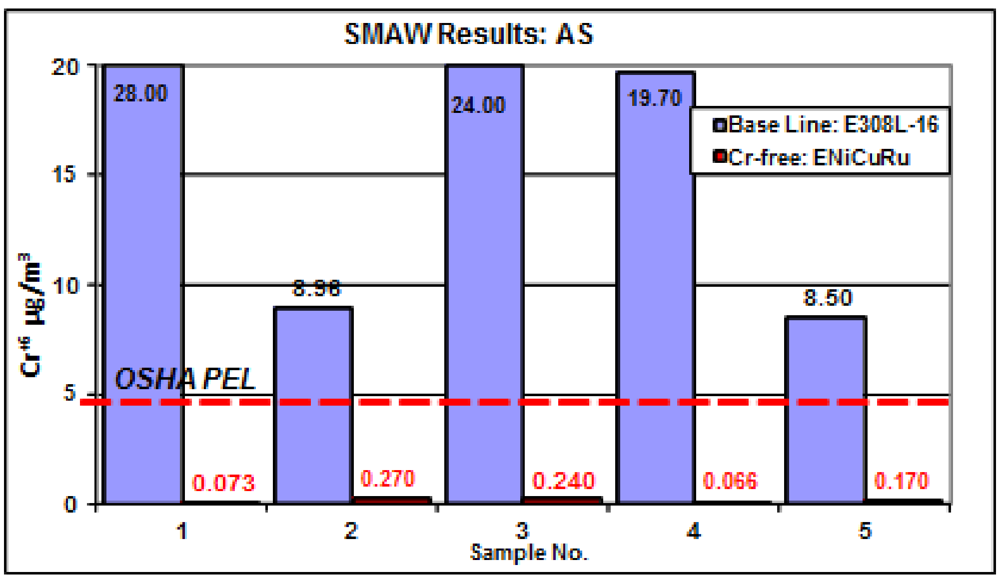


Figure 6.13 Cr(VI) Concentration in Welding Fume of E308L-16 and ENiCuRu Collected Using ELPI

Figure 6.14 Cr(VI) Concentration in the Welding Fume of E308L-16 and ENiCuRu Collected Using AS



In five tests, the Cr(VI) content in the fume of the E308L-16 electrode varied between 8.5 and 28 $\mu g/m^3$, thus exceeding the OSHA PEL between 1,7 and 5.6 times. The Cr(VI) content in the fume of ENiCuRu varied between 0.073 and 0.27 $\mu g/m^3$. This is 19 to 69 times below the OSHA PEL, which represents 94.6 to 98.5% exposure reduction. The Cr(VI) content in the fume of ENiCuRu was 33 to 384 times lower than in the baseline E308L-16 electrode, which represents exposure reduction of 94.6 to 98.5%.

The concentrations of Cr(VI) in the welding fume collected at near and far field locations from the welding arc using IH pumps are summarized in Figure 6.15. The Cr(VI) concentration in one of the E308L-16 near-field fume samples exceeded the OSHA PEL and the other two were above the 2.5 $\mu g/m^3$ action level. All E308L-16 far-field samples had Cr(VI) concentrations below the OSHA PEL and the 2.5 $\mu g/m^3$ action level. The Cr(VI) content in ENiCuRu fume collected at near and far field varied between 0.0514 $\mu g/m^3$ and 0.197 $\mu g/m^3$. One of the far-field samples was below the Cr(VI) detection limit. The near-field Cr(VI) concentrations were 25 to 90 times below the OSHA PEL (96 to 98.9% exposure reduction) and represent 14 to 154 times (92.7 to 99.3%) reduction compared to the welding fume of the baseline E308L-16 electrode. The far-field Cr(VI) concentrations were 33 to 97 times below the OSHA PEL (97 to 99% exposure reduction) and represent eight to 41times (87.6 to 98.9%) reduction compared to the welding fume of the baseline E308L-16 electrode.

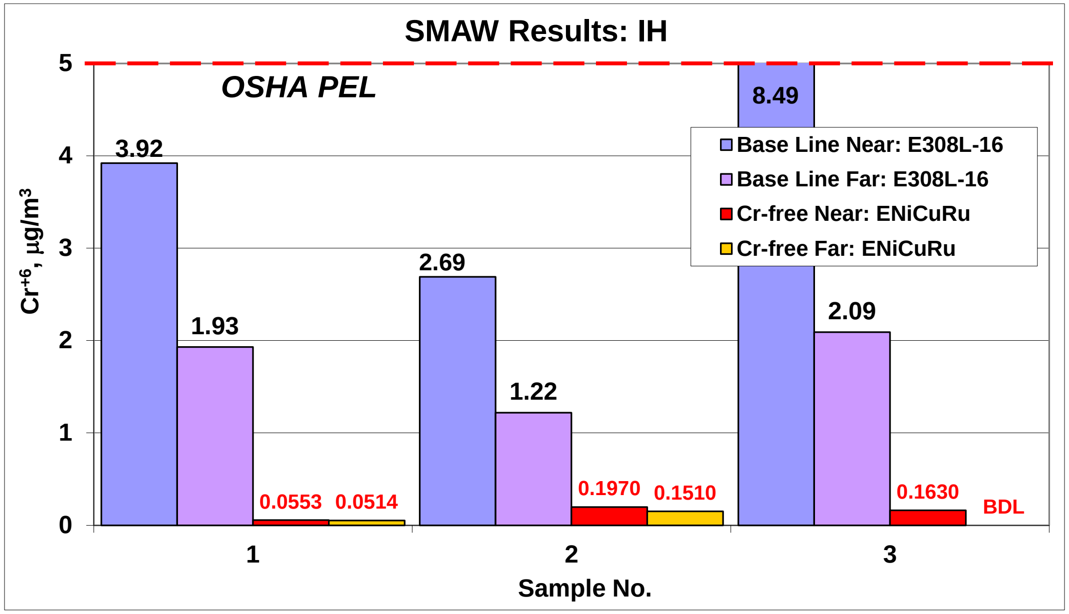


Figure 6.15 Cr(VI) Concentration in the Welding Fume of E308L-16 and ENiCuRu Collected Using IH Pumps at near and far Locations from the Welding Arc

Based on the three test methods the Cr-free SMAW electrode provided Cr(VI) levels of six to 97 times lower than the OSHA PEL (83.2 to 99% exposure reduction) and between 89.4 and 99.8% exposure reduction compared to the conventional E308L-16 electrode (

Possible sources of these variations in the test results could be the fume collection and fume analysis procedures. However, these test results still allow evaluation of the performance of the Cr-free ENiCuRu electrode in terms of reduction of Cr(VI) emission compared to the OSHA PEL of 0.5 μg/m^3 and compared to the Cr(VI) emission of the baseline E308L-16 electrode. Such comparison is provided in **Error! Not a valid bookmark self-reference.**.

The reduction in Cr(VI) emission of the test ENiCuRu electrode versus the OSHA PEL was calculated using the following equations:

Average Cr(VI) reduction = [1 –aver $Cr(VI)_{ENiCuRu}$/5] x100, % (1)

Max Cr(VI) reduction = [1 –min $Cr(VI)_{ENiCuRu}$/5] x100, % (2)

Min Cr(VI) reduction = [1 –max $Cr(VI)_{ENiCuRu}$/5] x100, % (2)

A similar approach was used to calculate the reduction in Cr(VI) emission of ENiCuRu versus the baseline E308L-16 electrode:

Average Cr(VI) reduction = [1 –aver $Cr(VI)_{ENiCuRu}$/aver $Cr(VI)_{E308L}$] x100, % (4)

Max Cr(VI) reduction = [1 –min $Cr(VI)_{ENiCuRu}$/max $Cr(VI)_{E308L}$] x100, % (5)

Min Cr(VI) reduction = [1 –max $Cr(VI)_{ENiCuRu}$/min $Cr(VI)_{E308L}$]x100, % (6)

$Cr(VI)_{ENiCuRu}$ and $Cr(VI)_{E308L}$ in Equations 1 through 6 are correspondingly the average, maximum, and minimum Cr(VI) contents in the welding fume of ENiCuRu and E308L-16 electrodes determined in this study (**Error! Not a valid bookmark self-reference.**). This calculation approach allowed the quantification of the reduction in Cr(VI) exposure provided by the ENiCuRu electrode based on the whole range of variations in the test results.

The ELPI measured Cr(VI) concentrations in the welding fume of E308L-16 and ENiCuRu electrodes are summarized in Figure 6.13 and Table 6.5 and **Error! Not a valid bookmark self-reference.**. It should be noted that the main application of the ELPI apparatus is quantification of the fume particle size and mass distribution. The ELPI separates the fume in 13 different filters/stages. In this study, the fume collected in all filters was analyzed to determine the cumulative Cr(VI) content in the welding fume. This could have introduced some of the variations in the Cr(VI) content in the welding fume collected with ELPI (Table 6.5).

In eight fume samples of E308L-16, the Cr(VI) concentration varied between 7.88 and 33.6 μg/m^3, thus exceeding between 1.6 and 6.7 times the OSHA PEL of 5 μg/m^3. In nine fume samples of the ENiCuRu electrode the Cr(VI) concentration varied between 0.059 and 0.839 μg/m^3, which is six to 85 times below the OSHA PEL. Compared to the OSHA PEL, the Cr-free electrode provided 83.2 to 98.8% reduction in Cr(VI) exposure. Compared to the baseline E308L-16 electrode, ENiCuRu provided 89.4 to 99.8% exposure reduction, which corresponds to a reduction factor of nine to 569.

A comparison of the Cr(VI) concentration in the welding fume of the tested electrodes measured using the AS is shown in Figure 6.14. The Cr(VI) values measured using the AS were lower than those measured with the ELPI, but showed the same trends.

Table 6.6). All maximum and average Cr(VI) exposure reduction values and five (out of eight) of the minimum exposure reduction values of the test ENiCuRu electrode determined during the field testing met the performance objective of 90% reduction in the Cr(VI) emission.

The minimum exposure reduction values of ENiCuRu determined in fume collected using ELPI were slightly below 90%. This can be related to the nature of fume collection with ELPI as explained above. The minimum exposure reduction of ENiCuRu versus E308L-16 fume colected in far-field IH was also slightly below 90%.

In summary, out of 20 fume samples generated by the ENiCuRu electrode, 18 samples exceeded the performance objective of 90% exposure reduction compared to OSHA PEL and 19 samples exceeded this objective compared to the E308L electrode. Two ELPI samples and one far-field IH sample were close below the 90% objective. Based on the analysis of the test results, it can be concluded that the Cr-free ENiCuRu electrode met the performance objective of a reduction in Cr(VI) exposure compared to the OSHA PEL and the conventional type E308L electrode.

Cr(VI) Content in Welding Fume of Gas Metal Arc Electrodes

The main source of Cr(VI) in the welding arc of shielded electrodes are compounds in the electrode coating that form alkali oxides such as K_2CrO_4 and Na_2CrO_4. Due to the absence of such alkali compounds in the gas metal welding arc, the GMAW process generates significantly lower emission of Cr(VI) compared to SMAW. This was confirmed in the field testing of baseline ER308LSi and Cr-free ERNiCuRu GMAW electrodes in this project.

The results of Cr(VI) analyses in welding fume generated by the ER308LSi baseline electrodes and by the Cr-free ERNiCuRu electrodes collected using the ELPI, the AS, and the IH near and far location pumps are provided in Appendix H. The Cr(VI) content in most of the ER308LSi and ERNiCuRu fume samples collected using IH pumps at near and far field locations was below the limit of detection or very close above it. For this reason, IH collected samples are not included in the analyses of test results.

The concentration of Cr(VI) in the fume collected using ELPI and AS is summarized in Figure 6.16 and Table 6.7 and

Table 6.8. The exposure reduction of the ERNiCuRu electrode provided in

Table 6.8 is evaluated using equations 1 through 6. The Cr(VI) concentration in the fume of all ER308LSi samples was below the OSHA PEL, but one was close to the 2.5 $\mu g/m^3$ action level. The Cr(VI) content in the ERNiCuRu fume samples collected using ELPI varied between 0.088 and 0.733 $\mu g/m^3$. This was 6.8 to 57 times below the OSHA PEL (85.3 to 98.2% exposure reduction) and represented a factor of up to 28 times (96.4%) reduction compared to the welding fume of the baseline ER308LSi electrode.

The Cr(VI) content in the ERNiCuRu fume samples collected using AS varied between 0.188 and 0.654 $\mu g/m^3$. This content was 7.6 to 42 times below the OSHA PEL (86.9 to 97.6% exposure reduction) and represented a factor of up to 13.6 times (92.6%) exposure reduction compared to ER308LSi.

Most of the Cr(VI) data in ERNiCuRu and ER308LSi generated in this study were below the detection limit of Cr(VI) or closely above it. However, based on the analyses, it can be concluded that the Cr-free ERNiCuRu electrode met the performance objectives of Cr(VI) exposure reduction stated in Table 3.3.

Table 6.7 Cr(VI) Content in Welding Fume of ERNiCuRu and ER308LSi Electrodes in μg/m^3

Collection	ELPI		AS	
Sample No.	ER308LSi	ERNiCuRu	ER308LSi	ERNiCuRu
1	2.470	0.088	0.98	0.118
2	1.330	0.723	1.60	0.654
3	0.738	0.733	1.30	
4	0.572		1.60	
5	0.961			
Max	**2.470**	**0.733**	**1.60**	**0.654**
Min	**0.572**	**0.088**	**0.98**	**0.118**
Average	**1.2142**	**0.51467**	**1.37**	**0.386**
St. deviation	**0.757**	**0.370**	**0.296**	**0.379**

*Fume collection day:	one	two	three	four	five

Table 6.8 Reduction in Percent of Cr(VI) Content in Welding Fume of ERNiCuRu versus the OSHA PEL and versus ER308LSi

Collection	ELPI		AS	
Comparison	vs. OSHA PEL	vs. ER308LSi	vs. OSHA PEL	vs. ER308LSi

Max, %	98.24	96.44	97.64	92.62
Min, %	85.34	-26.40	86.92	33.27
Average, %	89.71	57.61	92.28	71.28

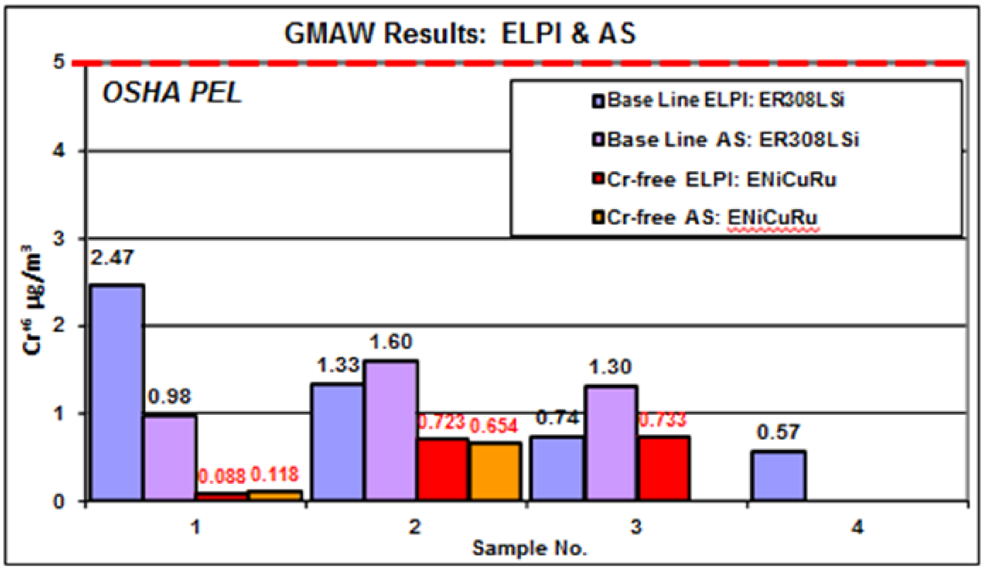


Figure 6.16 Cr(VI) Concentration in the Welding Fume of ER308LSi and ERNiCuRu Collected Using ELPI and AS

Metals Content in Welding Fume of Shielded Metal Arc Electrodes

The results of metals content in the welding fume of the baseline E308L-16 and the Cr-free ENiCuRu SMAW electrodes are summarized in Table 6.9 for the main alloying components in the two electrodes and in

The results from this study show that the metal emissions of the Cr-free ENiCuRu consumable are between two and four orders of magnitude below the corresponding (available) OSHA PELs. The Ru emission in ENiCuRu was similar to the conventional E308L-16 electrode (between 0.0002 and 0.0017 mg/m^3) and below the limit of quantitation. The Sr emission in ENiCuRu was also extremely low, between 0.002 and 0.02 mg/m^3. These results confirm that the Cr-free ENiCuRu electrode met objectives on reducing the hazardous air emissions and occupational exposure stated in Table 3.3

Table 6.10 and

Table 6.11 for impurities. All data of these analyses are presented in Appendix I.

The fume was collected using IH pumps at near and far distances and the AS. The content of all main alloying elements in the fume of both electrodes was between two and three orders of magnitude below the corresponding OSHA PEL (Table 6.9). The content of Cr, Fe, and Mn in the fume of E308L-16 was about one order of magnitude higher than in the fume of ENiCuRu. This is an expected result since these elements are not present in the composition of the Cr-free electrode. Similarly, the content of Cu and Ni in the ENiCuRu was about one order of magnitude higher than in the E308L-16 electrode. The Ru content was fairly similar in the fume of both electrodes and most of the measurements were below the limit of quantitation (total measured quantity in the fume <0.2 μg;

Table 6.11). There is currently no OSHA PEL for Ru. However, these results correlate well with the measurements of Ru in the welding fume of ENiCuRu (0.003 wt %) performed during the laboratory testing stage of this project (see Section 6.1.1)

For both electrodes, the content of the impurity elements As, Cd, Co, Mo, Pb, Ru, V, and Zn was below the limit of quantitation (<0.2 μg) except of some slight deviations above that limit in separate measurements for Pb, Mo, and Zn in the fume of the E403L-16 electrode and for Ru in the ENiCuRu electrode. The Sr content in the fume of the ENiCuRu electrode was above the limit of quantification for all measured values. The Sr concentration in the fume of ENiCuRu was one to two orders of magnitude higher than in the E308L-16 fume, but still very low (between 0.002 and 0.02 mg/m^3;

Table 6.11). The Sr in the welding fume originates from the presence of 19 wt % $SrCO_3$ in the coating of this electrode. There is currently no OSHA PEL for Sr.

Table 6.9 Metals (Alloying Elements) Content in Welding Fume of SMAW Electrodes (mg/m^3)

Electrode Method	Concentration mg/m^3	Chromium	Copper	Iron	Manganese	Nickel	Ruthenium
E308L-16 IH-M N	Average	0.01416	0.0011	0.03357	0.02337	0.0123833	
	Min	0.0216	0.0014	0.0486	0.0359	0.0297	<0.0003
	Max	0.00919	0.00079	0.0238	0.0151	0.00219	<0.0004
ENiCuRu IH-M N	Average	0.00255	0.0068	0.01383	0.00099	0.0382333	
	Min	0.00493	0.0087	0.0295	0.00204	0.0471	<0.0002
	Max	0.00106	0.0051	0.00415	0.00044	0.027	<0.0004
E308L-16 IH-M F	Average	0.00866	0.00029	0.00833	0.00855	0.0006687	
	Min	0.016	0.00032	0.00943	0.00988	0.000894	<0.0002
	Max	0.00418	0.00026	0.00678	0.0065	0.000483	<0.0003
ENiCuRu IH-M F	Average	0.00135	0.00253	0.00481	0.00075	0.0100633	
	Min	0.00241	0.0034	0.00931	0.00111	0.0137	<0.0002
	Max	0.00061	0.0011	0.00243	0.00038	0.00379	<0.0003

E308L-16 AS	Average	0.02068	0.00207	0.03994	0.03595		
	Min	0.0385	0.00259	0.0543	0.0695	<0.0013	<0.0013
	Max	0.00531	0.00155	0.027	0.00844	0.00503	<0.0018
ENiCuRu AS	Average	0.00269	0.01289			0.02684	
	Min	0.00363	0.025	<0.0027	<0.0005	0.0527	<0.0005
	Max	0.00186	0.00464	<0.0087	<0.0017	0.0114	<0.0017
OSHA PEL, mg/m^3		1	0.1	10	5	1	N.A.

The results from this study show that the metal emissions of the Cr-free ENiCuRu consumable are between two and four orders of magnitude below the corresponding (available) OSHA PELs. The Ru emission in ENiCuRu was similar to the conventional E308L-16 electrode (between 0.0002 and 0.0017 mg/m^3) and below the limit of quantitation. The Sr emission in ENiCuRu was also extremely low, between 0.002 and 0.02 mg/m^3. These results confirm that the Cr-free ENiCuRu electrode met objectives on reducing the hazardous air emissions and occupational exposure stated in Table 3.3

Table 6.10 Metals (Impurity) Content in Welding Fume of SMAW Electrodes (mg/m^3)

Electrode Method	Content / Concentration	Arsenic		Cadmium		Cobalt		Lead	
		µg	mg/m^3	µg	mg/m^3	µg	mg/m^3	µg	mg/m^3
E308L-16 IH-M N	Average	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003		0.00034
	Min	<0.2		<0.2		<0.2		<0.2	0.0004
	Max	<0.2		<0.2		<0.2		0.290	0.00028
ENiCuRu IH-M N	Average	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
	Min	<0.2		<0.2		<0.2		<0.2	
	Max	<0.2		<0.2		<0.2		<0.2	
E308L-16 IH-M F	Average	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
	Min	<0.2		<0.2		<0.2		<0.2	
	Max	<0.2		<0.2		<0.2		<0.2	
ENiCuRu IH-M F	Average	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
	Min	<0.2		<0.2		<0.2		<0.2	
	Max	<0.2		<0.2		<0.2		<0.2	
E308L-16 AS	Average	<0.2		<0.2		<0.2		<0.2	
	Min	<0.2	<0.0013	<0.2	<0.0013	<0.2	<0.0013	<0.2	<0.0013
	Max	<0.2	<0.0018	<0.2	<0.0018	<0.2	<0.0018	<0.2	<0.0018

ENiCuRu AS	Average	<0.2		<0.2		<0.2		<0.2	
	Min	<0.2	<0.0005	<0.2		<0.2	<0.0005	<0.2	<0.0005
	Max	<0.2	<0.0017	<0.2		<0.2	<0.0017	<0.2	<0.0017
OSHA PEL, mg/m^3					0.1		0.1		

Table 6.11 Metals (Impurity) Content in Welding Fume of SMAW Electrodes (mg/m^3)

Electrode Method	Content / Concentration	Molybdenum		Strontium		Ruthenium		Vanadium		Zinc	
		µg	mg/m^3	µg	mg/m^3	µg	mg/m^3	µg	mg/m^3	µg	mg/m^3
E308L-16 IH-M N	Average		0.00035	<0.2				<0.2		0.3	0.00049
	Min	<0.2	0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	0.23	0.00069
	Max	0.290	0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	0.37	0.00031
ENiCuRu IH-M N	Average	<0.2		7.97	0.01003			<0.2		<0.2	
	Min	<0.2	<0.0002	5.13	0.00664	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
	Max	<0.2	<0.0003	10.8	0.0142	0.310	<0.0004	<0.2	<0.0003	<0.2	<0.00045
E308L-16 IH-M F	Average	<0.2		<0.2		<0.2		<0.2			
	Min	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.00028	<0.2	<0.0002
	Max	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	0.23	<0.0003
ENiCuRu IH-M F	Average	<0.2		2.94	0.00387	<0.2		<0.2		<0.2	
	Min	<0.2	<0.0002	1.51	0.00191	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
	Max	<0.2	<0.0003	4.36	0.00495	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
E308L-16 AS	Average	<0.2		<0.2		<0.2		<0.2			
	Min	<0.2	<0.0013	<0.2	<0.0013	<0.2	<0.0013	<0.2	<0.0013	<0.2	<0.0013
	Max	<0.2	<0.0018	<0.2	<0.0018	<0.2	<0.0018	<0.2	<0.0018	0.34	0.0025
ENiCuRu AS	Average	<0.2		2.25	0.01094	<0.2		<0.2		<0.2	
	Min	<0.2	<0.0005	1.2	0.00324	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
	Max	<0.2	<0.0017	3.29	0.0234	<0.2	<0.0017	<0.2	<0.0017	<0.2	<0.0017
OSHA PEL, mg/m^3			15		N.A.		N.A.		1		5

Metals Content in Welding Fume of Gas Metal Arc Electrodes

The results of metals content in the welding fume of the baseline E308L-16 and the Cr-free ENiCuRu SMAW electrodes are summarized in Table 6.12 for the main alloying components in the two electrodes and in Table 6.13 and

Table 6.14 for impurities. All data of these analyses are presented in Appendix J.

The fume was collected using IH pumps at near and far distances, the AS and the ELPI. Two ELPI measurements were performed and the fume analyses were conducted separately for each of the 13 ELPI stages. The ELPI measured values in Table 6.12, Table 6.13, and

Table 6.14 represent the total content in all stages of a particular measurement.

The content of Cr, Fe, and Mn in the fume of both electrodes was between one and three orders of magnitude below the corresponding OSHA PEL (Table 6.12). The content of these elements in the fume of E308L-16 was one order of magnitude higher than in the fume of ENiCuRu. This is an expected result since these elements are not present in the composition of the Cr-free electrode.

The Ni content in the ENiCuRu was up to two orders of magnitude higher than in the E308L-16 electrode, and in the AS measurement exceeded the OSHA PEL of 1 mg/m^3. The Cu content in the ENiCuRu was up to two orders of magnitude higher than in the E308L-16 electrode. The Cu content in the fume of ERNiCuRu exceeded the OSHA PEL of 0.1 mg/m^3 in one of three measurements of IH near location measurements, in the single AS measurement, and the two ELPI measurements (as total content in 13 stages; Table 6.12). Such behavior is expected since ERNiCuRu is a Ni-based welding consumable with high alloying content of Cu. Similar behavior would be expected in GMAW with other Ni-based consumables. The source of Ni and Cu in the welding fume is vaporization of molten metal in the welding arc. Possible solution for reduction of Ni and Cu in the welding fume of ERNiCuRu is reduction of the arc power by using a low heat input welding process such as cold metal transfer.

The Ru content was fairly similar in the fume of both electrodes and most of the measurements were below the limit of quantitation (total measured quantity in the fume <0.2 μg;

Table 6.14). There is currently no OSHA PEL for Ru. However, these results correlate well with the measurements of Ru in the welding fume of ENiCuRu (0.003 wt %) performed during the laboratory testing stage of this project (see Section 6.1.1).

