FINAL REPORT

Innovative Welding Technologies Using Silicon Additives to Control Hazardous Air Pollutant (HAP) Emissions

ESTCP Project WP-200903

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TABLE OF CONTENTS

TABLE OF CONTENTS i
LIST OF FIGURES iv
LIST OF TABLES v
LIST OF ACRONYMS AND SYMBOLS vi
ACKNOWLEDGEMENTS viii
EXECUTIVE SUMMARY 1
BACKGROUND 1
OBJECTIVES OF THE DEMONSTRATION 1
DEMONSTRATION RESULTS 1
IMPLEMENTATION ISSUES 2
1.0 INTRODUCTION 3
1.1 BACKGROUND 3
1.2 OBJECTIVES OF THE DEMONSTRATION 5
1.3 REGULATORY DRIVERS 5
2.0 DEMONSTRATION TECHNOLOGY 7
2.1 TECHNOLOGY DESCRIPTION 7
2.2 TECHNOLOGY DEVELOPMENT 7
2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY 8
3.0 PERFORMANCE OBJECTIVES 11
4.0 SITE/PLATFORM DESCRIPTION 13
4.1 TEST PLATFORM/FACILITIES 13
4.2 PRESENT OPERATIONS 13
4.3 SITE-RELATED PERMITS AND REGULATIONS 14
5.0 TEST DESIGN 15
5.1 LABORATORY STUDY 15
5.1.1 Analysis of Cr^{6+} 17
5.1.2 Analysis of total metals and silica coating efficiencies 18
5.1.3 TEM imagery 18
5.1.4 Particle size distribution 19
5.1.5 *E. Coli* study 19

5.2 FIELD TEST 19
5.2.1 Low-flow sampling 20
5.2.2 High-flow sampling 23
5.2.3 Weld-quality test 24
5.2.4 Health and safety plan 26
5.3 STATISTICAL ANALYSIS 27
6.0 PERFORMANCE ASSESSMENT 29
6.1 LABORATORY TEST 29
6.1.1 Reduction of Cr^{6+} 29
6.1.2 Total metal and silica coating efficiencies 31
6.1.3 TEM imagery 31
6.1.4 Particle size distribution 32
6.1.5 *E. Coli* study 33
6.2 FIELD TEST 36
6.2.1 Low-flow sampling 36
6.2.2 High-flow sampling 37
6.2.3 Interview with the welder in the field 38
6.2.4 Weld quality test 39
7.0 COST ASSESSMENT 45
7.1 COST MODEL 45
7.2 COST ASSESSMENTS 46
7.2.1 Comparison of GMAW costs 46
7.2.2 Elimination of the need for special ventilation 49
Example of a 200 by 100-ft welding shop – Comparison of costs 50
Example of a 60 by 30-ft welding shop – Comparison of costs 51
7.2.3 Annual cost based on TMS technology 51
7.2.4 Qualification of new welding procedures 53
7.2.5 Locations where ventilation may be limited 53
7.3 Estimated overall economic impact 54
7.3.1 Air sampling 54
7.3.2 Cost of compliance 54

8.0 IMPLEMENTATION ISSUES 55
8.1 HEALTH AND SAFETY ISSUES 55
8.1.1 SAFE HANDLING OF TMS 55
8.1.2 TOXICOLOGICAL ISSUES WITH TMS 56
8.2 LOW WELD QUALITY 56
8.3 IMPLEMENTATION AND TECHNOLOGY TRANSFER 56
8.3.1 STAKEHOLDERS 57
9.0 REFERENCES 58
APPENDICES 61
Appendix A: Points of Contact 61
Appendix B: SOP for demonstration at TEAD 62
Appendix C: Health and Safety Plan for demonstration at TEAD 67
Appendix D: Lab Test Data (Cr^{6+}) 69
Appendix E: Lab Test Data (SMPS) 72
Appendix F: Field Test Data (Low-flow sampling) 87
Appendix G: MSDS for Tetramethylsilane (TMS) 103
Appendix H: Quote for TMS premixed cylinder gas 108
Appendix I: List of Publications and Presentations 110

LIST OF FIGURES

Figure 1 Welding arc zone and surrounding area[13] 3
Figure 2 Schema of shielding gas in the welding process [13]..... 4
Figure 3 Common scene of local exhaust ventilation in the welding process [13] 5
Figure 4 Diagram demonstrating the mechanism of silica precursor technology 9
Figure 5 (a) Apparatus for feeding TMS through impinger; (b) Schematic diagram of the welding fume chamber with a zoom view at the end of the torch; (c) Apparatus for feeding TMS cylinder gas; (d) Schematic diagram of the field demonstration system 10
Figure 6 Fume chamber and welding machine 15
Figure 7 Scene of (a) turntable with the base metal (b) welding gun mounted on the stand..... 16
Figure 8 The IDST torch 17
Figure 9 (a) Lincoln LEV collector and (b) sampling inlet on hood face..... 21
Figure 10 Setup of the pump and welder in low-flow sampling..... 22
Figure 11 The scene of (a) the near field pumps (b) far field 23
Figure 12 Setup of the pump and welder in high-flow sampling 24
Figure 13 Samples machined from the welded plates 25
Figure 14 The respirator and air cylinder worn by the welder 27
Figure 15 Cr^{6+} concentration as a function of the ratio of TMS to different shielding-gas flow rates 29
Figure 16 Deposition of silica powder in the torch (premix mode)..... 29
Figure 17 Schematic design of the IDST 30
Figure 18 TEM images of different conditions of welding-fume particles 32
Figure 19 Welding-fume particle size distributions at different shielding gas flow rates: (a) 20 Lpm, (b) 25 Lpm, and (c) 30 Lpm. 34
Figure 20 Growth of *E. coli* after 24-hr exposure to welding fume and silica particles as a function of particle concentrations: from top to down, amorphous silica, 4.2% TMS-added shielding gas, 2% TMS-added shielding gas and baseline (0% TMS-added shielding gas) 35
Figure 21 The correlation between LLC_{50} and (a) TMS additive fraction; and (b) Cr^{6+} concentration in fume particles 36
Figure 22 Comparison of Cr^{6+} and metal mass between baseline and TMS injection conditions (exclude Aug 11th sample) 37
Figure 23 Macrostructure of (a) F528, (b) F529, (c) F530, with weld material (WM), and base plate (BP) marked. 42
Figure 24 Microstructure of the weld zone in sample F528 (a) 5×, (b) 10×, (c) 20×..... 42
Figure 25 Macrostructure of (a) F540, (b) F541, (c) F542 43
Figure 26 Microstructure of the weld zone in sample F541 (a) 5×, (b) 10×, (c) 20×..... 43
Figure 27 General ventilation system (push-pull type)..... 50

LIST OF TABLES

Table 1 Performance objectives of the demonstration plan 11
Table 2 Summary of Type 304 stainless steel welding at TEAD 13
Table 3 Parameters for high-flow sampling in the field test 24
Table 4 Cr^{6+}:Cr^{3+} ratios in welding fume particles under various conditions 30
Table 5 Measured concentrations of metal elements digested by different acid mixtures and silica coating efficiencies 31
Table 6 Cr^{6+} mass captured on filter and the corresponding Cr^{6+} exposure estimate in the field. 38
Table 7 Mass of metal and silica (µg) on filter in the field test 38
Table 8 Composition profile of test welds and standard materials (%) 39
Table 9 Tensile values of baseline and TMS test welds – 3/16" transverse tension test specimen 44
Table 10 Radiographic analysis 44
Table 11 Unit cost used in the cost model 46
Table 12 Welded joint costs of Argon shielding gas and TMS technology (mixed at torch)..... 47
Table 13 Welded joint costs of Argon shielding gas and TMS technology (customized TMS shielding gas in cylinder) 47
Table 14 Welded joint costs of Argon shielding gas and TMS technology (commercial TMS shielding gas in cylinder) 47
Table 15 Ventilation system cost 51
Table 16 Summary of the cost comparison 53

LIST OF ACRONYMS AND SYMBOLS

ANOVA	Analysis of variance
APE	Ammunition peculiar equipment
ASTM	American Society for Testing and Materials
atm	atmospheric
a.u.	arbitrary unit
AWM	all weld metal
AWS	American Welding Society
BP	Base plate
CARB	California Air Resources Board
CFU	Colony forming unit
CFH	cubic feet per hour
CFM	see page 49
Cr6+	hexavalent chromium
DOD	Department of Defense
ECM	company acronym formerly, Environmental Cost Management
ELPI	Electrical low pressure impactor
EPA	Environmental Protection Agency
FL	Fusion line
GMAW	Gas metal arc welding
GTAW	Gas tungsten arc welding
HAP	Hazardous air pollutant
HAZ	Heat affected zone
HF	hydrofluoric acid
IC	Ion chromatography
ICP-AES	Inductively Coupled Plasma-Atomic Emission Spectroscopy
IDST	Insulated double shroud torch
IH	Industrial hygiene
Ipm	Inches per minute
KIGAM	Korean Institute of Geoscience and Mineral Resources
ksi	kilo (1,000) pounds per square inch
LB	Lysogeny Broth
LEV	Local exhaust ventilation
LFL	Lower flammable limit
LLC	lethal logarithmic concentrations
MAIC	Majority Analytical Instrument Center
MCE	Mixed cellulose
mg/L	milligrams per liter
MIG	Metal Inert Gas
mm	millimeters
ms	millisecond
NAMRU-D	Naval Medical Research Unit Dayton
NESHAP	National Emission Standards for Hazardous Air Pollutants
NIOSH	National Institute for Occupational Safety and Health
NO	Nitric oxide
nm	nanometers

OSHA	Occupational Safety and Health Administration
PEL	Permissible exposure limit
PERC	Particle Engineering Research Center
PPE	Personal Protective Equipment
PTFE	Polytetrafluoroethylene (Teflon)
PVC	Polyvinyl chloride
REL	Recommended exposure limit
SCE	Silica coating efficiency
SiO2	Silicon dioxide
SMAW	Shielded metal arc welding
SMPS	Scanning mobility particle sizer
SOP	Standard Operating Procedure
TEAD	Tooele Army Depot
TEM	Transmission electron microscopy
TEOS	Tetraethyloxysilane
TMS	Tetramethylsilane
TWA	Time weighted average
UIPI	Uniform Industrial Process Instruction
WM	Weld metal
XPS	X-ray photoelectron spectroscopy

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EXECUTIVE SUMMARY

BACKGROUND

The welding process in Department of Defense (DOD) repair and maintenance operations results in the formation of high concentrations of nano-sized particles loaded with toxic metals such as hexavalent chromium (Cr^{6+}), nickel, and manganese. Welding fumes pose serious health risks to welders at these DOD sites, because the fumes can cause respiratory and neurological ailments as well as cancer. Tightened occupational standards also require an exposure reduction of at least 90% and are not satisfied by current control technologies. There is potential public concern about the environmental risks associated with the release of welding fumes into ambient air.

Silica precursor technology has been demonstrated to be an effective means of controlling metal emissions in welding fumes. The two-fold approach of limiting oxidation potential and coating metal particles with an amorphous silica layer goes beyond previous control technologies by addressing all the toxic metals, regardless of their oxidation state. This project demonstrated, through both a laboratory study and field tests, the benefits of adding silica precursor during the welding process.

OBJECTIVES OF THE DEMONSTRATION

The overall objective of this demonstration was to develop an innovative silica precursor technology that can limit the oxidation of chromium by quenching oxygen species and coating metal particles in welding fumes with a thin, amorphous silica layer. An additional objective was to assess the benefit of increased particle size distribution. The demonstration verified the feasibility and practicality of implementing silica precursor technology into DOD welding operations.

DEMONSTRATION RESULTS

The laboratory study showed that use of an insulated double-shroud torch (IDST) to inject vapor-phase silica precursor tetramethylsilane (TMS) into the welding operation reduced Cr^{6+} exposure by over 90% and satisfied the OSHA permissible exposure limit of 5 $\mu g/m^3$. The calculated silica coating efficiencies gave quantitative evidence of the encapsulation of metals inside the silica shell, and the Transmission Electron Microscopy (TEM) images provided visual evidence. Scanning Mobility Particle Sizer (SMPS) data showed the particle size distribution shifted to a larger size range, and the mode size of fume particles increased to 180~300 nm from 20 nm. The *Escherichia coli (E. coli)* study provided a preliminary result supporting the reduced biotoxicity of welding fume particles using the novel silica precursor technology.

The results of the field study further confirmed the capability of this technology to reduce Cr^{6+} and to encapsulate toxic metals such as Mn, Ni, and Cr. Two different sampling approaches

were used in the field demonstration (low- and high-flow samplings). The results from the low-flow sampling were limited due to insufficient fume mass collection. The concentration of Cr^{6+} in most samples was lower than OSHA PEL (5 $\mu g/m^3$) in most samples, regardless of whether they were baseline or TMS-injected samples. The variation between samples was relatively large (Coefficient of Variance > 1). However, reduction of Cr^{6+} and other metals by TMS technology was still observed through use of the statistical method Analysis of Variance (ANOVA). The results of high-flow sampling clearly showed the silica precursor technology was capable of reducing Cr^{6+} exposure below the OSHA PEL with > 90% Cr^{6+} reduction efficiency, and resulted in about 31.8% of the metals sealed inside the silica shell.

Information extracted from interviews with welders in the field showed the use of TMS had no significant impact on welding operations. While TMS technology does not significantly deteriorate the mechanical quality of the welds, optimization of the different parameters to achieve the expected mechanical tensile parameters will be helpful. The cost assessment showed that use of TMS mixed at the nozzle and commercially available TMS cylinder gas did not significantly increase the overall cost of the welding operation. Also, it could potentially reduce the costs of retrofitting ventilation systems needed to meet new OSHA regulations.

IMPLEMENTATION ISSUES

One implementation issue considered was the safe handling of the TMS. A worst-case scenario was used to estimate the maximum possible TMS concentration. The TMS concentration in the case of a complete leak was still lower than the safety threshold value. In addition, there were no incidents caused by the TMS additive during the laboratory study and field demonstration.

The mechanical quality test suggested there is room for improving the TMS technology to achieve a higher weld quality. The weld qualities resulting from both baseline and TMS technology were lower than the minimum required by the standard for uniform metals, indicating that problems could have been partially due to welder error. Because this project was unexpectedly terminated before optimization and improvement could be achieved, the technology transfer will have to take a different path, which is currently being planned.

1.0 INTRODUCTION

1.1 BACKGROUND

Welding is a common repair and maintenance operation throughout the services at DOD depots and shipyards . It uses mild or stainless steel filler material to join pieces of metal (Figure 1). The intense energy expended in the welding process results in the formation of high concentrations of nano-sized particles loaded with hexavalent chromium (Cr^{6+}), nickel (Ni), manganese (Mn), and other toxic metals [1-5]. Cr^{6+} and Ni are known human carcinogens, as shown by extensive human and animal data [6]. Exposure to Mn can cause serious adverse neurological effects, including a Parkinson's-like disorder known as manganism [7, 8]. Welding fume particles range from < 0.001 to 100 µm in diameter. Approximately 85% of the particles by mass are less than 1 µm in diameter, indicating that most fume particles are respirable and are able to travel deeply into the respiratory system and interact with human cells [9]. Hence, the welding process poses serious health risks to welders from inhalation of the welding fumes. The welding fume characteristics, as well as weld quality, are affected by parameters such as current, voltage, and shielding-gas flow rate and composition [1, 10-12]. The complexity of the process creates a challenge for welder safety. Currently, the DOD spends approximately $36 million a year on personal protective equipment (PPE) for welding operations.

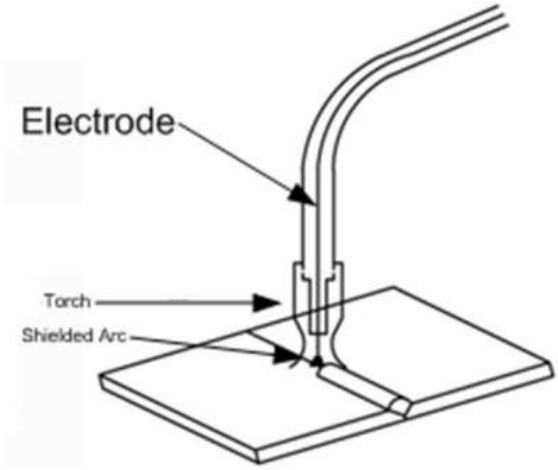

Figure 1 Welding arc zone and surrounding area[13]

In addition, welding fumes are also released into the atmosphere during the operations. While these hazardous air pollutants (HAPs) are usually not directly reported to the Environmental Protection Agency (EPA), facilities estimate the residual risk to public health, In certain states such as California [14], when the cancer risk exceeds a threshold of one in a million, facilities must report the findings to the public. When the threshold is exceeded, the facility is also expected to initiate measures to reduce the fugitive emissions.

Shielding gas is widely used in welding operations to protect the superheated weld site from ambient gaseous species that degrade the weld's mechanical properties and destabilize the welding arc (Figure 2). The shielding gas also helps limit the oxidation of metals by preventing the penetration of reactive oxygen species [12] and reducing the fume generation rate [15]. However, using shielding gas results in an undesirable increase in ultraviolet (UV) light due to the reduction of UV absorbent, and consequently increases ozone concentration [12, 16]. Various welding fume control technologies have been developed in attempts to address this issue.

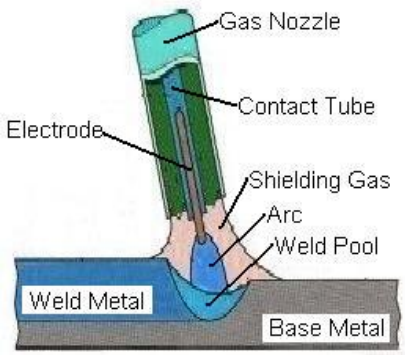

Figure 2 Schema of shielding gas in the welding process [13]

Local exhaust ventilation (LEV) technology (Figure 3) is available to remove fume particles from the welder's breathing zone [17, 18], but it is inconvenient and ineffective in field welding, where the movements of the welder are more frequent than during stationary welding [10]. The LEV has a high initial equipment cost of $5,000 to $20,000, costs about $8.45 per hour of welding time, and has about 50% removal efficiency.

The addition of reducing reagents such as methane or nitric oxide (NO) to shielding gas can consume oxygen species in the welding fume and hence limit formation of Cr^{6+} [19]. Similarly, the addition of reactive metals such as zinc (Zn) or aluminum (Al) to welding filler materials can reduce Cr^{6+} formation [20]. However, limiting the oxidation of metals does not alleviate the problems associated with toxic metals other than Cr^{6+} (e.g., Mn and Ni). Those technologies always require a specific operating condition due to the addition of external reagents, and they also pose other potential hazards (e.g., formation of NO_2 by adding NO). Furthermore, the mechanical profiles of welds produced under those technologies have not yet been validated.

In summary, there are currently no effective technologies for welding -fume control or respiratory protection. A well-balanced and feasible technology is critically needed to meet the following requirements:

- Better protection of DOD welders' health and safety,
- Satisfaction of the occupational standards,
- Reduction of the tremendous medical costs associated with the welding fume exposure,
- Reduction of the residual risk associated with the release of HAPs into the atmosphere.

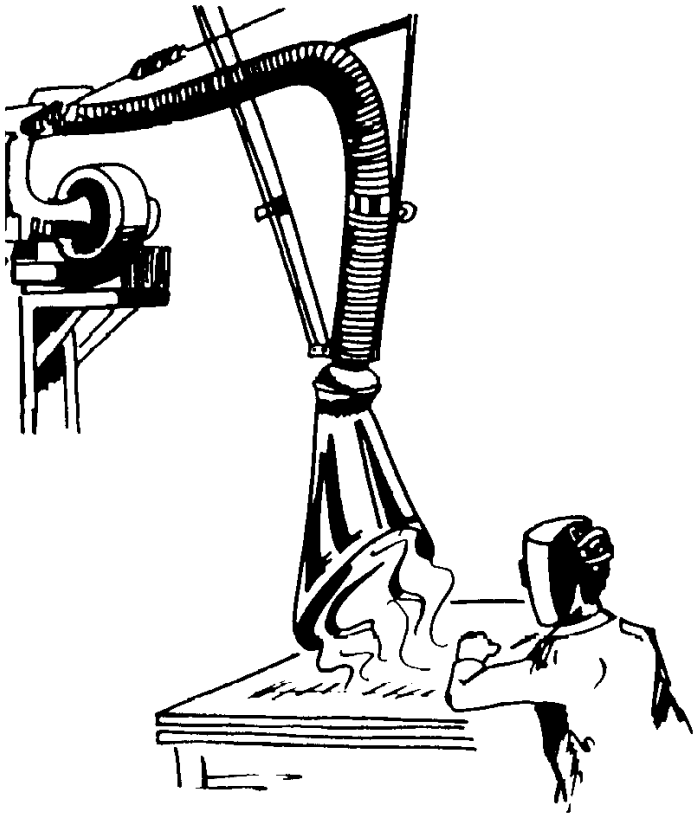

Figure 3 Common scene of local exhaust ventilation in the welding process [13]

1.2 OBJECTIVES OF THE DEMONSTRATION

The demonstration used the novel silica precursor technology to reduce the amount and toxicity of HAPs in the fume generated from the welding process, and to advance the research results from laboratory scale to DOD practice. Specifically, the demonstration strived to achieve the following objectives:

- Develop an innovative welding technology that allows optimal introduction of silica precursor to maximize the reduction of HAPs in welding fume,
- Evaluate the performance of this new system in minimizing metal oxidation, encapsulating fume particles, and increasing fume particle size,
- Evaluate the impact of changes induced by the silica precursor on the weld's mechanical properties
- Assess the operating costs for implementation.

1.3 REGULATORY DRIVERS

DOD facility operating permits (Title V and Synthetic Minor Permits) require that facilities identify new technologies to reduce emissions and public health impacts. A significant portion of the health risks in DOD and heavy manufacturing are attributable to welding and

metal-cutting emissions (such fumes are rich in metals with high toxicity). DOD facilities comply with HAPs emission regulations cited under National Emission Standards for Hazardous Air Pollutants (NESHAP). Welding operations for DOD shipbuilding and military equipment repair depots require HAP emissions reporting under expanding residual risk regulations. If the residual risk for a source category does not protect public health with an ample margin of safety, the EPA must promulgate health-based standards to further reduce HAPs.

Welding emission control is also required to meet tightening occupational exposure standards. For instance, the Occupational Safety and Health Administration (OSHA) lowered the 8-hour time-weighted average (8-hr TWA) permissible exposure limit (PEL) of Cr^{6+} from 52 $\mu g/m^3$ to 5 $\mu g/m^3$ in 2006 [21]. The National Institute for Occupational Safety and Health (NIOSH) also proposed an 8-hr TWA recommended exposure limit (REL) of 0.2 $\mu g/m^3$[22]. In 2009, NIOSH recommended all reasonable efforts should be made to reduce exposure to Cr^{6+} compounds below the REL through the use of work practice and engineering controls [23]. For nickel, the 8-hr TWA PEL is 1 mg/m^3, although the NIOSH REL is 0.015 mg/m^3. For manganese, the OSHA 8-hr TWA PEL is 5 mg/m^3 with the NIOSH REL of 1 mg/m^3.

2.0 DEMONSTRATION TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

During welding, metals vaporize at high temperatures and subsequently become oxidized. When the temperature drops, the vapor nucleates to form ultrafine particles. Silica precursor technology applied during welding feeds a minute amount of vapor-phase silica precursor, such as tetramethylsilane (TMS), into the welding shielding gas. The silica precursor scavenges oxygen species during oxidation, thus suppressing the oxidation of Cr. Silica coating occurs through the condensation of *in-situ*-generated amorphous silica onto metal particles. This scavenging and coating minimizes the subsequent oxidation encountered in the regular welding process. The amorphous silica layer insulates the metal species from human organisms when inhaled. Silica formed from this reaction also yields an amorphous web that effectively increases the size of metal particles. This two-fold approach of limiting oxidation potential and coating metal particles in an amorphous silica layer goes beyond previous control technologies by addressing effects on all toxic metals regardless of oxidation state. Figure 4 illustrates the mechanisms of the silica precursor technology. The silica precursor technology had already been demonstrated to be an effective measure for controlling nano-sized metal particles and reducing environmental pollution from combustion systems and incinerators [24-29] before the initiation of this demonstration.

To introduce the TMS vapor into the welding arc zone, minimal modification to existing welding equipment is required (as shown in Figure 5a). Argon gas flows through a Teflon impinger with TMS at the bottom, and the flow rate is controlled by a mass flow controller. The impinger is immersed in an ice bath to lower TMS vapor pressure to avoid getting excess TMS vapor in the system. The TMS carrier gas becomes saturated with TMS vapor and is delivered to the welding arc zone through a novel insulated double shroud torch (IDST). This mode of delivering TMS will be referred to as the “mixed at torch” approach hereafter.

An alternative to the impinger and reservoir is the introduction of TMS flow from a separate gas cylinder containing TMS vapor in argon (as shown in Figure 5d). This delivery mode of TMS will be referred to as “TMS cylinder gas” approach hereafter. The commercial application of TMS cylinder gas will require the shielding gas vendor to deliver the pre-mixed gas to the worksite in cylinders.

2.2 TECHNOLOGY DEVELOPMENT

Experiments sponsored by the California Air Resources Board (CARB) were conducted by Dr. Daniel Chang’s team at the University of California, Davis using shielding gas (Ar or 25% CO_2 + 75% Ar) with 1.4-1.6% TMS added. The results demonstrated a > 61% reduction in Cr^{6+} formation, and the reduction could be further improved by optimizing the feeding condition. A similar process has been successfully demonstrated for other applications (minimizing lead

emissions and leaching by use of tetraethyloxysilane (TEOS) to completely wrap lead particles in an amorphous silica network) [30, 31].