Table 6.12 Metals (Alloying Elements) Content in Welding Fume of GMAW Electrodes (mg/m^3)

Electrode Method	Concentration mg/m^3	Chromium	Copper	Iron	Manganese	Nickel	Ruthenium
ER308LSi IH-M N	Average	0.00450	0.00188	0.04571	0.00694	0.00351	
	Max	0.00887	0.00226	0.149	0.0115	0.00826	<0.0008
	Min	0.00193	0.0015	0.00966	0.00244	0.00063	<0.0003
ERNiCuRu IH-M N	Average	0.01529	0.06543	0.10503	0.00484	0.23310	
	Max	0.0326	**0.15**	0.25	0.00745	0.389	0.00266
	Min	0.00166	0.0116	0.0104	0.00222	0.0273	<0.0007
ER308LSi IH-M F	Average	0.00226		0.00842	0.00418	0.00081	
	Max	0.0049	<0.0003	0.0185	0.0108	0.0017	<0.0005
	Min	0.00103	0.00023	0.00348	0.0011	0.00031	<0.0002
ERNiCuRu IH-M F	Average	0.00145	0.00532	0.00860		0.07665	
	Max	0.00205	0.00859	0.0168	<0.0008	0.21	<0.0008
	Min	0.0009	0.00082	0.00391	<0.00045	0.00505	<0.0004
ER308LSi AS	Average	0.04198	0.00452	0.17768	0.13210	0.02287	
	Max	0.0858	0.0053	0.345	0.251	0.0357	<0.0083

	Min	0.0167	0.00374	0.0567	0.0454	0.0129	<0.0020
ERNiCuRu AS	Average						
	Max	0.0315	**0.500**	0.0589	0.0067	**1.32**	0.0044
	Min	-	-	-	-	-	-
ER308LSi ELPI	Average						
	Max	0.1315	0.0054	0.2293	0.5604	0.1598	<0.0003
	Min	0.00517	0.0031	0.0216	0.00105	0.00174	<0.0076
ERNiCuRu ELPI	Average						
	Max	0.0195	**0.33517**	0.05939	0.00687	0.97131	0.0024
	Min	0.01783	**0.23865**	0.04131	0.0012	0.63841	<0.0003
OSHA PEL, mg/m3		1	0.1	10	5	1	N.A.

The content of the impurity elements As, Cd, Co, Mo, Pb, Ru, Sr, V, and Zn was below the limit of quantitation (<0.2 μg) except for some slight deviations above that limit in separate measurements for Mo and Zn in the fume of the E403L-16 electrode and for Mo, Pb, Ru, Sr, and Zn in the ENiCuRu electrode. The Sr concentration in the fume of both electrodes was fairly similar and very low (between 0.002 and 0.0083 mg/m^3;

Table 6.14). There is currently no OSHA PEL for Sr.

Table 6.13 Metals (Impurity) Content in Welding Fume of GMAW Electrodes (mg/m^3)

Electrode Method	Content / Concentration	Arsenic		Cadmium		Cobalt		Lead	
		μg	mg/m^3	μg	mg/m^3	μg	mg/m^3	μg	mg/m^3
ER308LSi IH-M N	Average	<0.2		<0.2		<0.2		<0.2	<0.0008
	Max	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0003
	Min	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0008
ERNiCuRu IH-M N	Average	<0.2		<0.2		<0.2		<0.2	
	Max	<0.2	<0.0007	<0.2	<0.0007	<0.2	<0.0007	<0.2	<0.0007
	Min	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
ER308LSi IH-M F	Average	<0.2		<0.2		<0.2		<0.2	
	Max	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
	Min	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
ERNiCuRu IH-M F	Average	<0.2		<0.2		<0.2		<0.2	
	Max	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0008
	Min	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
ER308LSi	Average	<0.2		<0.2		<0.2		<0.2	

AS	Max	<0.2	<0.0083	<0.2	<0.0083	<0.2	<0.0083	<0.2	<0.0083
	Min	<0.2	<0.0020	<0.2	<0.0020	<0.2	<0.0020	<0.2	<0.0020
ERNiCuRu AS	Average								
	Max	<0.2	<0.0030	<0.2	<0.0030	<0.2	<0.0030	<0.2	<0.0030
	Min	-	-	-	-	-	-	-	-
ER308LSi ELPI	Average	<0.2		<0.2		<0.2		<0.2	
	Max	<0.2	<0.0076	<0.2	<0.0076	<0.2	<0.0076	<0.2	<0.0076
	Min	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
ERNiCuRu ELPI	Average								
	Max	0.22	<0.0003	0.21	<0.0003	0.21	<0.0003	0.31	<0.00041
	Min	<0.2	0.00029	<0.2	0.00027	<0.2	0.00027	<0.2	0.0003
OSHA PEL, mg/m^3					0.1		0.1		

Table 6.14 Metals (Impurity) Content in Welding Fume of GMAW Electrodes (mg/m^3)

Electrode Method	Content / Concentration	Molybdenum		Strontium		Ruthenium		Vanadium		Zinc	
		μg	mg/m^3	μg	mg/m^3	μg	mg/m^3	μg	mg/m^3	μg	mg/m^3
ER308LSi IH-M N	Average	<0.2		<0.2		<0.2		<0.2			
	Max	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0003
	Min	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	0.25	0.00059
ERNiCuRu IH-M N	Average							<0.2			
	Max	0.370	0.00065	1.00	0.00176	0.960	0.00266	<0.2	<0.0007	0.30	<0.0007
	Min	<0.2	<0.0006	<0.2	0.0006	<0.2	<0.0007	<0.2	<0.0004	<0.2	<0.00053
ER308LSi IH-M F	Average	<0.2		<0.2		<0.2		<0.2			
	Max	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0002
	Min	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	0.00064
ERNiCuRu IH-M F	Average	<0.2		<0.2		<0.2		<0.2			0.00603
	Max	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0008	<0.21	0.00037
	Min	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	0.0005
ER308LSi AS	Average										
	Max	<0.2	<0.0083	<0.2	<0.0083	<0.2	<0.0083	<0.2	<0.0083	0.52	0.0075
	Min	<0.2	<0.0020	<0.2	<0.0020	<0.2	<0.0020	<0.2	<0.0020	<0.2	0.0038
ERNiCuRu AS	Average										
	Max	<0.2	<0.0030	<0.2	<0.0030	0.290	<0.0044	<0.2	<0.0030	0.370	0.0056
	Min	-	-	-	-	<0.2	-	-	-	<0.2	-
ER308LSi ELPI	Average	<0.2		<0.2		<0.2		<0.2			
	Max	<0.2	<0.0076	<0.2	<0.0076	<0.2	<0.0076	<0.2	<0.0076	0.660	0.025
	Min	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	0.660	0.00192
ERNiCuRu ELPI	Average										
	Max	0.31	0.00041	0.21	0.00027	0.44	0.0024	<0.2	<0.0005	0.32	0.00073

	Min	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
OSHA PEL, mg/m^3			15		N.A.		N.A.		1		5

The results from this study show that the metal emissions of the Cr-free ENiCuRu consumable are between one and three orders of magnitude below the corresponding (available) PELs. The Ru emission in ENiCuRu was similar to the conventional E308L-16 electrode (between 0.0003 and 0.0044 mg/m^3) and below the limit of quantitation. The Sr emission in ENiCuRu was also extremely low, between 0.0003 and 0.0017 mg/m^3. These results confirm that the Cr-free ENiCuRu electrode met objectives on reducing the hazardous air emissions and occupational exposure stated in Table 3.3, except of separate measurements of Cu and Ni.

6.1.3 Field Demonstration Health and Safety Monitoring

Field Screening

The results of collective field screening for alpha, beta, and gamma radiation performed the Ludlum Model 44-9 Pancake probe in conjunction with the Ludlum Model 3-97 Survey Radiation NORM Meter are summarized in

Table 6.15 and Table 6.16. The peak counts measured at the welding table, welding rod, and the welding plates, and on the people working in the welding room were in the range of the background peak counts.

Table 6.15 Radiation Field Screening Results (Ludlum 44-9), μCi

Date	Time	Measurement Location	Background Peak Count*	Reading Peak Count*	Notes
8/9/2011		John	0.02	0.04	
8/10/2011		Kappy		0.02	
8/10/2011		John		0.01	
8/10/2011	16:39	John	0.04	0.00	
8/11/2011	8:18	John		0.03	
8/11/2011	12:30	John		0.02	
8/15/2011	10:30	John	0.01	0.02	
8/15/2011	11:40	John		0.01	
8/15/2011	11:40	Boian		0.01	
8/15/2011	17:20	welding table		0.01	
8/16/2011	11:15	John	0.01	0.01	

8/16/2011	11:15	Boian	0.02	0.02	
8/16/2011	11:15	Omar	0.02	0.02	
8/16/2011	12:00	welding rod		0.06	(steady)
8/16/2011	15:00	Boian		0.02	
8/16/2011	15:00	Omar		0.02	
8/16/2011	14:25	ELPI		0.00	
8/16/2011	16:25	John	0.02	0.03	
8/16/2011	16:25	Boian		0.02	
8/16/2011	16:25	Omar		0.03	
8/16/2011	16:25	welding table		0.02	
8/17/2011	7:00	welding rod	0.02	0.04	
8/17/2011	11:50	John		0.01	
8/17/2011	11:50	Boian		0.01	
8/17/2011	11:50	Omar		0.01	
8/17/2011	16:45	John		0.04	
8/17/2011	16:45	Boian		0.03	
8/17/2011	16:45	Omar		0.03	
8/17/2011	17:12	welding table		0.03	

Table 6.16 Radiation Field Screening Results (Ludlum 44-9), μCi

Date	Time	Measurement Location	Background Peak Count*	Reading Peak Count*	Notes
8/17/2011	17:12	welding rod		0.05	(steady)
8/18/2011	8:00	John	0.03	0.02	
8/18/2011	8:00	Boian		0.03	
8/18/2011	8:00	Omar		0.02	
8/18/2011	14:46	Steve		0.03	
8/18/2011	15:00	John		0.01	
8/18/2011	15:10	Kappy		0.02	
8/18/2011	15:10	Omar		0.02	
8/18/2011	16:30	Kappy		0.03	
8/18/2011	16:30	Omar		0.03	
8/18/2011	16:30	John		0.02	
8/18/2011	16:30	Boian		0.02	
8/18/2011	16:30	welding table		0.05	
8/18/2011	16:30	plates		0.01	
8/22/2011	7:30	Kappy		0.03	
8/22/2011	7:30	Omar		0.02	
8/22/2011	7:30	John		0.02	
8/22/2011	7:30	Plate prior to welding		0.03	
8/22/2011	9:00	Omar		0.02	
8/22/2011	9:00	John		0.02	
8/22/2011	9:00	Plate after welding		0.04	
8/25/2011	10:00	welding table		0.02	
8/25/2011	10:00	John		0.01	
8/25/2011	12:24	Area		0.02	

The Ludlum 2929 measurements of the amount of radiation each person received daily while in the room during welding are summarized in Table 6.17 through 6.19. The results indicated mostly beta radiation, and the DAC never exceeded the project action levels for Ru isotopes:

- DAC for 106 Ru: 5×10^{-9} μCi/mL
- Project action level: 10% of DAC = 5×10^{-10} μCi/mL

The amount of alpha and beta radiation received by the personnel participating in the Field Demonstration was in the range of the background measurements (Table 6.17 and 6.18). The concentration of radiation received by the welder was about one order of magnitude below the project action limit, and DAC hour exposure was zero (Table 6.19). These results show that the minor amounts of ruthenium and strontium found in the welding fume of the Cr-free ENiCuRu and ERNiCuRu electrodes cannot result in overexposure to radiation of the welding personnel and that the performance objectives regarding occupational exposure set in Table 3.3 have been met.

Table 6.17 Ludlum 2929 Measured Radiation Received by Field Test Participants during Welding, μCi

Date	Time	Measurement Location/Source	Background 1		Check Source		Background 2		Reading	
			α	β	α	β	α	β	α	β
8/9/2011	15:55	John	0	45	1	2466	0	49	0	61
8/10/2011	7:05	Initial Calibration check	0	0	2	2486	0	0	-	-
8/10/2011	11:53	John	0	42	1	2460	0	39	1	48
8/10/2011	11:53	Kappy							2	56
8/10/2011	11:53	unexposed Duct Tape							0	56
8/11/2011	6:58	Initial Calibration check	3	54	1	2445	0	46		
8/11/2011	12:30	Mid-day calibration	0	50	1	2501	0	45	1	43
8/11/2011	13:49	Rad_20110811	0	41			1	44	4	50
8/11/2011	16:20	End of welding	0	34	1	2498	0	54		
8/15/2011	8:00	Initial Calibration check	0	58	1	2417	0	50		
8/15/2011	12:13	John							0	36
8/15/2011	12:13	Boian							1	53
8/15/2011	12:13	Omar							0	34
8/15/2011	12:13	Rad_20110815	0	40	1	2008	2	44	2	57
8/16/2011	7:00	Initial Calibration check	0	52	0	1976	0	45		
8/16/2011	11:07	Mid-day calibration	0	31	3	1938	1	41		
8/16/2011	11:15	John							1	47
8/16/2011	11:15	Boian							0	40
8/16/2011	13:34	Pre-test readings	1	51	0	1934	1	46		
8/16/2011	13:40	AS							2	51

Table 6.18 Ludlum 2929 Measured Radiation Received by Field Test Participants during Welding, μCi

Date	Time	Measurement Location/Source	Background 1		Check Source		Background 2		Reading	
			α	β	α	β	α	β	α	β
8/16/2011	16:25	Background after welding test	0	41	2	1854	44			
8/16/2011	16:25	Kappy							2	55
8/16/2011	16:25	Omar							0	37
8/16/2011	16:25	John							0	41
8/16/2011	16:25	Boian							0	53
8/16/2011	17:25	Re-calibrate	1	44	2	2309	0	57		
8/17/2011	7:30	Background	0	41	0	2235	0	41		
8/17/2011	12:26	RAD_20110817 AM	0	42	1	2138	0	34	13	62
8/17/2011	17:15	Background	0	42	1	1967	0	46		
8/17/2011	17:15	RAD_20110817 PM							8	43
8/17/2011	17:15	John							5	64
8/17/2011	17:15	Boian							0	40
8/17/2011	17:15	Omar							6	46
8/18/2011	9:20	Background	0	54	1	2118	0	60		
8/18/2011	16:55	RAD_20110818 PM	0	54	2	2004	0	46	2	45
8/18/2011	16:55	Boian							2	56
8/18/2011	16:55	John							0	39
8/22/2011	16:20	Background	0	38	1	2053	0	54		
8/22/2011	16:20	RAD_20110822 A							8	47
8/22/2011	16:20	RAD_20110822 B	0	55	3	2169	0	40	3	46
8/22/2011	16:20	RAD_20110822 C	0	54	0	2071	1	35	2	44
8/22/2011	16:20	Kappy							0	40
8/22/2011	16:20	Omar							2	37
8/25/2011	12:20	RAD_20110825	0	45	1	2181	0	44	9	62
8/25/2011	12:20	John							3	42

Table 6.19 Ludlum 2929 Measured Radiation and DAC Exposure Received by Welder during Field Demonstration

Worker Name	Sample Date	Final Count Date	Time In	Time Out	Total Time (hrs)	Concentration (μCi/cm^3)	DAC-Hour Exposure	Notes
John	8/10/2011	8/10/2011	8:40	12:39	4.0	2.17E-11	0	
John	8/11/2011	8/11/2011	8:50	16:17	7.5	2.20E-11	0	
John	8/15/2011	8/15/2011	8:15	16:30	7.5	2.65E-11	0	less one hour for lunch
John	8/16/2011	8/16/2011	12:10	16:30	4.3	5.92E-11	0	
John	8/17/2011	8/17/2011	7:16	12:15	5.0	4.60E-11	0	
John	8/17/2011	8/17/2011	12:20	16:40	4.3	5.35E-11	0	
John	8/18/2011	8/18/2011	9:15	16:30	5.1	8.24E-11	0	less one hour for lunch
John	8/22/2011	8/22/2011	7:35	16:20	8.8	4.15E-11	0	
John	8/25/2011	8/25/2011	10:15	12:20	2.1	1.12E-10	0	

6.2 Weld Mechanical Properties

Testing of the mechanical properties in weldments produced with the Cr-free ENiCuRu and ERNiCuRu consumables and with conventional baseline E308L and ER308LSi consumables has been conducted both during the Laboratory Demonstration and during the Field Demonstration in this project. The results of these studies are discussed separately in the next subsections.

6.2.1 Laboratory Demonstration Testing of Weld Mechanical Properties

Tensile Testing

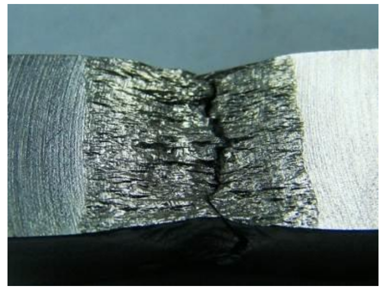
The results of tensile testing of the ENiCuRu all weld metal and of the ERNiCuRu cross weld tensile testing are summarized in

Table 6.20 and

Table 6.21.

Weld	YS MPa	YS ksi	UTS MPa	UTS ksi	Elong. %
ERNiCuRu (average of 3)	**327**	**53**	**584**	**83**	**34**
304L St. Steel Min. Values	170	24	480	69	40
AWS A5.4-92 Min: ER316L	-	-	490	70	30
AWS A5.4-92 Min: ER308L	-	-	520	75	30

a)



b)

Figure 6.17 shows tested samples of ENiCuRu and ERNiCuRu welds. The yield strength of ENiCuRu exceeded the minimum specified value of type 304L stainless steel by a factor of 2.17. The tensile strength of all weld metal in this consumable exceeded the minimum values of type 304L steel and of conventional E316L weld metal and was slightly below the minimum value of E308L. The elongation in the test weld was lower than in the reference materials. The performance objectives for ENiCuRu stated in Table 3.2 were met except for the all weld metal elongation.

Both the yield **and** tensile strength in cross weld samples of ERNiCuRu exceeded the minimum requirements for type 304L stainless steel and conventional ER308L and ER316L weld metal, and met the performance objective stated in Table 3.2. Due to non-uniform strain distribution between the weld and base metal during tensile testing of cross weld samples, the elongation values determined in such tests are not directly comparable to all weld metal values. Thus, the 34% elongation found in cross weld tensile testing of ERNiCuRu can be considered as proof of overall good joint ductility.

Table 6.20 Tensile Properties of All Weld Metal of Cr-free ENiCuRu Consumable

Weld	YS MPa	YS ksi	UTS MPa	UTS ksi	Elong. %
ENiCuRu	**370**	**53**	**501**	**72**	**25**
304L St. Steel Min. Values	170	24	480	69	40
AWS A5.4-92 Min: E316L	-	-	490	70	30
AWS A5.4-92 Min: E308L	-	-	520	75	35
Exceeded	Failed				

Table 6.21 Tensile Properties of Cross Welds of Cr-free ERNiCuRu Consumable

Weld	YS MPa	YS ksi	UTS MPa	UTS ksi	Elong. %
ERNiCuRu (average of 3)	**327**	**53**	**584**	**83**	**34**
304L St. Steel Min. Values	170	24	480	69	40
AWS A5.4-92 Min: ER316L	-	-	490	70	30
AWS A5.4-92 Min: ER308L	-	-	520	75	30

a) b)

Figure 6.17 Tensile Test Samples of: a) ENiCuRu All Weld Metal; and b) ERNiCuRu Cross Weld

Bend Testing

A side bend sample of ENiCuRu weld and a face bend sample of ERNiCuRu weld are shown in Figure 6.18. No cracks were found in any of the three ENiCuRu side bent samples and in the three ERNiCuRu face bend samples. The bend test results for both consumables met the performance objectives set in Table 3.2.

a)

b)

Figure 6.18 Bend Test Samples of: a) ENiCuRu All Weld Metal; and b) ERNiCuRu Cross Weld

6.2.2 Field Demonstration Testing of Weld Mechanical Properties

The mechanical testing of the weld test assemblies produced during the field testing trials at Tooele Army Depot was performed at the Naval Surface Warfare Center Carderock Division.

Tensile Testing

The tensile testing results of the all weld metal SMAW E308L baseline welds and ENiCuRu test welds are summarized in

Table 6.22. The yield strength of the baseline E308L welds exceeded the minimum requirement for Type 304L steel based metal. The tensile strength and the elongation of these welds exceeded the minimum requirements for Type 304L steel based metal and for E316L and E308L weld metal.

The yield strength of the all test ENiCuRu welds exceeded the minimum requirement for type 304L steel based metal. The tensile strength of three of these six welds exceeded the minimum requirement for Type 304L stainless steel and two of them exceeded the minimum requirements for E316L and E308L welds. The elongation of only one of these welds exceeded the minimum requirements for E316L and E308L weld metal and almost matched the minimum requirements for Type 304L steel.

These results prove that the optimized ENiCuRu electrode is capable of producing welds that meet and exceed the mechanical properties of the steel that it is intended to be used for (Type 304L stainless steel) and of the welding consumables that it is supposed to replace (E316L and E308L). This has also been proven in the laboratory tests (see Section 6.2.1). The lower tensile strength and elongation values in test weld T004 (

Table 6.22) can be related to the high level of weld defects found in this weld, as shown in Figure 6.24 through Figure 6.29. This weld failed the radiography test, as shown in Table 6.24. The weld defects found in the baseline welds and in the test welds and their potential effect on weld metal mechanical properties are presented in detail in Section 6.3.

Table 6.22 Tensile Testing Results for All Weld Metal Samples of E308L and ENiCuRu Welds

Process / Electrode	Weld I.D.	NSWCCD I.D.	Specimen I.D.	YS, ksi	UTS, ksi	El, %	RA, %
SMAW E308L-16	B003	F531	T1	64.5	89.5	43	60
			T2	61	85.5	42	63
	B004	F532	T1	66	88.5	44	60
			T2	65	88.5	43	59
	B005	F533	T1	64	89.5	44	66
			T2	64	88.5	45	63
			Average	64.1	88.3	43.5	61.8
SMAW ENiCuRu	T003	F534	T1	43.5	68.5	22	35
			T2	49.5	77	27	29
	T004	F535	T1	45.4	60.5	14	20
			T2	44.1	61.5	15	24
	T005	F536	T1	49.3	79	39	46
			T2	45.2	69	21	33
			Average	46.2	69.3	23.0	31.2
304L St. Steel Min. Values				24	69	40	-
AWS A5.4-92 Min: E316L				-	70	30	-
AWS A5.4-92 Min: E308L				-	75	35	-
Exceeded		Failed					

The tensile testing results of transverse samples of the baseline ER308LSi and the test ERNiCuRu welds are summarized in Table 6.23. All test samples of the baseline ER30LSi samples exceeded the minimum yield strength of Type 304L steel. However, all these samples failed to meet the minimum requirements for tensile strength and elongation of Type 304L stainless steel, and of ER316L and ER308L welds. All test welds had brittle failure in the weld metal. These poor mechanical properties can be related to the continuous lack of fusion welding defects found in the ER308L baseline welds as shown in Figure 6.25, 6.25 and Figure 6.30. All baseline welds failed the radiography test, Table 6.24.

All ERNiCuRu test welds exceeded the minimum required yield strength of type 304L stainless steel and the minimum tensile strength of type 304L stainless steel and of ER316L and ER308L weld metal. Due to non-uniform strain distribution between the weld and baseline metal during tensile testing of cross weld samples, the elongation values determined in such tests are not directly comparable to all weld metal values. Thus, the elongation values found in cross weld tensile testing can be considered as a characteristic of the overall joint ductility. The results in Table 6.23 show that the baseline ER208LSi welds had poor ductility and the test ERNiCuRu electrodes had significantly better but not satisfactory ductility. This can be attributed to the high level of defects found in the test welds of both electrodes, as shown in Figure 6.26, 6.30, and Figure 6.31. All ER308LSi baseline welds and all ERNiCuRu test welds failed the radiography test (Table 6.25). The mechanical testing results of all baseline and test welds are presented in detail in Section 6.3.

Table 6.23 Tensile Testing Results for Transverse Weld Samples of ER308LSi and ERNiCuRu Welds

Process / Electrode	Weld I.D.	NSWCCD I.D.	Specimen I.D.	YS, ksi	UTS, ksi	El, %	Failure Location	Fracture Mode
GMAW ER308LSi	B01E1	F527	T1	46.3	56	3.1	Weld	Brittle
			T2	45.5	52	2.1	Weld	Brittle
	B002	F525	T1	42.9	47.1	4.3	Weld	Brittle
			T2	46.8	53.5	3.6	Weld	Brittle
	B0E3	F526	T1	43.1	50	3.2	Weld	Brittle
			T2	44.7	47.4	4.1	Weld	Brittle
	Average			44.9	51	3.4	-	-
GMAW ERNiCuRu	T008G	F537	T1	46.9	78.5	22	Weld	Ductile
			T2	46	80	22	Weld	Ductile
	T009G	F538	T1	44.9	79	22	Weld	Ductile
			T2	45.9	80.5	25	Weld	Ductile
	T0010G	F539	T1	47.2	80	21	Weld	Ductile
			T2	44.4	77.5	19	Weld	Ductile
	Average			45.9	79.3	21.8	-	-
304L St. Steel Min. Values				24	69	40	-	-
AWS A5.4-92 Min: ER316L				-	70	30	-	-
AWS A5.4-92 Min: ER308L				-	75	30	-	-
Exceeded		Failed						

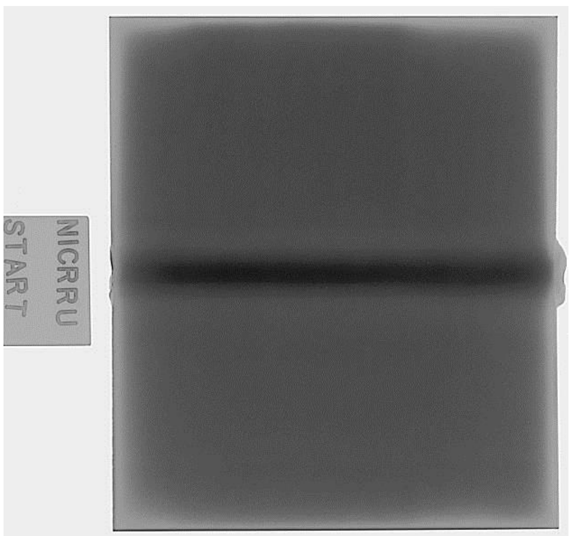
6.3 Weld Quality Evaluation

Quality evaluation in weldments produced with the Cr-free ENiCuRu and ERNiCuRu consumables and with conventional E308L and ER308LSi consumables for welding stainless steel has been conducted both during the Laboratory and the Field Demonstrations in this project. The weld quality was evaluated using radiography and macro-structural and micro-structural examination of test welds. The results of these studies are discussed separately in the next subsections.

6.3.1 Weld Quality Evaluation during Laboratory Demonstration

<u>*Radiography*</u>

Radiographic images of the weld test assemblies made with the ENiCuRu and ERNiCuRu are shown in Figure 6.19. The test report for the ENiCuRu test weld assembly is provided in Appendix K. One small slag inclusion was found in the ENiCuRu weld and slight undercuts were determined in the ERNiCuRu weld. No cracks, incomplete fusion, incomplete penetration, rounded indications, or other welding defects were found in both test assemblies. Both welds passed the requirements of ANSI/AWS B2.1-2000 and ANSI/AWS A5.11-97 and met the performance objectives set in Table 3.2.



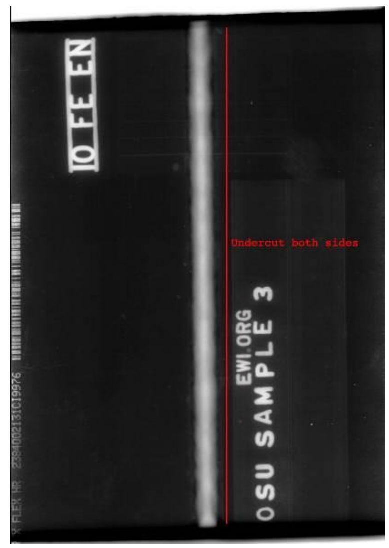


Figure 6.19 Radiographs of the ENiCuRu and ERNiCuRu Weld Test Assemblies

<u>*Weld Macro- and Microstructure Examination*</u>

Macro-sections of the ENiCuRu 0.75 in. test weld assembly, the ENiCuRu 0.25 in. fillet welds in flat, overhead, and vertical down positions, and the ERNiCuRu 0.25 in. test weld assembly are shown in Figure 6.20 through Figure 6.22. No welding defects such as porosity, cracks, slag inclusions, lack of fusion, and lack of penetration were found in any of these welds. Small undercuts were found in the ERNiCuRu welds that can be related to the sluggish welding pool of this consumable that is due to the high surface tension of the molten filler metal. All test welds met the performance objectives set in Table 3.2.

Undercuts in ERNiCuRu welds can be avoided with optimizing the shielding gas composition and the welding procedure. Multipass welding of V-grove joints in smaller weld beads and reduced arc voltage in combination with higher oxygen content in the shielding gas can help avoiding weld undercuts. Due to limited availability of ERNiCuRu filler wire, a welding procedure with single pass welds in X-groove was used in the Laboratory Demonstration stage of this project.

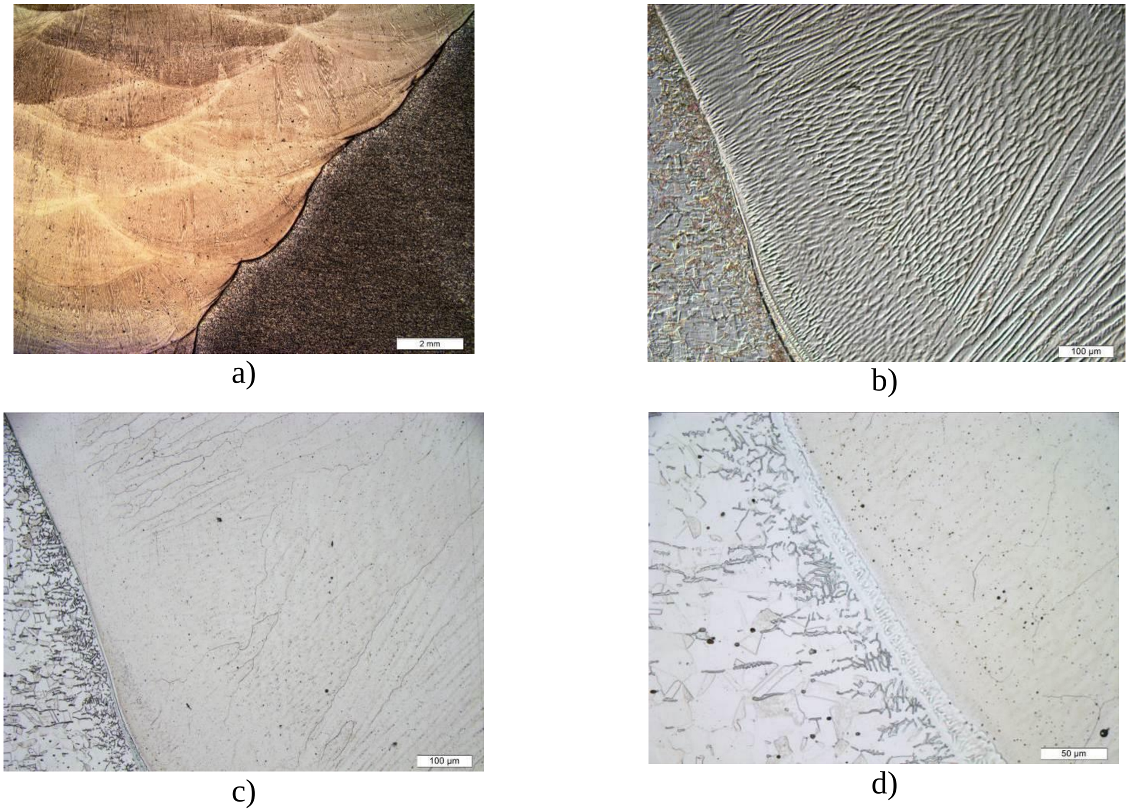


Figure 6.20 ENiCuRu Test Weld Assembly: a) Macrostructure; b), c), d) Microstructure

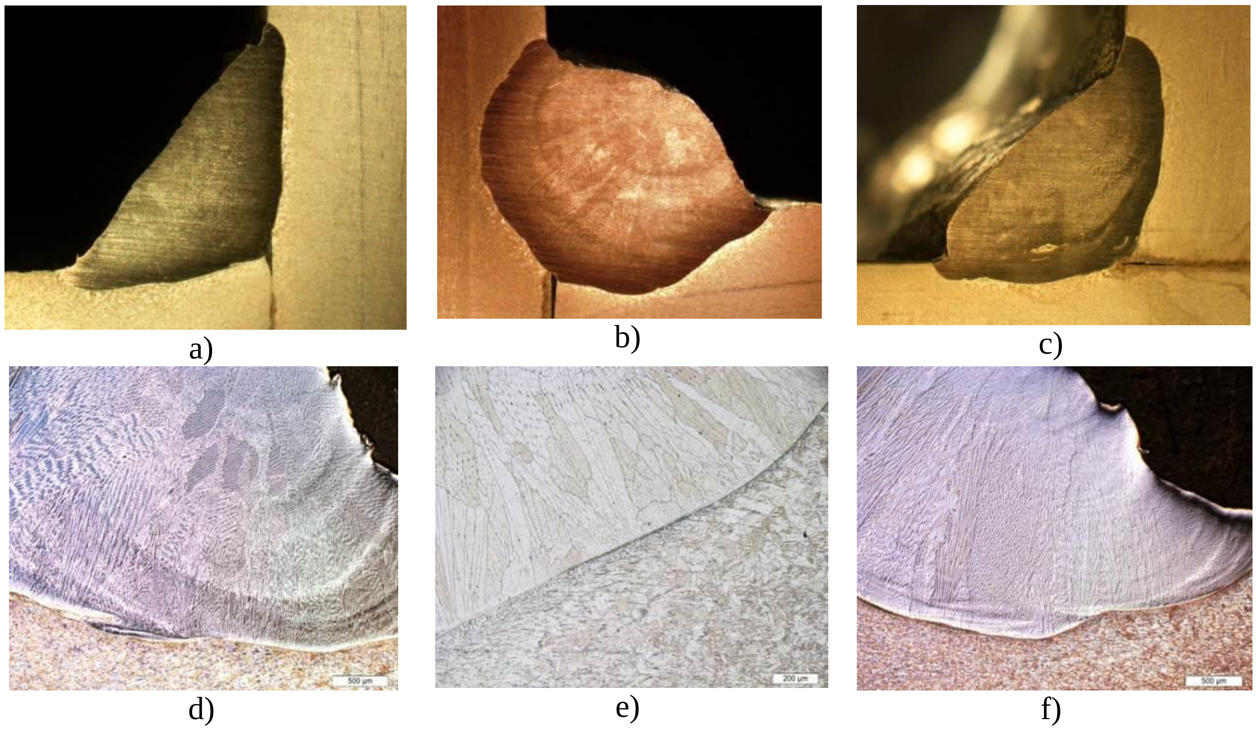


Figure 6.21 ENiCuRu Fillet Welds: a), b), and c) Macrostructure; d), e), f) Microstructure. Welding positions: a) and d) flat; b) and e) vertical down, c) and f) overhead

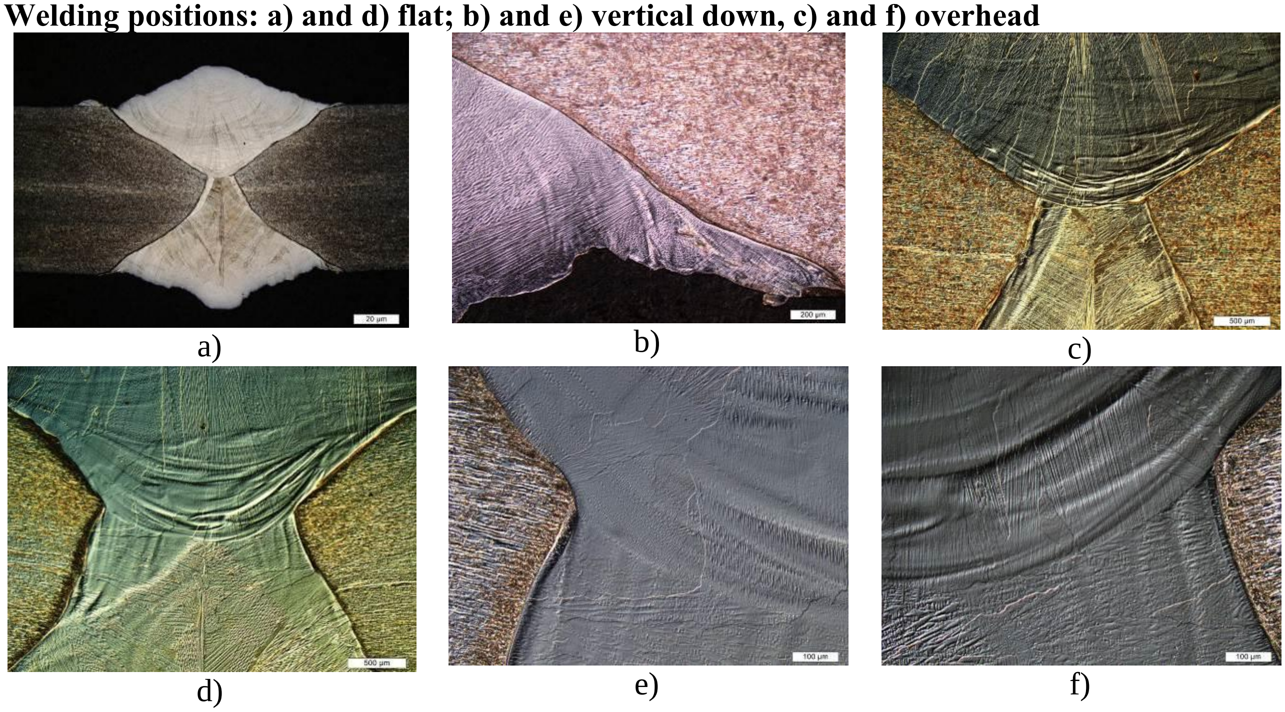


Figure 6.22 ENiCuRu Test Weld Assemblies: a) Macrostructure; b) Undercut; c) through f) Macro- and Micro-structure in the Weld Root Zone

6.3.2 Weld Quality Evaluation during Field Testing

The weld quality evaluation of the weld test assemblies produced during the field testing trials at Tooele Army Depot was performed at the Naval Surface Warfare Center Carderock Division.

<u>*Radiography*</u>

Radiographic images of the weld test assemblies made with the baseline E308L electrode and with the test ENiCuRu electrode are shown in Figure 6.23 and Figure 6.24. Test reports for the radiographic results of these test weld assemblies were developed by two different institutions. These test reports are provided in Table 6.24.

The nondestructive testing inspectors from Point Mugu, CA concluded that the radiographic films were too blurred to evaluate the quality of the baseline E308L-16 welds and the ENiCuRu test welds (Table 6.24). The nondestructive testing inspector from Naval Surface Warfare Center Carderock Division concluded that two of the baseline welds and one test weld passed the requirements of ANSI/AWS B2.1-2000 and ANSI/AWS A5.11-97. One test weld failed these requirements due to lack of fusion. This inspector could not provide a conclusion for one baseline weld containing porosity, insufficient fill, and possible lack of fusion, and for one test weld that had possible lack of fusion and porosity.

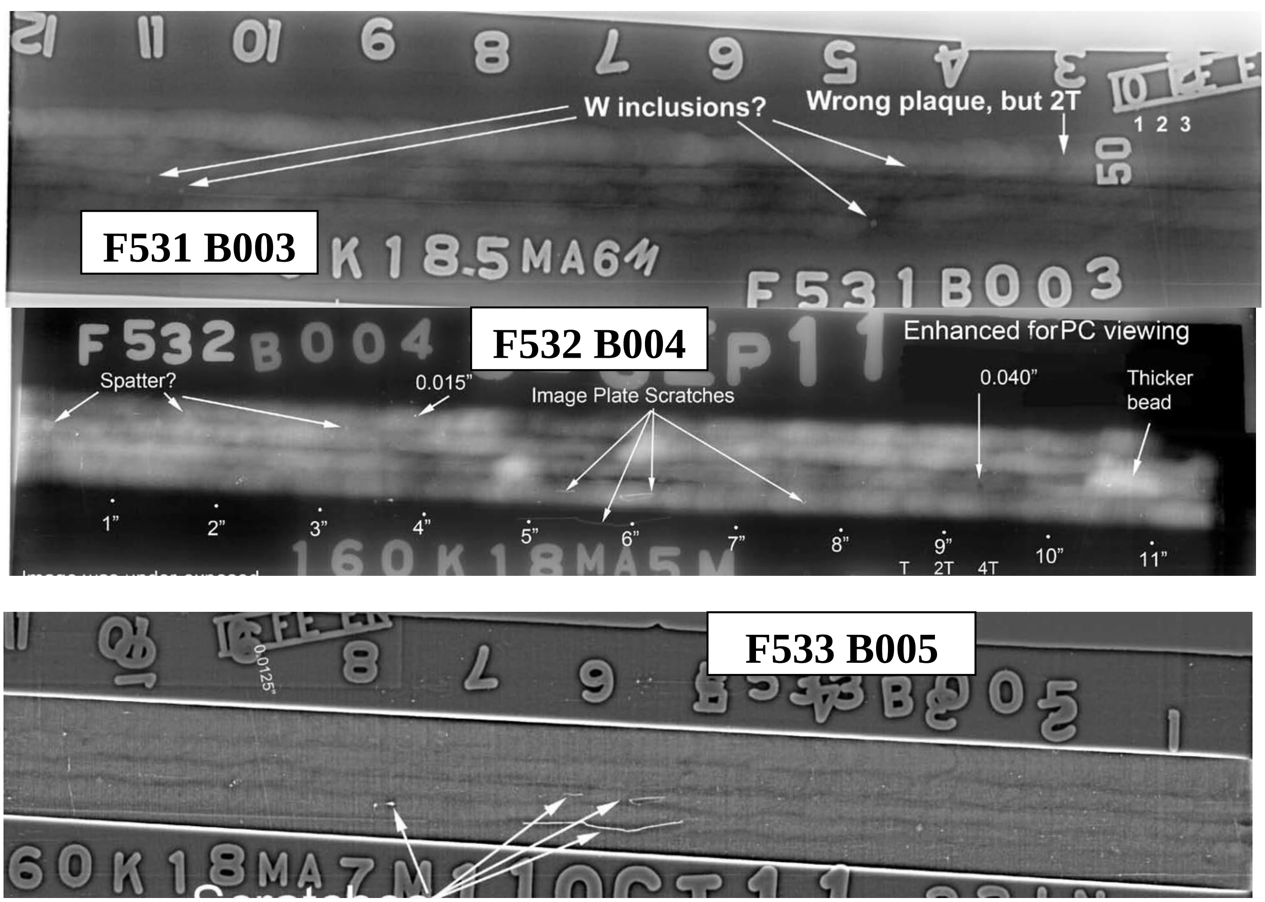


Figure 6.23 Radiography of the Baseline E308L-16 Welds

Table 6.24 Radiographic Test Report on Baseline E308L-16 and Test ENiCuRu Weld Assemblies

Electrode / Process	Sample ID	Inspector 1*		Inspector 2*	
		Pass (P) / Fail (F)	Remarks	Pass (P) / Fail (F)	Remarks
SMAW Baseline E308L-16	F531	?	Too blurred	P	Satisfactory
	F532	?	Too blurred	?	Porosity, insufficient fill, possible lack of fusion
	F533	?	Too blurred	P	
SMAW Test ENiCuRu	F534	?	Too blurred	P	Some lack of fusion
	F535	?	Too blurred	F	Lack of fusion
	F536	?	Too blurred	?	Possible lack of fusion, porosity

* H. Nguyen (Level II – NDE Inspector) and R. McConnehey (Level III– NDE Inspector), Point Mugu, CA
** G. Frank, Code 611; Welding, Processing and NDE Branch, NSWC, Carderock Division, Maryland

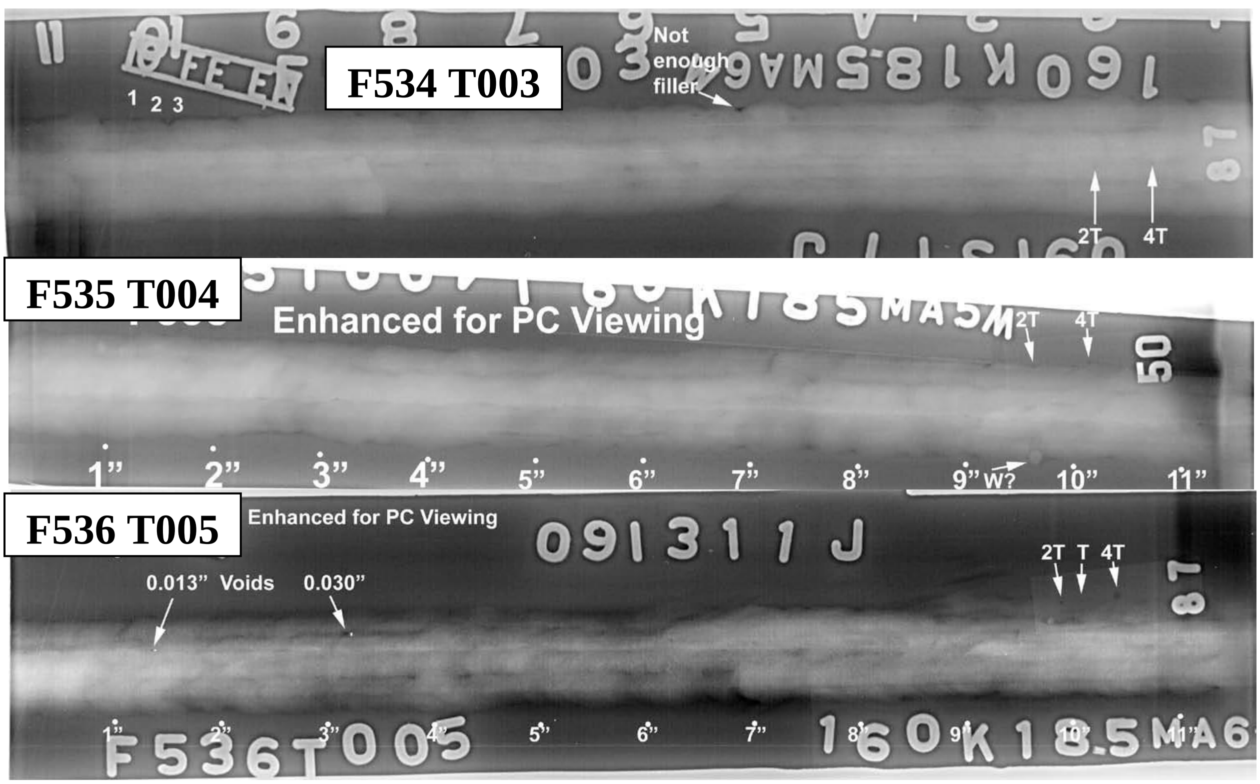


Figure 6.24 Radiography of the test ENiCuRu Welds

Radiographic images of the weld test assemblies made with the baseline ER308LSi and the test ERNiCuRu electrodes are shown in Figure 6.25 and Figure 6.26. Test reports for these test weld assemblies were developed by the two different institutions (

Table 6.25).

The reports of the two groups of Mugu nondestructive testing inspectors show that both the test ER30LSi welds and the ERNiCuRu welds failed to meet the requirements of ANSI/AWS B2.1-2000 and ANSI/AWS A5.11-97. There are, however, some differences in the types of defects found by these inspectors in the test weld assemblies. The inspectors from Point Mugu, CA found continuous lack of fusion defects in all baseline ER308LSi welds. Other than lack of fusion, the inspector from Naval Surface Warfare Center Carderock Division identified cracks in one of the baseline welds and porosity in the other two. The Point Mugu inspectors found porosity in all ERNiCuRu test welds, lack of fusion in one of them, and undercutting in the other two. The Naval Surface Warfare Center Carderock Division inspector identified excessive lack of fusion, insufficient fill, and undercuts in all test welds.

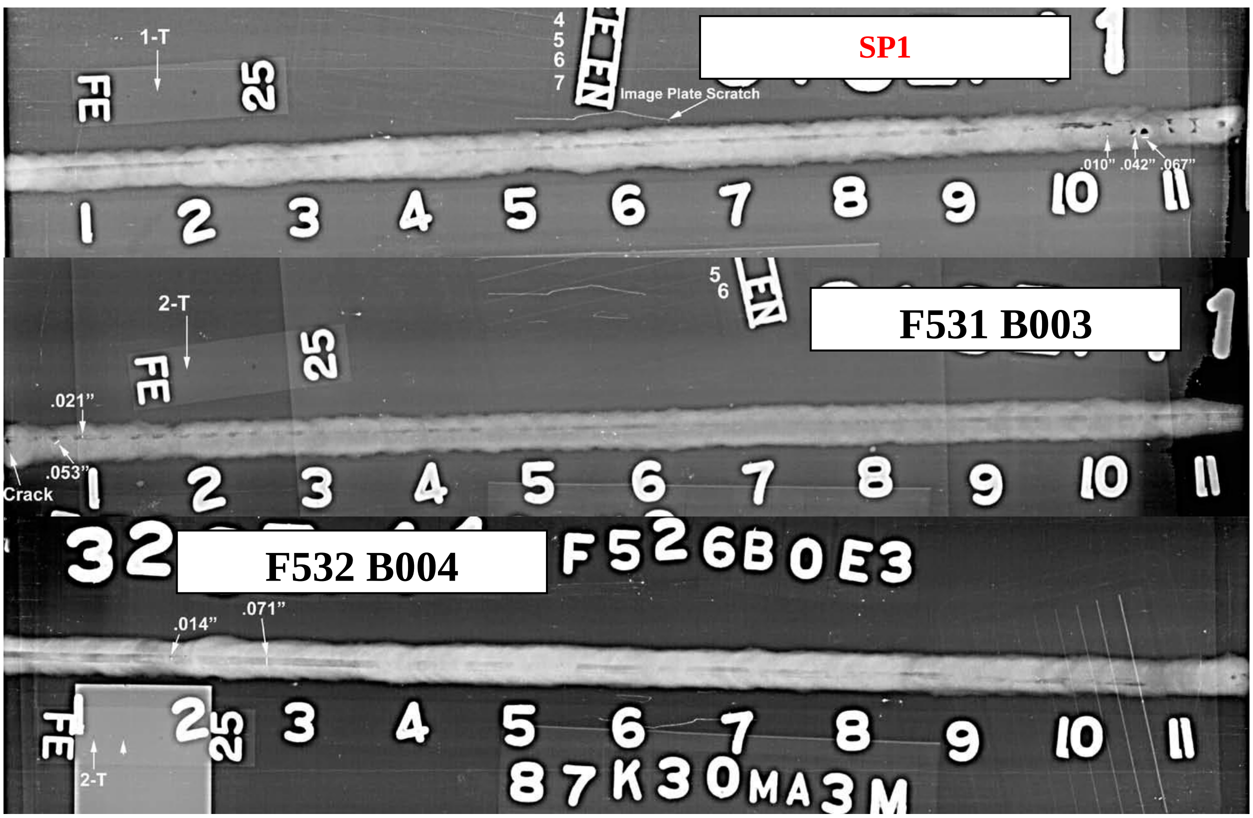


Figure 6.25 Radiography of the Baseline ER308LSi Welds

Table 6.25 Radiographic Test Report on Baseline ER308LSi and Test ERNiCuRu Weld Assemblies

Electrode / Process	Sample ID	Inspector 1*		Inspector 2*	
		Pass (P) / Fail (F)	Remarks	Pass (P) / Fail (F)	Remarks
GMAW Baseline ER308LSi	F525	F	Lack of fusion	F	Lack of fusion, cracks
	F526	F	Lack of fusion	F	Porosity, lack of fusion
	F527	F	Lack of fusion	F	Porosity, lack of fusion
GMAW Test ERNiCuRu	F537	F	Porosity and undercutting	F	Excessive lack of fusion, insufficient fill, undercut
	F538	F	Lack of fusion, porosity	F	Excessive lack of fusion, insufficient fill, undercut
	F539	F	Porosity and undercutting	F	Excessive lack of fusion, insufficient fill, undercut

* H. Nguyen (Level II – NDE Inspector) and R. McConnehey (Level III– NDE Inspector), Point Mugu, CA
** G. Frank, Code 611; Welding, Processing and NDE Branch, NSWC, Carderock Division, Maryland

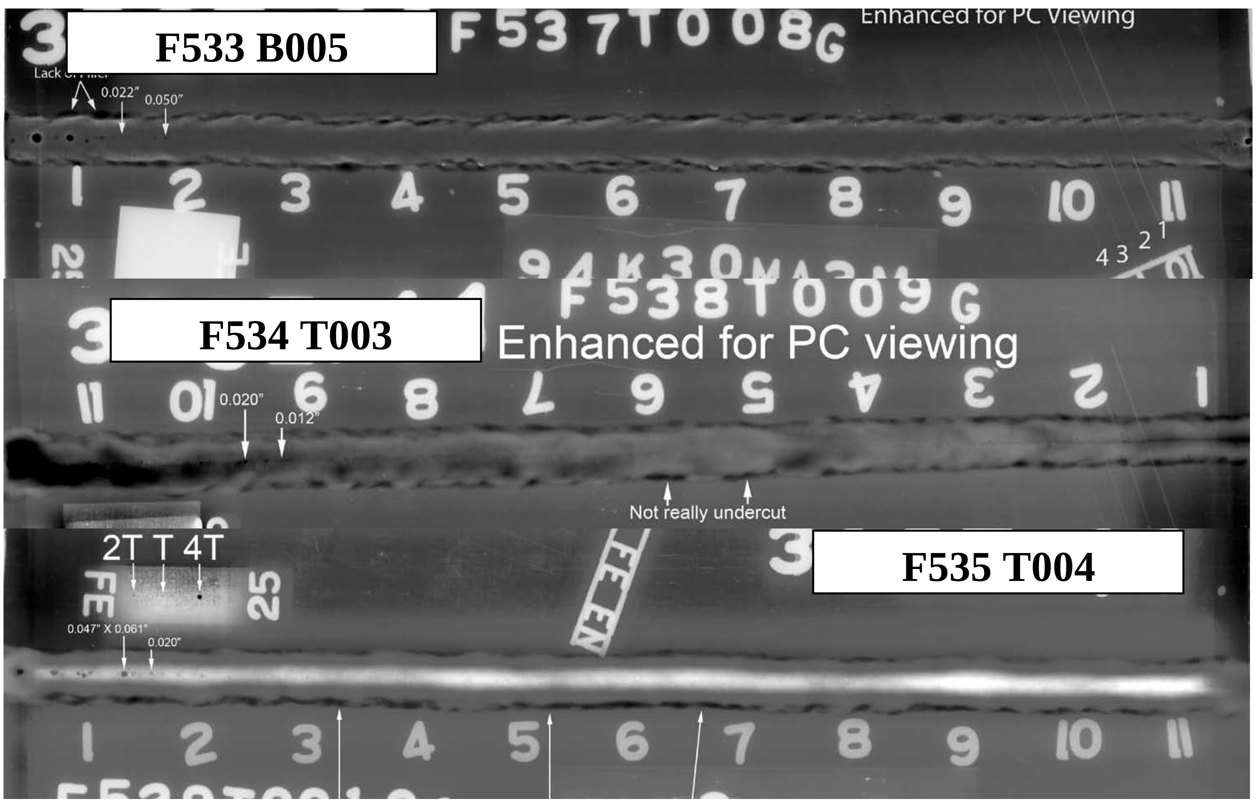


Figure 6.26 Radiography of the Test ERNiCuRu Welds

Weld Macro- and Microstructure Examination

Macro-sections of the test weld assemblies produced with baseline E308L-16 electrodes and test ENiCuRu electrodes are shown in Figure 6.27 through Figure 6.29. The weld metal macro-sections show large side-wall lack of fusion defects in two of the E308-16 baseline welds and in one of the ENiCuRu test welds. The low magnification in these macro-sections does not allow identification of small size weld metal lack of fusion and slag inclusion defects. An area of possible small size weld metal lack of fusion and slag inclusion defects in test weld T004 is shown in Figure 6.29. Such defects could be the reason for the lower tensile properties of this weld as compared to the other two ENiCuRu test welds.