Experiments sponsored by the Korean Institute of Geoscience and Mineral Resources (KIGAM) were conducted by Dr. Chang-Yu Wu's team at the University of Florida using TEOS-added shielding gas in gas tungsten arc welding (GTAW). Experimental results showed an approximately 45% reduction of Cr^{6+} when 3.0% TEOS was added to the shielding gas. Nitrate concentration also decreased by 53%, indicating that reactive oxygen species were also reduced. Transmission electron microscopy (TEM) images of collected fume aerosols showed SiO_2 coating on metal particles, verifying the efficacy of the proposed mechanism.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The advantages of the silica precursor technology include but are not limited to the following:

- The products from silica precursor decomposition are amorphous silica, carbon dioxide, and water, with no introduction of new hazards,
- The technology is not metal specific, so it reduces the toxicity of all the metals regardless of oxidation state, and
- The technology does not alter the welding operation or require specific welding parameters, so only minimal training of the welder is required.

The limitations of the technology include the requirement for minimal welding equipment modification, and the initial capital cost and the cost of consumables (i.e., TMS).

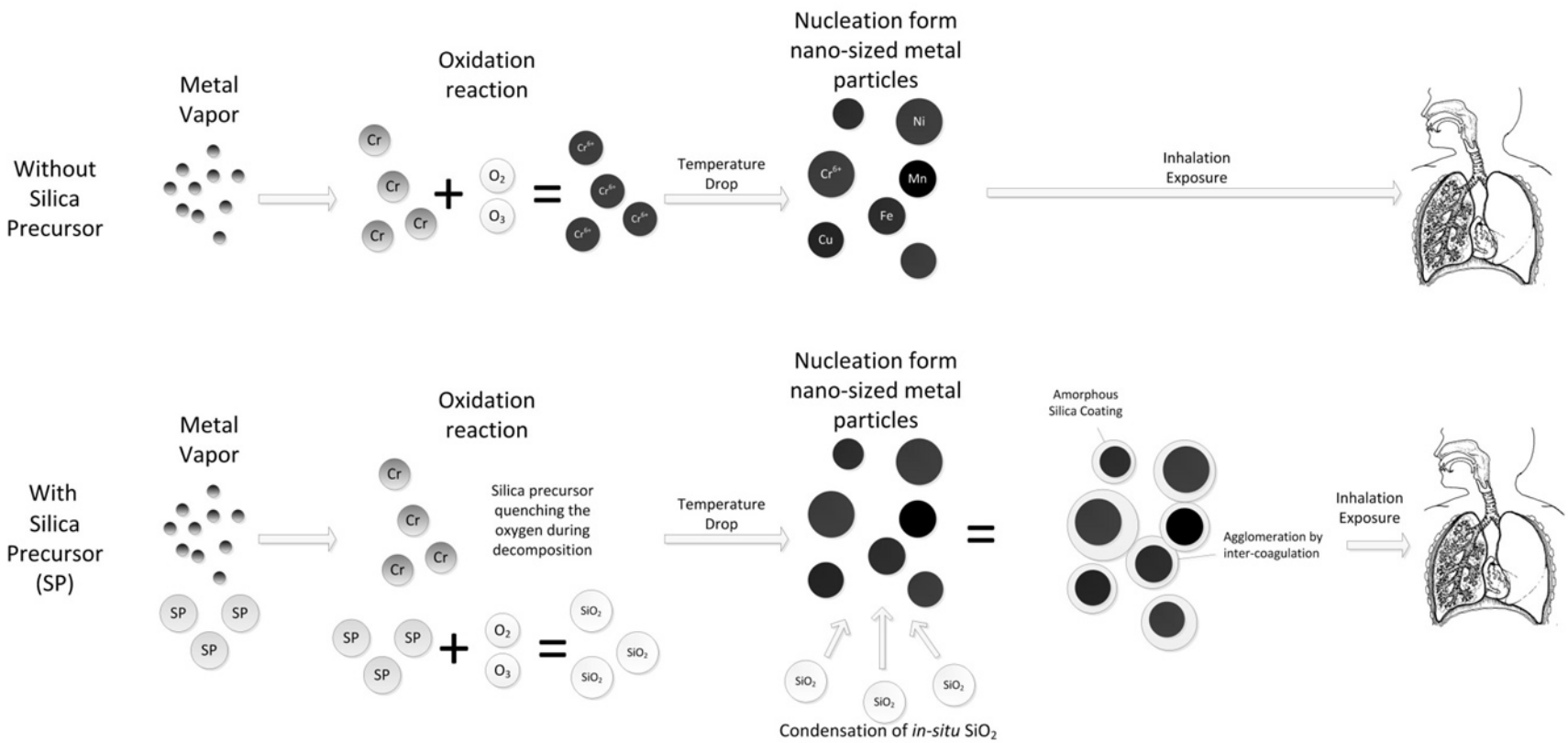

Figure 4 Diagram demonstrating the mechanism of silica precursor technology

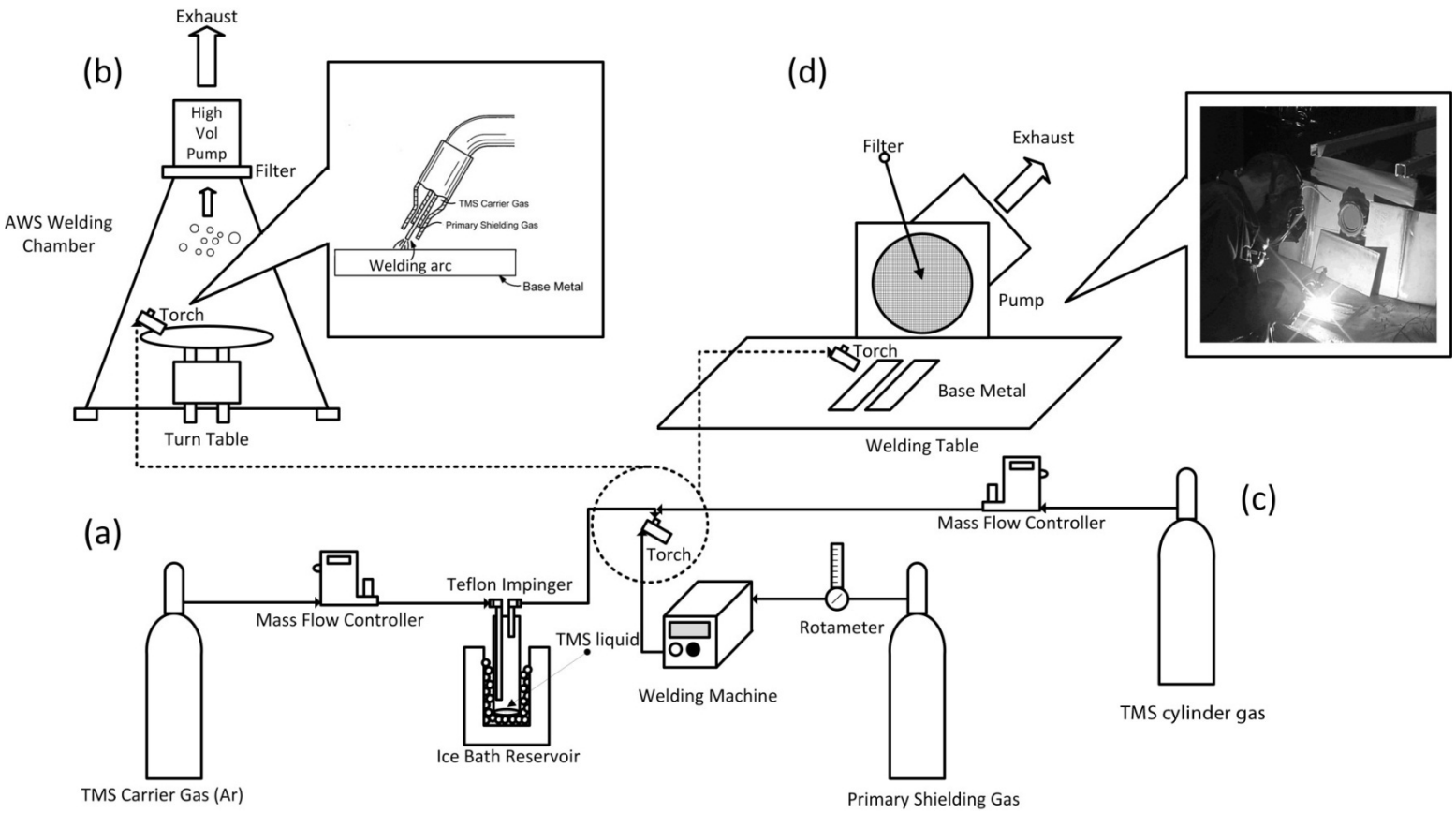

Figure 5 (a) Apparatus for feeding TMS through impinger; (b) Schematic diagram of the welding fume chamber with a zoom view at the end of the torch; (c) Apparatus for feeding TMS cylinder gas; (d) Schematic diagram of the field demonstration system

3.0 PERFORMANCE OBJECTIVES

The performance objectives include:

- evaluating the reduction of Cr^{6+} in welding fumes,
- determining silica coating efficiencies on metal particles,
- measuring particle size growth resulting from the silica network,
- testing the reduced biotoxicity of treated welding fumes,
- assessing the impact of the technology on welding operation, and
- examining the mechanical properties of the welds generated by silica precursor technology.

All of the performance objectives were achieved during the demonstration, and are summarized in Table 1.

Table 1 Demonstration Performance Objectives and Results

Performance Objectives	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Reduction of Cr^{6+} in welding fume	Cr^{6+} concentration in welding fume compared to baseline in the laboratory and during field demonstrations	Over 90% reduction efficiencies under all conditions; satisfying OSHA PEL	Met the criteria
Qualitative Performance Objectives			
Silica coating on metal particles	TEM images, silica coating efficiencies based on test plates joined in the laboratory and field	Visual evidence and bulk analysis of silica coating on particles	Met the criteria
Growth of welding fume particle size	SMPS particle size distribution	Mode size of welding fume particles under TMS condition shifted to the larger size range	Met the criterion
Reduced biotoxicity of welding fume	*E. coli* colony forming units, 50% lethal logarithmic concentrations based on welding fumes generated during welding in the laboratory	Growth rate of *E. coli* exposed to TMS-treated particles being higher compared to baseline welding fumes	Met the criterion
Minimum impact on welding operation	Response from welders participating in the field demonstration	Ease of implementation, no alteration of welding operation process	Met the criterion
No change in weld mechanical quality	Radiography analysis, macro- and micro-chemical analysis, transverse tensile and bend tests based on test plates joined during the demonstration	No deterioration of weld quality with TMS added compared to baseline weld	Met the criterion

4.0 SITE/PLATFORM DESCRIPTION

4.1 TEST PLATFORM/FACILITIES

Tooele Army Depot (TEAD) was selected as the test site for the field demonstration. TEAD is an active ammunition storage site responsible for shipping, storing, receiving, inspecting, demilitarizing, and maintaining training and war reserve conventional ammunition. This facility also performs a significant amount of welding with stainless steel base metals. TEAD engineers and technical staff design and manufacture ammunition-peculiar equipment (APE) used in maintenance and demilitarization of munitions for DOD. The "peculiar" equipment is typically one-of-a-kind or small batches of equipment to fill a specific need in demolishing outdated or unused ammunition.

4.2 PRESENT OPERATIONS

The TEAD technical staff and welders use conventional welding technology to maintain and demilitarize the APE. The welding operations in Type 304 steel are performed using shielded metal arc welding (SMAW), gas metal arc welding (GMAW), and gas tungsten arc welding (GTAW) processes with conventional welding consumables E308L (SMAW) and ER308L (GMAW and GTAW). In some years, TEAD may use up to 500 pounds of consumables for 304 base metals; in other years, the usage may be minimal. Some examples of parts fabricated from Type 304, 310, and 316 stainless steel using welding operations with conventional consumables are summarized in Table 2.

Table 2 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”, 5/16”, 1/4”, 10 GA	GMAW, SMAW	ER308L ER308	90/5/5, 98/2	Multiple
Heating chamber cover	304	11 GA	GTAW	ER308L	90/5/5, 98/2	Multiple
Autoclaves	304	Up to 1”	GMAW, GTAW	ER308L	90/5/5, 98/2	Multiple
Ventilation piping	304	SCH 10	GMAW, GTAW	ER308L	90/5/5, 98/2	Multiple
Wet scrubber piping	304	Up to 1/4”	GMAW, GTAW	ER308L	90/5/5, 98/2	Multiple
Furnace ducting	310	3/16”	GMAW	ER308L	90/5/5, 98/2	Multiple
Furnace ducting	316L	10 GA	GMAW	ER308L	90/5/5, 98/2	Multiple

While conventional, welding with stainless steel presents obstacles for compliance with the OSHA Hexavalent Chromium Standard, especially in enclosed spaces. This demonstration

intended to replace this conventional technology with the novel silica precursor welding technology to reduce on-site welders' exposure to welding fumes and decrease the amount of HAPs potentially released into the environment. The demonstration verifies the laboratory results and includes a collection of welders' opinions about the implementation of this technology (such as ease-of-use issues).

4.3 SITE-RELATED PERMITS AND REGULATIONS

Currently there is no site-specific permit or regulation for implementing this technology.

5.0 TEST DESIGN

A laboratory study was first conducted to optimize the process. This was followed by a field test based on the knowledge gained from laboratory testing.

5.1 LABORATORY STUDY

The welding-fume generation and sampling system followed the American Welding Society (AWS) fume hood design recommended in Method F1.2-1999 [32]. A conical chamber of 91.4 cm (36 inches) in diameter at the base, 20.3 cm (8 inches) in diameter at the sampling pump, and 91.4 cm (36 inches) in height was constructed. A Lincoln Power MIG 140C welder was used to produce welding fumes using ER308L (0.09 cm diameter, 18 gram per minute wire feed rate) stainless steel welding wire, which has an average chromium content of 19.5%-22.0%. This wire also contains 9.0-11.0% Ni, 1.0-2.5% Mn, and 0.35-0.65% Si, according to the material safety data sheet (MSDS). Figure 6 shows the chamber and the welding machine.

Figure 6 Fume chamber and welding machine

Mild steel base metal (not stainless steel) was used for sampling to avoid interference from chromium emitted by the base sheet metal. The base metal was placed on a rotating

turntable (MK Products Aircrafter T-25) inside the hood to maintain a constant weld speed. The base metal and turntable can be seen in Figure 7.

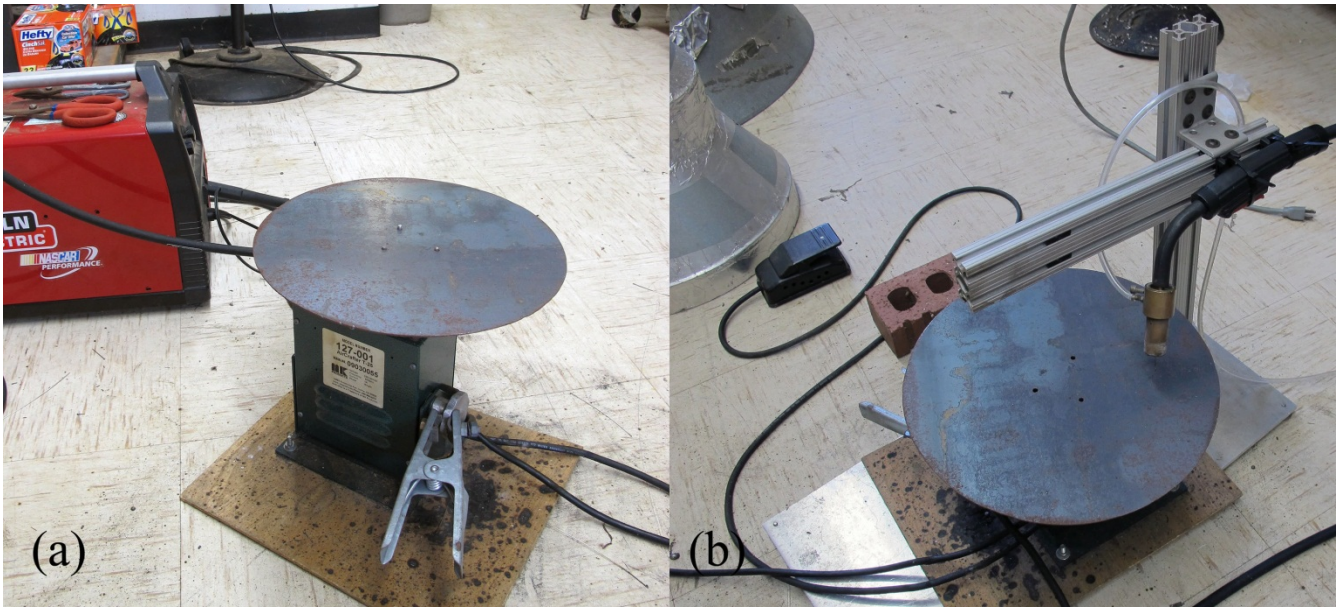

Figure 7 Scene of (a) turntable with the base metal (b) welding gun mounted on the stand

Fumes from the baseline study that used 75% Ar/25% CO_2 as a shielding gas (i.e. no TMS introduced) were collected to determine emissions of Cr^{6+} during normal welding operations. This scenario represented the standard welding method currently used by many DOD welders. There were two methods of introducing TMS into the shielding gas (75% Ar/25% CO2):

1. the premix, and
2. insulated double-shroud torch (IDST)

Both belong to the "mixed at torch" mode defined in Section 2.1. In the premix mode, the welding torch was modified to allow injection of TMS by insertion of a Y-fitting to connect the torch and the gas hose. In the IDST mode, a newly designed torch (Figure 8) was used to allow separate flows of shielding gas and TMS carrier gas. The detailed design will be described in Section 6.1.1.

Figure 8 The IDST torch

5.1.1 Analysis of Cr^{6+}

Ion chromatography (IC, Dionex ICS 1500, CS5A analytical column, DS6 conductivity detector) was used to measure the soluble hexavalent chromium species, chromate (CrO_4^{2-}). Sample extraction for IC analysis followed NIOSH Method 7604 [33]. The eluent chosen for the current study was mixture of sodium bicarbonate (5 mM) and sodium carbonate (1 mM), per manufacturer specifications for the analytical column used in this study. Soluble Cr^{6+} species were extracted with the eluent and heated in a water bath to 100 ˚C for one hour.

The eluent used (5 mM $NaHCO_3$ and 1 mM Na_2CO_3) was not capable of dissolving the silica shell. (The use of a strong acid, such as hydrofluoric acid (HF) could change the state of the original Cr^{6+} and damage the instrument.) In other words, IC cannot determine the amount of Cr^{6+} encapsulated in the silica shell. However, the fact that one must use HF to extract the Cr^{6+} from inside the silica shell presumably suggests that the human body will likewise not be able to extract and absorb the encapsulated Cr^{6+}.

X-ray photoelectron spectroscopy (XPS) is a non-destructive analytical process that allows examination of the valance state of Cr in the range of penetration depth of an X-ray. The welding-fume particles were scraped off the glass fiber filter and subsequently loaded onto a silicon substrate. Only samples from one baseline and one optimal injection rate were analyzed. The Perkin Elmer 5100 XPS system gives the intensity as an arbitrary unit (a.u.) for each peak; therefore, the relative ratio of Cr^{6+}/Cr^{3+} could be calculated.

5.1.2 Analysis of total metals and silica coating efficiencies

Analysis of total metals was carried out with Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES, Perkin-Elmer Plasma 3200). The metals analyzed by ICP-AES included Fe, Cu, Cr, Ni, and Mn. Two atomic-emission spectral lines for each element were used simultaneously to reduce spectral interference introduced by other co-existing elements in the matrix. The concentration of each metal in a sample was determined by averaging the results of five reading replicates.

A conservative method of quantifying the proportion of metals encapsulated inside the silica shell was developed [34]. Aqua regia was able to effectively dissolve metal particles not trapped in the silica shell. A mixture of HNO_3/HF was found to be an aggressive digestion method for metal particles even with silica coating. The mass difference between the results obtained from these two digestion methods was therefore used to calculate the silica coating efficiency. The following equation was used:

(1)

η: Silica coating efficiency, %

N: Number of metals involved

$C_{NF,i}$: Measured concentration of the ith metal digested by HNO_3/HF mixture

$C_{AR,i}$: Measured concentration of the ith metal digested by aqua regia

5.1.3 TEM imagery

Transmission electron microscopy (TEM, JEOL 2010F) was used to observe SiO_2 coating formed on fume particles and particle morphology. Specialty grids designed for TEM (Pelco, Lacey Carbon Type-A, 300 mesh) were inserted into the welding chamber. The grid was held for 10 seconds in the welding fume to load the particles for imaging. The continuous ultrathin carbon film on Lacey film allowed for the thinnest carbon support film that still had adequate strength to withstand specimen preparation. The film (less than 3 nm thick) lay across a carbon Lacey film supported by a 300-mesh gold grid. Welding-fume particles lying over the covered holes could be imaged in the TEM with almost no interference from the carbon film supporting it.

5.1.4 Particle size distribution

A scanning mobility particle sizer (SMPS, TSI Model 3081 Long DMA) was used to obtain aerosol-size distribution data. The SMPS is a high-resolution nanoparticle sizer that uses a discrete technique in which a number of concentrations are measured directly without assuming the shape of the particle size distribution. The method is independent of the refractive index of the particle, and has a high degree of absolute sizing accuracy and measurement repeatability. For fume particle size distribution measurement, welding was performed for 10 seconds and stopped, at which point the SMPS pump was turned on.

5.1.5 *E. Coli* study

Using an *E. coli* bioassay to study toxicity has advantages including common availability, easy incubation, fast growth, and sensitivity to hazardous materials. An ampicillin-resistant *E. coli* strain derived from XL1-Blue competent cells (Agilent Technologies, Santa Clara, CA) was used in the biotoxicity tests to avoid background contamination. *E. coli* was grown aerobically at 37 °C overnight in Lysogeny Broth (LB) medium, which contained 10 g/L tryptone, 10 g/L NaCl, 5 g/L yeast extract, and 50 mg/L ampicillin. The saturated cultures were concentrated by centrifugation (Fisher Scientific, Pittsburgh, PA, USA) at 6,000 rpm, washed with a phosphate buffer, and then re-suspended in the phosphate buffer to obtain a biosuspension for which a bacterial titer of 10^7 to 10^8 colony-forming units (CFU) per milliliter was measured.

The biotoxicity test was conducted by adding 1% by volume of the biosuspension to a 10-mL portion of welding-fume-particle suspension and agitating it with a Wrist Action Shaker (Burrell Scientific, Pittsburgh, PA, USA) at room temperature (20 ± 3 °C) for 24 hrs. It was then plated on LB medium in a petri dish and incubated for 24 hrs at 37 °C. The bacterial density after 24-hr exposure to the particles was determined by counting CFUs on a petri dish loaded with LB medium containing 50 mg/L ampicillin. The results from the treatment groups were used for direct comparison with each other without any special statistical analyses.

5.2 FIELD TEST

The field demonstration was performed at TEAD, Tooele, UT in August, 2011. Two types of sampling were conducted: low-flow sampling and high-flow sampling. The low-flow sampling was conducted by environmental contractors Environmental Cost Management (ECM), Inc. The baseline welding was performed on Aug 11th and 24th, and the welding with TMS technology was performed on Aug 23rd. The high-flow sampling was conducted by University of Florida researchers on Aug 25th.

A field visit prior to the demonstration was carried out in June 2010. The field demonstration plan included the Standard Operation Procedure (Appendix B) and the Health and Safety Plan (Appendix C), which were prepared and approved by TEAD's Occupational Safety,

Health and Environment (OSH&E) Department and Fire Protection Department. The welder received brief training how to use the TMS technology on Aug 23rd, 2011.

The original demonstration plan was designed to conduct testing under two broad indoor environmental operating conditions: (1) in a high bay and (2) in a semi-enclosed tent-like structure positioned inside in the bay. The enclosure was meant to emulate worst-case conditions in semi-confined spaces often found in welding operations. At the last minute, the TEAD facility managers moved the test site to a small garage-like room approximately 20 feet by 20 feet by ~12 feet high. At that point, the tent-like enclosure was abandoned since the garage emulated a semi-confined space. Furthermore, each testing event (welding a full plate) took about 25% longer than expected. Since we tested only one indoor environmental condition over the three week period, we were able to increase the number of samples for the semi-enclosed condition.

The area used for welding was a room at one end of a maintenance building that had two main 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 with duct tape and plastic sheeting. All doors were closed and openings taped shut, and no person was allowed to go in or out of the room during welding.

5.2.1 Low-flow sampling

Low-flow sampling included three different pieces of equipment running concurrently. The sampling system incorporated a portable LEV collector (Figure 9a). The collector, located inside the room, contained a pleated air filter. The hood location was such that the airflow was uniform. In addition, hood air flow rate was collected at the hood face, at the weld location, (~ 12 inches from the hood) and at the edge of the work table.