The microstructure at the fusion boundary of the baseline E308L-16 welds and test ENiCuRu welds is shown in Figure 6.28. The microstructure in the E308L-16 weld metal is austenitic with delta ferrite along the solidification subgrain boundaries (Figure 6.28a). There is evidence of epitaxial solidification along the fusion boundary. The microstructure of the ENiCuRu weld metal is fully austenitic. A transition zone between the type 304L base metal and the ENiCuRu weld metal is found along the fusion boundary, which is typical for dissimilar metal welds (Figure 6.28b).

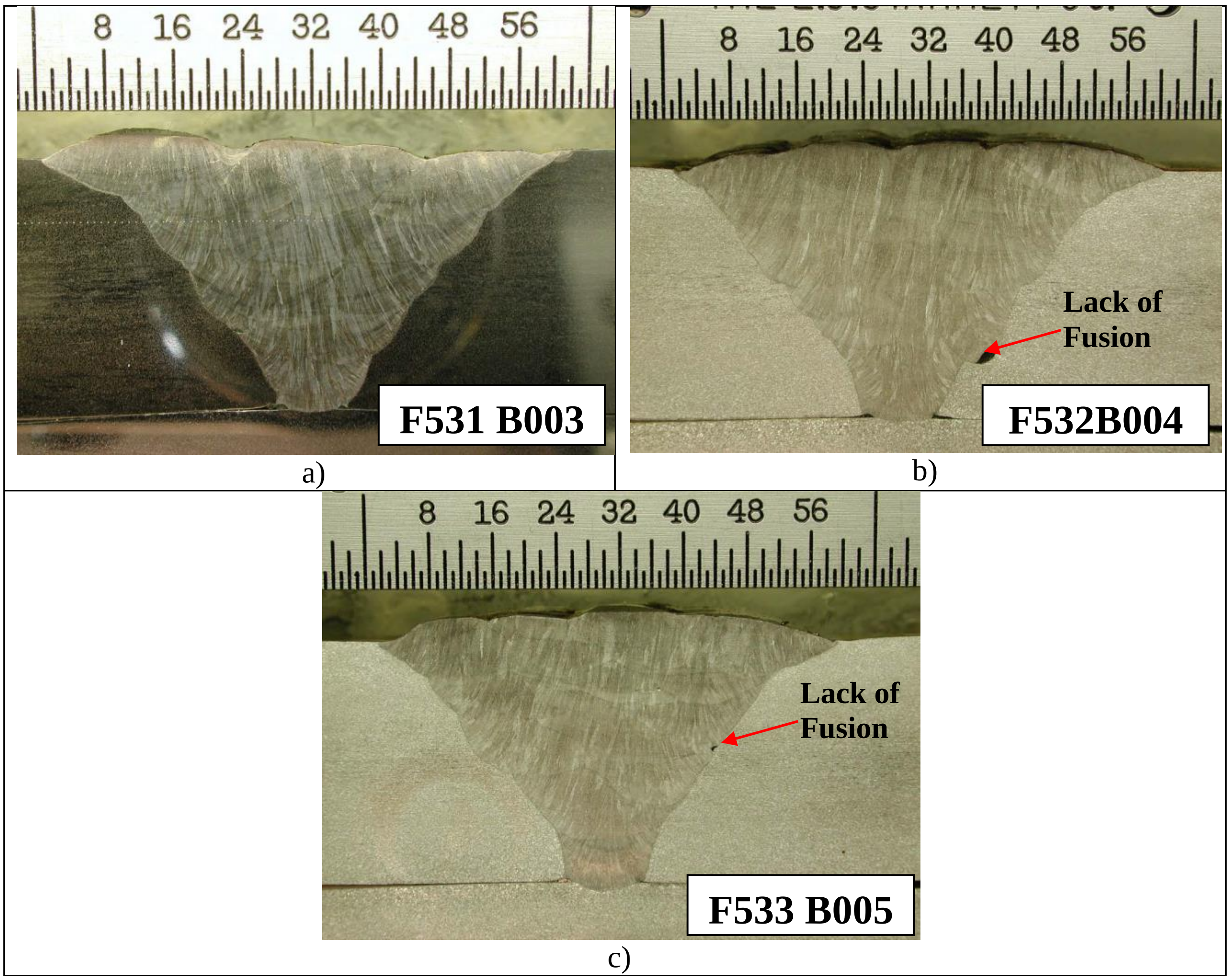


Figure 6.27 Macrostructure of the E308L-16 Baseline Welds Showing Sidewall Lack of Fusion Defects

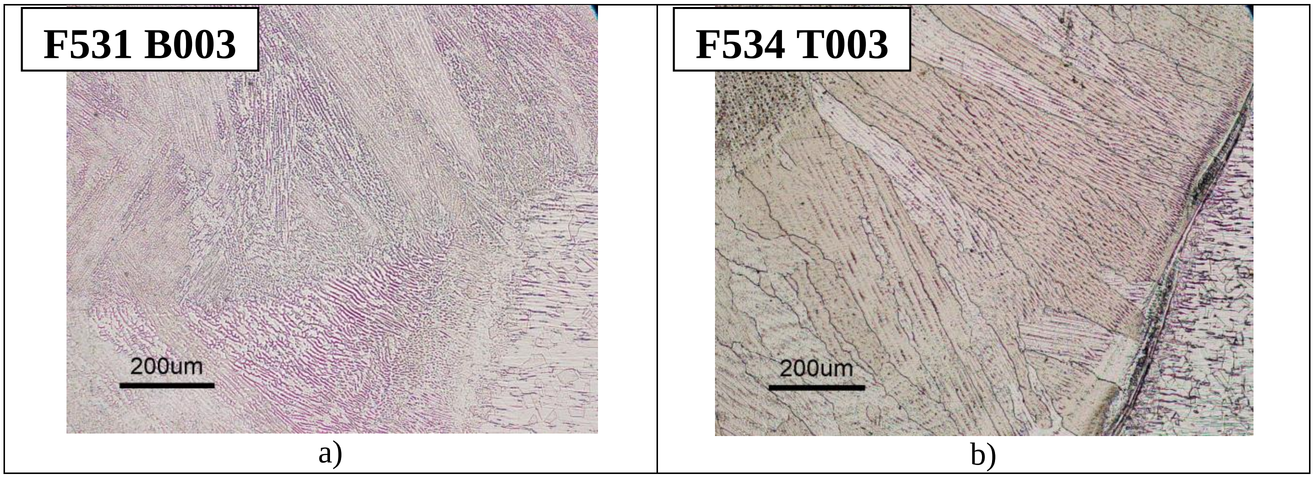


Figure 6.28 Microstructure: (a) of the E308L-16 Baseline Weld; and (b) of the ENiCuRu Test Weld

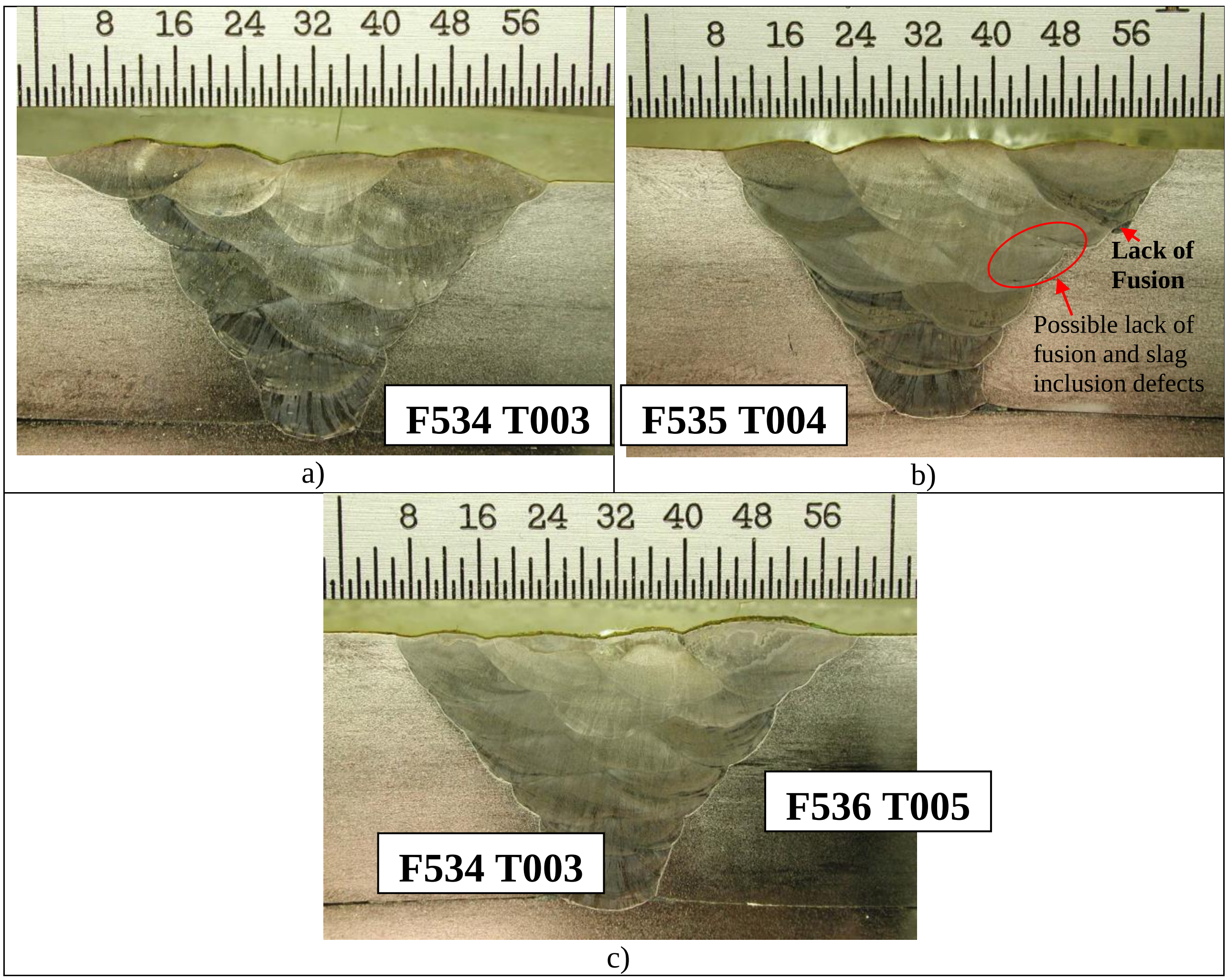


Figure 6.29 Macrostructure of the ENiCuRu wall Lack of Fusion Defects

(The magnification of these macrographs does not allow to identify possible weld metal lack of fusion and slag inclusion defects.)

Macrosections of the test weld assemblies produced with baseline ER308LSi electrodes and test ERNiCuRu electrodes are shown in Figure 6.30 and Figure 6.31. All baseline ER308LSi welds have large root/sidewall lack of fusion defects that formed during the deposition of the second pass (Figure 6.30). The sidewall lack of fusion defects are oriented along the point of applied stress during tensile testing, thus reducing the load-bearing weld cross section. The corners of these defects act as sharp stress concentrators. On the ER308LSi radiographs (Figure 6.25), these defects are seen as continuous longitudinal dark lines that stretch through the whole weld length. These sidewall lack of fusion defects are the reason for the low strength, extremely low ductility, and brittle fracture in the ER308LSi welds (Table 6.23).

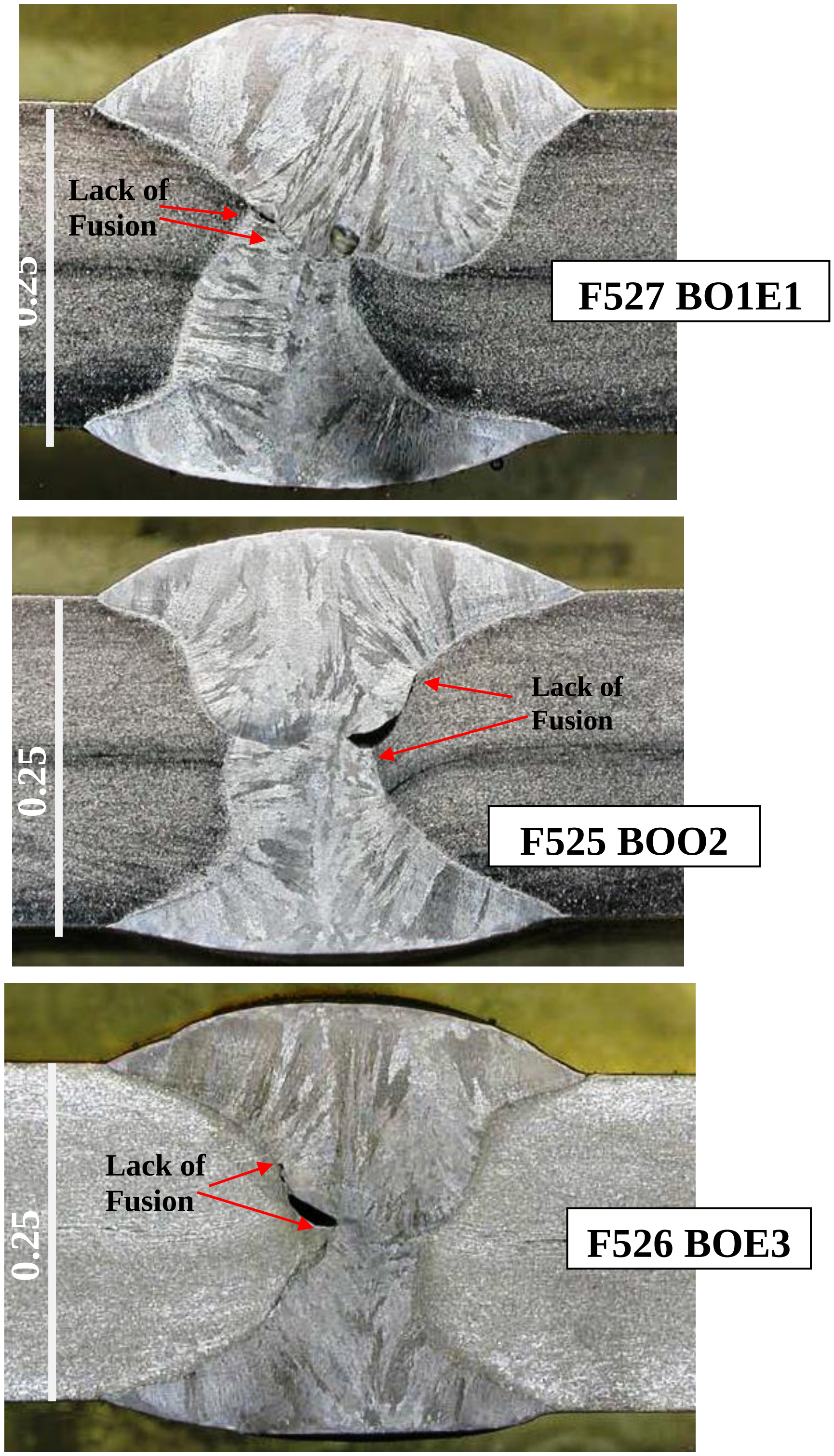


Figure 6.30 Macrostructure of the ER308LSi Baseline wall and Root Lack of Fusion Defects

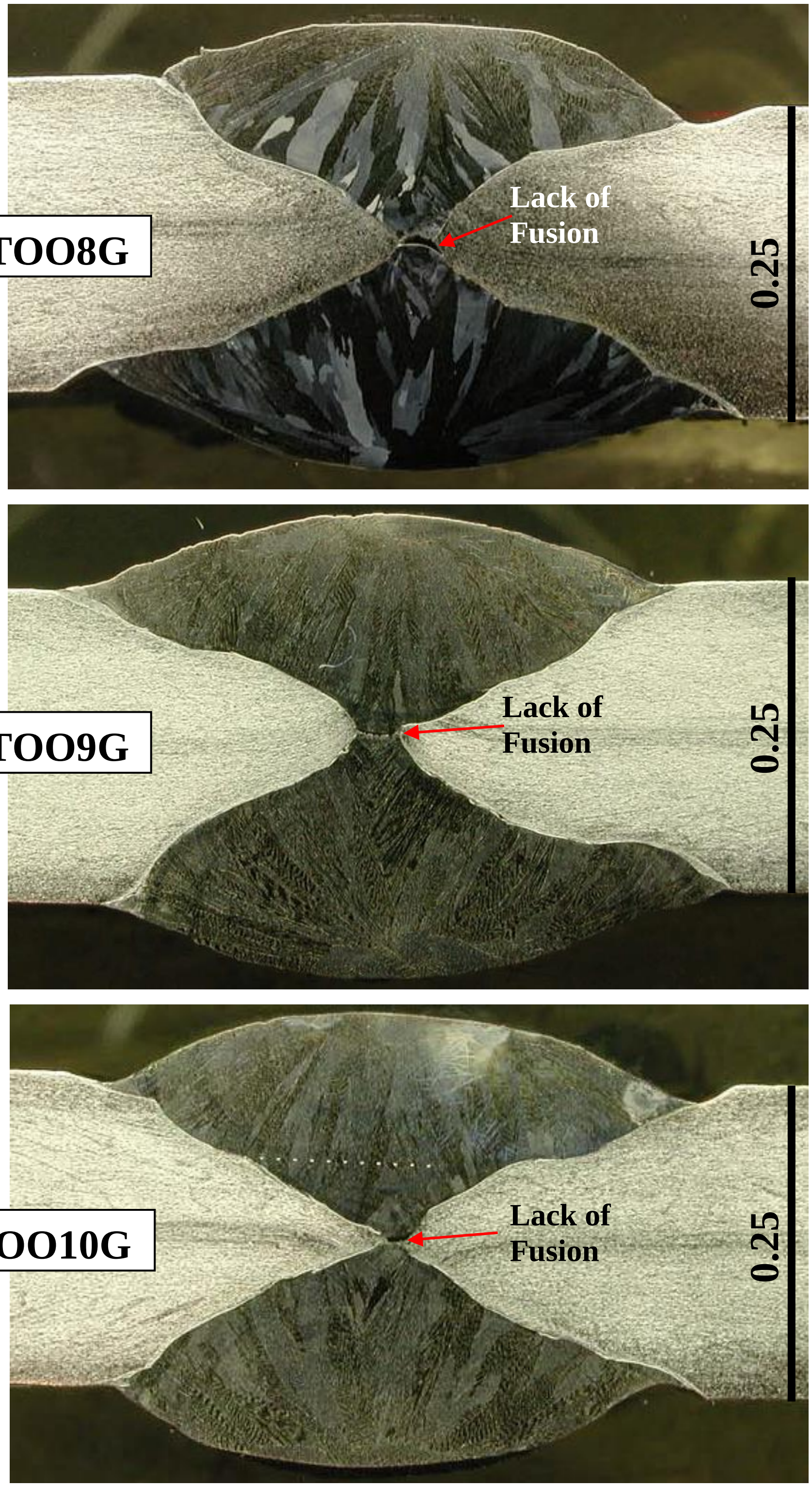


Figure 6.31 Macrostructure of the ERNiCuRu Test Welds Showing Root Lack of Fusion Defects and Undercuts in Welds TOO8G and TOO10G

The ERNiCuRu test welds did not show any sidewall lack of fusion defects (Figure 6.31). All three macrosections show root lack of fusion defects that are oriented parallel to the applied stress during tensile testing and do not reduce the load-bearing weld cross section. Undercut defects are found in welds TOO8G and TOO10G. The root lack of fusion and the undercut defects can be related to the lower ductility in the ERNiCuRu test welds as compared to the minimum requirements for type 304L steel and ER308L and ER316L weld metal (Table 6.23).

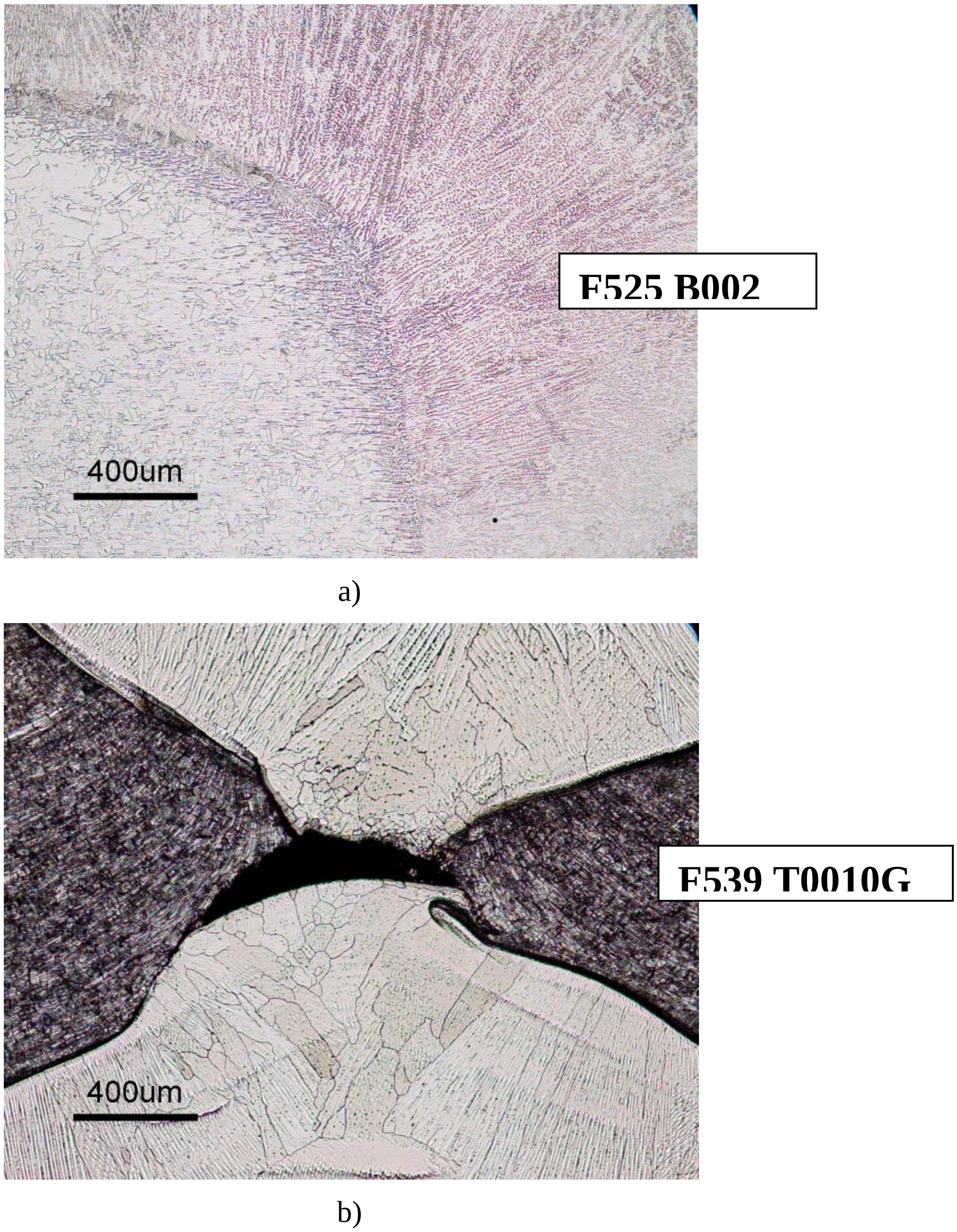


Figure 6.32 Microstructure: (a) of the ER308LSi Baseline Weld; and (b) of the ERNiCuRu Test Weld with a Root Lack of Fusion Defect

The microstructure at the fusion boundary of the baseline ER308LSi welds and test ERNiCuRu welds is shown in Figure 6.32. The microstructure in the ER308LSi weld metal is austenitic with delta ferrite along the solidification subgrain boundaries (Figure 6.32a). There is evidence of epitaxial solidification along the fusion boundary. The microstructure of the ERNiCuRu weld metal is fully austenitic. A transition zone between the type 304L base metal and the ERNiCuRu weld metal is found along the fusion boundary, which is typical for dissimilar metal welds (Figure 6.32b). This figure also shows higher magnification of a root lack of fusion defect shown previously in Figure 6.31.

6.4 Welding Operability Evaluation

The welding operability of ENiCuRu and ERNiCuRu was evaluated both during the Laboratory Demonstration and during the Field Demonstration stages of this project. The evaluation process included reporting by the welders who produced the test weld assemblies of Cr-free electrodes. A comparative study of the arc stability of ENiCuRu consumable was conducted during the Laboratory Demonstration stage.

6.4.1 Weld Operability Evaluation during Laboratory Demonstration

Welder's Evaluation

The rankings in Table 6.26 are based on a 1 to 10 scale, with the ranking of 1 corresponding to poor performance and the ranking of 10 corresponding of excellent performance. The welding operability of the ENiCuRu electrode in flat position was rated at 9.4 and 9.5 out of 10, which is comparable to other Ni-based SMA electrodes and very close to conventional stainless steel SMA electrodes. This electrode also performed well in out-of-position (vertical down and overhead) welding (Table 6.27). Difficult slag removal in the first weld beads is noted as a disadvantage in the operability of this consumable. It is due to higher base metal dilution in the first weld beads and improves to an acceptable level as the base metal dilution decreases in the subsequent weld beads.

Table 6.26 Welding Operability Evaluation of the ENiCuRu Consumable by Energy Solution Group Welders

Criterion	Ratings	
	Welder 1	Welder 2
Arc Starting	10	9
Arc Restart	10	10
Arc Stability	9	9
Arc Drive	10	9
Wetting Characteristics	9	10
Slag Cover	10	10
Slag Removal (Bead-on-plate)	8	10*
Slag Removal (Groove)	N/A	N/A
Bead Contour	10	9
Sparking	9	10

Spatter	9	8
Finger nailing (concentricity)	10	10
Slag Interference	N/A	N/A
Porosity	N/A	N/A
Surface Appearance	10	8
Total Points (out of 120)	**114**	**113**
Average Ranking	**9.5**	**9.4**

* - after weld quenching

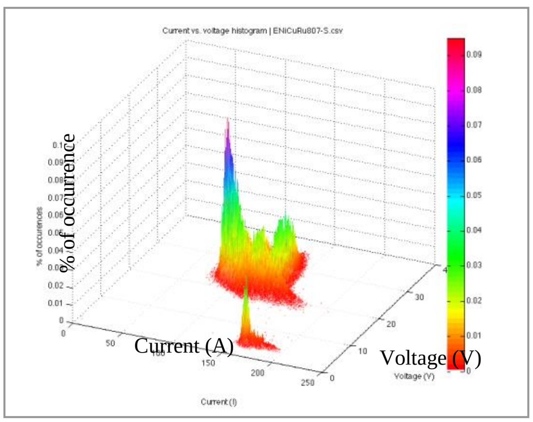
Table 6.27 Comments of Energy Solution Group Welders on Welding Operability of the ENiCuRu Consumable

Weld type	*Welding position*	Comments
0.75 inch test assembly	*Flat*	B1 & B2 did not clean very well. B3 was easier to remove slag, less base metal dilution. B10 started to get islands in the slag coverage, 350˚F & no base metal dilution, slag removal much better. B21 after lunch had cooled to 150˚F and still had islands in slag coverage. Over all rods welded good, wetting and tie-in good. Total of 37 beads to complete groove.
0.25 inch fillet welds	*Flat*	Welded good. Slag detachability poor, base material seems to affect it very much due to dilution of weld deposit.
	Vertical down	Vertical 1: Bead started out fair with bead shape, as plate got hotter had to slow travel speed to minimize undercut. (welder needs more practice with this rod out of position and slag formers need more development) Vertical 2: Widen weave to help flatten out bead shape and dwelled longer on each side, this helped considerably. A ¼ inch thick plate seems to be thinner than desirable for a 1/8 inch diameter rod and vertical weld.
	Overhead	Overhead bead shape good, slag detachability poor, had a few islands in the slag. Slag is too fluid, welded better than expected.
Overall remarks		Initial beads welded when dilution is at its highest are too difficult to remove the slag. As more welding is done and dilution is reduced the better the slag removes. In a groove weld when out in the middle where there is practically no dilution the slag removes with a shiny surface, but there are more island of uncovered base material. The arc is on the soft side and somewhat difficult to initially get it to bridge the corner when overhead.