An Electrical Low Pressure Impactor (ELPI, Dekati, Finland) and a Grimm Aerosol Spectrometer (Grimm, Germany) were set up in a small room adjacent to the welding area. The sampling inlet was on the hood face, as shown in Figure 9b

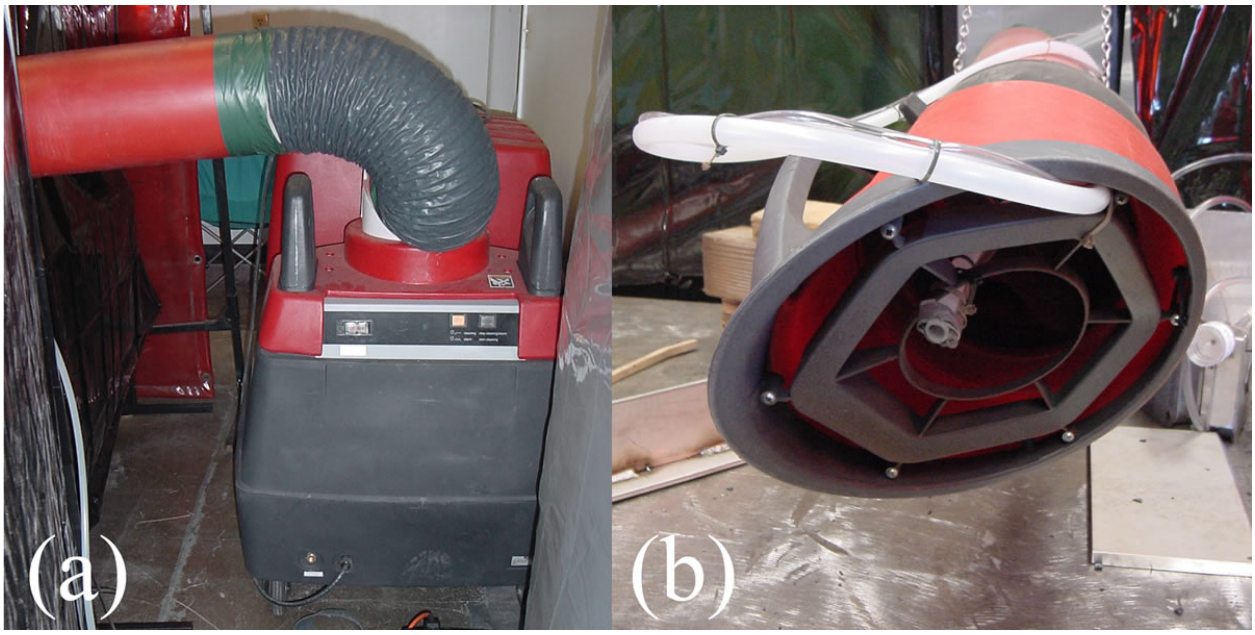

Figure 9 (a) Lincoln LEV collector and (b) sampling inlet on hood face

The ELPI uses a real-time impactor technology with particle charging and electrical detection. Measured current signals are converted to aerodynamic size distribution using particle-size dependent relationships. The ELPI has 13 stages with filters attached to each stage. The inlet of the ELPI was attached to a sampling duct next to the welder (Figure 10) and the air suction was provided by the low-volume pump within the ELPI. The particles collected on 25-mm filters ranged from 7 nm to 10 µm. The 13 stages and housing were decontaminated in 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. The ELPI was factory calibrated, so no field calibrations were required. During the analysis, the 13 stages were combined due to the low mass collected on each individual stage.

The Grimm Aerosol Spectrometer Model 1.109 is an instrument that detects airborne aerosols particles in 31 channels ranging in sizes from 0.25 to 32 µm. Its particle measurements are based on the orthogonal light principle and use an illuminated laser light and scattered signal. The Grimm can display particle numbers over the 30 channels every 6 seconds and can also display mass distribution for multiple channels. The three EPA dust fractions of PM_{10}, $PM_{2.5}$, and PM_1 can also be displayed. In addition, the three typical OSHA mass fractions (inhalable, thoracic, and alveolar) can be displayed and stored. After optical detection, an integrated 47-mm filter in the 31st channel can be used to collect samples for further laboratory evaluation. 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 samples to the lab. The filter mount was cleaned with pressurized air and then a new filter was 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.

Occupational Health and Safety (OSH) testing following the NIOSH Method 7300 included pumps placed in the near field (12 inches from the plate, Figure 11a) and far field (~10 feet from the worktable, Figure 11b). In total, six industrial hygiene (IH) pumps were provided for hexavalent chromium and other metals. Polyvinyl chloride (PVC) filters were required for hexavalent chromium evaluation, while mixed-cellulose (MCE) ester filters were used for other metals. Amorphous silica testing required a separate pump. Each pump usually ran half of the work day 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.

The collected samples were sent to the Comprehensive Industrial Hygiene Laboratory of the Navy and Marine Corps Public Health Center for analysis. The extraction and measurement of concentration of Cr^{6+}, total metals, and amorphous silica followed NIOSH methods 7604, 7303, and 7603, respectively. The mass of Cr^{6+} and other metals (Ar, Cd, Co, Cr, Ni, Mn, Cu, Zn, Fe, Pb) was determined using ICP-MS (Inductively Coupled Plasma – Mass Spectroscopy), and concentrations of these metals in the air were estimated from the sampling flow rate. In addition to metals, the concentration of respirable amorphous silica was measured to evaluate the potential for silica exposure caused by the TMS technology.

Figure 10 Setup of the pump and welder in low-flow sampling

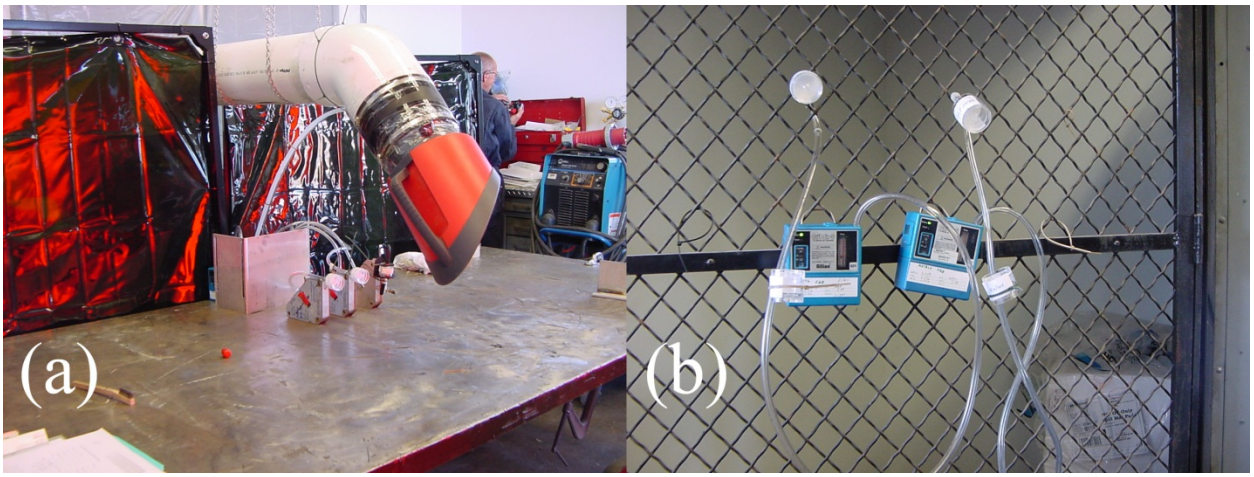

Figure 11 The scene of (a) the near field pumps (b) far field

The welder performed baseline welding and welding with TMS separately. The welding parameters remained constant throughout the whole test. The welding machine was a Miller Invision 456MP welder and a Miller 70 series 24 V wire feeder. The shielding gas used was Hellistar (U344119501, 68% Ar, 31% He, 1% CO_2). The shielding gas flow rate was 30 cubic feet per hour (CFH). The wire speed was 192 inches per minute (Ipm). Voltage was 26 V. The pulse program (RD919) was set to 299 Amps peak, 75 Amps background, and 1.84 ms pulse width. The base metal was 310 stainless steel with a thickness of 3/16 of an inch. The filler material was 0.045 inch 310 welding wire.

5.2.2 High-flow sampling

In addition to the low-flow sampling, the University of Florida team conducted a high-flow sampling to collect full samples. The low-flow sampling only collected partial samples, and isokinetic sampling was not considered.. A high-volume pump (General Metal Works 2000) was used in the field to collect the fume particles. The welding fume particles were sampled using a pump mounted next to the welder (Figure 5d and 12). The filters used were 90-mm glass fiber filters. Welding-fume particles were generated through beading on plates for about a 5-minute arc time for each sample. The five-minute arc time was based on that used in a previous enclosed chamber study. The sampling conditions are listed in Table 3.

All the filter samples were shipped overnight to the University of Florida lab and digested the next day. Analysis of Cr^{6+} was done three days after sampling, while analysis of total metals was completed within one week of sampling. The welding machine and parameters were identical to the low-flow sampling conditions. Results of Test 1 were abandoned due to contamination during digestion. The protocols for the analysis of Cr^{6+} and total metals remained the same as those used in the laboratory test (Section 5.1), and are not repeated here.

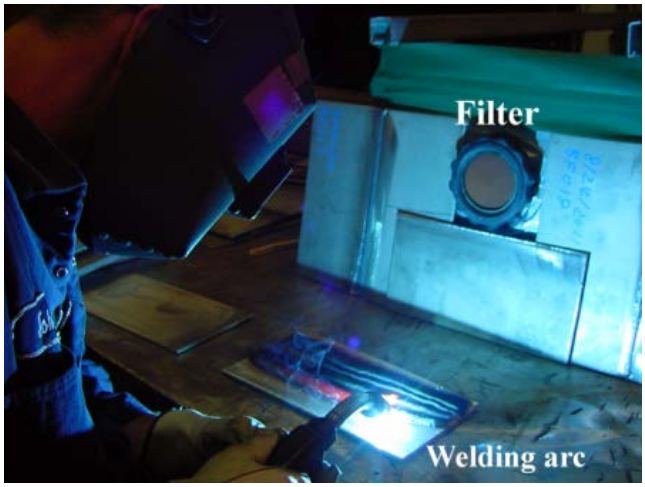

Figure 12 Setup of the pump and welder in high-flow sampling

Table 3 Parameters for high-flow sampling in the field test

ID	Filter Number	Arc time (min)	TMS rate (Lpm)
Baseline 1	13	5:01:90	0
Baseline 2	12	5:01:09	0
Baseline 3	9	5:01:96	0
Test 2	4	4:59:88	0.24
Test 3	10	5:01:63	0.24
Field blank 1	11	-	-
Field blank 2	2	-	-

5.2.3 Weld-quality test

A total of six plates were sent to the Naval Surface Warfare Center Carderock Division for weld-quality test evaluation. Three plates for the baseline group (F528, F529, F530) and 3 for the TMS-injected technology group (F540, F541, F542) were evaluated. The evaluation consisted of radiography tests, surface chemical analysis, and transverse tensile testing.

The six plates were machined according to the design in Figure 13 (F-528 plate). Radiographic analysis (ASTM E 1032) was conducted on the plates prior to machining the different samples. Different cuts of macro- and microstructures were taken to test tensile strength and to evaluate the weight percent of different solutes in the stainless-steel plates. The dimensions of these machined samples are shown in Figure 13.

Only two (F528 Baseline and F541 TMS injected) out of the six plates were analyzed for chemical composition according to ASTM E 1019-08 and ASTM E 1097-07. The tests were

performed by Luvak Inc., Boylston, Maryland. Metallographic techniques (macro and micro) were used to correlate the structure of the welded steel to the mechanical tensile properties. The ASTM E 407 test involved removing a section of metal or a weld followed by grinding, polishing, and etching it with an acid (Marble etch for 310 Stainless Steel). A number of weld features were examined using the macrostructure evaluations (ASTM E 407). These included depth of fusion, depth of penetration, effective throat, degree of fusion, and weld discontinuities.

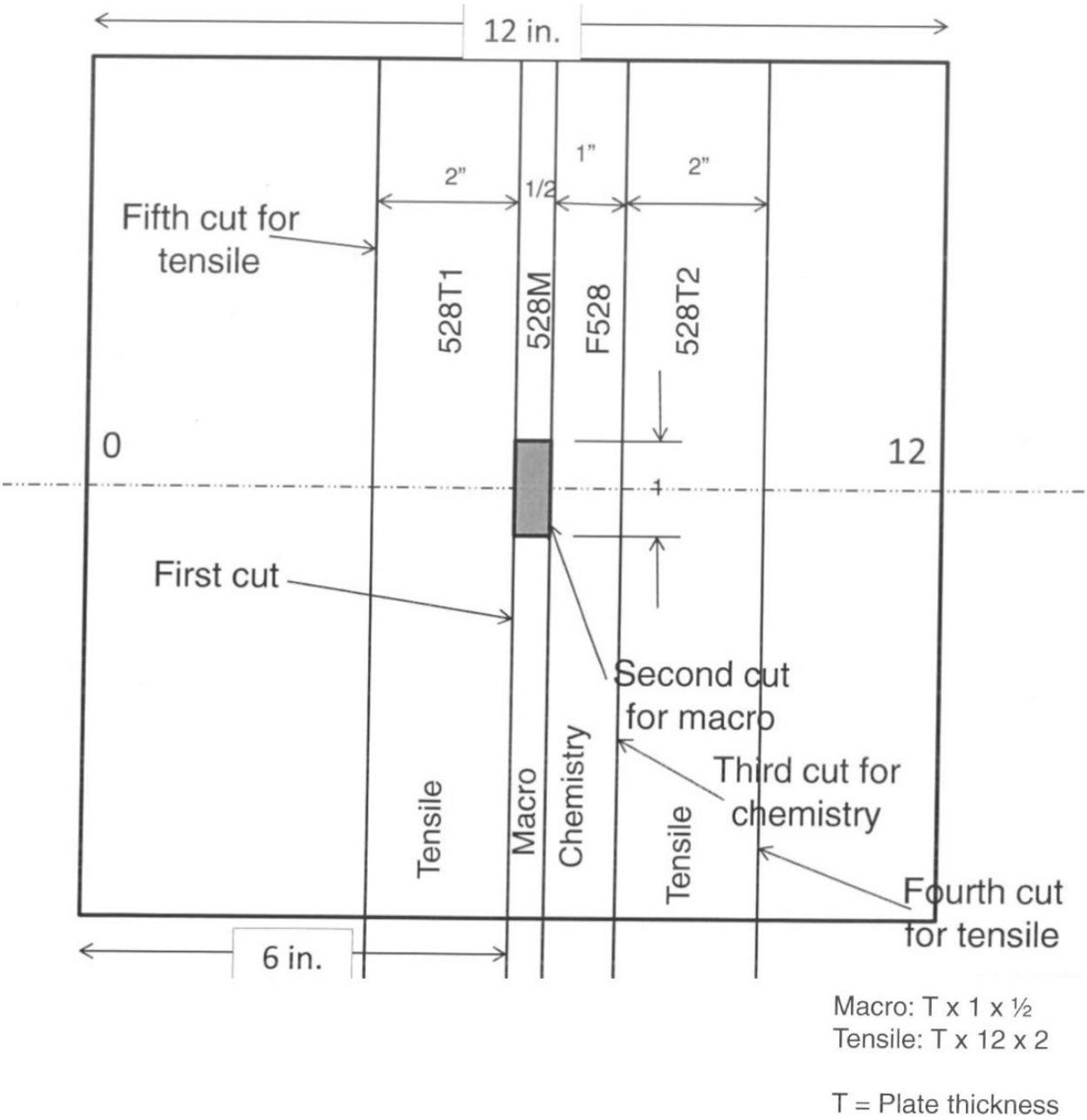

Figure 13 Samples machined from the welded plates

Transverse tensile tests were performed to determine if the mechanical properties of the TMS-injected samples were above the minimum expected standard values. This test was also performed to determine whether the weld zone matched the performance of the base metal in the TMS-injected samples. A specimen (strip) machined transverse to the longitudinal axis was tensile tested. The test was performed in accordance with the API 1104, Standard for Welding Pipelines and Related Facilities. This standard defines the criteria for a successful tensile test as follows: The specimen fails either (A) in the base metal, indicating that the weld is strong or (B) in the weld metal, as long as it fails at a strength level above the minimum standard strength of the base metal. The ANSI/ AWS B 4.0 standard explains in detail the requirements for the mechanical testing of welds. ASTM E 8/E 8M describes the general tensile testing of metallic materials, detailing the methods for obtaining the yield strength, ultimate strength, and the percent elongation values. Each of the six plates (F528-F530 and F540-F542) had two tensile specimens (T1 and T2 in Figure 23). The tensile tests AWS B 4.0 and ASTM E8 were performed at the Nadcap Laboratory Testing Inc., Hatfield, Pennsylvania. The flat tensile samples were of 3/16-inch thickness. The overall dimensions were 3/16 by 2 by 12 inches.

5.2.4 Health and safety plan

Prior to the demonstration at TEAD, a health and safety plan (Appendix C) was developed to help the implementer understand the health and safety strategy. The demonstration of TMS technology required the welder to be especially careful when handling TMS. Demonstration personnel each received a copy of the Standard Operating Procedures (SOP) and the safety plan on welding safety issues specific to TMS. Welders were expected to conduct this demonstration as they do on their regular workdays. Welding gloves and other personal protective equipment (PPE) are sufficient barriers against the TMS-saturated carrier gas that a welder may contact. The other occupants at the site were not exposed to TMS at any time because it was contained in a tightly sealed and closed system.

The estimated amount of TMS used in the TEAD demonstration was about 50 mL. TMS stock liquid not in use was stored in a safety cabinet in a separate room. It would have been preferable for the stock liquid to be refrigerated, but it was not mandatory. The TMS reservoir was never heated. The unused TMS liquid remaining after the experiment was collected in a waste bottle.

Leak and pressure tests were performed following the steps described in the SOP. TMS in use was contained in a 375-mL Teflon reservoir with Swagelok connection and Teflon-coated Tygon tubing. The pressure rating of the Teflon reservoir was 75 psi, and the pressure of the carrier-gas flow through the reservoir was roughly 30 psi. Teflon, unlike glass, does not break even if dropped. Since this system was a closed system, it eliminated the risk of TMS leaking into the working environment.

TMS itself will not explode unless mixed with strong oxidants. In the demonstration, the TMS introduced to the welding machine was pre-diluted with inert argon gas to approximately

1:25 (volume ratio), and therefore, there was no risk of explosion. The diluted TMS instantly decomposed in the welding arc. Hence, there was no worker exposure to TMS at the demonstration site. There was no possibility of TMS liquid coming into contact with static electricity during the demonstration because the TMS was contained in a sealed, closed, and insulated system (Teflon container, tubing, etc.). Class 1 Division 1 electrical equipment would be needed in the unlikely case of the TMS solution had a possibility of coming into direct contact with TMS.

Figure 14 The respirator and air cylinder worn by the welder

During the demonstration, all personnel working or observing in the welding room wore respirators with supplied air (Figure 14). The area was monitored for TMS fumes using the Landtec GEM 2000 combustible gas monitor. This instrument was set up in the welding room, approximately 5 feet from the work table. The instrument was set to trigger an alarm if oxygen, carbon dioxide, or the lower explosive limit (LEL) reached action levels that would possibly endanger anyone in the room. Periodic checks of the GEM were made through a window in the room. LEL levels remained at 0 ppm. This instrument was calibrated daily during times when it was used. ECM personnel were not allowed into the welding room during testing and did not enter after testing until one complete room volume (15,120 ft^3) was exhausted from the room. The rate on the Lincoln collector was measured at the end of the day, and then the time to clear the room was calculated, usually 20 to 40 minutes, before entry was allowed.

5.3 STATISTICAL ANALYSIS

All the experiments described in the test design were repeated at least three times to ensure statistical quality. All data collected in the laboratory tests and the field demonstration

tests were subjected to statistical examination. Statistical analysis was done using SAS 9.3 software at the University of Florida.

The comparison of baseline welding and welding with TMS technology was done by the ANalysis of VAriance (ANOVA) method. ANOVA is a statistical model in which the observed variance in a particular variable is partitioned into components attributable to different sources of variation. In this demonstration, ANOVA provided a statistical test to indicate whether or not the average concentration of Cr^{6+} and other metals in different conditions are statistically different.

6.0 PERFORMANCE ASSESSMENT

6.1 LABORATORY TEST

6.1.1 Reduction of Cr^{6+}

Figure 15 shows the Cr^{6+} concentration at three primary shielding-gas flow rates (20, 25, 30 Lpm) for both the premix mode and the insulated double-shroud torch (IDST) mode. The detailed data are documented in Appendix D. Regarding the premix mode, mixing about 4.2% of tetramethylsilane (TMS) carrier gas into primary shielding gas led to an over 93% reduction of Cr^{6+} concentration to 4.2 µg/m^3, which was below the new OSHA standard (5 µg/m^3) [35]. However, the high removal only occurred with the high primary shielding-gas flow rate, i.e., 30 Lpm. The inhibition of metal oxidation was not ideal under the medium and low shielding-gas flow rates because of the welding gun design. As shielding gas could not effectively disperse the heat generated from the welding process and insulate the heat transfer to the welding gun, the silica precursor that was premixed upstream decomposed before reaching an effective position (i.e., the welding arc zone). A large amount of silica powder was found deposited inside the welding gun under these conditions (Figure 16). These results suggest it would be best to avoid the premix mode in favor of effectiveness under all conditions.

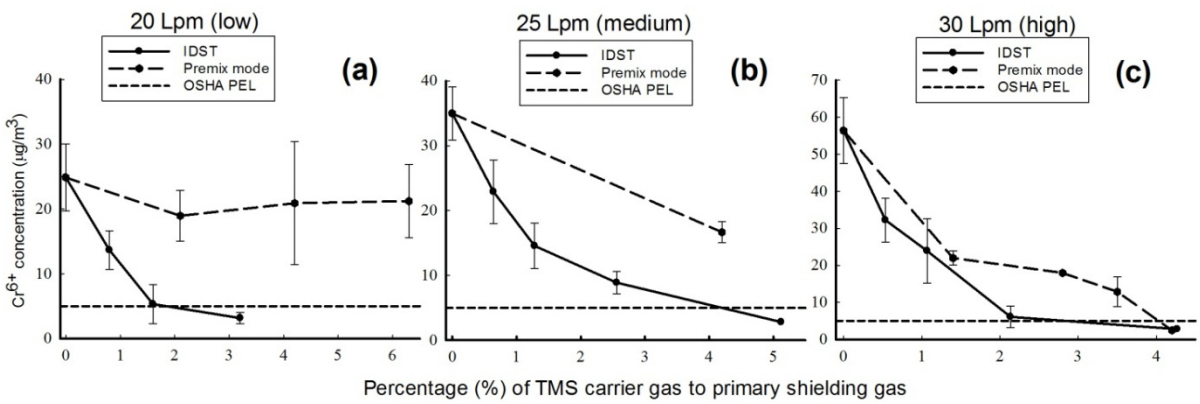

Figure 15 Cr^{6+} concentration as a function of the ratio of TMS to different shielding-gas flow rates

Figure 16 Deposition of silica powder in the torch (premix mode)

To avoid excess thermal energy from being transferred to the silica precursor, the precursor needs to flow separately from the primary shielding gas, which is a carrier of heat. Hence, the development of an innovative torch was proposed to overcome this challenge. Dennis et al. [19] first designed a double-shroud torch using two nozzles to introduce the primary shielding gas and secondary shielding gas. However, Dennis' torch was designed only for mixing and switching different gases conveniently. It did not consider heat insulation and showed no difference in this area from the premix mode. A new IDST designed at the University of Florida incorporates a new torch configuration and a ceramic material to minimize heat transfer between the primary and secondary shielding gas. Figure 17 shows the cross-sectional sketch of the new IDST.

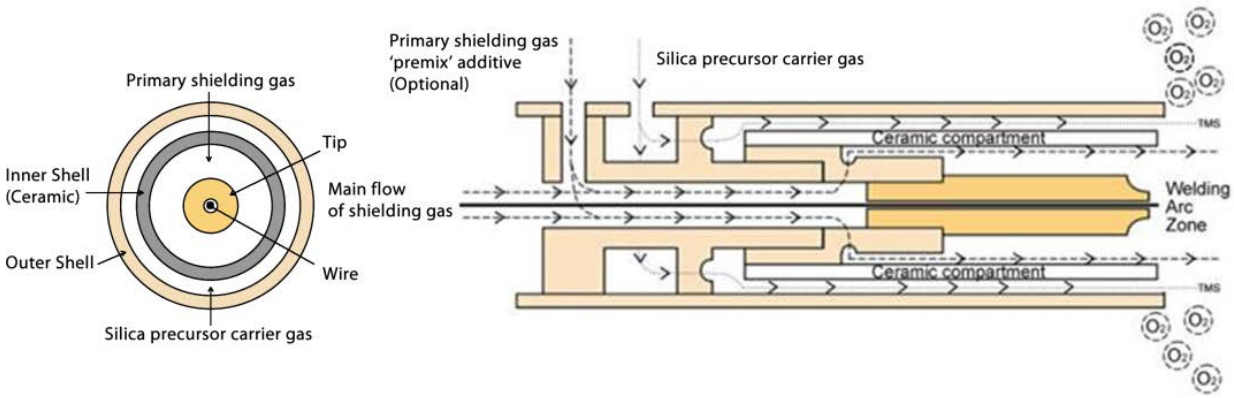

Figure 17 Schematic design of the IDST

Experiments using the IDST showed the silica precursor was able to reduce Cr^{6+} over 90%, which satisfied the OSHA PEL under all flow-rate conditions (Figure 26). Furthermore, the XPS results confirmed that Cr^{6+} inside the silica shell was reduced with a gradually increasing TMS ratio (Table 4). Visual inspection did not find any silica powder deposited on the ceramic compartment and the inner side of the welding torch. This is direct evidence of the IDST's ability to eliminate premature reaction of the silica precursor inside the welding gun. Increasing silica coating efficiency using IDST was also expected. The results suggested the IDST was able to eliminate the premature decomposition of silica precursor that occurred in the premix mode by delivering silica precursor to a position where it could interact effectively with metal particles under all shielding gas flow rates.

Table 4 Cr^{6+}:Cr^{3+} ratios in welding fume particles under various conditions

Primary shielding gas flow	TMS shielding gas flow	Cr^{6+}:Cr^{3+}
30 Lpm	0	45:55
30 Lpm	0.64 Lpm	27:73
30 Lpm	1.28 Lpm	0:100

6.1.2 Total metal and silica coating efficiencies

The mean value and standard deviation of metal concentration were obtained for all the samples in the premix mode and are shown in Table 5. Using the method to calculate silica coating efficiencies [34], the premix mode showed about 14 to 38% of the metals encapsulated, depending on the flow rate. The relatively low coating efficiency was caused by a mismatch of metal vapor's nucleation and silica formation, i.e., premature decomposition.

Table 5 Measured concentrations of metal elements digested by different acid mixtures and silica coating efficiencies

Metals	Concentration (mg L^{-1})		
	Low shielding gas flow (n=5)	Medium shielding gas flow (n=4)	High shielding gas flow (n=5)
$C_{NF, Fe}$	63.51 (1.91)	78.79 (8.67)	56.34 (1.13)
$C_{AR, Fe}$	59.38 (3.56)	51.79 (2.07)	33.28 (3.00)
$C_{NF, Cr}$	37.19 (2.98)	45.45 (1.36)	31.02 (1.55)
$C_{AR, Ct}$	28.56 (1.71)	31.33 (2.19)	28.13 (2.79)
$C_{NF, Ni}$	13.41 (0.54)	20.15 (0.81)	12.82 (0.38)
$C_{AR, Ni}$	14.82 (1.78)	17.43 (1.57)	n.d.
$C_{NF, Mn}$	17.65 (1.24)	20.92 (0.84)	19.73 (0.99)
$C_{AR, Mn}$	12.33 (1.11)	22.17 (3.10)	14.05 (1.83)
$C_{NF, Cu}$	1.78 (0.33)	n.d.	3.12 (1.03)
$C_{AR, Cu}$	n.d.	n.d.	n.d.
Silica coating efficiency	13.82% (3.79%)	25.76% (4.21%)	38.67% (6.76%)

Notes
n.d. Not detected in the samples or lower than the method detection limit.
Numbers in parentheses indicate the standard deviation among sample replicates.
NF Concentration measured in the samples digested by nitric acid and hydrofluoric acid
AR Concentration measured in the samples digested by aqua regia

6.1.3 TEM imagery

Figures 18a-d display the TEM imagery of welding-fume particles under various conditions. Because of the penetration ability of electrons when interacting with the particles, metals with high electron absorption are typically darker on a bright-field TEM image, while silica is lighter due to its low electron absorption [36].

Figure 18a depicts the welding-fume particles generated from the baseline technology without the introduction of TMS. The diameter of the welding-fume particles ranged from 10 to 100 nm. From the 2D image, it was difficult to determine if the particles were chain-like agglomerates or overlapped on different planes.

Figures 18b-c show welding-fume particles generated from 30 Lpm primary shielding gas and 0.64 Lpm TMS carrier gas flow with SCE of 76±7.9%. The images showed a silica-

encapsulated metal agglomerate, with a clear boundary between the amorphous silica layer and its metal components. Figure 18c also shows that encapsulated metal particles have different shapes, from spherical to polygonal. The nano-sized primary metal particles were bound to an agglomerate particle with a larger equivalent diameter through the inter-coagulation mechanism [37]. This resultant increase in particle size can protect users of traditional respirators with low filtration efficiency against nano-sized particles.

Figure 18d shows the welding-fume particles generated from 30 Lpm primary shielding gas and 0.96 Lpm TMS carrier gas flows with SCE of 43±9.0%. The particles are more randomly arranged, due to the high quantity of welding-fume particles generated and the possibly poor mixing interaction between the silica vapor and metal particles. In the event of excessive TMS feed, the silica vapor was more likely to form stand-alone silica particles than to condense on the surface of metal particles. This was also observed with the 0.96 Lpm TMS carrier gas flow with 20 and 25 Lpm primary shielding gas.

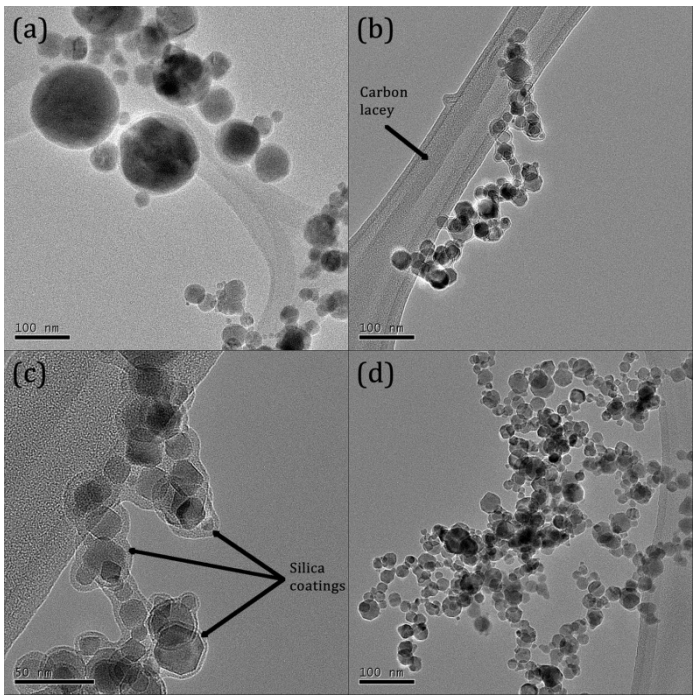

Figure 18 TEM images of different conditions of welding-fume particles

6.1.4 Particle size distribution

The silica precursor technology also increased fume-particle size from a mode (peak) of 20 nm under the baseline conditions to a mode of 180 to 300 nm when TMS was added in all shielding-gas flow rates tested (Figure 19). The detailed data are presented in Appendix E. SiO_2 particles formed in the process scavenged nano-sized fume particles through inter-coagulation. These results demonstrate the ability of vapor-phase silica precursor to reduce the health risks posed by welding fumes through elimination of nano-particles.

6.1.5 *E. Coli* study

The biotoxicity study of fume particles was conducted to evaluate the reduction of toxicity by the silica precursor technology [38]. Figure 20 shows the growth of *E. coli* exposed to different types of particles as a function of their concentrations. *E. coli* samples exposed to different concentrations of amorphous SiO_2 particles generated from the arc welding process exhibited similar responses. This response suggests that SiO_2 does not contribute to welding - fume particle toxicity. The trend of *E. coli* growth in different concentrations of baseline welding-fume particles showed that the most significant inhibition occurs at higher exposure concentrations. For *E. coli* exposed to fume particles generated in TMS-injected shielding gas, the growth rate was much higher than in baseline cases with the same particle concentration.

As seen in Figure 21, the 50% lethal logarithmic concentrations (LLC_{50}) were 823, 1605, and 1800 mg/L for baseline, 2%, and 4.2% TMS additive, respectively. *t*-tests showed that the difference between treatment groups is significant ($p<0.005$). These results indicated that adding TMS to the shielding gas could generate fume particles with lower biotoxicity.

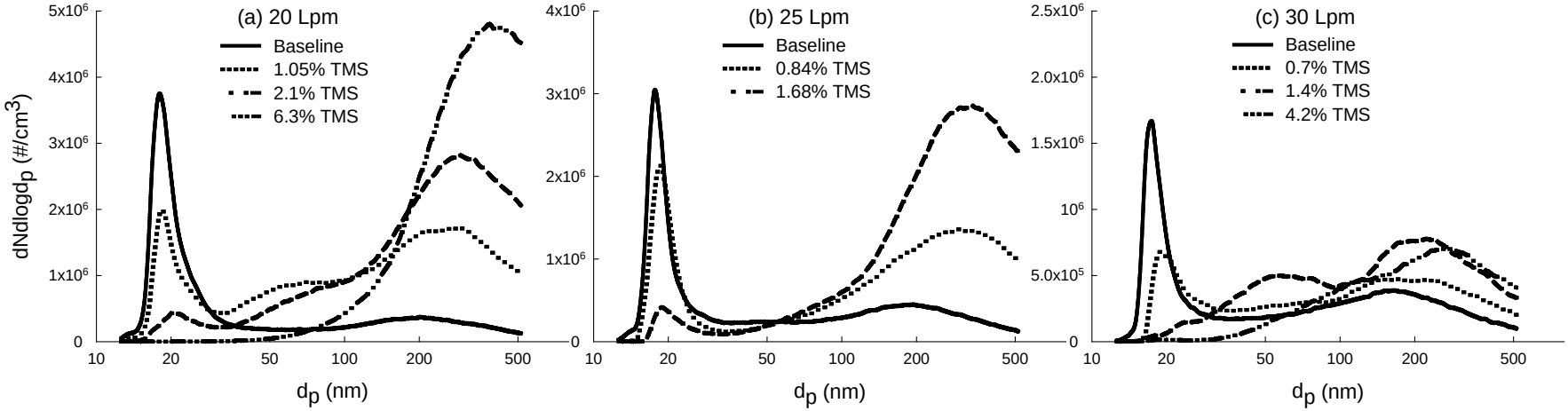

Figure 19 Welding-fume particle size distributions at different shielding gas flow rates: (a) 20 Lpm, (b) 25 Lpm, and (c) 30 Lpm.

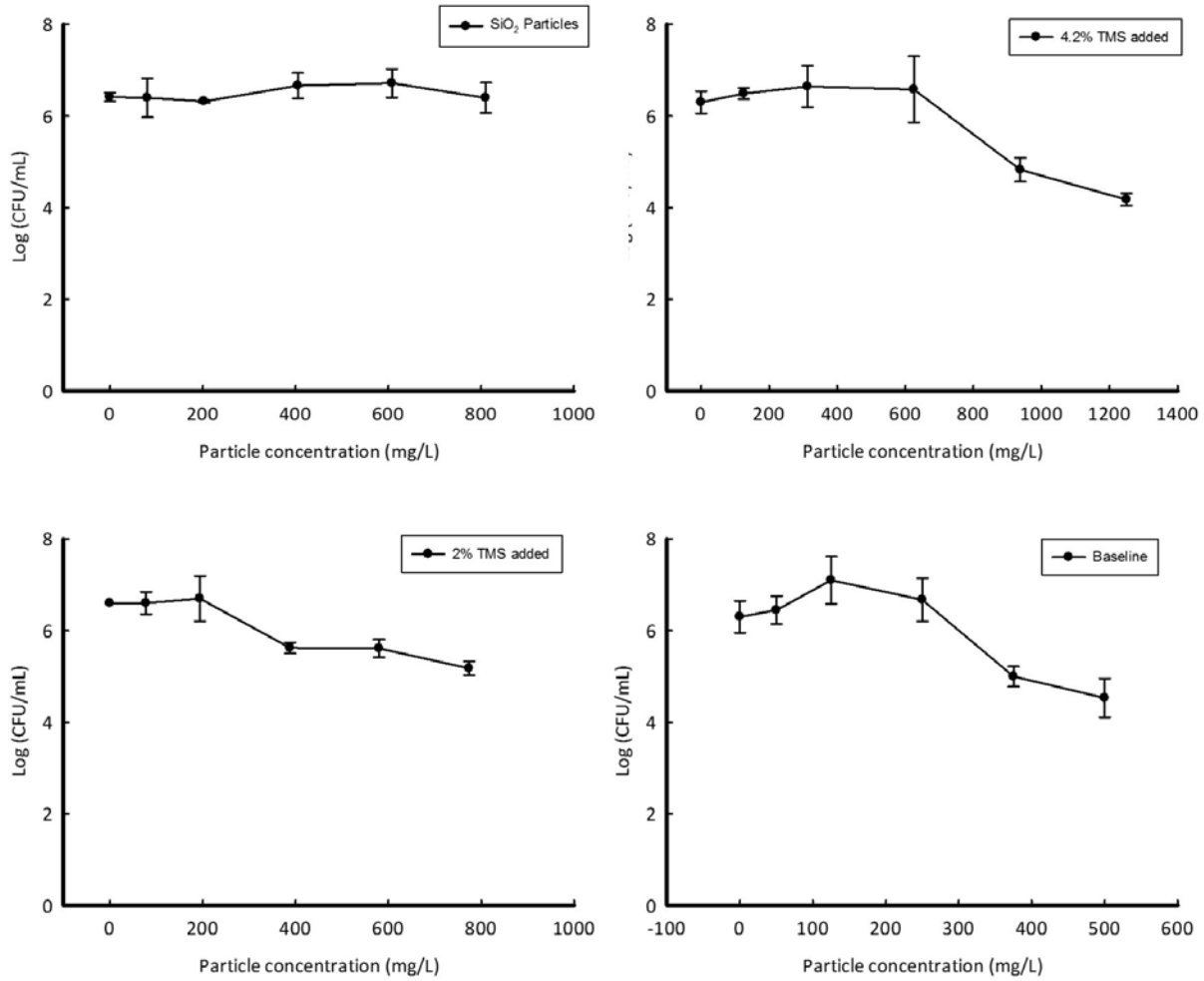

Figure 20 Growth of *E. coli* after 24-hr exposure to welding fume and silica particles as a function of particle concentrations: from top to down, amorphous silica, 4.2% TMS-added shielding gas, 2% TMS-added shielding gas and baseline (0% TMS-added shielding gas)

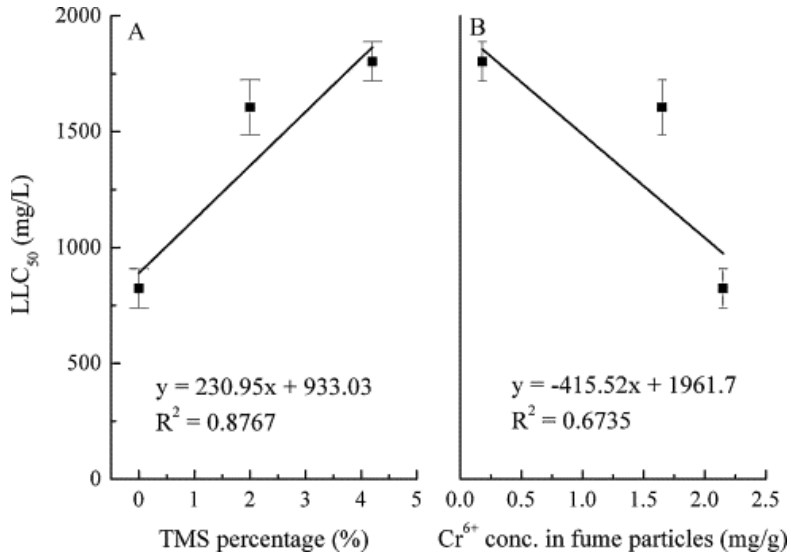

Figure 21 The correlation between LLC_{50} and (a) TMS additive fraction; and (b) Cr^{6+} concentration in fume particles

6.2 FIELD TEST

6.2.1 Low-flow sampling

The results from the low-flow sampling were limited due to insufficient fume mass collection. The concentration of Cr^{6+} in most samples was lower than OSHA PEL (5 µg/m^3) regardless of whether it was a baseline or TMS-injected sample. The variation between samples was relatively large (Coefficient of Variance > 1). However, reduction of Cr^{6+} and metals by TMS technology was still observed by use of ANOVA. The detailed data are documented in Appendix F.

The average Cr^{6+} mass collected during baseline and TMS-injected conditions was 0.56 (n = 11, n is the number of samples.) and 0.23 µg (n = 17), respectively. Figure 22a shows about a 59% reduction of the mean Cr^{6+} mass collected on filters (p<0.09). The average metal mass collected during baseline and TMS-injected conditions was 39.83 (n = 47) and 25.65 µg (n = 62), respectively. Figure 22b shows about a 35% reduction of the mean metal mass collected on filters (p<0.07). The reduction of metal emission was likely caused by silica encapsulation, since the digestion method (Aqua regia) of NIOSH 7303 cannot penetrate the silica shell.

Samples from Aug 11th were all below the detection limit (0.02 µg), which was abnormal because only baseline welding was performed on Aug 11th. Hence, it was excluded from the statistical analysis. There were no statistical differences between baseline samples and TMS samples for Cr^{6+} (p=0.85) and total metals (p=0.39). After August 11th, sample collection time was increased from 2 minutes to 20 minutes of arc time to increase the sample mass.

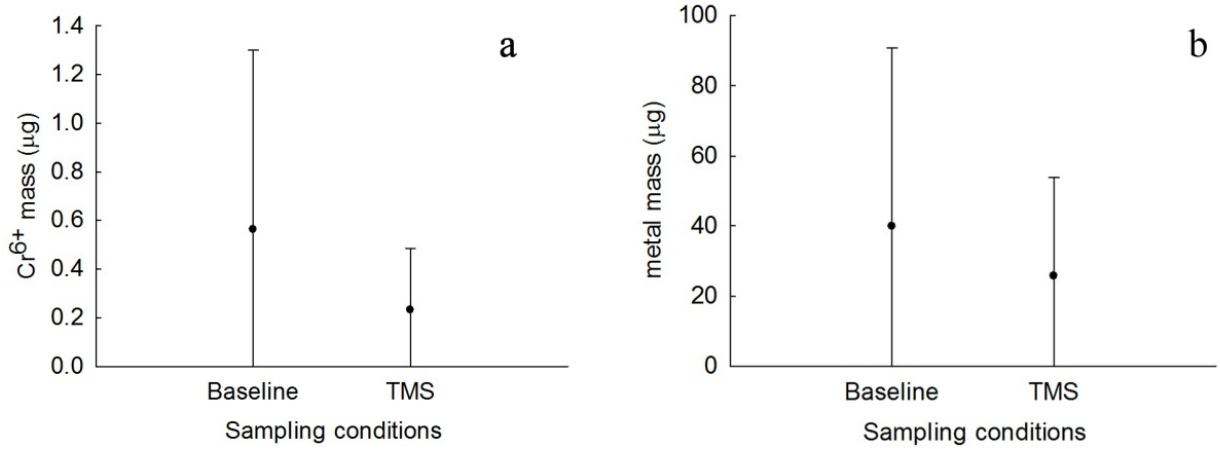

Figure 22 Comparison of Cr^{6+} and metal mass between baseline and TMS injection conditions (excludes Aug 11th sample)

Concentrations of amorphous silica in the environment were all below the detection limit for both baseline and TMS-injected conditions. The combustible gas monitor did not detect any fire hazard during the whole demonstration. These data all show that the hazard of using TMS in the welding process was minimal.

6.2.2 High-flow sampling

The results of high-flow sampling clearly show that without the silica precursor technology, the Cr^{6+} exposure was higher than the OSHA PEL. The silica precursor technology was capable of reducing Cr^{6+} exposure below the OSHA PEL with > 90% Cr^{6+} reduction efficiency, with about a third (31.8%) of the metals sealed inside the silica shell. The detection limit of the method was 0.33 mg/L, and the corresponding estimated Cr^{6+} exposure was 1.07 $\mu g/m^3$. The Cr^{6+} mass on each filter and the corresponding Cr^{6+} exposure are listed in Table 6. The mean estimated Cr^{6+} exposure of the baseline condition was 9.77 $\mu g/m^3$. Using the conservative estimation method, the mean Cr^{6+} exposure was 1.07 $\mu g/m^3$ (i.e. the method detection limit) and reduction efficiency was roughly 90%.

The masses of individual metals on each filter are listed in Table 7. Using Equation 1 to calculate silica coating efficiencies [34], 32.38% and 31.11% of metals were sealed inside the silica shell for tests 2 and 3, respectively. These results support the hypothesis that the silica precursor technology, by scavenging oxygen species and sealing metals in an amorphous silica layer, has the potential to lower welders' exposure to hazardous metals.

Table 6 Cr^{6+} mass captured on filter and the corresponding Cr^{6+} exposure estimate in the field

ID	Filter Number	Cr^{6+} mass on filter (µg)	Corresponding Cr^{6+} exposure (µg/m^3)
Baseline 1	13	47.11	7.59
Baseline 2	12	85.77	13.77
Baseline 3	9	49.46	7.94
Baseline average (±SD)		60.78(±21.67)	9.77(±3.47)
Test 2	4	Below detection limit	1.07
Test 3	10	Below detection limit	1.07
Test average		Below detection limit	1.07
Field blank 1	11	Below detection limit	
Field blank 2	2	Below detection limit	

Table 7 Mass of metal and silica (µg) on filter in the field test

ID	Filter Number	Digestion	Cr	Fe	Ni	Mn	Si	Cu
Baseline 1	13	Aqua regia	373.8	787.6	310.9	291.2	n.d.	n.d.
Baseline 1	13	HNO_3/HF	364.5	812.1	282.0	312.4	1797.7	n.d.
Baseline 2	12	Aqua regia	467.5	832.8	338.0	273.6	n.d.	n.d.
Baseline 2	12	HNO_3/HF	438.9	862.4	355.3	287.9	1339.1	n.d.
Baseline 3	9	Aqua regia	447.4	790.9	275.9	213.7	n.d.	n.d.
Baseline 3	9	HNO_3/HF	461.7	820.1	316.8	236.6	1549.5	n.d.
Baseline average			425.6	817.7	313.2	269.2	1562.1	n.d.
Standard deviation			45.0	27.9	30.9	37.0	229.6	-
Test 2	4	Aqua regia	396.1	898.0	310.9	324.2	n.d.	5.3
Test 2	4	HNO_3/HF	570.0	1285.8	437.3	567.1	1515.9	0.6
Test 3	10	Aqua regia	375.0	732.9	409.7	379.1	n.d.	9.2
Test 3	10	HNO_3/HF	521.0	1109.3	597.8	538.5	1854.3	n.d.
Test average		Aqua regia	385.6	815.5	360.3	351.7	n.d.	7.3
Standard deviation			15.0	116.7	69.9	38.8	-	2.8
Test average		HNO_3/HF	545.5	1197.7	517.7	552.8	1685.1	0.3
Standard deviation			34.6	124.8	113.5	20.2	239.2	-
Field blank 1	11	Aqua regia	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Field blank 1	11	HNO_3/HF	n.d.	n.d.	n.d.	n.d.	1878.1	n.d.
Field blank 2	2	Aqua regia	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Field blank 2	2	HNO_3/HF	n.d.	n.d.	n.d.	n.d.	1149.5	n.d.

6.2.3 Interview with the welder in the field

The welder commented on the ease of the change when welding with the TMS additive rather than conventional welding. The arc transfer was identical, except the TMS could burn as it came out of the torch. This effect could be minimized by setting the flow of TMS carrier gas appropriately. When the flow was too high, there was a very noticeable flame and the weld puddle was too hot. The welder recognized and adjusted the TMS carrier gas flow easily.

The welder also visually inspected the weld quality and saw no difference in the weld puddle. The appearance of the fusion zone in the weld plate was the same as that of the baseline weld (i.e., the buildup of the weld, no undercut, roping, or coarse-looking beads). Only a slight difference in color of the welded bead was observed in the weld. The color of the bead produced by TMS technology was more yellowish than that of the baseline bead. The welder believed the color was in part due to the extra heat added by the TMS. With some fine tuning of the process, a better color could be obtained.

Overall, it was very easy to adapt TMS technology to the welding operation with very little difference in the process. The welder believed the TMS technology could be used with little to no change, and good quality welds could be obtained.

6.2.4 Weld quality test

The chemical composition analyses of the F528 Baseline and F541 TMS-injected samples are shown in Table 8. The weight percentages of the solutes (chromium (Cr), nickel (Ni), molybdenum (Mo), manganese (Mn), etc.) were within the standard limits for the 310 stainless steel plate and wire (ASTM A 167 and ASW A 5.9) chemical composition.

Table 8 Composition profile of test welds and standard materials (%)

Weld ID	C	Cr	Ni	Mo	Mn	Si	P	S	Cu
Sample F528	0.073	26.5	20.0	0.14	1.19	0.47	0.016	0.0006	0.097
Sample F541	0.081	26.0	19.7	0.14	1.21	0.47	0.020	0.0007	0.10
ER310 consumables	0.25	24.0 – 26.0	19.0 – 22.0	---	2.00	1.50	0.045	0.030	---
Standard 310 Plate	0.08 – 0.15	25.0 – 28.0	20.0 – 22.5	0.75	1.0 – 2.5	0.30 – 0.65	0.03	0.03	0.75

The macrostructures of the three baseline plates (F528, F529, F530) are shown in Figure 23. The microstructures of the weld zone in sample F528 are shown in Figure 24. No analyses were performed to determine the phases of the microstructure (Ferrite, Austenite, and Bainite). The macrostructures (Figure 23) revealed a typical welded metal feature of columnar grains (controlled by growth due to the high temperature) adjacent to (but buffered by the heat affected zone (HAZ)) fine grains of the parent metal. The macrostructures of the three baseline plates (F528, F529, and F530) were similar and did not appear to contain any weld defects.

Figure 24 of the weld zone in sample F528 reveals a microstructure of welded metal with grains hundreds of micrometers' in length adjacent to the HAZ and the fusion line (FL). The HAZ and FL are of finer grain size. The microstructures also indicated the presence of inter-metallic particles where the grains probably nucleated on them. This is a typical feature of particles affected by nucleation of grains. No defects were evident in the microstructures shown.

The macrostructures of the TMS-injected plates (F540, F541, F542) are shown in Figure 25. The general features were similar to those of the baseline plates. However, a crack at the interface between the weld metal (WM) and the HAZ appeared and is shown in Figure 25b, sample F541. The microstructure of sample F541 revealed the length of the crack to be several hundred microns. It is shown with different magnifications, 5× in Figure 26a, 10× in Figure 26b and 20× in Figure 26c. The TMS addition, or problems with shielding gas, or improper welding technique might have caused gas pockets, which could have coalesced into a crack.