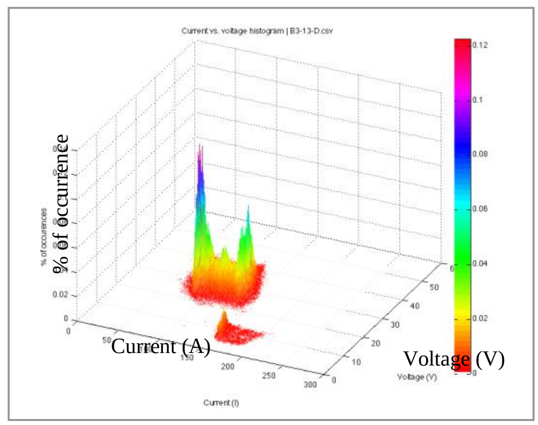
Arc Stability

The arc stability of ENiCuRu was compared to the arc stability of a conventional Ni-based SMAW electrode ENiMo-10. The results of this evaluation are shown in Figure 6.33 and Figure 6.34. Both electrodes have similar arc current distribution (percent occurrences of arc current values for particular arc time). However, the ENiCuRu consumable has a narrower arc voltage distribution as compared to ENiMo-10 and correspondingly a narrower voltage distribution. The ENiCuRu also has a narrower distribution of current and voltage, and correspondingly of power, during the welding arc short circuiting. All of these are indicators of better arc stability of the Cr-free ENiCuRu consumable in comparison to the conventional Ni-based ENiMo-10 electrode.

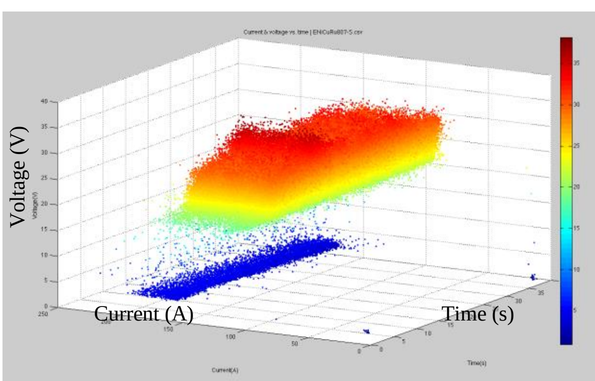
The results of this study show that the arc stability of the ENiCuRu consumable is comparable to that of conventional Ni-based SMA electrodes and meets the performance objectives set in Table 3.2.



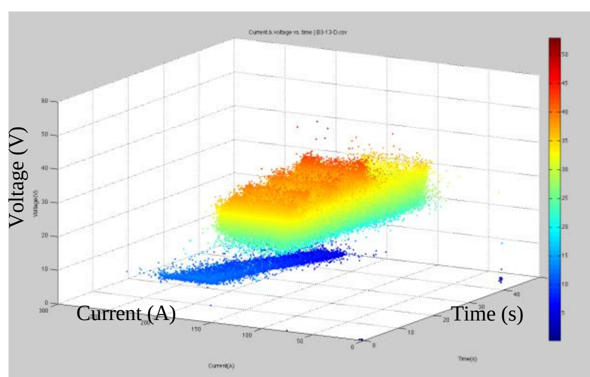
a) ENiCuRu



b) ENiMo-10

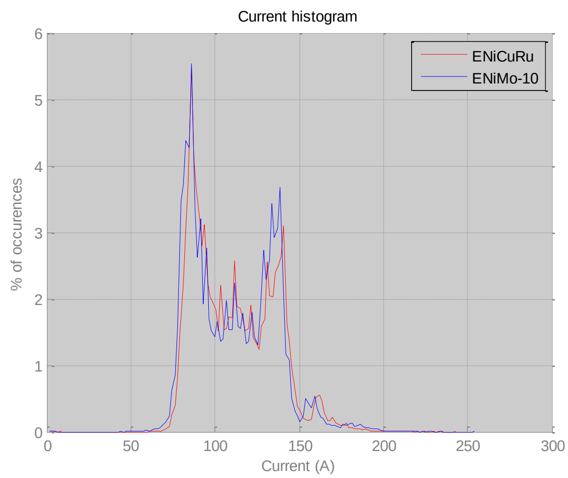


c) ENiCuRu

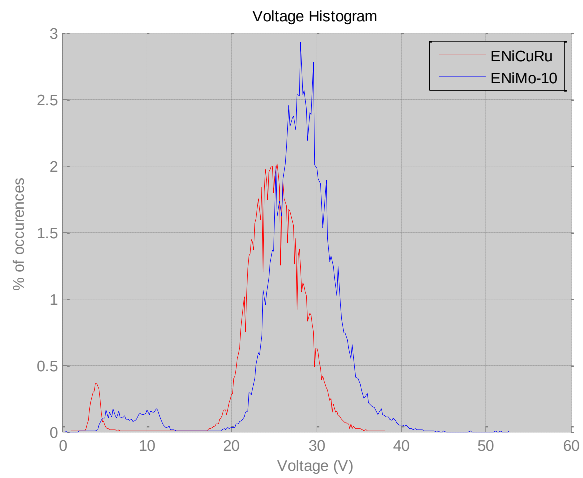


d) ENiMo-10

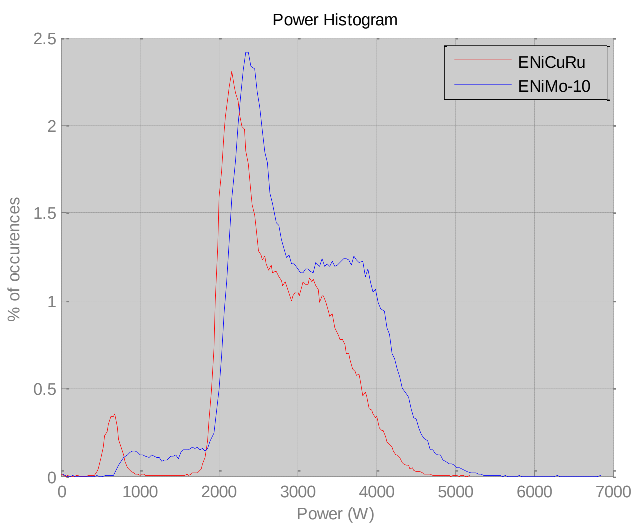
Figure 6.33 Comparison of Arc Stability in the Cr-free ENiCuRu Electrode to a Conventional Ni-based ENiMo-10 Electrode



a) Distribution of arc current



b) Distribution of arc voltage



c) Distribution of arc power

Figure 6.34 Comparison of Arc Stability in the Cr-free ENiCuRu Electrode to a Conventional Ni-based ENiMo-10 Electrode

6.4.2 Weld Operability Evaluation during Field Demonstration

During the Field Demonstration stage of this project, the welding operability of the tested electrodes was evaluated by the welder who produced the test welds. He was given a list of evaluation questions that he responded to after completion of the test welds. The evaluation questions and the welder's responses are provided in Table 6.28.

Table 6.28 Welder's Evaluation of the Welding Operability of Test ERNiCuRu Consumable

The welding program at the Ohio State University developed a new Cr-free welding consumable designed specifically for type 304 stainless steel. TEAD Safety required self-contained breathing apparatus (SCBA) respiratory protection because the process was an unknown. It is unlikely that SCBA will be required in the future.	
Test weld conditions	GMAW, 1/4 inch stainless steel (304L) plate, 12-inch weld, Double V-Joint, 60 degree included angle, 0.035 inch wire (ERNiCuRu)
Question 1	Please comment on training period – Ease of change from conventional welding processes.
	Welding with nickel filler material would take a lot more training period, because it is a lot different than welding with mild steel or even stainless. Nickel creates a more sluggish puddle faster freeze and less fill, and would take more time in learning how to weld with.
Question 2a	Quality of Weld – Your impressions on the quality of weld: your own work.
	It was a course weld by appearance, and with the low conductivity of nickel, I didn't feel like there was much penetration. With the fast freeze characteristic of the filler wire there wasn't any fill, so there was undercut especially with shielded metal arc welding.
Question 2b	Quality of Weld – Your impressions on the quality of weld: likelihood the technology it could be easily transferred to most DOD welders.
	Field welding, because the TMS (the welder means the TMS technology of UoF) wouldn't be practical in remote locations.
Question 3	Likelihood this technology could be used in DOD.
	Nickel is harder to weld, so unless it adds something beneficial to the weld it would not be the preference (especially not for the welder).
Question 4	Suggestions for changes.
	Don't know.
Question 5	Anything else you would like to comment on about this welding technology.
	I don't know what adding something as soft as nickel to something hard like stainless is doing to the weld or the base metal. Is this adding to the weld being made and the function of the part being welded? With some time and trial I think that welding with a high nickel filler could achieve a better weld than what I was able to make for you guys. Would it make the kind of welds the navy is looking for: don't know.

7. Cost Assessment

The total cost assessment associated with replacing type 308 stainless steel filler material with Cr-free welding consumables includes the following major categories: 1) the cost of the Cr-free filler wire versus the cost of type 308 filler material; and 2) the cost reduction associated with the reduced ventilation requirement (as compared to the new OSHA PEL of 5 $\mu g/m^3$ 8-hour-TWA) when welding with Cr-free welding consumables.

7.1 Cost Differential between Type 308 and Cr-free Welding Consumables

7.1.1 Background

A detailed cost analysis for the substitution of Cr-free welding consumables for standard type 308 filler metals for the welding of stainless steel was developed in 2006 under SERDP Project PP-1415 "Development of Chromium-Free Welding Consumables for Stainless Steels" [3]. Although it is anticipated that the cost of the Ni-Cu-Pd Cr-free filler material will come down when it is produced in larger quantities, an initial cost of $56/pound was estimated in 2006. This compares to an approximate retail cost of the type 308 filler material of $6/pound. In order to quantify how these different filler metal costs might translate into overall welding costs, 10 specific welding applications were analyzed. The industry sectors from which the applications were selected from included shipbuilding, transportation and storage tanks, and general fabrication. The joint designs included V-groove butt welds between both pipe and plate, as well as T joints with fillet welds. This analysis included the following list of assumptions and information:

- Cost estimates for the Cr-free welding consumables and commercially available type 308 filler metal.
- A worksheet for labor cost estimation in industry sectors listed above
- The Cr-free welding consumables will operate at deposition rate and with weld soundness equivalent to their counterpart stainless steel welding consumables. Such consumables could be produced with methods similar to those used for production of Ni-Cu alloys (e.g., Monel).
- Welding procedures currently used for welding stainless steels could be used with the Cr-free consumables with minor modifications.
- Costs for qualifying welding procedures utilizing the Cr-free consumables for each application have not been estimated. In critical applications such as military shipbuilding these costs could be significant.
- Welding cost estimates include tasks performed by welding shop personnel, including fitup, tacking, welding, grinding, and cleanup. Pre-welding machining and post-weld inspection are not included.
- The procedure recommendations and data for the cost analyses originate form handbooks and other publications utilized by welding professionals and publicly available information on wage rates, overhead and benefit costs.

- Excel worksheets for direct side-by-side comparison of specific welded joint configurations, filler metal requirements, labor rates, labor productivity and overhead.

7.1.2 Updated Status of Filler Metal Development and Cost

In 2011, weld testing of the new filler metal (91% Ni, 8% Cu, and 1% Ru) was conducted at a DoD facility to evaluate weld soundness and establish typical fume production in the field. A simple cost analysis similar to that described in Section 7.1.1 has been conducted on this new alloy utilizing updated 2011 commodity pricing. The estimated price per pound for the 91Ni-8Cr-1Ru filler metal is $37/lb, significantly lower than the Pd containing filler material used for the initial cost assessment. For SMAW electrodes, this lower material cost translates to a cost of approximately $31/lb, and for GMAW electrode wire, about $42/lb. Calculations were conducted on the applications evaluated previously to show the effect on cost when utilizing the 91Ni-8Cr-1Ru filler metal. This updated spreadsheet summarizing the results and reflecting the significantly lower cost (compared to the Pd containing wire) associated with the Ruthenium addition is shown on Table 7.1.

Table 7.1 Welded Joints Cost ($) Summary

			308 Filler/Material		91Ni-8Cu-1Ru Filler Material		
Industry	**Joint Description**	**Process**	**Cost/ft or cost/joint (plate)**	**Filler Metal Cost**	**Cost/ft or cost/joint (plate)**	**Filler Metal Cost**	**% cost increase**
Ship Building/ Pressure Vessels	6” dia pipe	SMAW	73.7	7.2	110.3	43.7	50
	6” dia pipe	GMAW	24.5	4.4	52.5	33.2	113
	12” dia pipe	GMAW	56.2	15.9	162.7	121	190
	3/16” fillet weld	GMAW	7.4	0.8	13.6	6.7	83
Tanks	3/16” butt weld	GMAW	5.4	0.3	8.4	2.9	56
	3/8” butt weld	SMAW	44.1	6.5	78.2	40	77
	3/8” butt weld	GMAW	8.8	3.7	35.7	30.2	306
General fabrication	3/16” fillet weld	GMAW	2.2	0.8	8.3	6.7	279
	1/4” fillet weld	SMAW	5.2	2.7	18.7	16.14	259
	¼” fillet weld	GMAW	4	1.5	15	12.2	276

7.1.3 Cost Reduction Associated with Application of Cr-Free Consumables

When OSHA established the new ventilation requirements for reducing exposure to Cr(VI) it stated that the primary methods for reducing such exposure are local exhaust ventilation and improvement of general dilution ventilation. In addition, it is anticipated that in many cases a welder will utilize personal protective equipment with a respirator when welding stainless steels. Therefore, this cost assessment is based on the assumption that a typical fabrication facility will incur additional costs for improved general and local ventilation, as well as personal protective equipment, as a result of the new OSHA regulation.

There are over 450,000 welders in the United States, and it is estimated that up to 5% of this welding work involves stainless steel, so it is clear that Cr(VI) affects a significant number of workers. There are numerous general considerations associated with ventilation decisions regarding the new OSHA ventilation requirements, including issues such as the size of the fabrication facility and whether welding is being conducted in a confined space. Every case will be different; analysis will be based on two typical cases: a relatively large fabrication space and a relatively small fabrication space. It is important to point out that this comparison represents very generic cases, and should only be used as a guideline. In addition to the overall size of the facility, many specific factors must be considered that will affect ventilation requirements for each location. Examples of other factors to consider include location and number of roof and wall ventilators, overhead doors and obstructions, make-up air exchange systems, welding parameters, working hours, annual consumable usage, type of welding processes used, etc.

For the purposes of this generic comparison, the two different weld shop sizes considered were a 60 ft by 30 ft shop with 12 welders, and a 200 ft x 100 ft shop with 36 welders. Assumptions in each case include: single shift, welding parameters which range between 90 and 150 amps, overhead obstructions (cranes) and no wall ventilators, and heating, ventilation and air conditioning present as an air exchange system. In the case of the larger shop, it is assumed there are five roof ventilators (@ 1000 CFM each), four overhead doors, and the annual consumable usage is estimated at 60,000 lb/year. For the smaller shop, it is assumed there are two roof ventilators (at 1000 CFM each), two overhead doors, and the annual consumable usage is estimated at 20,000 lb/year. In each case, it is assumed that SMAW, GMAW, and GTAW processes are being used. The extent to which the SMAW process is being used will play a significant role in filter replacement frequency (higher usages of SMAW will require more frequent filter replacements), but there was no attempt to quantify this detail.

Lincoln Electric provided quotes for ventilation systems used for the comparison. The system costs include both a general ventilation system and a source extraction system. The general system is a U-shaped "push-pull" type system and is shown in Figure 7.1. This will provide a continuous positive and negative air flow over the weld area. The source ventilation system includes pivoting and telescopic extraction arms for each welding booth. Other costs considered include the costs of personal protection ventilation suits and air monitoring. Considering all of the aforementioned assumptions and information, the summary below compares typical ventilation system purchase cost differences between a shop that welds stainless steel and therefore is subject to the new OSHA requirements, versus a shop that is not subject to such requirements. These results are also summarized on Table 7.2.

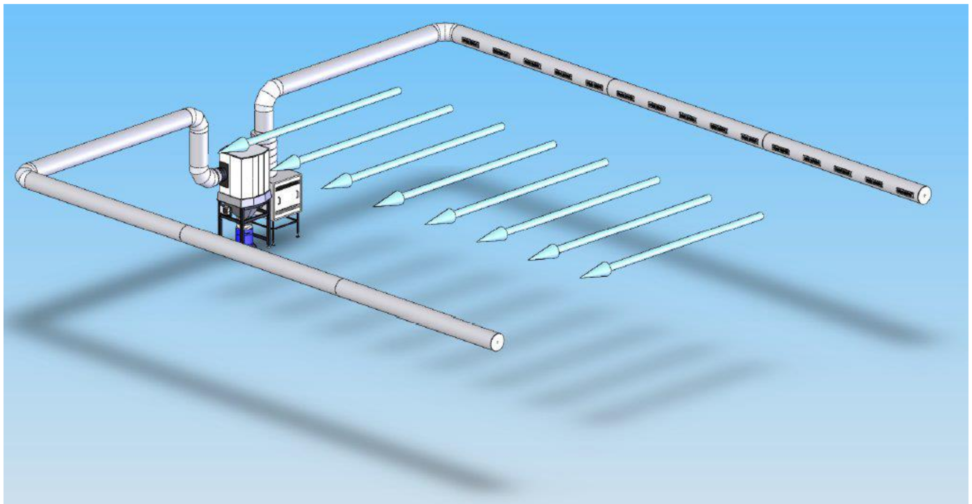


Figure 7.1 General Ventilation System "Push-Pull" Type

Example of 200 ft x 100 ft Welding Shop – Comparison of Costs

As mentioned, Lincoln Electric provided the ventilation system quotes that allowed this analysis. The total estimated cost for a ventilation system capable of meeting the new OSHA requirement is $660,000. This includes both general and source extraction systems. The ventilation systems include "self-cleaning" capability, but there would be additional costs associated with filter changes and the special high-efficiency particulate arrestance (HEPA) filters are much more expensive than conventional filters. Every case will be different, but for the purpose of this generic analysis, an annual filter replacement cost of $25,000 was utilized. The cost of personal protection ventilation suits for 36 welders is estimated to be $36,000. The cost associated with air monitoring is roughly estimated at $25,000/year. In summary, the initial cost associated with purchasing ventilation equipment to meet the new OSHA standard for a 200 ft x 100 ft welding shop with 36 welders is approximately $700,000. The recurring costs are estimated to be $50,000/year.

In comparison, the total estimated cost for a ventilation system not subject to the new OSHA requirement is $410,000, and the recurring costs are estimated at $20,000/year. To summarize, this analysis indicates the requirements for approximately $300,000 in additional funding to purchase ventilation equipment, and $30,000/year in additional expenses associated with conforming to the new OSHA standard for a welding shop of this size.

Example of 60 ft x 30 ft Welding Shop – Comparison of Costs

The total estimated cost based on the Lincoln quotes for a ventilation system capable of meeting the new OSHA requirement is $150,000. The personal protection suits for 12 welders are estimated to cost $12,000, bringing the total initial equipment cost to $162,000. The recurring costs discussed previously are estimated at $20,000/year for a shop this size.

The estimated ventilation system cost for a shop of this size not subject to the new OSHA requirement is $100,000 and the recurring costs are estimated at $10,000/year. In summary, the

OSHA ventilation requirement associated with Cr(VI) results in an estimated $50,000 additional capital equipment expense and an additional $10,000 year in recurring expenses.

Table 7.2 Ventilation Systems Cost ($) Summary

Weld Shop Size	Number of Welders	Ventilation System Designed to Meet New OSHA Standard?	Initial Purchase Expenses	Recurring Expenses
200' x 100'	36	Yes	$700,000	$50,000
		No	$410,000	$20,000
60' x 30'	12	Yes	$162,000	$20,000
		No	$100,000	$10,000

7.1.4 One Year Cost Analysis Based on Filler Metal Costs

For the purposes of better understanding the financial impact of the OSHA Cr(VI) lower exposure requirement versus the additional cost associated with the Cr-free wire, the two welding shop scenarios are compared:

Scenario #1 – 200 ft x 100 ft welding shop

Since an assumption was made that 60,000 lb of electrode would be consumed annually in the large sized shop, some simple calculations can be made to develop an understanding of costs over a 10-year period. Using an ER308 filler metal cost of $6/lb will result in a total filler metal cost of $360,000 per year. The Cr-free wire priced at $42/lb will result in a total filler metal cost of $2,520,000 per year. This amount obviously far exceeds the savings that would result from the reduced ventilation requirement.

Scenario #2 - 60 ft x 30 ft welding shop

In this case, it is assumed that 20,000 lb of electrode would be consumed annually. Therefore, the filler metal cost would come to $120,000 for the ER308 wire and $840,000 for the Cr-free wire, again far exceeding the ventilation equipment savings that would be realized by utilizing the Cr-free 91Ni-8Cu-1Ru wire.

In summary, this analysis indicates that the current estimated $42/lb cost (for GMAW wire, $31/lb for SMAW wire) of the 91Ni-8Cu-1Ru wire would be financially prohibitive in most cases, even considering the significant savings possible with the reduced ventilation requirement.

Scenario #3 – 60 ft x 30 ft welding shop in which only 10% of the welding is stainless steel

In this more realistic scenario, it is assumed that 90% of the welding in the shop is on metals other than stainless steel. In such a case, the ventilation requirements would not necessarily change, but the impact of the cost of the stainless steel filler material would be much less. Now the filler metal cost (assuming 2,000 lb of electrode is consumed annually) comparison that can be utilized is $12,000 for the ER308 wire and $84,000 for the Cr-free wire for a difference of $72,000.

This compares to the $62,000 additional purchase expense associated with the special ventilation equipment and the additional $10,000 of recurring costs. It should also be noted that there will be additional expenses associated with the depreciation of the more expensive special ventilation equipment as well. In summary, this scenario illustrates the obvious fact that shops that weld only a very small amount of stainless steel could potentially realize a cost reduction by switching to the Cr-free filler material.

7.2 Stainless Steel Welding in Locations with Limited Access to Ventilation

The assessments of Section 7.1 focused on the "trade-off" in costs associated with the additional cost of the Cr-free filler material versus the additional cost of ventilation required by OSHA when standard stainless steel filler materials are used. However, another very important consideration to the Navy that should be addressed is the possibility that there are many locations (boiler rooms, etc.) on Navy vessels where welding and/or welding repair work is conducted which don't offer the possibility to properly and/or easily ventilate. In these cases, self-contained personal protection could be utilized for the welders, but this still does not address the elimination of the Cr(VI) present in the welding fumes that would accumulate (and remain) in the area after the welding is completed. In such cases, it is possible that OSHA regulations will not allow welding to be conducted, and therefore, Cr-free filler materials may be the only solution.

8. Implementation Issues

Possible issues related to the implementation of the Cr-free ENiCuRu and ERNiCuRu welding consumables may be the absence of an OSHA PEL for Ru in the welding fume. This issue can be addressed by conducting related studies at the Toxicology Department of Navy and Marine Corps Public Health Center Comprehensive Industrial Hygiene Laboratory and/or at the Health Effects Laboratory Division of NIOSH. It is recommended that a PEL for Ru be explored at the Naval Medical Research Unit, Dayton, Ohio.

Another possible implementation issue for the Cr-free welding consumables could be the need of providing additional training to welders who have no experience in working with Ni-based welding consumables.

Finally, only about 3% of welding conducted at DoD facilities is stainless steel welding. However, those efforts are performed at highly specialized facilities such as TEAD where strict emission and occupational safety and health controls are enforced. Meeting the OSHA requirements for Cr(VI) emissions in such facilities may not always be possible or economically feasible by the use of ventilation systems. For example, repair work on Navy vessels in locations where installation of ventilation systems is impossible (i.e., boiler rooms) would require using Cr-free welding consumables. As shown in Section 7, in production and repair facilities that perform a comparatively small fraction of stainless steel welding, the usage of Cr-free consumables can be more economical compared to installation and maintenance of specialized ventilation systems for Cr(VI) mitigation. There are potential uses for this process at DoD original equipment manufacturers such as power plants for submarines and ships, particularly those using high temperature water and steam where piping is frequently stainless steel or a similar alloy.

9. References

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8. ANSI/AWS B2.1-2000, Specification for Welding Procedure and Performance Qualification/
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10. ANSI/AWS B4.0-98, Standard Methods for Mechanical Testing of Welds.
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Appendix A: Point of Contacts

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
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Dr. John Lippold	Ohio State University, Room 136 Welding Engineering Program, Dept. of Materials Science and Engineering 1248 Arthur E. Adams Drive, Columbus, OH 43221	614-292-2466 lippold.1@osu.edu	PI Supervisor for Cr-free Consumables
Gene Franke	NSWCCD Welding, Processing, & NDE Branch, Code 611 9500 MacArthur Blvd. West Bethesda, MD 20817-5700	301-227-5571 301-227-5576 Gene.Franke@navy.mil	Welding Engineer & Weld Quality Test Manager
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Dr. K. James Hay	ERDC/CERL, Environmental Processes Branch P.O. Box 9005, Champaign, IL 61826-9005	217-373-3485 217-373-3430 kent.j.hay@usace.army.mil	Army Liaison & Project QA/QC
Michael L.	USCG Aviation Logistics	252-312-9084	USCG

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Dr. Chang-Yu Wu	University of Florida, Dept of Environmental Engineering Sciences, Gainesville, FL 32611-6450	352-392-0845 352-392-3076 cywu@ufl.edu http://www.ees.ufl.edu/homepp/cywu	PI for TMS part of Demo
Dr. Charles A. Kubrock	Chemistry Team Leader, Health Surveillance Lab Navy Envi & Prev. Med. Unit # 5 3235 Albacore Alley, Naval Station San Diego, CA 92136-5199	619-556-1427 619-556-1497 charles.kubrock@med.navy.mil	Laboratory Analysis & OSH Testing Advisor

Appendix B: SMA Welding Procedure for 0.75 inch Weld Test Assembly

Specialty Welding & Machining, Inc.

Welding Schedule Worksheet

Machine Type: Miller XMT 350 Mpa

PQR#: OSU NiCuRu TP-1 Date: 7/20/2010

Operator: JWH

Base Material: 0.75 in. thick 304L

Filler Material: NiCuRu Size: 1/8 in. diameter

Heat #: 11813 Brand: EEI

Preheat: 100˚F Interpass: 350˚F max

PWHT: NA

Joint Type: 75˚ included w/1/4 in. root Position Qualified: Flat

Bead Type: Stringer

Process: SMAW DCRP

Weld Travel Speed: 8 to 10 ipm

POWER SUPPLY SETTINGS

Program: Stick

Arc Adjust:

Wire Feed:

Process:

Wire Type:

Wire Alloy:

Wire Size:

Gas Type:

Volts: 23.5 to 24.6

Amps: 108

Arc Control: Dig - 5

Appendix C: GMA Welding Procedure for 0.25 inch Weld Test Assembly

Electrode: ERNiCuPd; Base metal: 304L S.S.