The tensile data are shown in Table 9. The ultimate strength values of 5 out of 6 baseline specimens F528 (T1 and T2), F529 (T1 and T2) and F530 (T1 and T2) were above 80ksi, the minimum value for the E310-xx (AWS specification A5.4). The tensile strength of the sample that did not reach the minimum tensile strength was 75.5 ksi (94.4% of the minimum value). It should be noted that when comparing the properties of all-weld-metal (AWM) tests with those of transverse tests (as is in the case of all 12 samples in the six plates described in Table 9), the structures were different. In the AWM, there was a uniform material, while in the transverse samples were composites of base metal, HAZ, and the weld zone. These regions would stretch unequally in a tensile test, which was problematic for determining whether the mechanical tensile properties were acceptable or not. This is why yield strength and percent elongation properties are not usually reported in a transverse tensile test. The ultimate tensile strength is usually reported for comparison methods.

The ultimate tensile strength values of the TMS-injected samples were a little lower than those of the baseline samples. The ultimate strength values of two out of six samples exceeded the 80 ksi minimum. The other tensile strength values were close to the minimum: 76.5, 76.5, 64.0, and 73.5 ksi, which are 95.6%, 95.6%, 80%, and 91.9% respectively. The percent elongation (ductility) is not usually taken as a measure of the failure of a weld when samples are tested in the transverse section; however, it is worth mentioning that the average percent elongation for the three baseline plates (37%, 22%, 28%, 29%, 15%, and 32%) was 27% , which is close to the 30% minimum specified by AWS specification A5.4, Table 9. The average percent elongation of the three TMS-injected plates (17%, 18%, 9.0%, 37%, 24%, and 16%) was 20.2 %.

The results of the ultimate tensile strength levels and percent elongation levels again confirmed that TMS addition, problems with shielding gas, or improper welding technique caused the lower strength and ductility values in the TMS-injected samples. Although no minimum yield strength levels are specified in the AWS specification A5.4, it is interesting to note that the average yield strength values for the three baseline plates (44.8 ksi, 44.8 ksi, 46.2 ksi, 44.4 ksi, 44.9 ksi, and 43.2 ksi) and those for the three TMS-injected plates (43.5 ksi, 43.7 ksi, 45.3ksi, 45.1 ksi, 46.0 ksi, and 44.4 ksi) were similar with a value of 44.7 ksi.

The results indicated that significant defects existed in the six plates and it was equally significant that most of the specimens (5 out of 6) in the baseline and 1/3 of the TMS-injected

specimens (2 out of 6) had their tensile strength values exceed the 80 ksi minimum value. This is also interesting because according to Nadcap Laboratory Testing Inc., all the fractures in the 12 specimens of the 6 plates (F528-F530) and (F540-F542) were in the weld area and were ductile. Ductile fractures are essential and required to ensure that catastrophic brittle failures are avoided in welded structures. The radiographic analysis of the six welded plates is shown in Table 10.

In summary, while the TMS technology does not significantly deteriorate the mechanical quality of the welds, optimization of some parameters would is likely to achieve the expected mechanical tensile strength.

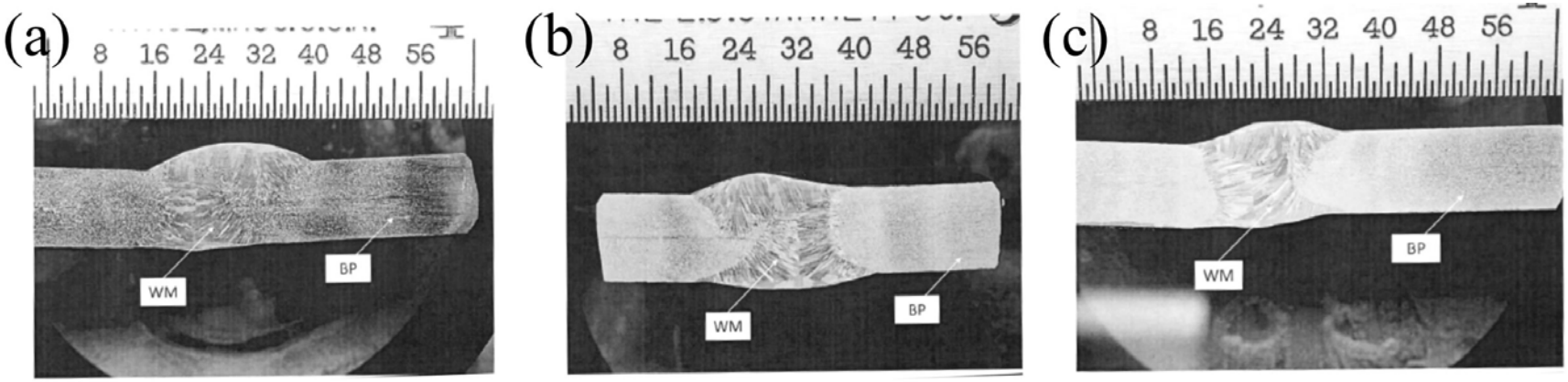

Figure 23 Macrostructure of (a) F528, (b) F529, (c) F530, with weld material (WM), and base plate (BP) marked.

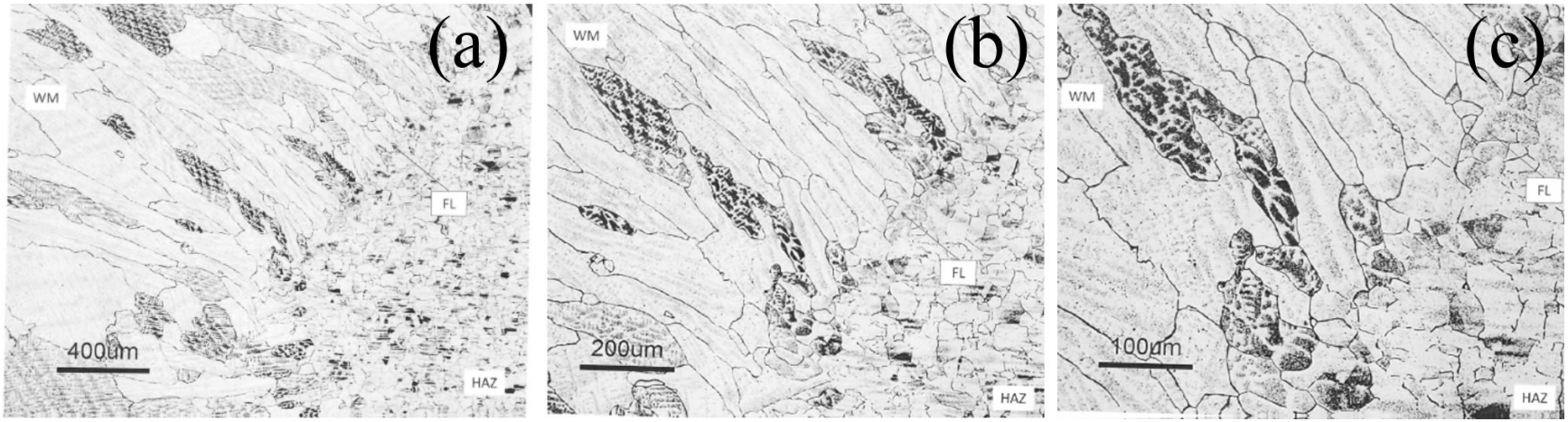

Figure 24 Microstructure of the weld zone in sample F528 (a) 5×, (b) 10×, (c) 20×.

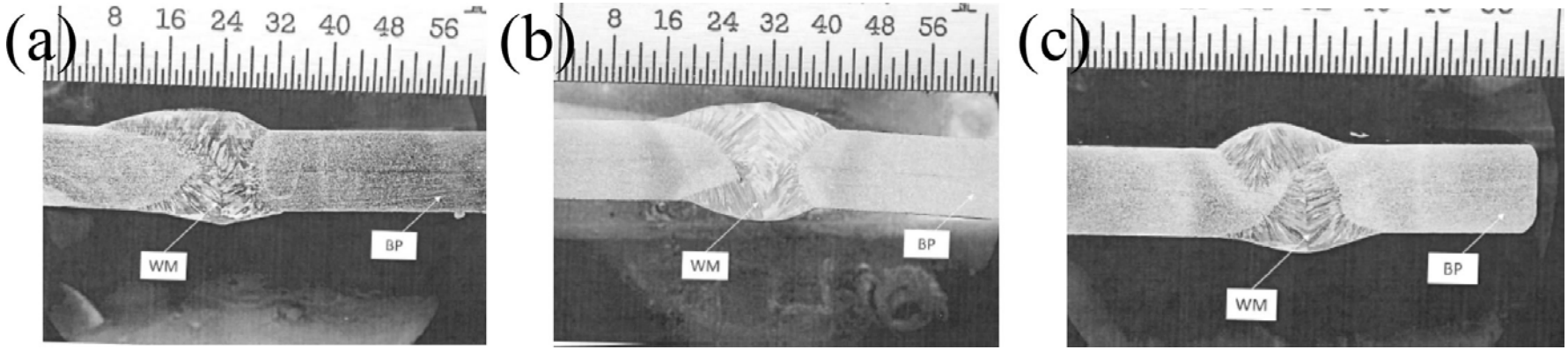

Figure 25 Macrostructure of (a) F540, (b) F541, (c) F542

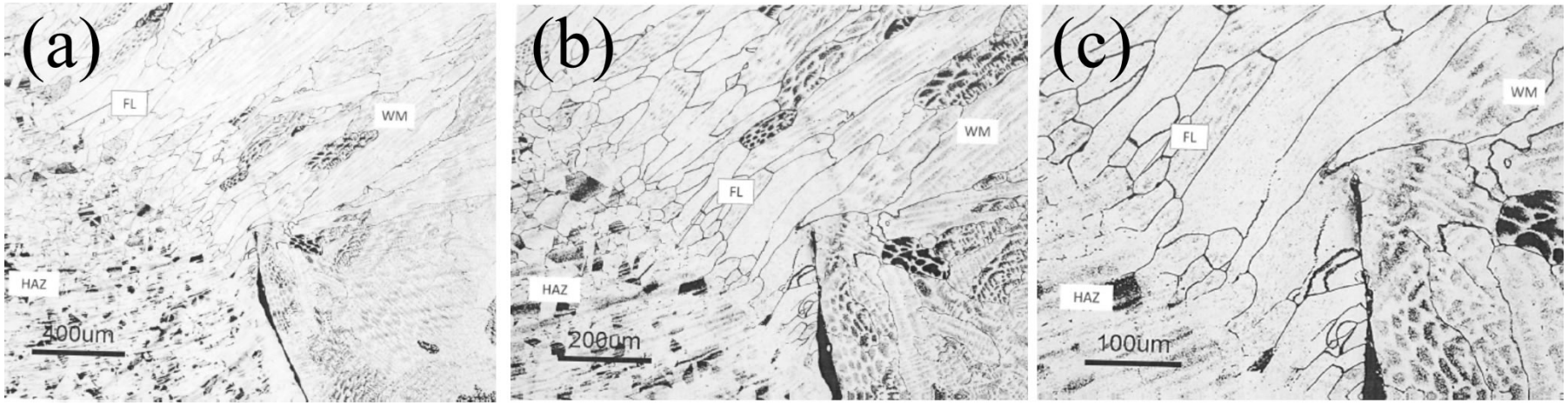

Figure 26 Microstructure of the weld zone in sample F541 (a) 5×, (b) 10×, (c) 20×.

Table 9 Tensile values of baseline and TMS test welds – 3/16” transverse tension test specimen

Sample	Process	Plate	Electrode	I.D.	Specimen	YS, ksi*	UTS, ksi	El, %*	Fracture Location	Fracture Mode
Baseline	GMAW	3/16” 310 SS	ER310 wire	F529	T1	44.8	86.5	37	Weld	Ductile
					T2	44.8	81.0	22	Weld	Ductile
				F530	T1	46.2	85.5	28	Weld	Ductile
					T2	44.4	86.5	29	Weld	Ductile
				F528	T1	44.9	75.5	15	Weld	Ductile
					T2	43.2	84.5	32	Weld	Ductile
TMS	GMAW	3/16” 310 SS	ER310 wire	F540	T1	43.5	76.5	17	Weld	Ductile
					T2	43.7	76.5	18	Weld	Ductile
				F542	T1	45.3	64.0	9.0	Weld	Ductile
					T2	45.1	87.5	37	Weld	Ductile
				F541	T1	46.0	83.0	24	Weld	Ductile
					T2	44.4	73.5	16	Weld	Ductile
** E310-XX (AWS specification A5.4)							Min 80	Min 30		

** Yield strength and elongation values may not be valid for transverse tension test specimens*

*** There are no tensile requirements for ER310 wire; this is a similar SMAW requirement (all-weld-metal)*

Table 10 Radiographic analysis

Sample ID	Pass (P)/ Fail (F)	Remarks
F528 Baseline	P	Some undercuts present
F529 Baseline	F	Lack of fusion in weld (LOF)
F530 Baseline	F	Lack of fusion in weld (LOF)
F540 TMS Injected	F	Too much undercut
F541 TMS Injected	P	Localized porosity and lack of fusion in restricted areas
F542 TMS Injected	F	Lack of fusion in weld (LOF) and excessive porosity

7.0 COST ASSESSMENT

This demonstration project intended to compare three baseline welding processes using the TMS technology. The demonstration was to be performed at three DOD facilities. The project was halted after the initial field demonstration. For this initial demonstration, information was developed for TEAD Tooele, Utah, only. The cost assessment includes the following major categories:

- The approximate cost differences between welding with both GMAW and GTAW using standard shielding gas vs. the TMS additive,
- The approximate cost differences between standard ventilation systems and ventilation systems designed to meet the new hexavalent chromium ventilation requirement,
- The approximate costs associated with the welding process requalification if a change is made to the TMS gas additive.

A major assumption of this analysis is that the TMS additive will allow for the use of conventional ventilation systems. Many other welding assumptions must be made for this type of analysis and are described below in section 7.1.

7.1 COST MODEL

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." Some aspects of this approach were used to assess and compare the costs associated with the TMS additive vs. the use of standard (argon) shielding gas. Ten different combinations of joint type and industry sector were evaluated. These same combinations were evaluated below to assess the effect on costs as a result of using the TMS technology. The industry sectors from which the applications were selected included shipbuilding, transportation and storage tanks, and general fabrication. The joint designs included V-groove butt welds between both pipe and plate configurations, as well as T joints with fillet welds. This analysis included the following list of assumptions and information:

- A worksheet for labor cost estimation in the industry sectors listed above. This included salary, benefits, and overhead costs.
- Welding costs incorporated welding speed and number of passes, filler metal volume, deposition efficiency, and shielding gas flow.
- Cost estimates for other tasks performed by welding shop personnel, including fit-up, tacking, welding, grinding, and clean-up were included. Pre-welding machining and post-weld inspection were not included. Costs for electricity were not included.
- Inspection costs were not included.

- Although the procedure recommendations and data used in PP-1415 probably changed slightly since 2006 when the original report was prepared, the cost comparison was still valid.

7.2 COST ASSESSMENTS

7.2.1 Comparison of GMAW costs

The criteria developed in the PP-1415 were used for the various GMAW joints with the additional costs associated with the three TMS approaches included. The unit costs of each scenario are listed in Table 11. These costs were then compared to costs of producing the same joints with standard shielding gas (argon). Scenario 1 represented the mixing of TMS at the torch. Scenario 2 used customized TMS cylinder gas, where the gas was supplied from the customized gas department of Airgas, a gas supply company. A detailed quote can be found in Appendix I. Scenario 3 was similar to Scenario 2, but with the estimated reduced cost of TMS cylinder gas once it is commercially available and in high-volume production ("commercial TMS cylinder gas"). The calculation of the commercial cost was based on a net profit rate of 50%, according to Airgas. Gas-flow costs were based on the estimated total arc times associated with each joint type, and did not include mass flow controller and nozzle equipment costs. The comparisons of costs are summarized in Tables 12 through 14. The results found that using TMS mixing at the torch would slightly increase costs, while using customized TMS cylinder gas would dramatically increase costs. The estimated commercial TMS cylinder gas can reduce the costs to the same level as TMS mixing at the torch. TMS in the cylinder would be more convenient to end users than the other means. While customized TMS cylinder gas is already available, currently it is only available through custom order. The result suggested that costs would be greatly reduced once the TMS precursor technology becomes widely adopted in the welding community, and TMS gas in cylinders becomes a commonly available commodity.

Table 11 Unit cost used in the cost model

	Unit price	Consumption rate	Cost per minute
Scenario 1			
Primary shielding gas (Ar/CO_2)	\$27/300 ft^3	29 Lpm	0.092226148
Carrier gas (Ar)	\$25/300 ft^3	1 Lpm	0.002944641
TMS	\$65.16/100 mL	0.02 mL/min	0.013032
Scenario 2			
Primary shielding gas (Ar/CO_2)	\$27/300 ft^3	29 Lpm	0.092226148
TMS premix cylinder gas	\$1264/44 L	1 Lpm	28.72727273
Scenario 3 (Commercial product of cylinder gas)			
Primary shielding gas (Ar/CO_2)	\$27/300 ft^3	29 Lpm	0.092226148
TMS premix cylinder gas	\$205/300 ft^3	1 Lpm	0.024146054

Table 12 Welded joint costs of Argon shielding gas and TMS technology (mixed at torch)

			Argon Shielding Gas		TMS Technology	
Industry	Joint description	Process	Cost/ft or cost/joint* ($)	gas cost ($)**	Cost/ft or cost/joint* ($)	gas cost ($)**
Ship building/pressure vessels	6" diameter pipe	GMAW	24.5	1.2	25.2	1.9
	12" diameter pipe	GMAW	56.2	2.3	57.8	3.9
	3/16" fillet weld	GMAW	7.4	0.5	7.7	0.8
Tanks	3/16" butt weld	GMAW	5.4	0.5	5.7	0.8
	3/8" butt weld	GMAW	8.8	0.5	9.1	0.8
General fabrication	3/16" fillet weld	GMAW	2.2	0.3	2.4	0.5
	1/4" fillet weld	GMAW	4	0.4	4.3	0.7

**Cost/ft is for plates, cost/joint is for pipe*

Table 13 Welded joint costs of Argon shielding gas and TMS technology (customized TMS shielding gas in cylinder)

			Argon Shielding Gas		TMS Technology	
Industry	Joint description	Process	Cost/ft or cost/joint* ($)	gas cost ($)**	Cost/ft or cost/joint* ($)	gas cost ($)**
Ship building/pressure vessels	6" diameter pipe	GMAW	24.5	1.2	542	509
	12" diameter pipe	GMAW	56.2	2.3	1092	1038
	3/16" fillet weld	GMAW	7.4	0.5	214	207
Tanks	3/16" butt weld	GMAW	5.4	0.5	223	218
	3/8" butt weld	GMAW	8.8	0.5	226	218
General fabrication	3/16" fillet weld	GMAW	2.2	0.3	122	120
	1/4" fillet weld	GMAW	4	0.4	185	181

**Cost/ft is for plates, cost/joint is for pipe*

Table 14 Welded joint costs of Argon shielding gas and TMS technology (commercial TMS shielding gas in cylinder)

	Argon Shielding Gas	TMS Technology

Industry	Joint description	Process	Cost/ft or cost/joint* ($)	gas cost ($)**	Cost/ft or cost/joint* ($)	gas cost ($)**
Ship building/pressure vessels	6" diameter pipe	GMAW	24.5	1.2	25.4	2.1
	12" diameter pipe	GMAW	56.2	2.3	58.1	4.2
	3/16" fillet weld	GMAW	7.4	0.5	7.7	0.8
Tanks	3/16" butt weld	GMAW	5.4	0.5	5.8	0.9
	3/8" butt weld	GMAW	8.8	0.5	9.2	0.9
General fabrication	3/16" fillet weld	GMAW	2.2	0.3	2.4	0.5
	1/4" fillet weld	GMAW	4	0.4	4.3	0.7

**Cost/ft. is for plates, cost/joint is for pipe*

7.2.2 Elimination of the need for special ventilation

When OSHA established the new ventilation requirements for reducing exposure to hexavalent chromium, it stated that the primary methods for reducing such an exposure would be local exhaust ventilation and improvement of general dilution ventilation. In addition, it was anticipated that in many cases, a welder would use PPE with a respirator when welding stainless steels. Therefore, this cost assessment was based on the assumption that a typical fabrication facility would incur additional costs for improved general and local ventilation, as well as PPE, 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 their welding involves stainless steel, so it is clear that the issue of hexavalent chromium 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 or not welding is being conducted in confined space. Every case will be different. This analysis was 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, there are many specific factors that must be considered that will affect ventilation requirements for each location. Examples of other factors to be considered included the 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 by 30-ft shop with 12 welders, and a 200 by 100-ft shop with 36 welders. Assumptions in each case included a single shift, welding parameters ranging from 90 to 150 amps, overhead obstructions (cranes), no wall ventilators, and an HVAC system (heating) present as an air exchange system. In the case of the larger shop, it was assumed there were five roof ventilators at 1000 CFM each, 4 overhead doors, and the annual consumable usage was estimated at 60,000 lb/year. For the smaller shop, it was assumed there were 2 roof ventilators at 1000 CFM each, 2 overhead doors, and the annual consumable usage was estimated at 20,000 lb/year. In each case, it was assumed that SMAW, GMAW, and GTAW processes were used. The extent to which the SMAW process is 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. One more major assumption was that 100% of the welding in these two shops was stainless steel, which in many cases would not be accurate.

Lincoln Electric provided quotes for ventilation systems that were used for comparison. The system costs included both a general ventilation system and a source extraction system. The general system was a U-shaped "push-pull"-type system and is shown in Figure 27. This would

provide a continuous positive and negative air flow over the weld area. The source ventilation system included pivoting and telescopic extraction arms for each welding booth. Other costs considered included the costs of personal protection ventilation suits and air monitoring. The summary below incorporates the aforementioned assumptions and information and compares the typical ventilation system purchase cost differences between a shop that welds stainless steel (and therefore is subject to the new OSHA requirements) to those of a shop not subject to such requirements. These results are also summarized on Table 15.

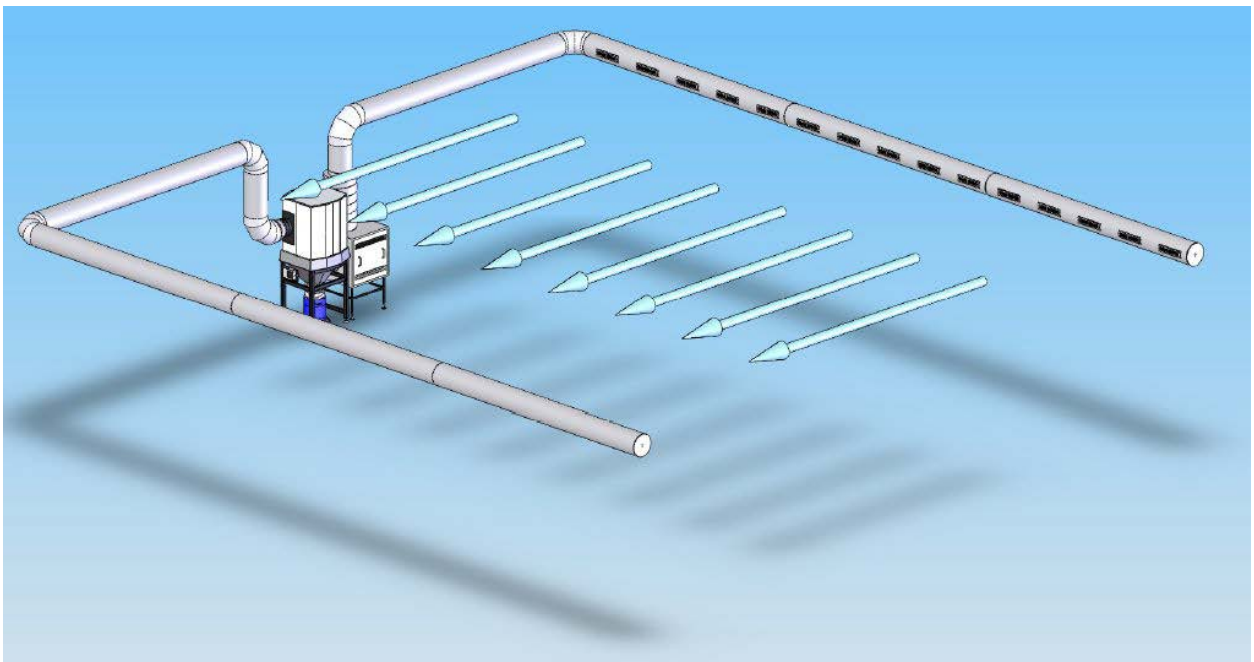

Figure 27 General ventilation system (push-pull type)

Example of a 200 by 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 was $660,000. This included both general and source extraction systems. The ventilation systems included "self-cleaning" capability, but there would be additional costs associated with filter changes and the special HEPA filters would be 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 assumed. The cost of personal protection ventilation suits for 36 welders was estimated to be $36,000. The cost associated with air monitoring was roughly estimated to be $25,000/year. In summary, the initial cost associated with purchasing ventilation equipment to meet the new OSHA standard for a 200 by 100-ft welding shop with 36 welders was approximately $700,000. The recurring costs were estimated to be $50,000/year.

In comparison, the total estimated cost for a ventilation system not subject to the new OSHA requirement was $410,000, and the recurring costs were estimated at $20,000/year. To summarize, this analysis indicated requirements for approximately $290,000 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 a 60 by 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 was $150,000. The personal protection suits for 12 welders were estimated to cost $12,000, bringing the total initial equipment cost to $162,000. The recurring costs discussed previously were estimated at $20,000/year for a shop this size.

The estimated ventilation system costs for a shop of this size not subject to the new OSHA requirement were $100,000, and the recurring costs were estimated at $10,000/year. In summary, the OSHA ventilation requirement associated with hexavalent chromium resulted in an estimated $62,000 in additional capital equipment expenses and an additional $10,000 per year in recurring expenses.

Table 15 Ventilation system cost

Weld shop size	Number of welders	Ventilation system designed to meet new OSHA standard	Initial purchase expense ($)	Recurring expenses ($)
200’ × 100’	36	Yes	700,000	50,000
		No	410,000	20,000
60’ × 30’	12	Yes	162,000	20,000
		No	100,000	10,000

7.2.3 Annual cost based on TMS technology

For the purposes of better understanding the financial impact of the OSHA hexavalent chromium lower exposure requirement vs. the additional costs associated with the TMS shielding gas technology, six scenarios involving the two welding shop sizes were compared. The results are summarized in Table 16.

Scenario 1 – 200 by 100-ft welding shop, TMS shielding gas mixed at torch

Since an assumption was made that 60,000 lbs. of electrode would be consumed annually in a large shop, some simple calculations could be made to develop an understanding of the annual and one-time costs associated with using the TMS technology. A very rough estimate could be made, using 6-inch-diameter pipe as an example, that with the annual consumption of 60,000 lbs. of electrode, 84,000 joints could be produced and the additional costs associated with

TMS gas (shielding gas mixed at the torch) would be approximately $59,000 (as compared to welding with argon).

In addition, it was assumed that there would be 36 welders in the large shop, which would require 36 sets of equipment (mass flow controller, PTFE impinger, double-shroud nozzle) at a total cost of approximately $50,000. his would bring the total additional costs to approximately $109,000, with $59,000 of that being an annual cost. These costs were offset by the approximate savings of $290,000 in ventilation system expenses (a one-time cost) from avoiding the need to ventilate to meet the new OSHA standard, which would have incurred an additional associated expense of approximately $50,000 annually.

Scenario 2 – 200 by 100-ft welding shop, customized TMS shielding gas in cylinder

Assuming the same model used in Scenario 1, the additional annual shielding gas cost associated with the customized shielding gas was projected to be approximately $44 million/year. The reduction in equipment cost was insignificant relative to this figure, as was the reduction in ventilation costs.

Scenario 3 – 200 by 100-ft welding shop, commercial TMS shielding gas in cylinder

In this scenario, the additional shielding gas costs associated with producing 84,000 6-inch-diameter pipe joints was projected to be approximately $76,000/year. The total cost would be $126,000, with $76,000 of that cost being an annual cost. These costs were offset by the approximate savings of $290,000 in ventilation system costs (a one-time expense) from avoiding the need to ventilate to meet the new OSHA standard, which would have incurred approximately $50,000 in additional associated expenses annually.

Scenario 4 – 60 by 30-ft welding shop, TMS shielding gas mixed at torch

In this case, it was assumed that 20,000 lbs. of electrode would be consumed annually, resulting in an additional shielding gas cost of approximately $20,000/year. It was assumed the smaller shop would include 12 welding booths, resulting in a TMS total equipment cost of about $17,000. This would bring the total additional cost to $37,000, with $20,000 of that being an annual cost. These costs would be offset by ventilation-related savings of approximately $62,000 (for one-time costs) and $10,000 annually.

Scenario 5 – 60 by 30-ft welding shop, customized TMS shielding gas in cylinder

The additional shielding gas costs in this case would be approximately $15 million/year, and again, the reduction in TMS equipment costs relative to this figure was insignificant, as was the reduction in ventilation costs.

Scenario 6 – 60 by 30-ft welding shop, commercial TMS shielding gas in cylinder

The additional annual shielding gas costs associated with the estimated commercial cost of TMS shielding gas in cylinder would be approximately $25,000. Including the TMS equipment cost of $17,000, the total cost would be $42,000, with $25,000 of that cost coming from annual costs. These costs would be offset by one-time savings of approximately $62,000 in ventilation costs, and annual cost savings of $10,000.

Table 16 Summary of the cost comparison

Scenario	Weld shop size	Mixing mode of the TMS technology	Initial cost of the TMS technology	Annual recurring cost of the TMS technology	Ventilation cost without retrofit the welding technology
1	200' x 100'	Mix at the torch	$109k	$59k	$290k
2		Customized gas cylinder	$44000k	Insignificant	Insignificant
3		Commercial gas cylinder	$126k	$76k	$290k
4	60' x 30'	Mix at the torch	$37k	$20k	$62k
5		Customized gas cylinder	$15000k	Insignificant	Insignificant
6		Commercial gas cylinder	$42k	$25k	$62k

7.2.4 Qualification of new welding procedures

When a change in shielding gas is made to a procedure that was previously qualified, most welding codes will require requalification of that procedure. The qualification requirements and costs will vary depending on the code and other factors, but typically qualification (or requalification) will involve welding a test plate (or plates); the welds would be subject to tensile, bend, and possibly Charpy impact testing. The cost associated with requalification of a procedure can be expected to vary considerably, but for the purposes of this analysis, a cost of $3,000/procedure was estimated. Thus, the magnitude of this cost is simply a matter of how many procedures each shop would need to requalify. The current qualification cost does not take into account the efforts on further promoting the weld quality of the TMS technology, as the previous sections showed there remains room for improvement.

7.2.5 Locations where ventilation may be limited

Another very important consideration for the Navy that should be addressed is the possibility that there are many locations on Navy vessels where welding and/or welding repair work is conducted (such as boiler rooms) that can’t provide proper or easy ventilation. In these cases, welders could use self-contained personal protection, but this still does not address the

elimination of the hexavalent chromium present in the welding fumes that would accumulate and remain in the area after completion of the welding. In such cases, OSHA regulations could potentially disallow welding. Therefore, the use of TMS shielding gas may be the only possible solution.

7.3 Estimated overall economic impact

This section summarizes selected conclusions from NSRP (National Ship Building Research Program) Report #0463, published in 1996 [41]. The report was prepared by the Navy Joining Center and a Navy/Industry task group that focuses on shipyard workers.

7.3.1 Air sampling

It was estimated that an increase of approximately 1,200 monitoring samples per year would be required by the new standard. With a sampling rate of 2/day, the worker-days/year comes to 600, or 4,800 worker-hours/year. A contract labor rate for a technician at $50/hour was used for the 1996 report; for the purposes of this report, an estimated $60/hour rate was used. Using the $60/hour rate × 4,800 worker-hours/year resulted in an estimated cost of $288,000/year for air sampling. As the report pointed out, the actual number of samples needed would be operation and site specific.

7.3.2 Cost of compliance

The task group that participated in this study estimated the number of workers in 17 Navy facilities, 5 Navy contractors, and 6 small marine businesses that would be potentially exposed to hexavalent chromium levels above 5.0 $\mu g/m^3$ at 3,200. This number was not all-inclusive, but represents a large portion of affected Navy facilities and a portion of the shipbuilding industry.

The costs of compliance include administrative costs (such as training, medical surveillance, hygiene facilities, and enforcement of regulated areas); engineering control costs (such as equipment procurement, installation, and maintenance); clothing and personal protection equipment costs, and productivity costs (such as increased set-up time and reduced efficiency, schedule delays, and restricted access areas). The total annual costs were estimated at $17,000,000, and the total one-time costs were estimated at $5,000,000.

The report also concluded that the productivity impact could be as high as 2 hours of lost productivity/day, which would drive these estimated costs even higher. It was also reported that a DOD computer model maintained by the Human Systems Center at Brooks Air Force Base, Texas, used algorithms that estimated hexavalent chromium compliance could run well into the trillions of dollars.

8.0 IMPLEMENTATION ISSUES

8.1 HEALTH AND SAFETY ISSUES

8.1.1 SAFE HANDLING OF TMS

One potential concern in implementation is the safe handling of TMS. Tetramethylsilane (TMS) is a flammable and volatile liquid. High concentration of TMS vapor may cause flash fires or explosions in oxidizing environments. Exposure to TMS may cause skin, eye, and respiratory tract irritation, although the toxicological properties of TMS have not been fully investigated. The MSDS (Appendix G) suggests that workers should avoid inhalation of TMS. There is no standard or published document for handling welding with TMS shielding gas since it is still under development. Nevertheless, there has been no incident of fire or explosion involved in welding with TMS shielding gas to date.

We carried out a calculation of TMS concentration in a typical room in a scenario in which all TMS leaked into a room without decomposition. Vapor pressure (V_p) of TMS was calculated using the Antoine equation,

where A, B, C were 3.97703, 1047.242, -36.057 [39], respectively. Temperature was set to 273 K because the TMS was in an ice bath. Accordingly, V_p was 271 mmHg. The ideal gas law was used to calculate the concentration of TMS in saturated carrier gas,

where pressure (P) is equal to 271/760=0.356 atm; gas constant (R) is equal to 82.0575 atm·cm^3/(K·mol); temperature (T) is equal to 273 K. Accordingly,

Consider the worst case scenario, in which all the TMS has leaked into the air without forming silica: Welding to join two test plates takes a maximum of about 3 min. According to the standard operation procedure (Appendix B) in field demonstration, the TMS flow would be stopped between two welding events while the welder replaced the plates and supplies. For a room of 9 by 9 by 3 m and a pre-set carrier gas flow rate of 1.08 Lpm, the TMS concentration in the tent/room would be

The value is orders of magnitude lower than the TMS lower flammable limit/lower explosion limit (LFL/LEL) of 1%. It should be noted this calculation is based on the worst case scenario, which is unlikely to occur. A ventilation system is recommended in the field to reduce accumulated TMS concentration, other gases and welding metal emissions.

8.1.2 TOXICOLOGICAL ISSUES WITH TMS

Several members of the ESTCP Review Board expressed concern about possible long term effects of amorphous silica coated particles in the pulmonary and gastric system. The team recommends further toxicological studies beyond the E. coli testing already done and discussed in Section 6.1.5. Informal discussions with the Naval Medical Research Unit Dayton (NAMRU-D) recommend the following preliminary assessment before proceeding with full implementation:

- Genotoxicity - The Ames test for mutagenicity evaluates the potential carcinogenicity of TMS
- Dissolution Assessment and Cytotoxicity – Fume particles (collected on filters) from TMS welding and conventional filler material in current use are dissolved in artificial lung and stomach fluids and artificial saliva to evaluate cellular toxicity.
- Dermal irritancy - Commercially available models of the human epidermis mimic the biochemical and physiological properties of the upper parts of the human skin.

8.2 LOW WELD QUALITY

Despite the small number of weld tests in the mechanical quality test, the result suggests there is room for improving TMS technology to achieve higher weld quality. The weld quality of both baseline and TMS technology were lower than the minimum required by the standard for uniform metals, indicating problems could be partially due to welder issues.

Future work on further promoting the applicability of the TMS technology includes the following: (1) An in-depth experimental and modeling study of the welding process (heating, metal transfer, pool cooling, etc.) while welding with TMS technology. (2) Conducting a more comprehensive mechanical quality test, in terms of more welds and welders involved.

8.3 IMPLEMENTATION AND TECHNOLOGY TRANSFER

Once the optimization and improvement of the TMS technology is finalized, the technology transfer process can begin. Several shielding gas companies (Airgas, Praxair, Air

Liquide) are willing to adopt any new and demonstrated shielding gas recipe, as long as the technology has a viable market. However, due to the fact that this project was unexpectedly terminated before the optimization and improvement could be achieved, the technology transfer will take a different path.

The University of Florida is pursuing other applications for the TMS technology including using TMS as a catalyst to control mercury in fly ash generated during incineration processes. Understanding the behavior of TMS in these systems may promote better understanding of how it behaves during welding operations and will increase the knowledge of how TMS can be handled safely in industrial operations.

8.3.1 STAKEHOLDERS

The primary stakeholders for this technology are people working in facilities conducting welding operations where welding emissions from hexavalent chromium, manganese, nickel, copper and other occupational stressors cannot be eliminated using filler material substitution and worker isolation. Other stakeholders include people working in facilities where ultra fine particle air pollution control cannot be employed. These are heavy industrial facilities typically found in Navy shipyards, Army tank repair operations, and a few other smaller operations throughout DoD. An additional industrial subset of workers is stainless steel welders who work on high pressure pipes and ammunition demolition equipment found at TEAD. These groups have strict standard operating procedures (SOPs), such as Uniform Industrial Process Instructions (UIPI) at shipyards. SOPs must be developed and vetted before introducing this technology into industrial operations.

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APPENDICES

Appendix A: Points of Contact

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
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Gene Franke	Naval Surface Warfare Center/ Carderock Division 9500 MacArthur Blvd West Bethesda, MS 20817	(301) 227-5571 gene.franke@navy.mil	Weld Quality Engineer
Jun Wang	University of Florida 406 Black Hall Gainesville, FL 32611	j.wang@ufl.edu (352) 870-0024	Doctoral Candidate Air Quality
Brent Hunt	Tooele Army Depot 1 Tooele Army Depot Tooele, UT 84074	(435) 833-5045 brent.hunt1@us.army.mil	TEAD Site Co-ordinator

Appendix B: SOP for demonstration at TEAD

1 Personnel Responsibility
2 Handling of TMS Feed System
3 Handling of TMS
4 Baseline Welding Procedure
5 Modified Welding Procedure with TMS Feed

Prepared by Jun Wang Date: 07/11/2011
Reviewed by Chang-Yu Wu Date: 07/11/2011
Submitted by Kathleen Paulson

1 Personnel Responsibility

1.1Welder

The welder is only responsible for performing the welding practice. The welder should get familiar with the modified welding gun and the chemicals involved in the demonstration plan, but the welder will not handle TMS and its feed system. The only thing that the welder will perform beyond regular welding practice is to operate the quick switch near welding nozzle following procedures in Section 5.1.f. and 5.2.a. in the SOP.

1.2 UF personnel

UF personnel will be in charge of preparing TMS feed system, leak and pressure test on-site. UF personnel will handle the chemicals before and after welding. UF personnel will act as the welder's helper to assist performing the modified welding procedure, i.e., operating the mass flow controller and carrier gas tank. UF personnel will observe any unusual phenomena during welding, if any, and advise the responding action. A brief introduction on safety and health of chemicals will be provided by UF personnel, and distribute to the welder at the beginning of demonstration.

2 Handling of TMS feed System

In welding operation with tetramethylsilane (TMS) as shielding gas, a TMS feed system is used to prepare TMS concentration in the desired level (Figure 1). All the male connections in the TMS feed system are either quick connect fittings or Swagelock fittings. UF will prepare and ship the TMS feed system to TEAD.

2.1 Assembling the TMS feed system

a. Connect the modified welding gun to the welding machine following the standard procedure in the welding machine manual. Trigger the welding gun to make sure wire comes out from the welding nozzle.

b. Connect the outlet of Teflon impinger to the welding nozzle through Teflon tubing mounted with a quick switch. The outlet of the Teflon impinger is labeled with 'Outlet'.

c. Connect the inlet of Teflon impinger to the mass flow controller through Teflon tubing. The inlet of the Teflon impinger is labeled with 'Inlet'.

d. Connect the mass flow controller to the carrier gas tank through Teflon tubing.

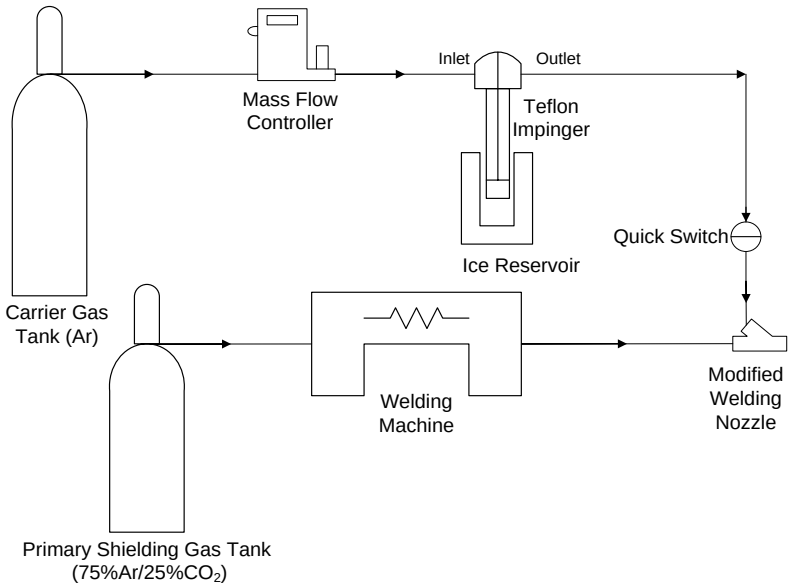

Figure 1 Welding System with TMS feed

2.2 Disassembling the TMS feed system

Disassembling is the reverse order of assembling the TMS feed system.

2.3 Leak test of the TMS feed system

Leak test should be performed at the beginning of the day by UF personnel before TMS refill. It is planned to have one TMS refill per day, unless there is unexpected work load, e.g. more samples needed than planned. Bubble emission test method (ASTM E515-05) is used in the leaking test. Below is quoted from the statement in ASTM E515-05:

"9 Liquid Application Technique

9.1 Application—This technique is applicable to any test specimen on which a pressure differential can be created across the area to be examined. An example of this technique is the application of leak-test solutions to pressurized gas-line joints. It is most useful on piping systems, pressure vessels, tanks, spheres, pumps, or other large apparatus on which the immersion techniques are impractical.

9.2 Location of Bubble Test Fluid—Apply the test liquid to the low-pressure side of the area to be examined and then examine the area for bubbles in the fluid. Take care in applying the fluid to prevent formation of bubbles. Flow the solution to the test area. Joints must be completely coated. The pressure differential should be created before the fluid is applied, to prevent clogging of small leaks.

9.3 Type of Bubble Test Fluid—A solution of commercial leak-testing fluids may be used. The use of soap buds or household detergents and water is not considered a satisfactory

leak-test fluid for a bubble test, because of lack of sensitivity due to masking by foam. The fluid should be capable of being applied free of bubbles so that a bubble appears only at a leak. The fluid selected should not bubble except in response to a leakage."

The following procedure is set up based on the standard procedure stated in ASTM E515-05.

a. Turn off the quick switch at nozzle, open the carrier gas cylinder and gradually adjust the regulator pressure to 30 psi. Let the carrier gas fill the system to create pressure differential.
b. Apply Leak-Tek bubble solution gently to all joints in the system.
c. If bubbles are visually detected, tighten the affected connections until no more bubbles are observed.
d. Shut off the carrier gas tank. Wipe off the residual Leak-Tek bubble solution from connection surface.
e. Record the number of turns made on screw cap of the Teflon impinger, and use a marker to mark down the location.

2.4 Pressure test of the TMS feed system

The pressure rating of all parts in the TMS feed system is above 75 psi. The leak test also serves as the pressure test to ensure the system can hold 30 psi of carrier gas.

3 Handling of TMS

TMS is used in the demonstration to deliver in-situ generated silicon dioxide. The safety information of TMS can be found in the health and safety plan and MSDS.

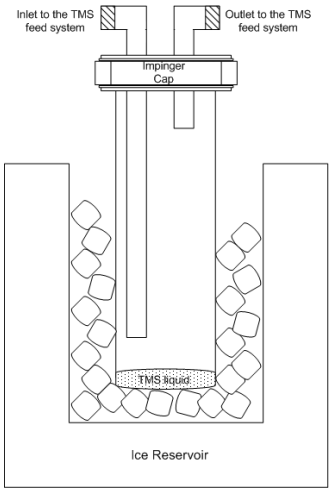

Figure 2 Teflon impinger in an ice reservoir

3.1 Handling of TMS: pre-welding

This process will be conducted in a fireproof cabinet located at the same building where welding practice will be performed (Building 539), and it will be conducted by UF personnel.

a. Disconnect the inlet and outlet of the Teflon impinger from TMS feed system as shown in Figure 2. Transport the Teflon impinger enclosed in a cooler to the fireproof cabinet.

b. Retrieve the stock TMS bottle from the fireproof cabinet. Peel off the Teflon sealant tape on the cap of the TMS bottle and take off the cap.
c. Unscrew the cap of the Teflon impinger. Gently transfer approximately 10 mL TMS liquid to the impinger from the TMS bottle. The liquid should cover the bottom of the impinger.
d. Screw the cap of the impinger following the recorded number of turns and the mark made during leak test (Section 2.3.e.). Seal the inlet and outlet using Teflon sealant tape until the impinger is transported to welding site.
e. Cap the TMS bottle. Use Teflon sealant tape to seal the bottle by applying the tape to the cap. Put the TMS bottle back to fire proof cabinet.
f. Transport the Teflon impinger in a cooler to the welding site. Connect both outlet and inlet of the impinger to the TMS feed system. Put the impinger to ice reservoir if the ambient temperature is above 0 °C.
g. If the TMS liquid cannot cover the bottom of the impinger during welding, stop the welding practice and follow steps b through f to refill it.

3.2 Handling of TMS: post-welding

This process should be conducted in the fireproof cabinet and only be conducted by UF personnel. A waste bottle will be used to collect the unused TMS liquid and stored in the fireproof cabinet. Unused TMS liquid cannot be reused or recycled, and will be returned to the supplier using accepted commercial shipping practices.

a. Check the carrier gas tank and mass flow controller to ensure the flow is completely shut off.
b. Disconnect the outlet and inlet of the Teflon impinger.
c. Transport the Teflon impinger in a cooler to the fireproof cabinet. Unscrew the cap of the Teflon impinger. Gently pour the TMS liquid in the impinger to the waste bottle.
c. Seal the waste bottle with Teflon sealant tape. Put the waste bottle in the fireproof cabinet.

4 Baseline Welding Procedure

Baseline welding will be conducted with 75% argon and 25% carbon dioxide shielding gas. The operation uses the modified welding torch. All procedures are the same as in a normal welding following the procedures in the welding machine manual except that the quick switch should be set in the ‘Off’ position during the entire period of experiment.

5 Modified Welding Procedure with TMS Feed

The modified welding procedure mainly consists of two aspects of control. The primary shielding gas flow is controlled by the welding machine, which is initiated and stopped by the trigger of the welding gun. The TMS saturated carrier gas flow is controlled by a mass flow controller and an On/Off control by a quick switch near the welding nozzle. The flow rate of the mass flow controller is pre-set to the optimal condition of the TMS carrier gas/primary shielding gas proportion. There is no power switch on the mass flow controller. The On/Off of the mass flow controller is done by plug/unplug of the power plug. The start and stop of both flows should

be done simultaneously. During the demonstration, UF researcher will be on site to be the helper. When precise control of simultaneous actions is not feasible, the UF personnel will follow the sequence below, except that the welder will perform Section 5.1.f.

5.1 Start the modified welding procedure

a. Set up the TMS feed system following the steps described in Section 1. Fill the Teflon impinger with TMS liquid following the steps described in Section 3.1.
b. Power on the welding machine. Open the primary shielding gas tank. Adjust the primary shielding gas flow to the work level**.** Then, use the purge function of welding machine to flush and clean the system.
c. Check the mass flow controller and ensure the power plug is unplugged. Check the quick switch near the welding nozzle to ensure it is in 'Off' position.
d. Open the carrier gas tank and gradually increase the pressure to 30 psi.
e. Plug in the power plug of the mass flow controller. Observe the readings on the screen of the mass flow controller until stable.
f. Turn the quick switch near the welding nozzle to 'On' position.
g. Start welding. During welding, the welder's helper (UF personnel) will observe the pressure of carrier gas and readings on the screen of mass flow controller to ensure there is a constant flow of TMS.

5.2 Stop the modified welding procedure

Once the welding is completed, the process described in this section should be immediately performed without delay. There might be diminishing flame coming out from the welding nozzle after welding due to the residue TMS vapor in the pipeline. However, it will extinguish automatically within few seconds when the following steps are performed.

a. Turn the quick switch near the welding nozzle to "Off" position.
b. The welder's helper will unplug the power plug of the mass flow controller and shut the carrier gas tank at the same time.
c. Purge the system with primary shielding gas for 2-3 seconds.
d. Power down the welding machine.
e. Dispose the unused TMS liquid following the steps described in Section 3.2. When the testing is completed, any remaining TMS will be returned to the supplier using accepted commercial shipping practices.

5.3 Cleaning of the welding nozzle

Because of the decomposition of the TMS during welding, there may be amorphous silicon dioxide deposited inside the welding nozzle and tips. Silicon dioxide thus formed is tiny white powder. To ensure the experiments are conducted in a consistent fashion, silicon dioxide powder should be wiped off once observed after welding. The welding tips should be changed if necessary. UF personnel will be responsible for the cleaning process.

Appendix C: Health and Safety Plan for demonstration at TEAD

1 General Fact of TMS
2 General Safety Guideline for TEAD
3 Safety Plan in Handling TMS

Prepared by Jun Wang Date: 11/11/2010
Reviewed by Chang-Yu Wu Date: 11/11/2010

1 General Fact of TMS

Tetramethylsilane (TMS) is a flammable and volatile liquid. High concentration of TMS vapor may cause flash fire or explosion in oxidizing environment. Exposure to TMS may cause skin, eye, and respiratory tract irritation, although the toxicological properties of TMS have not been fully investigated. There is no standard or published document for handling welding with TMS shielding gas since it is still under development. Nevertheless, there has been no incident of fire or explosion involved in the welding with TMS shielding gas to date.