Weld Process________GMAW-P

Wire Diameter_______0.045 in.

Travel Speed _______17.5 ipm

Wire Feed Speed_____170 IPM

Peak Current________352 A

Background Current__66 A

Pulse Rate__________62 Hz

Pulse Width_________3.2 ms

CTWD_________________0.3125 in.

OC Voltage__________32 V

Shielding Gas_______Ar/38He/2CO2

Shielding Gas Flow__30 CFH Ar

Purge Gas___________Ar

Purge Gas Flow______40 CFH Ar

Joint Geometry

Thickness___________.025 in. Nominal

Joint Type__________Double Vee Groove

Included Angle______60 DEG

Land_________________N/A

Root Opening________0.050 in.

Appendix D: Evaluation Criteria for SMA Electrode Welding Operability

Arc Starting	10	No cleaning of the tip is required. Always starts on the first try. A stable arc and weld pool are established immediately with no special manipulation.
	9-7	No cleaning or preparation of the tip is required. Usually starts on the first try. A stable arc and weld pool can be established quickly.
	6-4	Some end cleaning may be required. Usually takes a few attempts to start. Some effort or manipulation is required to establish the weld pool.
	1-3	Significant end cleaning may be required. Significant effort is required to start the arc and establish the weld pool. Electrodes stick to the plate and need to be discarded.
Arc Restart	10	No cleaning or chipping of the tip is required. Always starts on the first try. A stable arc and weld pool are established immediately with no special manipulation.
	9-7	No cleaning or chipping of the tip is required. Usually starts on the first try. A stable arc and weld pool can be established quickly.
	6-4	*Boms* end cleaning or chipping may be required. Usually takes a few attempts to start. Some effort or manipulation is required to establish the weld pool.
	1-3	Significant end cleaning may be required. Significant effort is required to start the arc and establish the weld pool. Electrodes stick to the plate and need to be discarded.
Arc Stability	10	The arc can be manipulated at any desired length and angle, and it is nearly impossible to short out or stick to the plate. Metal transfer is very smooth and spray-like with an extremely steady arc.
	9-7	It is easy to maintain the arc at various arc lengths and angles. Electrode never shorts out or sticks to the plate once the arc is established. Metal transfer is smooth and spray-like in fine droplets. The arc may flicker in intensity, but no extinctions occur.
	6-4	Some manipulation may be required to maintain the arc, but sticking is still unusual. Metal transfer may be more coarse and globular, and some momentary Weld pool manipulation is easy. The arc has no tendency to wander, and the weld pool can be manipulated in the direction that the electrode is pointed with ease.
	6-4	Weld pool manipulation requires some skill and effort. The arc may have a slight tendency to wander, but can be controlled.
	1-3	Manipulation of the weld pool is very difficult. The arc has a consistent tendency to wander, and is difficult to control.

Wetting Characteristics	10	Smoothest possible transition across the weld toes. There is no tendency toward undercut, and grinding or preparation between weld beads is never needed.
	9-7	A smooth, radius transition occurs at the weld toe that has no tendency toward undercut. Some light grinding or preparation between weld beads is needed, but only on occasion.
	5-4	The toe of the weld makes a broad, obtuse angle with the plate. Light grinding is commonly required between passes.
	1-3	The toe of the weld makes a sharp angle or is undercut. Heavy grinding is usually required between weld beads to the point where productivity is significantly impacted.
Slag Cover	10	Slag covers the bead completely in a smooth and uniform layer, and wets out onto the plate a short distance beyond the toes of the bead. The smoothest and most uniform slag layer possible.
	9-7	Slag covers the bead completely in a smooth and uniform layer, and wets out onto the plate a short distance beyond to toes of the bead. The slag layer may have a slightly non-uniform thickness or appearance, but coverage is still complete.
	6-4	Coverage is generally good, but there may occasionally be one or two small areas of exposed metal, or the slag may not always cover the toes of the bead completely.
	1-3	Exposed areas of weld metal are frequently present. The slag balls up in lumps.
Slag Removal (Bead-on-plate)	10	The slag is self-peeling and can be removed with the fingers.
	9-7	Slag is easily removed in large pieces with a few light blows of the chipping hammer and some light wire brushing.
	6-4	Some work is required with the chipping hammer. Small bits of slag may adhere to the weld bead or at the toes, and require some power wire brushing or light grinding.
	1-3	Heavy chipping is required, resulting in a weld bead that appeal's beaten and denied. Tenacious pieces of slag need to be removed with the grinder and metal is removed m the process.
Slag Removal (Groove)	10	The slag is self-peeling and can be removed with the fingers.
	9-7	Slag is easily removed in large pieces with a few light blows of the chipping hammer and some light wire brushing.
	6-4	Some work is required with the chipping hammer. Small bits of slag may adhere to the weld bead or at the toes, and require some power wire brushing or light grinding.
	1-3	Heavy chipping is required, resulting in a weld bead that appears beaten and dented. Tenacious pieces of slag need to be removed with the grinder and metal is removed in the process.

Bead Contour	10	A flawless, smooth shape that is easily integrated into subsequent beads.
	9-7	A broad crown transitions smoothly to the plate on either side. The bead cross section is uniform and there are no sharp changes in width or height along the length. Grinding is rarely if ever needed between passes to correct bead shape.
	6-4	The crown may be a little sharp or humped, and a few irregularities may exist. The shape may cause slight difficulty in integrating the preceding weld bead into a subsequent one, but grinding is only needed on occasion.
	1-3	The shapes of the weld bead are irregular and frequently interfere with subsequent weld beads, requiring grinding and re-work.
Sparking	10	No sparking is observed.
	9-7	Sparking occurs on rare occasions, but does not cause difficulty.
	6-4	Sparking occurs with some regularity.
	1-3	Sparking interferes with the ability to deposit a sound weld bead.
Spatter	10	There is no visible spatter.
	9-7	Some fine particles are expelled from the welding arc, but do not adhere to the base metal.
	6-4	In addition to fine panicles, some larger globular particles are expelled and may occasionally stick to the base metal.
	1-3	Large globs of slag and metal are frequently expelled from the welding arc and some chipping and grinding is required to remove them from the surrounding metal after welding.
Finger nailing (concentricity)	10	Flux is consumed uniformly around the circumference of the electrode tip, resulting in formation of a uniform, round flux cup on the electrode tip.
	9-7	On rare occasions the flux is melted back on one side more than another, but the difficulty is easily overcome with some manipulation.
	6-4	Occasionally flux melts back on one side more than other causing problems with weld pool manipulation and bead profile.
	1-3	The core wire is frequently not centered in the electrode coating, causing the flux to bum back on one side. Some electrodes are unusable.

Slag Interference	10	The molten slag never interferes with weld pool manipulation or visibility.
	9-7	Slag may occasionally creep around in front of the \veld pool, but it does not cause any problems or can be easily overcome with minimal effort. The slag does not interfere with visibility of the weld pool.
	6-4	Some manipulation is required to prevent slag from being incorporated into the weld bead, to prevent slag from bridging the arc gap, or interfering with visibility of the weld pool. However, the difficulties can be overcome with a reasonable effort.
	1 -3	Behavior of the molten slag interferes with the deposition of a sound weld bead, and the problems are extremely difficult to overcome with a reasonable degree of skill and manipulation.
Porosity	10	There is no visible porosity in the finished weld bead.
	9-7	Tiny, superficial pinhole porosity may be present on the surface of the bead, but it is easily removed by light grinding.
	6-4	Light porosity may be present in starts or stops, but can easily be removed with light grinding.
	1-3	Gross porosity is present throughout the weld bead.
Surface Appearance	10	The weld bead has an extremely smooth and uniform rippled pattern. The metal is bright and shiny without any oxidation or discoloration with no need of wire brushing.
	9-7	The weld bead has a smooth and uniform rippled appearance. Slight oxidation or discoloration may be present, but is easily removed with light wire brushing.
	6-4	The rippled pattern is somewhat irregular and non-uniform. The bead may be oxidized or discolored and require heavy wire brushing.
	1-3	Grinding is usually required to remove heavy oxidation or smooth out a rough bead surface.

Appendix E: Field Testing Welding Procedures

Plan for SMA Welding Type 304L Steel with ENiCuRu Electrode

Machine Type: Miller Phoenix 456 CC/CV

PQR#:		Date:	1/06/2011
Base Material:	304L	BM Thickness:	0.5 in.
Joint Type:	75˚ included w/1/8” root		
Filler Metal:	ENiCuRu	Size:	1/8 in.
Preheat:	100˚F	Interpass:	350˚F max
Position:	Flat	Bead Type:	Stringer
Process:	SMAW DCRP	Travel Speed:	8 to 10 ipm
POWER SUPPLY SETTINGS			
Program:	Stick	Arc Control:	Dig - 5
Volts:	23.5 to 24.6	Amps:	108

Plan for Base Line SMA Welding Type 304L Steel with E308L-16 Electrode

Machine Type: Miller Phoenix 456 CC/CV

PQR#:		Date:	1/06/2011
Base Material:	304L	BM Thickness:	0.5 in.
Joint Type:	75˚ included w/1/8” root		
Filler Metal:	E308L-16	Size:	1/8 in.
Preheat:	100˚F	Interpass:	350˚F max
Position:	Flat	Bead Type:	Stringer
Process:	SMAW DCRP	Travel Speed:	8 to 10 ipm
POWER SUPPLY SETTINGS			
Program:	Stick	Arc Control:	
Volts:	22	Amps:	109

Plan for Welding Type 304L Steel with ERNiCuRu Electrode

Machine Type: Miller Phoenix 456 CC/CV

PQR#:		Date:	
Base Material:	304L	BM Thickness:	0.25 in.
Joint Type:	60˚ included double-V	Root:	1/16 opening, 1/32 land
Filler Metal:	ERNiCuRu	Size:	0.045 in.
Preheat:	100˚F	Interpass:	350˚F max
Position:	Flat	Bead Type:	Stringer
Root preparation:	Back grind the root of first pass and die penetrant test before welding second pass		

POWER SUPPLY SETTINGS

Process:	Pulsed GMAW		
Volts:	33.4	Wire Feeding Speed, in/min:	175
Peak Current, A:	340	Base current, A:	95
Pulse Frequency, Hz:	75	Pulse Width, ms:	2.3
Inductance setting:	55	Trim:	55
Travel Speed, in/min:	12	Work to contact tip distance, in:	0.3125
Shielding Gas:	Helistar Praxair Ar/33He/0.9CO_2	Shielding gas flow rate, ft^3/hr:	30

Plan for Base Line SMA Welding Type 304L Steel with ER308LSi Electrode

Machine Type: Miller Phoenix 456 CC/CV

PQR#:		Date:	1/06/2011
Base Material:	304L	BM Thickness:	0.25 in.
Joint Type:	60˚ included double-V	Root:	3/32 to 1/8 opening, 1/32 land
Filler Metal:	ER308LSi	Size:	0.035 in.
Preheat:	100˚F	Interpass:	350˚F max
Position:	Flat	Bead Type:	Stringer
Root preparation:	Back grind the root of first pass and die penetrant test before welding second pass		

POWER SUPPLY SETTINGS

Process:	Pulsed GMAW		
Volts:	32	Wire Feeding Speed, in/min:	200
Peak Current, A:	300	Base current, A:	53
Pulse Frequency, Hz:	115	Pulse Width, ms:	1.8
Inductance setting:	92	Trim:	20
Travel Speed, in/min:	16	Work to contact tip distance, in:	0.3125
Shielding Gas:	Helistar Praxair Ar/33He/0.9CO_2	Shielding gas flow rate, ft^3/hr:	30

Appendix F: Tensile Test Sample Deign in Field Demonstration

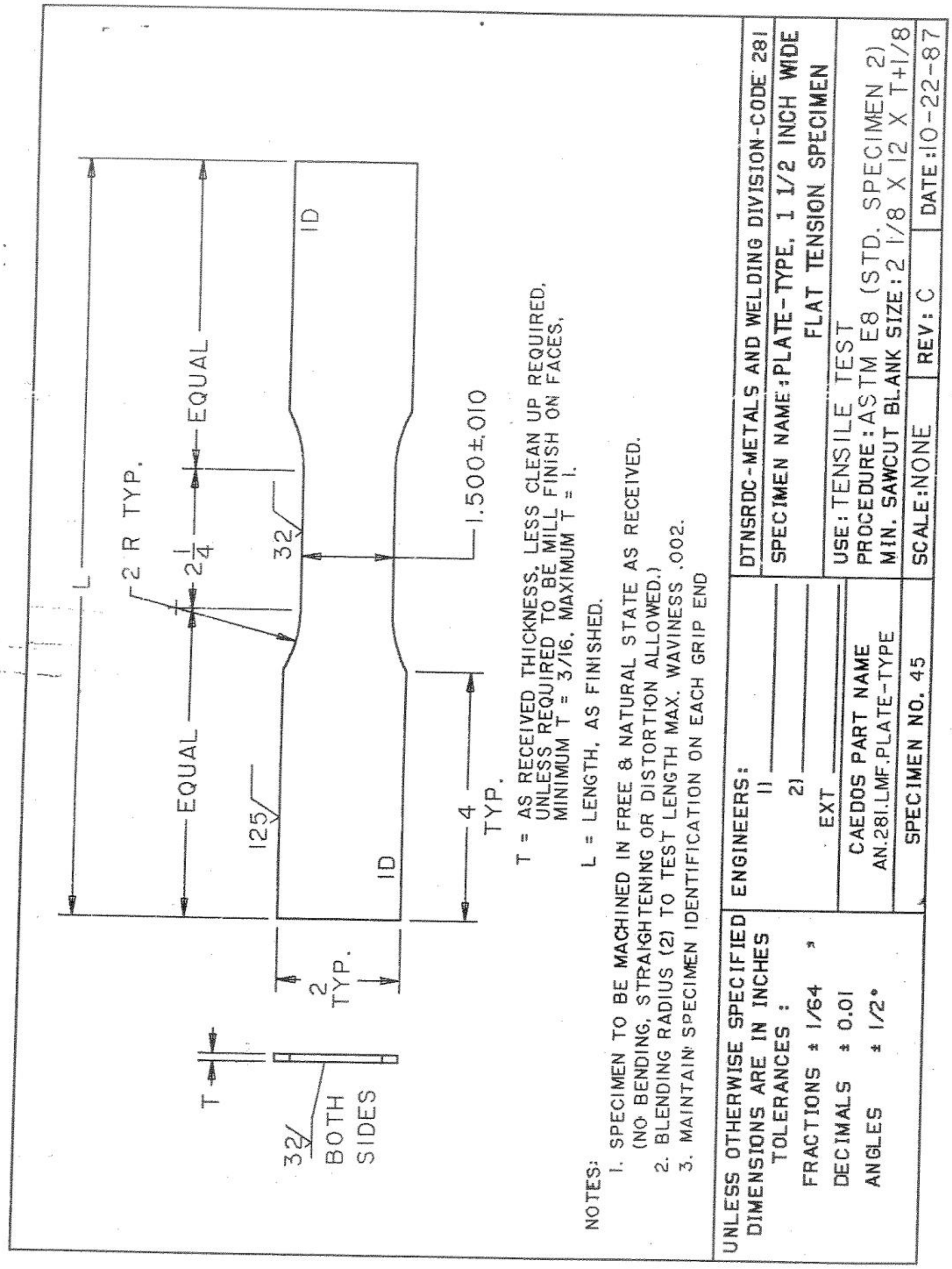

Figure A5.1: Design of transverse tensile test sample in GMA welds.

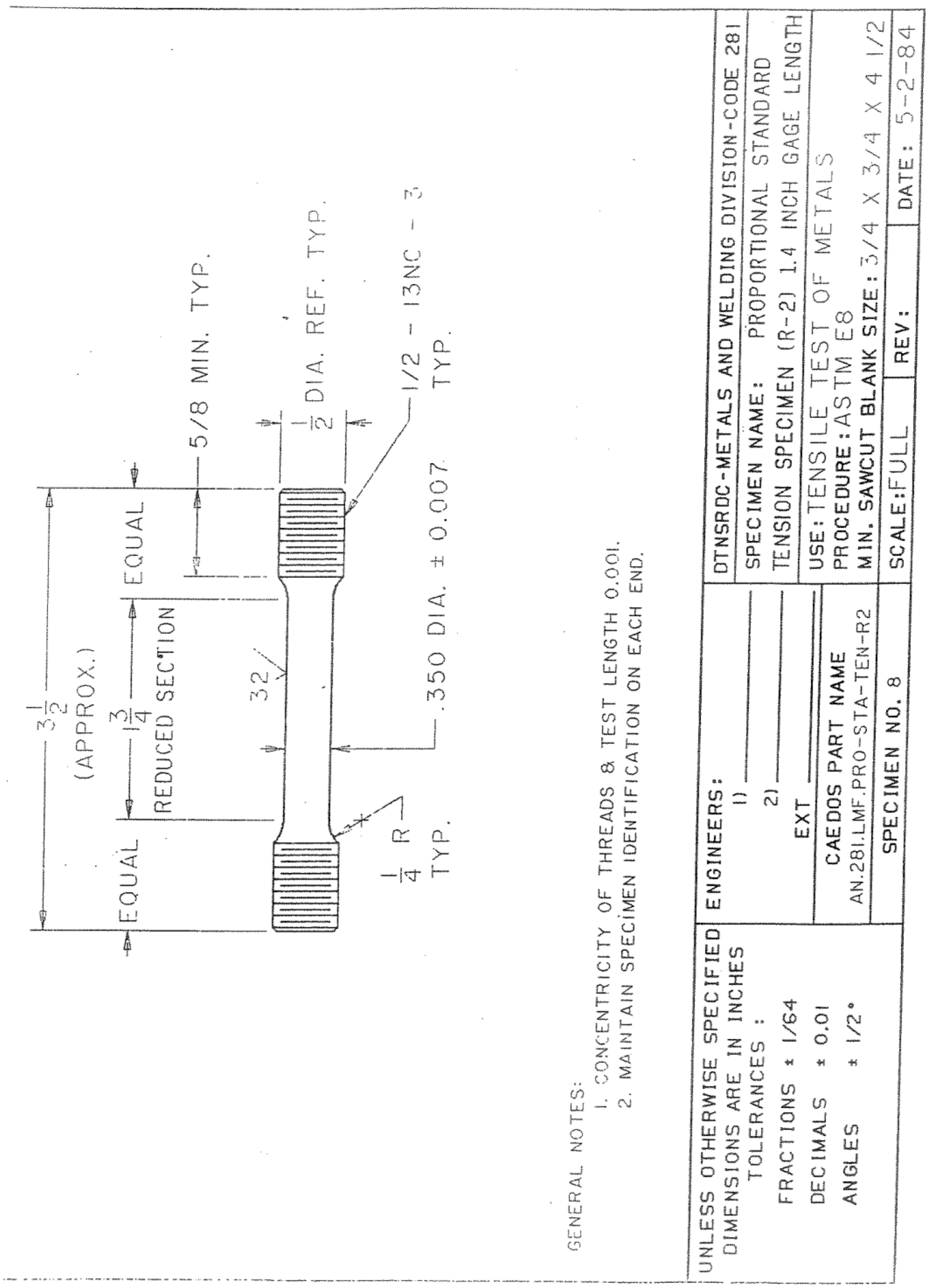

Figure A5.2: Design of all weld metal tensile test sample in SMA welds.

Appendix G: Cr(VI) Content in Fume of Base Line and Cr-free SMAW Electrodes

Table A6.1 Cr(VI) Content in Fume of Base Line E308L-16 Electrode

Sample ID	Date of Sample Collection	Sample Event	Fume Test	Sampler Location	Results			
					Air Volume (L)	Chromium VI (µg)	Chromium VI (mg/m³)	Chromium VI (mg/m³)
BSNELN080A-M	15-Aug-11	SMAW Baseline	ELPI	N	220	2.03	0.00921	9.2100
BSNELN081A-M	15-Aug-11	SMAW Baseline	ELPI	N	176	1.39	0.00788	7.8800
BSNELN072A-M	15-Aug-11	SMAW Baseline	ELPI	N	114.4	0.906	0.00792	7.9200
BSNELN083A-M	15-Aug-11	SMAW Baseline	ELPI	N	228.8	3.56	0.0156	15.6000
BSNELN084A-M	15-Aug-11	SMAW Baseline	ELPI	N	140.8	4.72	0.0336	33.6000
BSNELN092A-M	16-Aug-11	SMAW Baseline	ELPI	N	255.2	2.44	0.00954	9.5400
BSNELN093A-M	16-Aug-11	SMAW Baseline	ELPI	N	158.4	1.44	0.0091	9.1000
BSNELN095A-M	16-Aug-11	SMAW Baseline	ELPI	N	264	2.98	0.0113	11.3000
BSNICN067	15-Aug-11	SMAW Baseline	IH-Cr	N	513.4	2.01	0.00392	3.9200
BSNICN076	15-Aug-11	SMAW Baseline	IH-Cr	N	570.2	1.53	0.00269	2.6900
BSNICN086	16-Aug-11	SMAW Baseline	IH-Cr	N	504.6	4.29	0.00849	8.4900
BSNICF069	15-Aug-11	SMAW Baseline	IH-Cr	F	495.8	0.956	0.00193	1.9300
BSNICF077	15-Aug-11	SMAW Baseline	IH-Cr	F	549.72	0.673	0.00122	1.2200
BSNICF087	16-Aug-11	SMAW Baseline	IH-Cr	F	485.5	1.02	0.00209	2.0900
BSNGRN071	15-Aug-11	SMAW Baseline	AS	N	155	4.35	0.028	28.0000
BSNCB074	15-Aug-11	Blank			0	0.275	-	
BSNGRN075	15-Aug-11	SMAW Baseline	AS	N	123.5	1.11	0.00896	8.9600
BSNGRN082	15-Aug-11	SMAW Baseline	AS	N	111.7	2.71	0.0243	24.3000
BSNGRN085	15-Aug-11	SMAW Baseline	AS	N	135.3	2.67	0.0197	19.7000
BSNCB090	16-Aug-11	Blank			0	<0.02	-	
BSNGRN094	16-Aug-11	SMAW Baseline	AS	N	156.4	1.33	0.0085	8.5000

Table A6.2 Cr(VI) Content in Fume of Cr-free ENiCuRu Electrode

Sample ID	Date of Sample Collection	Sample Event	Fume Test	Sampler Location	Results			
					Air Volume (L)	Chromium VI (µg)	Chromium VI (mg/m^3)	Chromium VI (mg/m^3)
OSNELN101A-M	16-Aug-11	SMAW OSU	ELPI	N	167.2	0.134	0.000801	0.8010
OSNELN102A-M	16-Aug-11	SMAW OSU	ELPI	N	369.6	0.05	0.000135	0.1350
OSNELN108A-M	17-Aug-11	SMAW OSU	ELPI	N	114.4	0.096	0.000839	0.8390
OSNELN109A-M	17-Aug-11	SMAW OSU	ELPI	N	272.8	0.057	0.000209	0.2090
ELPIBLANK110	17-Aug-11	Blank	ELPI		0	<0.02	-	
OSNELN113A-M	17-Aug-11	SMAW OSU	ELPI	N	114.4	0.062	0.000542	0.5420
OSNELN114A-M	17-Aug-11	SMAW OSU	ELPI	N	167.2	0.087	0.00052	0.5200
OSNELN122A-M	17-Aug-11	SMAW OSU	ELPI	N	140.8	0.054	0.000384	0.3840
OSNELN123A-M	17-Aug-11	SMAW OSU	ELPI	N	149.6	0.023	0.00015	0.1500
OSNELN124A-M	17-Aug-11	SMAW OSU	ELPI	N	774.4	0.046	0.000059	0.0590
OSNICN096	16-Aug-11	SMAW OSU	IH-Cr	N	542.6	0.03	0.0000553	0.0553
OSNICN103	17-Aug-11	SMAW OSU	IH-Cr	N	624	0.123	0.000197	0.1970
OSNICN115	17-Aug-11	SMAW OSU	IH-Cr	N	540	0.088	0.000163	0.1630
OSNICF097	16-Aug-11	SMAW OSU	IH-Cr	F	531.4	<0.02	<0.0000376	BDL
OSNICF104	17-Aug-11	SMAW OSU	IH-Cr	F	623	0.032	0.0000514	0.0514
OSNICF116	17-Aug-11	SMAW OSU	IH-Cr	F	538	0.081	0.000151	0.1510
OSNGR100	16-Aug-11	SMAW OSU	AS		370.5	0.027	0.000073	0.0730
OSNGRN107	17-Aug-11	SMAW OSU	AS	N	140.6	0.038	0.00027	0.2700
ASBLK111	17-Aug-11	Blank	AS		0	<0.02	-	
OSNGRN112	17-Aug-11	SMAW OSU	AS	N	227.3	0.055	0.00024	0.2400
OSNCB120	17-Aug-11	Blank			0	<0.02	-	
OSNGRN121	17-Aug-11	SMAW OSU	AS	N	300.9	<0.02	<0.000066	0.0660
OSNGRN125	17-Aug-11	SMAW OSU	AS	N	115.6	0.02	0.00017	0.1700

Appendix H: Cr(VI) Content in Fume of Base Line and Cr-free GMAW Electrodes

Table A7.1 Cr(VI) Content in Fume of Base Line ER308Li Electrode

Sample ID	Date of Sample Collection	Sample Event	Fume Test	Sampler Location	Results		
					Air Volume (L)	Chromium VI (µg)	Chromium VI (mg/m^3)
BGNICN007	9-Aug-11	GMAW Baseline			281.5	0.023	0.000082
BGNICF008	9-Aug-11	GMAW Baseline			285.9	<0.02	<0.00007
BGNICB009	9-Aug-11	Blank			0	<0.02	-
BGNGRN010	9-Aug-11	GMAW Baseline			69.6	0.038	0.00055
BGNELN011A	10-Aug-11	GMAW Baseline	ELPI	N	35.2	<0.02	<0.00057
BGNELN011B	10-Aug-11	GMAW Baseline	ELPI	N	35.2	<0.02	<0.00057
BGNELN011C	10-Aug-11	GMAW Baseline	ELPI	N	35.2	0.032	0.00091
BGNELN011D	10-Aug-11	GMAW Baseline	ELPI	N	35.2	0.032	0.00091
BGNELN011E	10-Aug-11	GMAW Baseline	ELPI	N	35.2	0.023	0.00065
BGNELN011F	10-Aug-11	GMAW Baseline	ELPI	N	35.2	<0.02	<0.00057
BGNELN011G	10-Aug-11	GMAW Baseline	ELPI	N	35.2	<0.02	<0.00057
BGNELN011H	10-Aug-11	GMAW Baseline	ELPI	N	35.2	<0.02	<0.00057
BGNELN011I	10-Aug-11	GMAW Baseline	ELPI	N	35.2	<0.02	<0.00057
BGNELN011J	10-Aug-11	GMAW Baseline	ELPI	N	35.2	<0.02	<0.00057
BGNELN011K	10-Aug-11	GMAW Baseline	ELPI	N	35.2	<0.02	<0.00057
BGNELN011L	10-Aug-11	GMAW Baseline	ELPI	N	35.2	<0.02	<0.00057
BGNELN011M	10-Aug-11	GMAW Baseline	ELPI	N	35.2	<0.02	<0.00057
BGNELN012A-M	10-Aug-11	GMAW Baseline	ELPI	N	26.4	<0.02	<0.00076
BGNELN014A-M	10-Aug-11	GMAW Baseline	ELPI	N	26.4	<0.02	<0.00076
BGNELN015A-M	10-Aug-11	GMAW Baseline	ELPI	N	26.4	0.035	0.00133
BGEELN017A-M	10-Aug-11	GMAW Baseline	ELPI	N	61.6	<0.02	<0.00032
BGEELN018A-M	10-Aug-11	GMAW Baseline	ELPI	N	35.2	<0.02	<0.00057
BGEELN019A-M	10-Aug-11	GMAW Baseline	ELPI	N	35.2	<0.02	<0.00057

Sample ID	Date of Sample Collection	Sample Event	Fume Test	Sampler Location	Results		
					Air Volume (L)	Chromium VI (µg)	Chromium VI (mg/m^3)
BGEELN020A-M	10-Aug-11	GMAW Baseline	ELPI	N	44	<0.02	<0.00045
BGNELN163A-M	22-Aug-11	GMAW Baseline	ELPI	N	448.8	0.331	0.000738
BGNELN165A-M	22-Aug-11	GMAW Baseline	ELPI	N	492.8	0.282	0.000572
BGELN169A-M	22-Aug-11	GMAW Baseline	ELPI	N	132	<0.02	<0.000152
BGNELN167A-M	22-Aug-11	GMAW Baseline	ELPI	N	660	0.634	0.000961
BGNICB031	10-Aug-11	Blank	IH - Cr		0	<0.02	-
BGNICN032	10-Aug-11	GMAW Baseline	IH - Cr	N	498.1	<0.02	<0.00004
BGEICN039	10-Aug-11	GMAW Baseline	IH - Cr	N	591.1	<0.02	<0.000034
BGNICN155	22-Aug-11	GMAW Baseline	IH - Cr	N	674.7	<0.02	<0.00003
BGNICN170	22-Aug-11	GMAW Baseline	IH - Cr	N	188	0.03	0.00016
BGNICF033	10-Aug-11	GMAW Baseline	IH - Cr	F	492.6	<0.02	<0.000041
BGEICF040	10-Aug-11	GMAW Baseline	IH - Cr	F	509.2	<0.02	<0.000039
BGNICF156	22-Aug-11	GMAW Baseline	IH - Cr	F	662.2	<0.02	<0.00003
BGNICF171	22-Aug-11	GMAW Baseline	IH - Cr	F	184.5	<0.02	<0.00011
BGNGRB024	10-Aug-11	Blank	AS		0	<0.02	-
BGNGRN034	10-Aug-11	GMAW Baseline	AS	N	20.4	0.02	0.00098
BGEGRN041	10-Aug-11	GMAW Baseline	AS	N	24	<0.02	<0.00083
BGNGRN164	22-Aug-11	GMAW Baseline	AS	N	61.8	0.1	0.0016
BGNGRN166	22-Aug-11	GMAW Baseline	AS	N	74.2	0.097	0.0013
BGNGRN168	22-Aug-11	GMAW Baseline	AS	N	97.6	0.15	0.0016
BGNGRB161	22-Aug-11	Blank	AS		0	0.021	-
BGNCB157	22-Aug-11	Blank			0	<0.02	-
BGNLCN162	22-Aug-11	GMAW Baseline	Lincoln	N	-	<0.02	-
BGNLC176	22-Aug-11	GMAW Baseline	Lincoln	C	-	<0.02	-

Table A7.2 Cr(VI) Content in Fume of Cr-free ERNiCuRu Electrode

Sample ID	Date of Sample Collection	Sample Event	Fume Test	Sampler Location	Results		
					Air Volume (L)	Chromium VI (µg)	Chromium VI (mg/m^3)
OGNELN132A-M	18-Aug-11	GMAW OSU	ELPI	N	1645.6	0.144	0.000088
OGNELN152A-M	22-Aug-11	GMAW OSU	ELPI	N	440	0.318	0.000723
OGNELN242A-M	25-Aug-11	GMAW OSU	ELPI	N	765.6	0.561	0.000733
OGNICN138	18-Aug-11	GMAW OSU	IH - Cr	N	403.2	0.052	0.00013
OGNICN145	22-Aug-11	GMAW OSU	IH - Cr	N	174.2	<0.02	<0.00011
OGNICN237	25-Aug-11	GMAW OSU	IH - Cr	N	258.3	0.042	0.00016
OGNICF139	18-Aug-11	GMAW OSU	IH - Cr	F	391.2	0.024	0.000061
OGNICF146	22-Aug-11	GMAW OSU	IH - Cr	F	168.3	<0.02	<0.00012
OGNICF238	25-Aug-11	GMAW OSU	IH - Cr	F	255.4	<0.02	<0.000078
OGNGRB134	18-Aug-11	Blank	AS		0	0.033	
OGNGRN133	18-Aug-11	GMAW OSU	AS	N	245.7	0.062	0.00025
OGNGRN151	22-Aug-11	GMAW OSU	AS	N	65.75	0.068	0.001
OGNGRB154	22-Aug-11	Blank	AS		0	0.025	-
OGNLCN140	18-Aug-11	GMAW OSU	Lincoln	N	-	<0.02	-
OGNLC153	22-Aug-11	GMAW OSU	Lincoln	N	-	<0.02	-
OGNLCN243	25-Aug-11	GMAW OSU	Lincoln	N	-	<0.02	-
OGNCB144	18-Aug-11	Blank			0	<0.02	-
OGNCB147	22-Aug-11	Blank			0	<0.02	-

Appendix I: Metals Content in Fume of Cr-free ENiCuRu and Baseline E308L-16 SMAW Electrodes

Sample ID	Sample	Equipment	Arsenic		Cadmium		Chromium		Cobalt		Copper	
			(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)
BSNIMN068	Baseline	IH-M N	<0.2	<0.0003	<0.2	<0.0003	8.76	0.0117	<0.2	<0.0003	0.59	0.00079
BSNMetB073	Blank	IH-M	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
BSNIMN078	Baseline	IH-M N	<0.2	<0.0004	<0.2	<0.0004	4.95	0.00919	<0.2	<0.0004	0.74	0.0014
BSNIMN088	Baseline	IH-M N	<0.2	<0.0003	<0.2	<0.0003	15.7	0.0216	<0.2	<0.0003	0.81	0.0011
BSNIMF070	Baseline	IH-M F	<0.2	<0.0003	<0.2	<0.0003	4.41	0.016	<0.2	<0.0003	<0.2	<0.0003
BSNIMF079	Baseline	IH-M F	<0.2	<0.0002	<0.2	<0.0002	3.38	0.00418	<0.2	<0.0002	0.21	0.00026
BSNIMF089	Baseline	IH-M F	<0.2	<0.0003	<0.2	<0.0003	4.21	0.00579	<0.2	<0.0003	0.23	0.00032
BSNMB091	Blank	IH-M	<0.2*	-	<0.2*	-	0.210	-	<0.2*	-	<0.2*	-
OSNIMN098	OSU	IH-M N	<0.2	<0.0003	<0.2	<0.0003	1.28	0.00166	<0.2	<0.0003	4.0	0.0051
OSNIMN105	OSU	IH-M N	<0.2	<0.0002	<0.2	<0.0002	0.930	0.00106	<0.2	<0.0002	5.8	0.0066
OSNIMN117	OSU	IH-M N	<0.2	<0.0003	<0.2	<0.0003	3.75	0.00493	<0.2	<0.0003	6.6	0.0087
OSNIMF099	OSU	IH-M F	<0.2	<0.0003	<0.2	<0.0003	0.480	0.000607	<0.2	<0.0003	0.84	0.0011
OSNIMF106	OSU	IH-M F	<0.2	<0.0002	<0.2	<0.0002	0.940	0.00102	<0.2	<0.0002	3.2	0.0034
OSNIMF118	OSU	IH-M F	<0.2	<0.0002	<0.2	<0.0002	1.93	0.00241	<0.2	<0.0002	2.5	0.0031
OSNIMB119	Blank	IH-M	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
BSNGRN071	Baseline	AS	<0.2	<0.0013	<0.2	<0.0013	5.970	0.0385	<0.2	<0.0013	0.240	0.00155
BSNGRN075	Baseline	AS	<0.2	<0.0016	<0.2	<0.0016	1.84	0.0149	<0.2	<0.0016	<0.2	<0.0016
BSNGRN082**	Baseline	AS	<0.2	<0.0018	<0.2	<0.0018	2.79	0.0249	<0.2	<0.0018	<0.2	<0.0018
BSNGRN085	Baseline	AS	<0.2	<0.0015	<0.2	<0.0015	2.68	0.0198	<0.2	<0.0015	0.350	0.00259
BSNGRN094	Baseline	AS	<0.2	<0.0013	<0.2	<0.0013	0.830	0.00531	<0.2	<0.0013	<0.2	<0.0013
OSNGR100	OSU	AS	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	1.72	0.00464
OSNGRN107	OSU	AS	<0.2	<0.0014	<0.2	<0.0014	0.420	0.00299	<0.2	<0.0014	3.52	0.0250
ASBLANK111	Blank	AS	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
OSNGRN112	OSU	AS	<0.2	<0.0009	<0.2	<0.0009	0.520	0.00229	<0.2	<0.0009	2.55	0.0112

OSNGRN121	OSU	AS	<0.2	<0.0007	<0.2	<0.0007	0.560	0.00186	<0.2	<0.0007	3.28	0.0109
OSNGRN125	OSU	AS	<0.2	<0.0017	<0.2	<0.0017	0.420	0.00363	<0.2	<0.0017	1.47	0.0127

Sample ID	**Sample**	**Equipment**	**Iron**		**Lead**		**Manganese**		**Molybdenum**		**Nickel**	
			(μg)	**(mg/m^3)**	**(μg)**	**(mg/m^3)**	**(μg)**	**(mg/m^3)**	**(μg)**	**(mg/m^3)**	**(μg)**	**(mg/m^3)**
BSNIMN068	Baseline	IH-M N	21.2	0.0283	0.210	0.00028	14.4	0.0191	<0.2	<0.0003	2.23	0.0297
BSNMetB073	Blank	IH-M	<1*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
BSNIMN078	Baseline	IH-M N	12.8	0.0238	<0.2	<0.0004	8.12	0.0151	<0.2	<0.0004	1.18	0.00219
BSNIMN088	Baseline	IH-M N	35.2	0.0486	0.290	0.000399	26.0	0.0359	0.290	0.000399	3.82	0.00526
BSNIMF070	Baseline	IH-M F	6.29	0.00879	<0.2	<0.0003	7.07	0.00988	<0.2	<0.0003	0.450	0.00063
BSNIMF079	Baseline	IH-M F	5.48	0.00678	<0.2	<0.0002	5.25	0.0065	<0.2	<0.0002	0.390	0.000483
BSNIMF089	Baseline	IH-M F	6.86	0.00943	<0.2	<0.0003	6.74	0.00927	<0.2	<0.0003	0.650	0.000894
BSNMB091	Blank	IH-M	<1*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
OSNIMN098	OSU	IH-M N	6.05	0.00783	<0.2	<0.0003	0.340	0.00044	<0.2	<0.0003	31.4	0.0406
OSNIMN105	OSU	IH-M N	3.65	0.00415	<0.2	<0.0002	0.430	0.000489	<0.2	<0.0002	23.8	0.0270
OSNIMN117	OSU	IH-M N	22.4	0.0295	<0.2	<0.0003	1.55	0.00204	<0.2	<0.0003	35.8	0.0471
OSNIMF099	OSU	IH-M F	1.92	0.00243	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	3.00	0.00379
OSNIMF106	OSU	IH-M F	2.47	0.00268	<0.2	<0.0002	0.350	0.00038	<0.2	<0.0002	11.6	0.0127
OSNIMF118	OSU	IH-M F	7.45	0.00931	<0.2	<0.0002	0.890	0.00111	<0.2	<0.0002	11.0	0.0137
OSNIMB119	Blank	IH-M	<1*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
BSNGRN071	Baseline	AS	8.42	0.0543	<0.2	<0.0013	10.8	0.0695	<0.2	<0.0013	0.780	0.00503
BSNGRN075	Baseline	AS	3.33	0.0270	<0.2	<0.0016	2.42	0.0196	<0.2	<0.0016	0.330	0.00267
BSNGRN082**	Baseline	AS	3.94	0.0353	<0.2	<0.0018	4.98	0.0446	<0.2	<0.0018	0.360	0.00322
BSNGRN085	Baseline	AS	4.00	0.0296	<0.2	<0.0015	5.09	0.0376	<0.2	<0.0015	0.350	0.00259
BSNGRN094	Baseline	AS	8.36	0.0535	<0.2	<0.0013	1.32	0.00844	<0.2	<0.0013	<0.2	<0.0013
OSNGR100	OSU	AS	<1	<0.0027	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	4.24	0.0114
OSNGRN107	OSU	AS	<1	<0.0071	<0.2	<0.0014	<0.2	<0.0014	<0.2	<0.0014	7.41	0.0527
ASBLANK	Blank	AS	<1*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-

OSNGRN112	OSU	AS	<1	<0.0044	<0.2	<0.0009	<0.2	<0.0009	<0.2	<0.0009	4.09	0.0180
OSNGRN121	OSU	AS	<1	<0.0033	<0.2	<0.0007	<0.2	<0.0007	<0.2	<0.0007	7.64	0.0254
OSNGRN125	OSU	AS	<1	<0.0087	<0.2	<0.0017	<0.2	<0.0017	<0.2	<0.0017	3.09	0.0267

Sample ID	Sample	Equipment	Strontium		Vanadium		Zinc		Ruthenium	
			(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)
BSNIMN068	Baseline	IH-M N	<0.2	<0.0003	<0.2	<0.0003	0.23	0.00031	<0.2	<0.0003
BSNMetB073	Blank	IH-M	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
BSNIMN078	Baseline	IH-M N	<0.2	<0.0004	<0.2	<0.0004	0.37	0.00069	<0.2	<0.0004
BSNIMN088	Baseline	IH-M N	<0.2	<0.0003	<0.2	<0.0003	0.34	0.00047	<0.2	<0.0003
BSNIMF070	Baseline	IH-M F	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BSNIMF079	Baseline	IH-M F	<0.2	<0.0002	<0.2	<0.0002	0.23	0.00028	<0.2	<0.0002
BSNIMF089	Baseline	IH-M F	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BSNMB091	Blank	IH-M	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
OSNIMN098	OSU	IH-M N	5.13	0.00664	<0.2	<0.0003	<0.2	<0.0003	0.310	0.000401
OSNIMN105	OSU	IH-M N	8.13	0.00924	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
OSNIMN117	OSU	IH-M N	10.8	0.0142	<0.2	<0.0003	0.34	0.00045	0.300	0.000395
OSNIMF099	OSU	IH-M F	1.51	0.00191	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
OSNIMF106	OSU	IH-M F	4.36	0.00474	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
OSNIMF118	OSU	IH-M F	3.96	0.00495	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
OSNIMB119	Blank	IH-M	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
BSNGRN071	Baseline	AS	<0.2	<0.0013	<0.2	<0.0013	0.22	0.0014	<0.2	<0.0013
BSNGRN075	Baseline	AS	<0.2	<0.0016	<0.2	<0.0016	<0.2	<0.0016	<0.2	<0.0016
BSNGRN082**	Baseline	AS	<0.2	<0.0018	<0.2	<0.0018	<0.2	<0.0018	<0.2	<0.0018
BSNGRN085	Baseline	AS	<0.2	<0.0015	<0.2	<0.0015	0.34	0.0025	<0.2	<0.0015
BSNGRN094	Baseline	AS	<0.2	<0.0013	<0.2	<0.0013	<0.2	<0.0013	<0.2	<0.0013
OSNGR100	OSU	AS	1.20	0.00324	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
OSNGRN107	OSU	AS	3.29	0.0234	<0.2	<0.0014	<0.2	<0.0014	<0.2	<0.0014

ASBLANK111	Blank	AS	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
OSNGRN112	OSU	AS	2.47	0.0109	<0.2	<0.0009	<0.2	<0.0009	<0.2	<0.0009
OSNGRN121	OSU	AS	1.80	0.00598	<0.2	<0.0007	<0.2	<0.0007	<0.2	<0.0007
OSNGRN125	OSU	AS	1.30	0.0112	<0.2	<0.0017	<0.2	<0.0017	<0.2	<0.0017

Appendix J: Metals Content in Fume of Cr-free ERNiCuRu and Baseline ER308LSi GMAW Electrodes

Table A9.1: Metals Content in Fume of Baseline ER308LSi GMAW Electrode

Sample ID	Sample	Equipment	Arsenic		Cadmium		Chromium		Cobalt		Copper	
			(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)
BGNIMB004	Baseline	IH-M N	<0.2*	-	<0.2*	-	0.41*	-	<0.2*	-	<0.2*	-
BGNIMN005	Baseline	IH-M N	<0.2	<0.0005	<0.2	<0.0005	2.7	0.0063	<0.2	<0.0005	<0.2	<0.0005
BGNIMN029	Baseline	IH-M N	<0.2	<0.0003	<0.2	<0.0003	1.42	0.00193	<0.2	<0.0003	<0.2	<0.0003
BGEIMN037	Baseline	IH-M N	<0.2	<0.0003	<0.2	<0.0003	1.58	0.00210	<0.2	<0.0003	<0.2	<0.0003
BGNIMN158	Baseline	IH-M N	<0.2	<0.0006	<0.2	<0.0006	1.51	0.00467	<0.2	<0.0006	0.730	0.00226
BGNIMN172	Baseline	IH-M N	<0.2	<0.0008	<0.2	<0.0008	2.34	0.00887	<0.2	<0.0008	0.39	0.0015
BGNIMN173	Baseline	IH-M N	<0.2	<0.0007	<0.2	<0.0007	0.850	0.00315	<0.2	<0.0007	<0.2	<0.0007
BGNIMF006	Baseline	IH-M F	<0.2	<0.0005	<0.2	<0.0005	2.0	0.0049	<0.2	<0.0005	<0.2	<0.0005
BGNIMB028	Blank	IH-M F	<0.2*	-	<0.2*	-	0.37*	-	<0.2*	-	<0.2*	-
BGNIMF030	Baseline	IH-M F	<0.2	<0.0003	<0.2	<0.0003	1.44	0.00198	<0.2	<0.0003	<0.2	<0.0003
BGEIMF038	Baseline	IH-M F	<0.2	<0.0003	<0.2	<0.0003	0.770	0.00103	<0.2	<0.0003	<0.2	<0.0003
BGNIMF159	Baseline	IH-M F	<0.2	<0.0002	<0.2	<0.0002	1.11	0.00114	<0.2	<0.0002	0.22	0.00023
BGNMB160	Blank	IH-M F	<0.2*	-	<0.2*	-	0.270*	-	<0.2*	-	<0.2*	-
BGNGRN010	Baseline	AS	<0.2	<0.0029	<0.2	<0.0029	2.7	0.0390	<0.2	<0.0029	0.260	0.00374
BGNGRB024	Blank	AS	<0.2*	-	<0.2*	-	0.50*	-	<0.2*	-	<0.2*	-
BGEGRN041	Baseline	AS	<0.2	<0.0083	<0.2	<0.0083	0.400	0.0167	<0.2	<0.0083	<0.2	<0.0083
BGNGRB161	Blank	AS	<0.2*	-	<0.2*	-	0.650*	-	<0.2	-	0.64*	-
BGNGRN164	Baseline	AS	<0.2	<0.0032	<0.2	<0.0032	1.63	0.0264	<0.2	<0.0032	<0.2	<0.0032
BGNGRN168	Baseline	AS	<0.2	<0.0020	<0.2	<0.0020	8.37	0.0858	<0.2	<0.0020	0.52	0.0053
BGNELN015A-M	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	1.74	**0.00507**	<0.2	<0.006	<0.2	<0.006
BGNELN013A	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013B	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013C	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	0.30	0.0085	<0.2	<0.006	<0.2	<0.006
BGNELN013D	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	0.37	0.011	<0.2	<0.006	<0.2	<0.006

Sample ID	Sample	Equipment	Arsenic		Cadmium		Chromium		Cobalt		Copper	
			(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)
BGNELN013E	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	0.44	0.012	<0.2	<0.006	<0.2	<0.006
BGNELN013F	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	0.32	0.0091	<0.2	<0.006	<0.2	<0.006
BGNELN013G	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	0.26	0.0074	<0.2	<0.006	<0.2	<0.006
BGNELN013H	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013I	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013J	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013K	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013L	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013M	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN015A	Baseline	ELPI	<0.2	<0.0076	<0.2	<0.0076	1.74	**0.0659**	<0.2	<0.0076	<0.2	<0.0076
BGNELN163A	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	1.550	0.003450	<0.2	<0.0004	<0.2	<0.0004
BGNELN163B	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	1.920	0.004280	<0.2	<0.0004	<0.2	<0.0004
BGNELN163C	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	7.260	0.016200	<0.2	<0.0004	0.510	0.001140
BGNELN163D	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	2.780	0.006190	<0.2	<0.0004	0.210	0.000468
BGNELN163E	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	3.390	0.007550	<0.2	<0.0004	0.220	0.000490
BGNELN163F	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	2.500	0.005570	<0.2	<0.0004	0.280	0.000624
BGNELN163G	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	1.640	0.003650	<0.2	<0.0004	<0.2	<0.0004
BGNELN163H	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.550	0.001230	<0.2	<0.0004	<0.2	<0.0004
BGNELN163I	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.430	0.000958	<0.2	<0.0004	<0.2	<0.0004
BGNELN163J	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.400	0.000891	<0.2	<0.0004	<0.2	<0.0004
BGNELN163K	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.410	0.000914	<0.2	<0.0004	<0.2	<0.0004
BGNELN163L	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.390	0.000869	<0.2	<0.0004	<0.2	<0.0004
BGNELN163M	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.500	0.001110	<0.2	<0.0004	2.090	0.004660
BGNELN165A	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN165B	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	4.200	0.085200	<0.2	<0.0004	0.350	0.000710
BGNELN165C	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	1.560	0.003170	<0.2	<0.0004	<0.2	<0.0004
BGNELN165D	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	8.450	0.017100	<0.2	<0.0004	0.570	0.001160
BGNELN165E	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	6.950	0.014100	<0.2	<0.0004	0.380	0.000771

Sample ID	Sample	Equipment	Arsenic		Cadmium		Chromium		Cobalt		Copper	
			(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)
BGNELN165F	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	1.900	0.003860	<0.2	<0.0004	<0.2	<0.0004
BGNELN165G	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	1.450	0.002940	<0.2	<0.0004	<0.2	<0.0004
BGNELN165H	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.400	0.000812	<0.2	<0.0004	<0.2	<0.0004
BGNELN165I	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.580	0.001180	<0.2	<0.0004	<0.2	<0.0004
BGNELN165J	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.460	0.000933	<0.2	<0.0004	0.23	0.00047
BGNELN165K	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.360	0.000731	<0.2	<0.0004	<0.2	<0.0004
BGNELN165L	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.360	0.000731	<0.2	<0.0004	<0.2	<0.0004
BGNELN165M	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.350	0.000710	<0.2	<0.0004	<0.2	<0.0004
BGNGRN166	Baseline	ELPI	<0.2	<0.0027	<0.2	<0.0027	4.96	**0.0668**	<0.2	<0.0027	0.40	**0.0054**
BGNELN167A	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	1.080	0.001640	<0.2	<0.0003	<0.2	<0.0003
BGNELN167B	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	1.240	0.001880	<0.2	<0.0003	<0.2	<0.0003
BGNELN167C	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	14.700	0.022300	<0.2	<0.0003	1.16	0.00176
BGNELN167D	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	5.800	0.008790	<0.2	<0.0003	0.320	0.000485
BGNELN167E	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	9.020	0.013700	<0.2	<0.0003	0.470	0.000712
BGNELN167F	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	4.780	0.007240	<0.2	<0.0003	0.29	0.00044
BGNELN167G	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	2.590	0.003920	<0.2	<0.0003	<0.2	<0.0003
BGNELN167H	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.660	0.001000	<0.2	<0.0003	<0.2	<0.0003
BGNELN167I	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.940	0.001420	<0.2	<0.0003	<0.2	<0.0003
BGNELN167J	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.640	0.000970	<0.2	<0.0003	<0.2	<0.0003
BGNELN167K	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.400	0.000606	<0.2	<0.0003	<0.2	<0.0003
BGNELN167L	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.360	0.000545	<0.2	<0.0003	<0.2	<0.0003
BGNELN167M	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.340	0.000515	<0.2	<0.0003	0.45	0.00068
BGNELN169A	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	0.31	0.0024	<0.2	<0.0015	<0.2	<0.0015
BGNELN169B	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	0.21	0.0016	<0.2	<0.0015	<0.2	<0.0015
BGNELN169C	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	0.36	0.0027	<0.2	<0.0015	<0.2	<0.0015
BGNELN169D	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	0.31	0.0024	<0.2	<0.0015	<0.2	<0.0015
BGNELN169E	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	0.28	0.0021	<0.2	<0.0015	<0.2	<0.0015
BGNELN169F	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	0.27	0.0021	<0.2	<0.0015	<0.2	<0.0015
BGNELN169G	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	0.31	0.0024	<0.2	<0.0015	<0.2	<0.0015

Sample ID	Sample	Equipment	Arsenic		Cadmium		Chromium		Cobalt		Copper	
			(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)
BGNELN169H	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	0.37	0.0028	<0.2	<0.0015	<0.2	<0.0015
BGNELN169I	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	0.30	0.0023	<0.2	<0.0015	<0.2	<0.0015
BGNELN169J	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	0.25	0.0019	<0.2	<0.0015	<0.2	<0.0015
BGNELN169K	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	0.39	0.0030	<0.2	<0.0015	<0.2	<0.0015
BGNELN169L	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	0.34	0.0026	<0.2	<0.0015	<0.2	<0.0015
BGNELN169M	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	0.31	0.0024	<0.2	<0.0015	<0.2	<0.0015

Strontium	Sample	Equipment	Iron		Lead		Manganese		Molybdenum		Nickel	
			(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)
BGNIMB004	Baseline	IH-M N	<1*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
BGNIMN005	Baseline	IH-M N	10.3	0.0243	<0.2	<0.0005	4.87	0.0115	<0.2	<0.0005	0.99	0.0023
BGNIMN029	Baseline	IH-M N	8.72	0.0119	<0.2	<0.0003	1.79	0.00244	<0.2	<0.0003	0.46	0.00063
BGEIMN037	Baseline	IH-M N	11.2	0.149	<0.2	<0.0003	1.88	0.00250	<0.2	<0.0003	0.56	0.00074
BGNIMN158	Baseline	IH-M N	11.9	0.0367	<0.2	<0.0006	3.54	0.0110	<0.2	<0.0006	2.39	0.00740
BGNIMN172	Baseline	IH-M N	11.3	0.0427	<0.2	<0.0008	2.50	0.00947	<0.2	<0.0008	2.18	0.00826
BGNIMN173	Baseline	IH-M N	2.61	0.00966	<0.2	<0.0007	1.27	0.00470	<0.2	<0.0007	0.470	0.00174
BGNIMF006	Baseline	IH-M F	7.75	0.0185	<0.2	<0.0005	4.52	0.0108	<0.2	<0.0005	0.73	0.0017
BGNIMB028	Blank	IH-M F	<1*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
BGNIMF030	Baseline	IH-M F	5.07	0.00697	<0.2	<0.0003	1.70	0.00234	<0.2	<0.0003	0.38	0.00052
BGEIMF038	Baseline	IH-M F	2.60	0.00348	<0.2	<0.0003	0.820	0.00110	<0.2	<0.0003	0.23	0.00031
BGNIMF159	Baseline	IH-M F	4.57	0.00471	<0.2	<0.0002	2.41	0.00249	<0.2	<0.0002	0.700	0.000722
BGNMB160	Blank	IH-M F	<1*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
BGNGRN010	Baseline	AS	12.8	0.1840	<0.2	<0.0029	7.68	0.110	<0.2	<0.0029	1.4	0.020
BGNGRB024	Blank	AS	1.46*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
BGEGRN041	Baseline	AS	1.36	0.0567	<0.2	<0.0083	1.09	0.0454	<0.2	<0.0083	<0.2	<0.0083
BGNGRB161	Blank	AS	6.20*	-	<0.2*	-	0.370*	-	<0.2*	-	6.57*	-
BGNGRN164	Baseline	AS	7.74	0.125	<0.2	<0.0032	7.51	0.122	<0.2	<0.0032	0.800	0.0129