Auto ignition point of TMS is 345 °C (653 °F), and flashing point of TMS is -27 °C (-16.6 °F). The lower flammable limit of TMS is 1% and upper flammable limit is 37.9%. The combustion products of TMS are mainly silicon dioxide and carbon dioxide, with very little carbon monoxide. The vapor density of TMS in the saturated carrier gas is about 0.0014 g cm-3.

2 General Safety Guideline for TEAD

The field test will follow the OSH&E regulations established by TEAD. The TMS technique demonstration requires the welder to be especially careful when handling the TMS. The demonstration personnel will receive a Standard Operating Procedure and safety plan on welding safety issues specific to TMS. Welders are expected to conduct this demonstration as they would on their regular workdays. Personal protective equipment is recommended for the welder to avoid contact with TMS saturated carrier gas. The other occupants at the site will not be exposed to TMS at any time because TMS is contained in a tightly-sealed and closed system. TMS welding operations will release trace amount of carbon monoxide which will be directed to the building ventilation system through the sampling pump.

3 Safety Plan in Handling TMS

The estimated amount of TMS to be used in TEAD demonstration is 200 mL (50 mL per bottle, 4 bottles in total). TMS stock liquid not in use should be stored in a safety cabinet in a separate room. If refrigerated it will be better but it is not mandatory.

Leaking test and pressure test will be performed following the steps described in the Standard Operating Procedure. TMS in use will be contained in a 375 mL Teflon reservoir with Swagelok connection and Teflon coated Tygon tubing. The pressure rating of the Teflon reservoir is 75 psi, and the pressure of carrier gas flow through the reservoir is roughly 30 psi. Teflon, unlike glass, does not break even dropped. As this system is a closed system, it can prevent the risk of TMS leaking into the working environment.

The TMS reservoir should never be heated. TMS stock liquid should be stored either in a separate cabinet or fridge away from the welding area. The unused TMS liquid after the experiment should be collected in a waste bottle.

TMS itself will not explode unless it is mixed with strong oxidants. In the demonstration, the TMS introduced to the welding machine is pre-diluted with inert argon gas to approximately 1:25 (volume ratio) and therefore there is no risk of explosion. The diluted TMS instantly decomposes in the welding arc. Hence, there is no exposure of any worker there to this material.

There is no possibility of TMS liquid to be in contact with static electricity during the demonstration because TMS is contained in a sealed and closed system (Teflon container, tubing, etc.) Class 1 Division 1 electrical equipment is needed only if it has possibility to directly contact TMS.

Appendix D: Lab Test Data (Cr^{6+})

Table D1 Cr^{6+} concentration in the chamber study using premixed mode

Primary shielding gas flow rate (Lpm)	Ratio of TMS carrier gas to primary shielding gas (%)	Cr^{6+} concentration (µg/m^3)
20	0	22.71
20	0	29.32
20	0	31.34
20	0	19.23
20	0	21.78
20	2.1	17.97
20	2.1	23.01
20	2.1	15.92
20	2.1	17.54
20	2.1	15.79
20	2.1	26.29
20	2.1	22.24
20	2.1	17.14
20	2.1	14.84
20	4.2	7.98
20	4.2	30.70
20	4.2	21.18
20	4.2	23.79
20	6.3	26.43
20	6.3	28.19
20	6.3	16.57
20	6.3	18.57
20	6.3	16.38
25	0	39.20
25	0	33.40
25	0	37.30
25	0	28.70
25	0	36.30
25	4.2	18.59
25	4.2	14.23
25	4.2	17.58
25	4.2	16.19
25	4.2	16.67
30	0	44.0
30	0	56.76
30	0	68.42
30	0	59.37
30	0	53.24
30	1.4	20.82
30	1.4	24.12
30	1.4	21.00
30	2.8	17.98

30	2.8	17.92
30	2.8	18.01
30	3.5	17.76
30	3.5	15.91
30	3.5	8.16
30	3.5	6.28
30	3.5	11.42
30	3.5	13.02
30	3.5	14.59
30	3.5	15.79
30	4.2	Below detection limit
30	4.2	Below detection limit
30	4.2	Below detection limit
30	4.2	Below detection limit

Table D2 Cr^{6+} concentration using IDST mode

Primary shielding gas flow rate (Lpm)	Ratio of TMS carrier gas to primary shielding gas (%)	Cr^{6+} concentration (µg/m^3)
20	0	27.13
20	0	29.32
20	0	31.34
20	0	19.23
20	0	21.78
20	0.8	17.34
20	0.8	13.42
20	0.8	15.41
20	0.8	9.36
20	0.8	12.78
20	1.6	6.21
20	1.6	3.32
20	1.6	4.17
20	1.6	10.23
20	1.6	Below detection limit
20	3.2	Below detection limit
20	3.2	Below detection limit
20	3.2	4.71
20	3.2	Below detection limit
20	3.2	Below detection limit
25	0	39.20
25	0	33.40
25	0	37.30
25	0	28.70
25	0	36.30
25	0.6	19.65
25	0.6	22.89
25	0.6	31.13

25	0.6	18.75
25	0.6	22.14
25	1.3	13.87
25	1.3	19.23
25	1.3	16.57
25	1.3	13.21
25	1.3	9.89
25	2.6	6.75
25	2.6	11.32
25	2.6	7.81
25	2.6	9.30
25	2.6	9.21
25	5.1	Below detection limit
25	5.1	Below detection limit
25	5.1	Below detection limit
25	5.1	Below detection limit
25	5.1	Below detection limit
30	0	44
30	0	56.76
30	0	68.42
30	0	59.37
30	0	53.24
30	0.5	29.35
30	0.5	27.68
30	0.5	32.51
30	0.5	29.32
30	0.5	42.36
30	1.1	21.56
30	1.1	20.74
30	1.1	39.28
30	1.1	17.65
30	1.1	20.34
30	2.1	8.42
30	2.1	6.78
30	2.1	3.42
30	2.1	9.17
30	2.1	Below detection limit
30	4.3	Below detection limit
30	4.3	Below detection limit
30	4.3	Below detection limit
30	4.3	Below detection limit

Appendix E: Lab Test Data (SMPS)

The tables below list the median, mean, geometric mean, mode, geometric standard deviation for particle size distributions based on number count, diameter, surface, and mass. The number-based particle size distribution was measured by the SMPS, while others are converted using Hatch-Choate Conversion Equation [40] available in the SMPS operating software.

Table E1. SMPS particle size statistics for baseline 20 Lpm shield gas flow rate.

	Number-based size distribution	Diameter-based size distribution	Surface-based size distribution	Mass-based size distribution
Median (nm)	22.5	218.9	333.1	393.1
Mean (nm)	79.9	228.7	329.9	381.6
Geo. mean (nm)	40.7	155.8	293.9	360.2
Mode (nm)	18.1	333.8	429.4	552.3
Geo. st. dev.	2.89	2.86	1.75	1.45
Total conc.	8.14e+05(#/cm³)	65.0(mm/cm³)	4.67e+10(nm²/cm³)	3.08e+03(μg/m³)

Table E2. SMPS particle size statistics for 20 Lpm shield gas flow rate with 1.05% TMS carrier gas.

	Number-based size distribution	Diameter-based size distribution	Surface-based size distribution	Mass-based size distribution
Median (nm)	145.9	290.4	369.1	420.3
Mean (nm)	178.1	293.6	361.4	404.0
Geo. mean (nm)	114.8	247.2	333.9	385.7
Mode (nm)	18.1	514.0	552.3	552.3
Geo. st. dev.	2.85	1.97	1.55	1.39
Total conc.	1.70e+06(#/cm³)	303.4(mm/cm³)	2.80e+11(nm²/cm³)	2.02e+04(μg/m³)

Table E3. SMPS particle size statistics for 20 Lpm shield gas flow rate with 2.1% TMS carrier gas.

	Number-based size distribution	Diameter-based size distribution	Surface-based size distribution	Mass-based size distribution
Median (nm)	233.0	328.4	391.3	433.4
Mean (nm)	245.1	328.1	380.3	416.0
Geo. mean (nm)	192.0	294.3	358.1	400.3
Mode (nm)	289.0	532.8	552.3	552.3
Geo. st. dev.	2.23	1.68	1.46	1.34
Total conc.	1.91e+06(#/cm³)	469.3(mm/cm³)	4.84e+11(nm²/cm³)	3.68e+04(μg/m³)

Table E4. SMPS particle size statistics for 20 Lpm shield gas flow rate with 6.3% TMS carrier gas.

	Number-based size distribution	Diameter-based size distribution	Surface-based size distribution	Mass-based size distribution
Median (nm)	319.2	377.9	421.4	451.8
Mean (nm)	323.8	371.4	407.1	433.9
Geo. mean (nm)	295.9	350.1	391.1	421.9
Mode (nm)	385.4	552.3	552.3	552.3
Geo. st. dev.	1.58	1.44	1.35	1.28
Total conc.	2.28e+06(#/cm³)	739.1(mm/cm³)	8.62e+11(nm²/cm³)	7.02e+04(μg/m³)

Table E5. SMPS particle size statistics for baseline 25 Lpm shield gas flow rate.

	Number-based size distribution	Diameter-based size distribution	Surface-based size distribution	Mass-based size distribution
Median (nm)	33.8	220.3	319.9	384.2
Mean (nm)	98.7	234.1	322.1	374.6
Geo. mean (nm)	52.1	173.3	288.1	352.1
Mode (nm)	17.5	299.6	552.3	552.3
Geo. st. dev.	3.06	2.52	1.7	1.46
Total conc.	7.10e+05(#/cm^3)	70.1(mm/cm^3)	5.16e+10(nm^2/cm^3)	3.32e+03(µg/m^3)

Table E6. SMPS particle size statistics for 25 Lpm shield gas flow rate with 0.84% TMS carrier gas.

	Number particle size	Diameter particle size	Surface particle size	Mass particle size
Median (nm)	132.1	286.6	367.0	417.3
Mean (nm)	165.5	291.2	359.1	401.8
Geo. mean (nm)	97.3	243.0	331.9	383.3
Mode (nm)	18.1	385.4	552.3	552.3
Geo. st. dev.	3.16	2.04	1.55	1.39
Total conc.	1.71e+06(#/cm³)	282.9(mm/cm³)	2.59e+11(nm²/cm³)	1.86e+04(µg/m³)

Table E7. SMPS particle size statistics for 25 Lpm shield gas flow rate with 1.68% TMS carrier gas.

	Number particle size	Diameter particle size	Surface particle size	Mass particle size
Median (nm)	182.1	320.9	388.3	430.1
Mean (nm)	201.7	318.4	376.6	413.6
Geo. mean (nm)	125.9	276.6	353	397.5
Mode (nm)	18.8	429.4	552.3	552.3
Geo. st. dev.	3.12	1.87	1.48	1.35
Total conc.	1.18e+06(#/cm³)	238.9(mm/cm³)	2.39e+11(nm²/cm³)	1.80e+04(µg/m³)

Table E8. SMPS particle size statistics for 25 Lpm shield gas flow rate with 5.04% TMS carrier gas.

	Number particle size	Diameter particle size	Surface particle size	Mass particle size
Median (nm)	266.3	346.6	400.9	438.3
Mean (nm)	274.1	344.2	389.3	421.4
Geo. mean (nm)	226.1	315.8	369.7	407.1
Mode (nm)	333.8	532.8	552.3	552.3
Geo. st. dev.	2.07	1.58	1.41	1.32
Total conc.	1.71e+06(#/cm³)	467.5(mm/cm³)	5.06e+11(nm²/cm³)	3.94e+04(µg/m³)

Table E9. SMPS particle size statistics for baseline 30 Lpm shield gas flow rate.

	Number particle size	Diameter particle size	Surface particle size	Mass particle size
Median (nm)	59.2	211.8	312	383.5
Mean (nm)	108.6	231.6	316.6	372.2
Geo. mean (nm)	60.9	176.9	281.9	348.1
Mode (nm)	17.5	259.5	461.4	552.3
Geo. st. dev.	3.01	2.36	1.71	1.48
Total conc.	5.13e+05(#/cm³)	55.7(mm/cm³)	4.05e+10(nm²/cm³)	2.57e+03(µg/m³)

Table E10. SMPS particle size statistics for 30 Lpm shield gas flow rate with 0.7% TMS carrier gas.

	Number particle size	Diameter particle size	Surface particle size	Mass particle size
Median (nm)	110.3	250	343.8	403.5
Mean (nm)	148.1	262.8	339.4	388.8
Geo. mean (nm)	94	213.4	307.8	367.6
Mode (nm)	18.8	358.7	532.8	552.3
Geo. st. dev.	2.78	2.1	1.63	1.44
Total conc.	5.42e+05(#/cm³)	80.2(mm/cm³)	6.62e+10(nm²/cm³)	4.49e+03(µg/m³)

Table E11. SMPS particle size statistics for 30 Lpm shield gas flow rate with 1.4% TMS carrier gas.

	Number particle size	Diameter particle size	Surface particle size	Mass particle size
Median (nm)	150.7	254.2	329.8	380.4
Mean (nm)	175.2	262.9	325.1	366.9
Geo. mean (nm)	130.6	224.1	298.8	348.8
Mode (nm)	224.7	385.4	514	514
Geo. st. dev.	2.27	1.88	1.57	1.41
Total conc.	6.70e+05(#/cm³)	117.4(mm/cm³)	9.70e+10(nm²/cm³)	6.31e+03(µg/m³)

Table E12. SMPS particle size statistics for 30 Lpm shield gas flow rate with 4.2% TMS carrier gas.

	Number particle size	Diameter particle size	Surface particle size	Mass particle size
Median (nm)	201.1	287.3	349.8	393.8
Mean (nm)	220.3	290.3	342.4	379.1
Geo. mean (nm)	182.5	258.8	319.7	363
Mode (nm)	269	461.4	514	514
Geo. st. dev.	1.93	1.68	1.49	1.37
Total conc.	4.96e+05(#/cm^3)	109.2(mm/cm^3)	9.96e+10(nm^2/cm^3)	6.82e+03(µg/m^3)

Table E13. Raw SMPS particle size distribution data for 20 Lpm shield gas flow rate.

	Baseline	1.05% TMS	2.1% TMS	6.3% TMS
Diameter (nm)	#/cm³	#/cm³	#/cm³	#/cm³
12.6	5.24E+04	2.42E+04	2.56E+03	3.86E+02
13.1	9.51E+04	3.61E+04	2.07E+03	3.60E+02
13.6	1.22E+05	5.00E+04	1.77E+03	3.95E+02
14.1	1.35E+05	5.38E+04	3.64E+03	1.22E+02
14.6	1.73E+05	8.44E+04	6.58E+03	0.00E+00
15.1	2.94E+05	1.22E+05	1.95E+04	0.00E+00
15.7	6.88E+05	2.39E+05	4.57E+04	1.01E+02
16.3	1.65E+06	5.55E+05	1.05E+05	9.55E+01
16.8	2.70E+06	1.06E+06	1.64E+05	2.72E+02
17.5	3.56E+06	1.67E+06	2.17E+05	1.72E+02
18.1	3.74E+06	1.98E+06	2.69E+05	5.76E+02
18.8	3.45E+06	1.92E+06	3.29E+05	5.51E+02
19.5	2.88E+06	1.66E+06	3.79E+05	1.33E+03
20.2	2.36E+06	1.38E+06	4.38E+05	1.10E+03
20.9	1.89E+06	1.17E+06	4.28E+05	2.47E+03
21.7	1.54E+06	1.01E+06	4.14E+05	1.75E+03
22.5	1.31E+06	9.13E+05	3.83E+05	2.38E+03
23.3	1.14E+06	8.35E+05	3.32E+05	2.30E+03
24.1	9.82E+05	7.51E+05	3.12E+05	2.51E+03
25.0	8.61E+05	6.77E+05	3.01E+05	2.00E+03
25.9	7.41E+05	6.03E+05	2.70E+05	3.19E+03
26.9	6.18E+05	5.44E+05	2.56E+05	2.36E+03
27.9	5.16E+05	4.92E+05	2.39E+05	3.14E+03
28.9	4.51E+05	4.66E+05	2.26E+05	4.42E+03
30.0	3.83E+05	4.44E+05	2.18E+05	4.28E+03
31.1	3.40E+05	4.33E+05	2.13E+05	4.70E+03
32.2	3.08E+05	4.34E+05	2.16E+05	6.82E+03
33.4	2.74E+05	4.32E+05	2.16E+05	7.91E+03
34.6	2.56E+05	4.63E+05	2.24E+05	8.68E+03
35.9	2.39E+05	4.83E+05	2.34E+05	1.09E+04
37.2	2.25E+05	5.16E+05	2.56E+05	1.41E+04
38.5	2.15E+05	5.61E+05	2.82E+05	1.42E+04
40.0	2.03E+05	5.92E+05	3.06E+05	1.71E+04
41.4	2.02E+05	6.17E+05	3.28E+05	2.07E+04
42.9	1.98E+05	6.51E+05	3.53E+05	2.55E+04

44.5	1.96E+05	6.73E+05	3.77E+05	2.78E+04
46.1	1.91E+05	6.98E+05	4.17E+05	3.26E+04
47.8	1.88E+05	7.32E+05	4.35E+05	3.92E+04
49.6	1.86E+05	7.71E+05	4.83E+05	4.49E+04
51.4	1.83E+05	7.87E+05	5.03E+05	5.09E+04
53.3	1.84E+05	8.11E+05	5.40E+05	5.78E+04
55.2	1.85E+05	8.35E+05	5.72E+05	6.76E+04
57.3	1.80E+05	8.42E+05	6.03E+05	7.76E+04
59.4	1.76E+05	8.57E+05	6.15E+05	8.63E+04
61.5	1.82E+05	8.53E+05	6.45E+05	1.00E+05
63.8	1.84E+05	8.70E+05	6.67E+05	1.14E+05
66.1	1.86E+05	8.75E+05	6.91E+05	1.29E+05
68.5	1.82E+05	8.91E+05	7.13E+05	1.43E+05
71.0	1.83E+05	9.01E+05	7.36E+05	1.65E+05
73.7	1.86E+05	8.89E+05	7.50E+05	1.82E+05
76.4	1.88E+05	8.94E+05	7.94E+05	2.03E+05
79.1	1.86E+05	8.96E+05	8.09E+05	2.31E+05
82.0	1.90E+05	8.84E+05	8.19E+05	2.54E+05
85.1	1.89E+05	8.93E+05	8.34E+05	2.79E+05
88.2	1.95E+05	9.01E+05	8.46E+05	3.06E+05
91.4	2.01E+05	9.05E+05	8.61E+05	3.34E+05
94.7	2.08E+05	9.19E+05	8.81E+05	3.72E+05
98.2	2.13E+05	9.25E+05	8.94E+05	4.02E+05
101.8	2.19E+05	9.31E+05	9.16E+05	4.52E+05
105.5	2.30E+05	9.60E+05	9.35E+05	4.95E+05
109.4	2.35E+05	9.79E+05	9.75E+05	5.54E+05
113.4	2.45E+05	1.00E+06	1.02E+06	5.98E+05
117.6	2.56E+05	1.02E+06	1.05E+06	6.44E+05
121.9	2.67E+05	1.05E+06	1.10E+06	6.95E+05
126.3	2.78E+05	1.08E+06	1.17E+06	7.59E+05
131.0	2.85E+05	1.11E+06	1.21E+06	8.28E+05
135.8	3.02E+05	1.15E+06	1.28E+06	9.11E+05
140.7	3.08E+05	1.20E+06	1.36E+06	1.00E+06
145.9	3.22E+05	1.25E+06	1.42E+06	1.09E+06
151.2	3.26E+05	1.29E+06	1.51E+06	1.18E+06
156.8	3.38E+05	1.33E+06	1.59E+06	1.32E+06
162.5	3.40E+05	1.38E+06	1.69E+06	1.46E+06
168.5	3.39E+05	1.42E+06	1.78E+06	1.60E+06
174.7	3.47E+05	1.48E+06	1.88E+06	1.79E+06

181.1	3.52E+05	1.52E+06	1.97E+06	1.98E+06
187.7	3.59E+05	1.57E+06	2.06E+06	2.15E+06
194.6	3.57E+05	1.60E+06	2.15E+06	2.33E+06
201.7	3.71E+05	1.64E+06	2.24E+06	2.52E+06
209.1	3.62E+05	1.66E+06	2.33E+06	2.68E+06
216.7	3.59E+05	1.67E+06	2.42E+06	2.88E+06
224.7	3.52E+05	1.67E+06	2.49E+06	3.07E+06
232.9	3.44E+05	1.67E+06	2.55E+06	3.24E+06
241.4	3.39E+05	1.68E+06	2.64E+06	3.44E+06
250.3	3.25E+05	1.68E+06	2.69E+06	3.59E+06
259.5	3.27E+05	1.70E+06	2.73E+06	3.78E+06
269.0	3.12E+05	1.71E+06	2.77E+06	3.95E+06
278.8	3.00E+05	1.71E+06	2.79E+06	4.06E+06
289.0	2.94E+05	1.71E+06	2.82E+06	4.23E+06
299.6	2.81E+05	1.71E+06	2.80E+06	4.35E+06
310.6	2.76E+05	1.68E+06	2.77E+06	4.41E+06
322.0	2.68E+05	1.63E+06	2.76E+06	4.52E+06
333.8	2.64E+05	1.58E+06	2.76E+06	4.62E+06
346.0	2.48E+05	1.53E+06	2.68E+06	4.68E+06
358.7	2.42E+05	1.49E+06	2.63E+06	4.71E+06
371.8	2.34E+05	1.44E+06	2.58E+06	4.76E+06
385.4	2.18E+05	1.38E+06	2.52E+06	4.80E+06
399.5	2.09E+05	1.32E+06	2.46E+06	4.73E+06
414.2	1.95E+05	1.27E+06	2.41E+06	4.72E+06
429.4	1.84E+05	1.23E+06	2.35E+06	4.76E+06
445.1	1.69E+05	1.19E+06	2.30E+06	4.71E+06
461.4	1.56E+05	1.15E+06	2.25E+06	4.67E+06
478.3	1.48E+05	1.10E+06	2.19E+06	4.65E+06
495.8	1.36E+05	1.07E+06	2.13E+06	4.56E+06
514.0	1.27E+05	1.05E+06	2.06E+06	4.52E+06

Table E14. Raw SMPS particle size distribution data for 25 Lpm shield gas flow rate.