BGNGRN168	Baseline	AS	33.6	0.345	<0.2	<0.0020	24.5	0.251	<0.2	<0.0020	3.48	0.0357
BGNELN015A-M	Baseline	ELPI	<5	<0.0146	<0.2	<0.006	0.36	**0.00105**	<0.2	<0.006	0.72	**0.0021**
BGNELN013A	Baseline	ELPI	<1	<0.028	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013B	Baseline	ELPI	<1	<0.028	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013C	Baseline	ELPI	<1	<0.028	<0.2	<0.006	0.430	0.0122	<0.2	<0.006	<0.2	<0.006
BGNELN013D	Baseline	ELPI	1.75	0.0497	<0.2	<0.006	0.620	0.0176	<0.2	<0.006	<0.2	<0.006
BGNELN013E	Baseline	ELPI	1.25	0.0355	<0.2	<0.006	0.680	0.0193	<0.2	<0.006	<0.2	<0.006
BGNELN013F	Baseline	ELPI	<1	<0.028	<0.2	<0.006	0.380	0.0108	<0.2	<0.006	<0.2	<0.006
BGNELN013G	Baseline	ELPI	<1	<0.028	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013H	Baseline	ELPI	<1	<0.028	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013I	Baseline	ELPI	<1	<0.028	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013J	Baseline	ELPI	<1	<0.028	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013K	Baseline	ELPI	<1	<0.028	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013L	Baseline	ELPI	<1	<0.028	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013M	Baseline	ELPI	<1	<0.028	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN015A	Baseline	ELPI	4.60	**0.174**	<0.2	<0.0076	0.360	**0.0136**	<0.2	<0.0076	0.720	**0.0273**
BGNELN163A	Baseline	ELPI	5.35	0.011900	<0.2	<0.0004	4.01	0.00893	<0.2	<0.0004	0.68	0.001582
BGNELN163B	Baseline	ELPI	7	0.015600	<0.2	<0.0004	5.39	0.012	<0.2	<0.0004	0.9	0.00201
BGNELN163C	Baseline	ELPI	27.8	0.062100	<0.2	<0.0004	22.2	0.0495	<0.2	<0.0004	2.95	0.00657
BGNELN163D	Baseline	ELPI	12	0.026700	<0.2	<0.0004	10.2	0.0226	<0.2	<0.0004	1.31	0.00292
BGNELN163E	Baseline	ELPI	15.8	0.035300	<0.2	<0.0004	11.9	0.0266	<0.2	<0.0004	1.54	0.00343
BGNELN163F	Baseline	ELPI	9.45	0.021100	<0.2	<0.0004	6.87	0.0153	<0.2	<0.0004	2.56	0.0057
BGNELN163G	Baseline	ELPI	5.99	0.013300	<0.2	<0.0004	4.5	0.01	<0.2	<0.0004	0.68	0.00152
BGNELN163H	Baseline	ELPI	1.48	0.003300	<0.2	<0.0004	0.88	0.00196	<0.2	<0.0004	0.33	0.000735
BGNELN163I	Baseline	ELPI	1.03	0.002300	<0.2	<0.0004	0.44	0.00098	<0.2	<0.0004	<0.2	<0.0004
BGNELN163J	Baseline	ELPI	1.41	0.003140	<0.2	<0.0004	0.38	0.00085	<0.2	<0.0004	<0.2	<0.0004
BGNELN163K	Baseline	ELPI	<1	<0.0022	<0.2	<0.0004	0.25	0.00056	<0.2	<0.0004	0.3	0.000668
BGNELN163L	Baseline	ELPI	<1	<0.0022	<0.2	<0.0004	0.26	0.00058	<0.2	<0.0004	0.31	0.000691
BGNELN163M	Baseline	ELPI	1.18	0.002630	<0.2	<0.0004	0.25	0.00056	<0.2	<0.0004	6.02	0.134
BGNELN165A	Baseline	ELPI	<1	<0.0022	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004

BGNELN165B	Baseline	ELPI	15.6	0.031800	<0.2	<0.0004	13.3	0.027	<0.2	<0.0004	1.81	0.00367
BGNELN165C	Baseline	ELPI	5.48	0.011100	<0.2	<0.0004	4.35	0.00883	<0.2	<0.0004	0.68	0.00138
BGNELN165D	Baseline	ELPI	37.2	0.075400	<0.2	<0.0004	30	0.0609	<0.2	<0.0004	3.68	0.00747
BGNELN165E	Baseline	ELPI	29.3	0.059500	<0.2	<0.0004	23.4	0.0476	<0.2	<0.0004	2.84	0.00576
BGNELN165F	Baseline	ELPI	9.36	0.019000	<0.2	<0.0004	7.02	0.0142	<0.2	<0.0004	0.96	0.00195
BGNELN165G	Baseline	ELPI	5.88	0.011900	<0.2	<0.0004	4.6	0.00933	<0.2	<0.0004	0.72	0.00146
BGNELN165H	Baseline	ELPI	1.24	0.002520	<0.2	<0.0004	0.71	0.00144	<0.2	<0.0004	0.25	0.000507
BGNELN165I	Baseline	ELPI	3.08	0.006250	<0.2	<0.0004	1.05	0.00213	<0.2	<0.0004	0.42	0.000852
BGNELN165J	Baseline	ELPI	2.78	0.005640	<0.2	<0.0004	0.91	0.00185	<0.2	<0.0004	0.6	0.00122
BGNELN165K	Baseline	ELPI	1.03	0.002090	<0.2	<0.0004	0.32	0.00065	<0.2	<0.0004	0.26	0.000528
BGNELN165L	Baseline	ELPI	<1	<0.0022	<0.2	<0.0004	0.26	0.00053	<0.2	<0.0004	0.28	0.000568
BGNELN165M	Baseline	ELPI	2.01	0.004080	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	0.21	0.000426
BGNGRN166	Baseline	ELPI	21.4	**0.288**	<0.2	<0.0027	17.2	**0.232**	<0.2	<0.0027	2.19	**0.0295**
BGNELN167A	Baseline	ELPI	3.26	0.004940	<0.2	<0.0003	2.25	0.00341	<0.2	<0.0003	0.4	0.000606
BGNELN167B	Baseline	ELPI	3.59	0.005440	<0.2	<0.0003	2.72	0.00412	<0.2	<0.0003	0.49	0.000742
BGNELN167C	Baseline	ELPI	60.4	0.091500	<0.2	<0.0003	47.2	0.0715	<0.2	<0.0003	8.22	0.0125
BGNELN167D	Baseline	ELPI	27.5	0.041600	<0.2	<0.0003	18.0	0.0272	<0.2	<0.0003	2.46	0.00373
BGNELN167E	Baseline	ELPI	39.9	0.060500	<0.2	<0.0003	27.3	0.413	<0.2	<0.0003	3.81	0.00577
BGNELN167F	Baseline	ELPI	19.6	0.029800	<0.2	<0.0003	13.4	0.0203	<0.2	<0.0003	2.69	0.00408
BGNELN167G	Baseline	ELPI	9.79	0.014800	<0.2	<0.0003	7.56	0.0115	<0.2	<0.0003	1.57	0.00238
BGNELN167H	Baseline	ELPI	2.66	0.004030	<0.2	<0.0003	1.93	0.00292	<0.2	<0.0003	0.31	0.00047
BGNELN167I	Baseline	ELPI	3.49	0.005290	<0.2	<0.0003	1.88	0.00285	<0.2	<0.0003	0.45	0.000682
BGNELN167J	Baseline	ELPI	2.69	0.004080	<0.2	<0.0003	1.33	0.00202	<0.2	<0.0003	0.39	0.000591
BGNELN167K	Baseline	ELPI	1.63	0.002470	<0.2	<0.0003	0.62	0.00094	<0.2	<0.0003	0.28	0.000424
BGNELN167L	Baseline	ELPI	1.03	0.001560	<0.2	<0.0003	0.41	0.00062	<0.2	<0.0003	<0.2	<0.0003
BGNELN167M	Baseline	ELPI	<1	<0.0015	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BGNELN169A	Baseline	ELPI	<1	<0.0076	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169B	Baseline	ELPI	<1	<0.0076	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169C	Baseline	ELPI	<1	<0.0076	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169D	Baseline	ELPI	<1	<0.0076	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169E	Baseline	ELPI	<1	<0.0076	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015

BGNELN169F	Baseline	ELPI	<1	<0.0076	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169G	Baseline	ELPI	<1	<0.0076	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	0.23	0.00174
BGNELN169H	Baseline	ELPI	1.5	0.0114	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169I	Baseline	ELPI	<1	<0.0076	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169J	Baseline	ELPI	<1	<0.0076	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169K	Baseline	ELPI	1.35	0.0102	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169L	Baseline	ELPI	<1	<0.0076	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169M	Baseline	ELPI	<1	<0.0076	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015

Sample ID	**Sample**	**Equipment**	**Strontium**		**Vanadium**		**Zinc**		**Ruthenium**	
			(µg)	**(mg/m^3)**	**(µg)**	**(mg/m^3)**	**(µg)**	**(mg/m^3)**	**(µg)**	**(mg/m^3)**
BGNIMB004	Baseline	IH-M N	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
BGNIMN005	Baseline	IH-M N	<0.2	<0.0005	<0.2	<0.0005	0.25	0.00059	<0.2	<0.0005
BGNIMN029	Baseline	IH-M N	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BGEIMN037	Baseline	IH-M N	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BGNIMN158	Baseline	IH-M N	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006
BGNIMN172	Baseline	IH-M N	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0008
BGNIMN173	Baseline	IH-M N	<0.2	<0.0007	<0.2	<0.0007	<0.2	<0.0007	<0.2	<0.0007
BGNIMF006	Baseline	IH-M F	<0.2	<0.0005	<0.2	<0.0005	0.27	0.00064	<0.2	<0.0005
BGNIMB028	Blank	IH-M F	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
BGNIMF030	Baseline	IH-M F	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BGEIMF038	Baseline	IH-M F	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BGNIMF159	Baseline	IH-M F	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
BGNMB160	Blank	IH-M F	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
BGNGRN010	Baseline	AS	<0.2	<0.0029	<0.2	<0.0029	0.52	0.0075	<0.2	<0.0029
BGNGRB024	Blank	AS	<0.2*	-	<0.2*	-	0.26*	-	<0.2*	-
BGEGRN041	Baseline	AS	<0.2	<0.0083	<0.2	<0.0083	<0.2	<0.0083	<0.2	<0.0083
BGNGRB161	Blank	AS	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
BGNGRN164	Baseline	AS	<0.2	<0.0032	<0.2	<0.0032	0.42	0.0068	<0.2	<0.0032
BGNGRN168	Baseline	AS	<0.2	<0.0020	<0.2	<0.0020	0.37	0.0038	<0.2	<0.0020

Sample ID	Sample	Equipment	Strontium		Vanadium		Zinc		Ruthenium	
			(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)
BGNELN015A-M	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	0.66	**0.00192**	<0.2	<0.006
BGNELN013A	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013B	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013C	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013D	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013E	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013F	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013G	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	0.620	0.0176	<0.2	<0.006
BGNELN013H	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013I	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013J	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013K	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013L	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN013M	Baseline	ELPI	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006	<0.2	<0.006
BGNELN015A	Baseline	ELPI	<0.2	<0.0076	<0.2	<0.0076	0.660	**0.025**	<0.2	<0.0076
BGNELN163A	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.21	0.00047	<0.2	<0.0004
BGNELN163B	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.21	0.00047	<0.2	<0.0004
BGNELN163C	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.32	0.00071	<0.2	<0.0004
BGNELN163D	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.38	0.00085	<0.2	<0.0004
BGNELN163E	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN163F	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN163G	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN163H	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN163I	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN163J	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN163K	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN163L	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN163M	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	1.13	0.00252	<0.2	<0.0004

Sample ID	Sample	Equipment	Strontium		Vanadium		Zinc		Ruthenium	
			(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)
BGNELN165A	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN165B	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.3	0.00061	<0.2	<0.0004
BGNELN165C	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN165D	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.31	0.00063	<0.2	<0.0004
BGNELN165E	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN165F	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN165G	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	0.43	0.00087	<0.2	<0.0004
BGNELN165H	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN165I	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN165J	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN165K	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN165L	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN165M	Baseline	ELPI	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNGRN166	Baseline	ELPI	<0.2	<0.0027	<0.2	<0.0027	0.29	**0.0039**	<0.2	<0.0027
BGNELN167A	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BGNELN167B	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BGNELN167C	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.59	0.00089	<0.2	<0.0003
BGNELN167D	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.32	0.00049	<0.2	<0.0003
BGNELN167E	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.31	0.00047	<0.2	<0.0003
BGNELN167F	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BGNELN167G	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BGNELN167H	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BGNELN167I	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.21	0.00032	<0.2	<0.0003
BGNELN167J	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BGNELN167K	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BGNELN167L	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BGNELN167M	Baseline	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.35	0.00053	<0.2	<0.0003
BGNELN169A	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169B	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015

Sample ID	Sample	Equipment	Strontium		Vanadium		Zinc		Ruthenium	
			(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)
BGNELN169C	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169D	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169E	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169F	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169G	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169H	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169I	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169J	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169K	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169L	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015
BGNELN169M	Baseline	ELPI	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015	<0.2	<0.0015

Table A9.2: Metals Content in Fume of Cr-free ERNiCuRu GMAW Electrode

Sample ID	Sample	Equipment	Arsenic		Cadmium		Chromium		Cobalt		Copper	
			(μg)	**(mg/m³)**	**(μg)**	**(mg/m³)**	**(μg)**	**(mg/m³)**	**(μg)**	**(mg/m³)**	**(μg)**	**(mg/m³)**
OGNIMN141	GMAW OSU	IH-M N	<0.2	<0.0004	<0.2	<0.0004	18.6	0.0326	<0.2	<0.0004	85.6	0.150
OGNIMN148	GMAW OSU	IH-M N	<0.2	<0.0007	<0.2	<0.0007	0.460	0.00166	<0.2	<0.0007	3.22	0.0116
OGNIMN239	GMAW OSU	IH-M N	<0.2	<0.0006	<0.2	<0.0006	4.19	0.0116	<0.2	<0.0006	12.5	0.0347
OGNIMF142	GMAW OSU	IH-M F	<0.2	<0.0004	<0.2	<0.0004	1.17	0.00205	<0.2	<0.0004	3.74	0.00655
OGNMB143	Blank	IH-M F	<0.2*	-	<0.2*	-	0.860*	-	<0.2*	-	<0.2*	-
OGNIMF149	GMAW OSU	IH-M F	<0.2	<0.0008	<0.2	<0.0008	0.350	0.00141	<0.2	<0.0008	2.13	0.00859
OGNMB150	Blank	IH-M F	<0.2*	-	<0.2*	-	0.430*	-	<0.2*	-	<0.2*	-
OGNIMF240	GMAW OSU	IH-M F	<0.2	<0.0005	<0.2	<0.0005	0.340	0.000899	<0.2	<0.0005	0.310	0.000819
OGNGRN151	GMAW OSU	AS	<0.2	<0.0030	<0.2	<0.0030	2.07	**0.0315**	<0.2	<0.0030	33	**0.5000**
OGNGRB154	Blank	AS	<0.2*	-	<0.2*	-	0.420*	-	<0.2*	-	<0.2*	-
ONGELN152A	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	0.23	0.00052
ONGELN152B	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	0.81	0.00184	<0.2	<0.0005	9.62	0.0219
ONGELN152C	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	0.7	0.00159	<0.2	<0.0005	6.36	0.0145
ONGELN152D	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	2.12	0.00482	<0.2	<0.0005	40.7	0.0926
ONGELN152E	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	0.92	0.00209	<0.2	<0.0005	13.9	0.0315
ONGELN152F	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	0.92	0.00209	<0.2	<0.0005	16.8	0.0382
ONGELN152G	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	0.69	0.00157	<0.2	<0.0005	9.54	0.0217
ONGELN152H	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	0.52	0.00118	<0.2	<0.0005	3.57	0.00811
ONGELN152I	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	0.38	0.00086	<0.2	<0.0005	1.25	0.00284
ONGELN152J	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	0.4	0.00091	<0.2	<0.0005	1.12	0.00255
ONGELN152K	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	0.36	0.00082	<0.2	<0.0005	0.83	0.00189
ONGELN152L	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	0.36	0.00082	<0.2	<0.0005	0.43	0.00098
ONGELN152M	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	0.4	0.00091	<0.2	<0.0005	0.6	0.00136
OGNELN242A	GMAW OSU	ELPI	0.22	0.00029	0.21	0.00027	0.49	0.0006	<0.2	<0.0003	1.38	0.0018
OGNELN242B	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	1.08	0.0014	<0.2	<0.0003	19.7	0.0257
OGNELN242C	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	2.09	0.0027	<0.2	<0.0003	42.3	0.0553
OGNELN242D	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.96	0.0013	<0.2	<0.0003	18.2	0.0238
OGNELN242E	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	3.85	0.0050	<0.2	<0.0003	107	0.14

OGNELN242F	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	1.26	0.0017	<0.2	<0.0003	29.8	0.0389
OGNELN242G	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.71	0.0009	<0.2	<0.0003	14.9	0.0194
OGNELN242H	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.64	0.0008	<0.2	<0.0003	8.28	0.0108
OGNELN242I	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.77	0.0010	<0.2	<0.0003	7.82	0.0102
OGNELN242J	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.62	0.0008	<0.2	<0.0003	3.64	0.00475
OGNELN242K	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.5	0.0007	<0.2	<0.0003	2.14	0.0028
OGNELN242L	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.4	0.00052	<0.2	<0.0003	1.00	0.00131
OGNELN242M	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.280	0.000366	<0.2	<0.0003	0.310	0.000405

Sample ID	**Sample**	**Equipment**	**Iron**		**Lead**		**Manganese**		**Molybdenum**		**Nickel**	
			(µg)	**(mg/m^3)**	**(µg)**	**(mg/m^3)**	**(µg)**	**(mg/m^3)**	**(µg)**	**(mg/m^3)**	**(µg)**	**(mg/m^3)**
OGNIMN141	GMAW OSU	IH-M N	142	0.250	<0.2	<0.0004	4.24	0.00745	0.370	0.00065	222	0.389
OGNIMN148	GMAW OSU	IH-M N	2.87	0.0104	<0.2	<0.0007	<0.2	<0.0007	<0.2	<0.0007	7.57	0.0273
OGNIMN239	GMAW OSU	IH-M N	19.7	0.0547	<0.2	<0.0006	0.800	0.00222	<0.2	<0.0006	102	0.283
OGNIMF142	GMAW OSU	IH-M F	9.59	0.0168	<0.2	<0.0004	0.260	0.000455	<0.2	<0.0004	8.49	0.0149
OGNMB143	Blank	IH-M F	<1*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
OGNIMF149	GMAW OSU	IH-M F	1.26	0.00508	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0008	5.21	0.210
OGNMB150	Blank	IH-M F	<1*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
OGNIMF240	GMAW OSU	IH-M F	1.48	0.00391	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	1.91	0.00505
OGNGRN151	GMAW OSU	AS	3.87	**0.0589**	<0.2	<0.0030	0.440	**0.0067**	<0.2	<0.0030	86.6	**1.3200**
OGNGRB154	Blank	AS	<1*	-	<0.2*	-	<0.2*	-	<0.2*	-	0.680*	-
ONGELN152A	GMAW OSU	ELPI	<1	<0.0023	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
ONGELN152B	GMAW OSU	ELPI	1.64	0.00373	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	18.3	0.0416
ONGELN152C	GMAW OSU	ELPI	1.4	0.00318	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	13.2	0.0301
ONGELN152D	GMAW OSU	ELPI	4.64	0.0105	<0.2	<0.0005	0.53	0.0012	<0.2	<0.0005	93.7	0.213
ONGELN152E	GMAW OSU	ELPI	2.14	0.00486	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	41.1	0.0941
ONGELN152F	GMAW OSU	ELPI	2.29	0.0052	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	50.9	0.116
ONGELN152G	GMAW OSU	ELPI	1.5	0.00341	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	26.2	0.0595
ONGELN152H	GMAW OSU	ELPI	1.23	0.0028	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	11.1	0.0252
ONGELN152I	GMAW OSU	ELPI	<1	<0.0023	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	5.5	0.0125

ONGELN152J	GMAW OSU	ELPI	<1	<0.0023	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	7.23	0.0164
ONGELN152K	GMAW OSU	ELPI	1.15	0.00261	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	6.08	0.0138
ONGELN152L	GMAW OSU	ELPI	<1	<0.0023	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	3.15	0.00716
ONGELN152M	GMAW OSU	ELPI	2.21	0.00502	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	3.98	0.00905
OGNELN242A	GMAW OSU	ELPI	2.46	0.00321	0.21	0.00027	0.26	0.00034	0.31	0.00041	2.62	0.00342
OGNELN242B	GMAW OSU	ELPI	2.26	0.00295	<0.2	<0.0003	0.32	0.00042	<0.2	<0.0003	42.1	0.055
OGNELN242C	GMAW OSU	ELPI	6.57	0.00858	<0.2	<0.0003	0.55	0.00072	<0.2	<0.0003	94.6	0.123
OGNELN242D	GMAW OSU	ELPI	2.47	0.00323	<0.2	<0.0003	0.25	0.00033	<0.2	<0.0003	49.9	0.0652
OGNELN242E	GMAW OSU	ELPI	12.7	0.0166	<0.2	<0.0003	1.1	0.00144	<0.2	<0.0003	327	0.427
OGNELN242F	GMAW OSU	ELPI	3.89	0.00508	<0.2	<0.0003	0.32	0.00042	<0.2	<0.0003	92.6	0.121
OGNELN242G	GMAW OSU	ELPI	2.77	0.00362	<0.2	<0.0003	0.24	0.0003	<0.2	<0.0003	41.4	0.0541
OGNELN242H	GMAW OSU	ELPI	2.6	0.0034	<0.2	<0.0003	0.37	0.00048	<0.2	<0.0003	24.4	0.0319
OGNELN242I	GMAW OSU	ELPI	2.7	0.00353	<0.2	<0.0003	0.87	0.00114	<0.2	<0.0003	28.3	0.0369
OGNELN242J	GMAW OSU	ELPI	2.46	0.00321	<0.2	<0.0003	0.62	0.00081	<0.2	<0.0003	18.6	0.0243
OGNELN242K	GMAW OSU	ELPI	2.07	0.0027	<0.2	<0.0003	0.36	0.00047	<0.2	<0.0003	14.9	0.0195
OGNELN242L	GMAW OSU	ELPI	1.41	0.00184	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	6.5	0.00849
OGNELN242M	GMAW OSU	ELPI	1.1	0.00144	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	1.15	0.0015

Sample ID	**Sample**	**Equipment**	**Strontium**		**Vanadium**		**Zinc**		**Ruthenium**	
			(µg)	**(mg/m^3)**	**(µg)**	**(mg/m^3)**	**(µg)**	**(mg/m^3)**	**(µg)**	**(mg/m^3)**
OGNIMN141	GMAW OSU	IH-M N	1.00	0.00176	<0.2	<0.0004	0.30	0.00053	0.830	0.00146
OGNIMN148	GMAW OSU	IH-M N	<0.2	<0.0007	<0.2	<0.0007	<0.2	<0.0007	<0.2	<0.0007
OGNIMN239	GMAW OSU	IH-M N	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006	0.960	0.00266
OGNIMF142	GMAW OSU	IH-M F	<0.2	<0.0004	<0.2	<0.0004	0.21	0.00037	<0.2	<0.0004
OGNMB143	Blank	IH-M F	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
OGNIMF149	GMAW OSU	IH-M F	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0008
OGNMB150	Blank	IH-M F	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
OGNIMF240	GMAW OSU	IH-M F	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
OGNGRN151	GMAW OSU	AS	<0.2	<0.0030	<0.2	<0.0030	0.37	**0.0056**	0.290	**0.0044**
OGNGRB154	Blank	AS	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-

Sample ID	Sample	Equipment	Strontium		Vanadium		Zinc		Ruthenium	
			(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)	(µg)	(mg/m^3)
ONGELN152A	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
ONGELN152B	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
ONGELN152C	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
ONGELN152D	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	0.32	0.00073	<0.2	<0.0005
ONGELN152E	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
ONGELN152F	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
ONGELN152G	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
ONGELN152H	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
ONGELN152I	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
ONGELN152J	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
ONGELN152K	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
ONGELN152L	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
ONGELN152M	GMAW OSU	ELPI	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
OGNELN242A	GMAW OSU	ELPI	0.21	0.00027	<0.2	<0.0003	0.28	0.0004	0.22	0.00029
OGNELN242B	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
OGNELN242C	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
OGNELN242D	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
OGNELN242E	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	0.28	0.0004	0.44	0.00058
OGNELN242F	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
OGNELN242G	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
OGNELN242H	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	0.23	0.0003
OGNELN242I	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	0.33	0.00043
OGNELN242J	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	0.34	0.00044
OGNELN242K	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	0.28	0.00037
OGNELN242L	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
OGNELN242M	GMAW OSU	ELPI	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003

Appendix K: X-ray Report on ENiCuRu Weld Test Assembly

InspecTech Corp.
"Excellence in Inspection Technology"
ISO/IEC 17025 Accredited

LABORATORY ACCREDITATION BUREAU ACCREDITED
Certificate #: L2035.03-1 Testing

RADIOGRAPHIC WELD INSPECTION REPORT

Customer: Energy Solutions Group, LLC
P.O. No.: SWM2010-50

Procedure No.	Rev.	Specification	Acceptance	Date: 07/21/10
ITC-RT-060	0	ITC-RT-060, REV. 0		

Radiation Source	Kv	Ma	Focal Size	SFD	Ug	Film Type	Size
LV	320	10	4mm	42	.003	14X17	14X17

W.O. No.: 3876

Exposure Time	Penetrameter	Pene. Location	Shim Thickness	Material Type	Material Thickness
8 sec.	20-10	BLOCKS	N/A	Steel	.750

Sheet 1 of 1

Technique (Single Wall; etc.)	Pb Screens, Front/Back	Load (Single/Double)	DWG. No.
DWE/DWV	.010 Front	Cr	

Technician	SNT-TC-1A Level	A.I. Review / Date
Thomas Yearwood	II	7/21/10

Item or Part No.	Welder Symbol	Weld No.	View	Porosity	Slag	Crack	Incomp. Fusion	Incomp. Penet.	Burn Thru	Suck Back	Under Cut	Sur-face	Density		Acc.	Rej.
													PEN	WEL		
T&T					1											

Comments:

Castings processed IAW InspecTech QSM ITC-QA-010, Rev. 9, Dated 12/20/05.

Sketch:

353 North Industrial Park Drive • Etowah, TN 37331 • 423-263-0534 • Fax 423-263-0586