	Baseline	0.84% TMS	1.68% TMS	5.04% TMS
Diameter (nm)	#/cm³	#/cm³	#/cm³	#/cm³
12.6	2.21E+04	5.05E+03	3.89E+03	0.00E+00
13.1	5.46E+04	7.75E+03	3.28E+03	0.00E+00
13.6	9.45E+04	9.60E+03	3.51E+03	2.63E+02

14.1	1.25E+05	1.72E+04	7.98E+03	0.00E+00
14.6	1.51E+05	2.46E+04	1.81E+04	1.49E+02
15.1	2.65E+05	6.06E+04	7.08E+04	1.63E+03
15.7	7.01E+05	2.90E+05	3.39E+05	4.52E+03
16.3	1.52E+06	1.06E+06	6.99E+05	2.75E+04
16.8	2.39E+06	2.34E+06	1.17E+06	1.19E+05
17.5	3.01E+06	3.54E+06	1.76E+06	2.66E+05
18.1	2.91E+06	3.80E+06	2.07E+06	3.68E+05
18.8	2.43E+06	3.58E+06	2.11E+06	4.13E+05
19.5	1.81E+06	3.14E+06	1.83E+06	3.90E+05
20.2	1.31E+06	2.66E+06	1.49E+06	3.50E+05
20.9	9.66E+05	2.15E+06	1.16E+06	3.04E+05
21.7	7.47E+05	1.70E+06	8.69E+05	2.72E+05
22.5	6.29E+05	1.33E+06	6.46E+05	2.34E+05
23.3	5.25E+05	1.03E+06	5.12E+05	1.99E+05
24.1	4.50E+05	7.81E+05	3.83E+05	1.74E+05
25.0	3.99E+05	6.14E+05	3.04E+05	1.53E+05
25.9	3.57E+05	5.01E+05	2.44E+05	1.38E+05
26.9	3.35E+05	4.31E+05	2.09E+05	1.15E+05
27.9	3.14E+05	3.76E+05	1.86E+05	1.06E+05
28.9	2.86E+05	3.48E+05	1.62E+05	1.02E+05
30.0	2.64E+05	3.12E+05	1.48E+05	9.70E+04
31.1	2.50E+05	2.90E+05	1.32E+05	8.81E+04
32.2	2.42E+05	2.79E+05	1.30E+05	9.32E+04
33.4	2.28E+05	2.74E+05	1.22E+05	8.94E+04
34.6	2.27E+05	2.74E+05	1.22E+05	9.46E+04
35.9	2.25E+05	2.83E+05	1.27E+05	9.93E+04
37.2	2.30E+05	2.95E+05	1.27E+05	1.04E+05
38.5	2.29E+05	3.11E+05	1.31E+05	1.08E+05
40.0	2.31E+05	3.31E+05	1.35E+05	1.18E+05
41.4	2.28E+05	3.43E+05	1.38E+05	1.30E+05
42.9	2.34E+05	3.55E+05	1.48E+05	1.39E+05
44.5	2.38E+05	3.80E+05	1.60E+05	1.47E+05
46.1	2.37E+05	4.04E+05	1.65E+05	1.58E+05
47.8	2.41E+05	4.26E+05	1.80E+05	1.74E+05
49.6	2.37E+05	4.43E+05	1.93E+05	1.94E+05
51.4	2.35E+05	4.71E+05	2.11E+05	2.03E+05
53.3	2.36E+05	4.81E+05	2.22E+05	2.16E+05
55.2	2.40E+05	4.98E+05	2.36E+05	2.38E+05

57.3	2.47E+05	5.19E+05	2.43E+05	2.55E+05
59.4	2.38E+05	5.43E+05	2.58E+05	2.81E+05
61.5	2.36E+05	5.56E+05	2.72E+05	2.96E+05
63.8	2.34E+05	5.79E+05	2.82E+05	3.07E+05
66.1	2.35E+05	5.94E+05	2.92E+05	3.27E+05
68.5	2.40E+05	6.15E+05	3.11E+05	3.55E+05
71.0	2.39E+05	6.36E+05	3.22E+05	3.67E+05
73.7	2.40E+05	6.57E+05	3.38E+05	3.97E+05
76.4	2.43E+05	6.76E+05	3.47E+05	4.22E+05
79.1	2.50E+05	7.02E+05	3.78E+05	4.40E+05
82.0	2.53E+05	7.13E+05	3.91E+05	4.55E+05
85.1	2.61E+05	7.46E+05	4.15E+05	4.84E+05
88.2	2.71E+05	7.76E+05	4.48E+05	5.05E+05
91.4	2.70E+05	7.86E+05	4.62E+05	5.26E+05
94.7	2.82E+05	8.17E+05	4.86E+05	5.45E+05
98.2	2.85E+05	8.42E+05	5.06E+05	5.83E+05
101.8	2.93E+05	8.79E+05	5.37E+05	6.11E+05
105.5	3.01E+05	9.22E+05	5.63E+05	6.39E+05
109.4	3.10E+05	9.35E+05	5.87E+05	6.84E+05
113.4	3.23E+05	9.78E+05	6.17E+05	7.31E+05
117.6	3.32E+05	1.01E+06	6.46E+05	7.62E+05
121.9	3.49E+05	1.05E+06	6.83E+05	8.14E+05
126.3	3.68E+05	1.10E+06	7.15E+05	8.72E+05
131.0	3.78E+05	1.14E+06	7.35E+05	9.33E+05
135.8	3.80E+05	1.17E+06	7.69E+05	1.00E+06
140.7	3.92E+05	1.21E+06	8.04E+05	1.08E+06
145.9	4.12E+05	1.26E+06	8.63E+05	1.17E+06
151.2	4.18E+05	1.30E+06	8.96E+05	1.26E+06
156.8	4.24E+05	1.35E+06	9.35E+05	1.35E+06
162.5	4.29E+05	1.39E+06	9.86E+05	1.45E+06
168.5	4.32E+05	1.44E+06	1.01E+06	1.55E+06
174.7	4.38E+05	1.46E+06	1.04E+06	1.66E+06
181.1	4.42E+05	1.47E+06	1.07E+06	1.76E+06
187.7	4.44E+05	1.51E+06	1.09E+06	1.85E+06
194.6	4.48E+05	1.53E+06	1.11E+06	1.94E+06
201.7	4.38E+05	1.55E+06	1.15E+06	2.04E+06
209.1	4.34E+05	1.55E+06	1.17E+06	2.14E+06
216.7	4.23E+05	1.56E+06	1.21E+06	2.24E+06
224.7	4.15E+05	1.58E+06	1.24E+06	2.34E+06

232.9	4.07E+05	1.61E+06	1.27E+06	2.46E+06
241.4	4.05E+05	1.60E+06	1.29E+06	2.54E+06
250.3	3.88E+05	1.62E+06	1.30E+06	2.63E+06
259.5	3.71E+05	1.62E+06	1.32E+06	2.68E+06
269.0	3.57E+05	1.64E+06	1.33E+06	2.74E+06
278.8	3.41E+05	1.61E+06	1.33E+06	2.77E+06
289.0	3.32E+05	1.60E+06	1.35E+06	2.79E+06
299.6	3.27E+05	1.55E+06	1.36E+06	2.83E+06
310.6	3.12E+05	1.52E+06	1.34E+06	2.82E+06
322.0	2.92E+05	1.46E+06	1.34E+06	2.84E+06
333.8	2.77E+05	1.45E+06	1.34E+06	2.86E+06
346.0	2.69E+05	1.40E+06	1.32E+06	2.83E+06
358.7	2.56E+05	1.36E+06	1.32E+06	2.82E+06
371.8	2.40E+05	1.35E+06	1.30E+06	2.78E+06
385.4	2.25E+05	1.31E+06	1.27E+06	2.75E+06
399.5	2.09E+05	1.24E+06	1.25E+06	2.70E+06
414.2	2.03E+05	1.20E+06	1.22E+06	2.66E+06
429.4	1.85E+05	1.15E+06	1.19E+06	2.59E+06
445.1	1.74E+05	1.09E+06	1.14E+06	2.51E+06
461.4	1.61E+05	1.05E+06	1.10E+06	2.46E+06
478.3	1.50E+05	9.90E+05	1.05E+06	2.40E+06
495.8	1.42E+05	9.76E+05	1.02E+06	2.35E+06
514.0	1.25E+05	9.30E+05	9.69E+05	2.29E+06

Table E15. Raw SMPS particle size distribution data for 30 Lpm shield gas flow rate.

	Baseline	0.7% TMS	1.4% TMS	4.2% TMS
Diameter (nm)	#/cm³	#/cm³	#/cm³	#/cm³
12.6	6.84E+03	3.18E+03	1.10E+03	1.56E+03
13.1	1.39E+04	4.78E+03	1.18E+03	5.71E+02
13.6	3.09E+04	2.96E+03	1.21E+03	5.27E+02
14.1	4.81E+04	2.73E+03	2.72E+03	7.17E+02
14.6	8.28E+04	2.92E+03	2.95E+03	1.50E+03
15.1	1.81E+05	5.62E+03	3.52E+03	1.93E+03
15.7	5.83E+05	1.14E+04	7.72E+03	2.76E+03
16.3	1.23E+06	5.09E+04	1.87E+04	4.39E+03
16.8	1.58E+06	1.88E+05	3.05E+04	8.03E+03
17.5	1.66E+06	4.49E+05	4.01E+04	1.19E+04

18.1	1.44E+06	6.10E+05	4.68E+04	1.48E+04
18.8	1.18E+06	6.82E+05	4.47E+04	1.48E+04
19.5	9.33E+05	6.56E+05	5.57E+04	1.34E+04
20.2	7.29E+05	6.33E+05	6.81E+04	1.29E+04
20.9	5.84E+05	5.92E+05	8.89E+04	1.38E+04
21.7	4.71E+05	5.20E+05	1.13E+05	1.26E+04
22.5	3.82E+05	4.61E+05	1.29E+05	1.27E+04
23.3	3.30E+05	4.02E+05	1.43E+05	1.00E+04
24.1	2.99E+05	3.66E+05	1.47E+05	9.13E+03
25.0	2.63E+05	3.36E+05	1.46E+05	9.27E+03
25.9	2.50E+05	3.21E+05	1.52E+05	9.97E+03
26.9	2.21E+05	3.10E+05	1.54E+05	1.16E+04
27.9	2.09E+05	2.88E+05	1.64E+05	1.35E+04
28.9	2.02E+05	2.80E+05	1.80E+05	1.62E+04
30.0	1.90E+05	2.57E+05	2.01E+05	1.63E+04
31.1	1.80E+05	2.49E+05	2.23E+05	1.78E+04
32.2	1.80E+05	2.42E+05	2.40E+05	2.37E+04
33.4	1.77E+05	2.37E+05	2.60E+05	2.69E+04
34.6	1.73E+05	2.35E+05	2.84E+05	3.14E+04
35.9	1.71E+05	2.34E+05	2.99E+05	4.00E+04
37.2	1.72E+05	2.34E+05	3.27E+05	4.54E+04
38.5	1.74E+05	2.35E+05	3.45E+05	5.31E+04
40.0	1.72E+05	2.42E+05	3.62E+05	6.03E+04
41.4	1.76E+05	2.38E+05	3.75E+05	7.09E+04
42.9	1.76E+05	2.46E+05	4.04E+05	8.04E+04
44.5	1.77E+05	2.45E+05	4.28E+05	9.02E+04
46.1	1.78E+05	2.50E+05	4.42E+05	1.02E+05
47.8	1.79E+05	2.60E+05	4.67E+05	1.16E+05
49.6	1.82E+05	2.63E+05	4.75E+05	1.29E+05
51.4	1.88E+05	2.67E+05	4.86E+05	1.43E+05
53.3	1.89E+05	2.73E+05	4.94E+05	1.64E+05
55.2	1.91E+05	2.73E+05	4.95E+05	1.72E+05
57.3	1.97E+05	2.73E+05	4.98E+05	1.87E+05
59.4	2.00E+05	2.77E+05	4.95E+05	1.96E+05
61.5	2.06E+05	2.76E+05	4.93E+05	2.06E+05
63.8	2.05E+05	2.84E+05	4.97E+05	2.21E+05
66.1	2.11E+05	2.87E+05	4.89E+05	2.36E+05
68.5	2.19E+05	2.92E+05	4.81E+05	2.49E+05
71.0	2.28E+05	2.99E+05	4.75E+05	2.68E+05

73.7	2.30E+05	2.96E+05	4.76E+05	2.79E+05
76.4	2.37E+05	3.01E+05	4.77E+05	2.99E+05
79.1	2.53E+05	3.04E+05	4.70E+05	3.10E+05
82.0	2.56E+05	3.01E+05	4.50E+05	3.22E+05
85.1	2.64E+05	2.97E+05	4.40E+05	3.38E+05
88.2	2.71E+05	2.97E+05	4.26E+05	3.54E+05
91.4	2.74E+05	3.04E+05	4.16E+05	3.66E+05
94.7	2.80E+05	3.15E+05	4.07E+05	3.72E+05
98.2	2.87E+05	3.19E+05	4.16E+05	3.97E+05
101.8	2.94E+05	3.37E+05	4.28E+05	4.01E+05
105.5	3.01E+05	3.44E+05	4.33E+05	4.24E+05
109.4	3.08E+05	3.71E+05	4.36E+05	4.41E+05
113.4	3.16E+05	3.79E+05	4.46E+05	4.49E+05
117.6	3.23E+05	3.93E+05	4.58E+05	4.51E+05
121.9	3.30E+05	4.17E+05	4.68E+05	4.59E+05
126.3	3.37E+05	4.24E+05	4.86E+05	4.63E+05
131.0	3.42E+05	4.37E+05	5.17E+05	4.64E+05
135.8	3.63E+05	4.50E+05	5.47E+05	4.74E+05
140.7	3.69E+05	4.61E+05	5.83E+05	4.87E+05
145.9	3.73E+05	4.68E+05	6.33E+05	4.97E+05
151.2	3.83E+05	4.69E+05	6.60E+05	5.06E+05
156.8	3.82E+05	4.72E+05	6.90E+05	5.07E+05
162.5	3.86E+05	4.65E+05	7.10E+05	5.31E+05
168.5	3.85E+05	4.73E+05	7.38E+05	5.37E+05
174.7	3.77E+05	4.67E+05	7.50E+05	5.60E+05
181.1	3.77E+05	4.63E+05	7.49E+05	5.84E+05
187.7	3.69E+05	4.60E+05	7.57E+05	5.84E+05
194.6	3.62E+05	4.59E+05	7.61E+05	6.09E+05
201.7	3.54E+05	4.65E+05	7.60E+05	6.25E+05
209.1	3.42E+05	4.55E+05	7.61E+05	6.38E+05
216.7	3.33E+05	4.66E+05	7.71E+05	6.50E+05
224.7	3.31E+05	4.61E+05	7.76E+05	6.63E+05
232.9	3.15E+05	4.62E+05	7.70E+05	6.86E+05
241.4	3.09E+05	4.62E+05	7.71E+05	6.90E+05
250.3	2.98E+05	4.53E+05	7.48E+05	6.99E+05
259.5	2.90E+05	4.45E+05	7.32E+05	7.00E+05
269.0	2.72E+05	4.23E+05	7.08E+05	7.06E+05
278.8	2.58E+05	4.16E+05	6.82E+05	6.98E+05
289.0	2.54E+05	3.99E+05	6.59E+05	6.92E+05

299.6	2.44E+05	3.97E+05	6.50E+05	6.79E+05
310.6	2.35E+05	3.77E+05	6.19E+05	6.72E+05
322.0	2.19E+05	3.70E+05	5.93E+05	6.58E+05
333.8	2.06E+05	3.53E+05	5.80E+05	6.41E+05
346.0	1.94E+05	3.49E+05	5.58E+05	6.04E+05
358.7	1.83E+05	3.39E+05	5.41E+05	5.83E+05
371.8	1.72E+05	3.17E+05	5.27E+05	5.69E+05
385.4	1.71E+05	3.08E+05	5.11E+05	5.41E+05
399.5	1.54E+05	2.94E+05	4.84E+05	5.26E+05
414.2	1.43E+05	2.85E+05	4.56E+05	5.02E+05
429.4	1.42E+05	2.67E+05	4.27E+05	4.90E+05
445.1	1.35E+05	2.49E+05	4.02E+05	4.80E+05
461.4	1.28E+05	2.40E+05	3.82E+05	4.64E+05
478.3	1.14E+05	2.34E+05	3.56E+05	4.44E+05
495.8	1.09E+05	2.13E+05	3.44E+05	4.16E+05
514.0	9.90E+04	2.02E+05	3.31E+05	4.09E+05

Appendix F: Field Test Data (Low-flow sampling)

Table G1 Field test data for Cr^{6+}

Sample ID	Date of Sample Collection	Sample Event	Results		
			Air Volume (L)	Mass of Chromium VI (µg)	Chromium VI Exposure (mg/m^3)
BGEICB048	11-Aug-11	Blank	0	<0.02	-
BGEICN049	11-Aug-11	GMAW Baseline UF	550.5	0.024	0.000044
BGEICF050	11-Aug-11	GMAW Baseline UF	526	<0.02	<0.000038
BGEELN051A-M	11-Aug-11	GMAW Baseline UF	34.24	<0.02	<0.00058
BGEELN052A-M	11-Aug-11	GMAW Baseline UF	51.36	<0.02	<0.00039
BGEELN053A-M	11-Aug-11	GMAW Baseline UF	25.68	<0.02	<0.00078
BGEELN054A-M	11-Aug-11	GMAW Baseline UF	34.24	<0.02	<0.00058
BGEGRN055	11-Aug-11	GMAW Baseline UF	24	<0.02	<0.00083
BGNICN060	11-Aug-11	GMAW Baseline UF	387	<0.02	<0.000052
BGNICF061	11-Aug-11	GMAW Baseline UF	375.5	<0.02	<0.000053
BGNELN062A-M	11-Aug-11	GMAW Baseline UF	25.68	<0.02	<0.00078
BGNELN063A-M	11-Aug-11	GMAW Baseline UF	25.68	<0.02	<0.00078
BGNELN064A-M	11-Aug-11	GMAW Baseline UF	25.68	<0.02	<0.00078
BGNELN065A-M	11-Aug-11	GMAW Baseline UF	25.68	<0.02	<0.00078
BGNGRN066	11-Aug-11	GMAW Baseline UF	21.6	<0.02	<0.00093
FGNICN177	23-Aug-11	GMAW UF	369.9	0.038	0.0001
FGNICF178	23-Aug-11	GMAW UF	368.8	<0.02	<0.000054
FGNCB179	23-Aug-11	Blank	0	<0.02	-
FGNGRB183	23-Aug-11	Blank	0	<0.02	-
FGNLCN184	23-Aug-11	GMAW UF	-	<0.02	-
FGNGRN185	23-Aug-11	GMAW UF	153.5	0.25	0.0016

FGNELN186A-M	23-Aug-11	GMAW UF	1064.8	0.494	0.000464
FGNICN189	23-Aug-11	GMAW UF	543.4	0.13	0.00025
FGNICF190	23-Aug-11	GMAW UF	536.1	0.027	0.00005
FGNLC193	23-Aug-11	GMAW UF	-	<0.02	-
FGNGRN196	23-Aug-11	GMAW UF	97.6	0.25	0.0026
FGNELN197A-M	23-Aug-11	GMAW UF	897.6	0.388	0.000432
FGNGRN198	23-Aug-11	GMAW UF	115.8	0.43	0.0037
FGNELN199A-M	23-Aug-11	GMAW UF	783.2	0.421	0.000538
FGNICN200	24-Aug-11	GMAW UF	182.1	0.03	0.00016
FGNICF201	24-Aug-11	GMAW UF	177.7	<0.02	<0.00011
FGNCB202	24-Aug-11	Blank	0	<0.02	-
FGNGRB206	24-Aug-11	Blank	0	<0.02	-
FGNLCN207	24-Aug-11	GMAW UF	-	<0.02	-
FGNGRN210	24-Aug-11	GMAW UF	104.1	0.48	0.0046
FGNELN211A-M	24-Aug-11	GMAW UF	704	0.9	0.00128
BGNICN212	24-Aug-11	GMAW Baseline UF	626.9	0.087	0.00014
BGNICF213	24-Aug-11	GMAW Baseline UF	618.4	<0.02	<0.000032
BGNLCN216	24-Aug-11	GMAW Baseline UF	-	<0.02	-
BGNELN217A-M	24-Aug-11	GMAW Baseline UF	1399.2	1.27	0.000905
BGNGRN218	24-Aug-11	GMAW Baseline UF	206.9	0.44	0.0021
BGNELN221A-M	24-Aug-11	GMAW Baseline UF	968	0.947	0.000978
BGNGRN222	24-Aug-11	GMAW Baseline UF	144.4	<0.02	<0.00014
BGNICN223	25-Aug-11	GMAW Baseline UF	262.6	0.024	0.000091
BGNICF224	25-Aug-11	GMAW Baseline UF	262	<0.02	<0.000076
BGNLCN229	25-Aug-11	GMAW Baseline UF	-	<0.02	-
BGNELN231A-M	25-Aug-11	GMAW Baseline UF	369.6	2.24	0.00605
BGNGRN230	25-Aug-11	GMAW Baseline UF	54.6	1.1	0.02
PVCBL233	25-Aug-11	Blank	0	<0.02	-
ELPI234	25-Aug-11	Blank	0	<0.02	-

BGNELN236A-M	25-Aug-11	GMAW Baseline UF	308	0.964	0.00313

Table G2 Field test data for metals (Part I)

Sample ID	Date of Sample Collection	Sample Event	Results															
			Arsenic		Cadmium		Chromium		Cobalt		Copper		Iron		Lead		Manganese	
			(µg)	(mg/m3)	(µg)	(mg/m3)	(µg)	(mg/m3)	(µg)	(mg/m3)	(µg)	(mg/m3)	(µg)	(mg/m3)	(µg)	(mg/m3)	(µg)	(mg/m3)
BGEIMB045	11-Aug-11	GMAW Baseline UF	<0.2*	-	<0.2*	-	0.460	-	<0.2*	-	<0.2*	-	<1*	-	<0.2*	-	<0.2*	-
BGEIMN046	11-Aug-11	GMAW Baseline UF	<0.2	<0.0003	<0.2	<0.0003	2.93	0.00390	<0.2	<0.0003	<0.2	<0.0003	13.6	0.0181	<0.2	<0.0003	2.05	0.00273
BGEIMF047	11-Aug-11	GMAW Baseline UF	<0.2	<0.0003	<0.2	<0.0003	1.17	0.00154	<0.2	<0.0003	<0.2	<0.0003	2.73	0.00360	<0.2	<0.0003	0.610	0.000804
BGEELN051A-M	11-Aug-11	GMAW Baseline UF	<0.2	<0.0058	<0.2	<0.0058	1.36	0.0397	<0.2	<0.0058	<0.2	<0.0058	1.53	0.0447	<0.2	<0.0058	<0.2	<0.0058
BGEELN052A-M	11-Aug-11	GMAW Baseline UF	<0.2	<0.0039	<0.2	<0.0039	1.26	0.0245	<0.2	<0.0039	0.27	0.0053	3.84	0.0748	<0.2	<0.0039	<0.2	<0.0039
BGEELN053A-M	11-Aug-11	GMAW Baseline UF	<0.2	<0.0078	<0.2	<0.0078	1.63	0.0635	<0.2	<0.0078	0.22	0.0086	1.58	0.0615	<0.2	<0.0078	0.220	0.00857
BGEELN054A-M	11-Aug-11	GMAW Baseline UF	<0.2	<0.0058	<0.2	<0.0058	1.35	0.0394	<0.2	<0.0058	<0.2	<0.0058	1.54	0.0450	<0.2	<0.0058	0.260	0.00759
BGEGRN055	11-Aug-11	GMAW Baseline UF	<0.2	<0.0083	<0.2	<0.0083	0.500	0.0208	<0.2	<0.0083	<0.2	<0.0083	1.24	0.0517	<0.2	<0.0083	0.410	0.0171
BGNIMN058	11-Aug-11	GMAW Baseline UF	<0.2	<0.0004	<0.2	<0.0004	1.45	0.00263	<0.2	<0.0004	<0.2	<0.0004	6.24	0.0113	<0.2	<0.0004	1.06	0.00192
BGNIMF059	11-Aug-11	GMAW Baseline UF	<0.2	<0.0004	<0.2	<0.0004	0.780	0.00144	<0.2	<0.0004	<0.2	<0.0004	2.47	0.00457	<0.2	<0.0004	0.400	0.00074
BGNELN062A-M	11-Aug-11	GMAW Baseline UF	<0.2	<0.0078	<0.2	<0.0078	1.57	0.0611	<0.2	<0.0078	0.40	0.016	2.76	0.107	<0.2	<0.0078	0.260	0.0101
BGNELN063A-M	11-Aug-11	GMAW Baseline UF	<0.2	<0.0078	<0.2	<0.0078	1.87	0.0728	<0.2	<0.0078	<0.2	<0.0078	1.30	0.0506	<0.2	<0.0078	<0.2	<0.0078

BGNELN064A-M	11-Aug-11	GMAW Baseline UF	<0.2	<0.0078	<0.2	<0.0078	1.51	0.0588	<0.2	<0.0078	<0.2	<0.0078	1.57	0.0611	<0.2	<0.0078	0.390	0.0152
BGNELN065A-M	11-Aug-11	GMAW Baseline UF	<0.2	<0.0078	<0.2	<0.0078	0.980	0.0382	<0.2	<0.0078	<0.2	<0.0078	<1	<0.0389	<0.2	<0.0078	<0.2	<0.0078
BGNGRN066	11-Aug-11	GMAW Baseline UF	<0.2	<0.0093	<0.2	<0.0093	0.740	0.0343	<0.2	<0.0093	<0.2	<0.0093	1.54	0.0713	<0.2	<0.0093	0.400	0.0185
FGNIMN180	23-Aug-11	GMAW UF	<0.2	<0.0004	<0.2	<0.0004	3.32	0.00645	<0.2	<0.0004	0.45	0.00087	32.9	0.0639	<0.2	<0.0004	4.41	0.00857
FGNIMF181	23-Aug-11	GMAW UF	<0.2	<0.0004	<0.2	<0.0004	1.27	0.00236	<0.2	<0.0004	<0.2	<0.0004	4.80	0.00894	<0.2	<0.0004	1.88	0.00350
FGNIMB182	23-Aug-11	Blank	<0.2*	-	<0.2*	-	0.230*	-	<0.2*	-	<0.2*	-	<1*	-	<0.2*	-	<0.2*	-
FGNGRB183	23-Aug-11	Blank	<0.2*	-	<0.2*	-	0.230*	-	<0.2*	-	<0.2*	-	<1*	-	<0.2*	-	<0.2*	-
FGNGRB185	23-Aug-11	GMAW UF	<0.2	<0.0013	<0.2	<0.0013	10.3	0.0672	<0.2	<0.0013	0.42	0.0027	38.8	0.253	<0.2	<0.0013	23.7	0.155
FGNELN186A	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	1.630	0.001530	<0.2	<0.0002	<0.2	<0.0002	4.56	0.004280	<0.2	<0.0002	3.33	0.00313
FGNELN186B	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	5.910	0.005550	<0.2	<0.0002	0.220	0.000207	17.8	0.016700	<0.2	<0.0002	13.1	0.0123
FGNELN186C	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	7.970	0.007480	<0.2	<0.0002	0.260	0.000244	23.8	0.224000	<0.2	<0.0002	17.6	0.0165
FGNELN186D	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	9.280	0.008720	<0.2	<0.0002	0.280	0.000263	30.7	0.028800	<0.2	<0.0002	19.4	0.0183
FGNELN186E	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	5.380	0.005050	<0.2	<0.0002	<0.2	<0.0002	22.3	0.020900	<0.2	<0.0002	11	0.0103
FGNELN186F	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	4.140	0.003890	<0.2	<0.0002	<0.2	<0.0002	19.6	0.018400	<0.2	<0.0002	8.63	0.0081
FGNELN186G	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	2.250	0.002110	<0.2	<0.0002	<0.2	<0.0002	13.7	0.012900	<0.2	<0.0002	4.88	0.00458
FGNELN186H	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	1.160	0.001090	<0.2	<0.0002	<0.2	<0.0002	3.87	0.003630	<0.2	<0.0002	1.99	0.00187
FGNELN186I	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	1.000	0.000939	<0.2	<0.0002	<0.2	<0.0002	3.93	0.003690	<0.2	<0.0002	1.57	0.00147
FGNELN186J	23-Aug-	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	0.610	0.00057	<0.2	<0.0002	<0.2	<0.0002	2.56	0.00240	<0.2	<0.0002	0.7	0.00066

	11							3						0				
FGNELN186K	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	0.640	0.000601	<0.2	<0.0002	<0.2	<0.0002	2.67	0.002510	<0.2	<0.0002	0.7	0.00066
FGNELN186L	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	0.520	0.000488	<0.2	<0.0002	<0.2	<0.0002	1.56	0.001470	<0.2	<0.0002	0.44	0.00041
FGNELN186M	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	0.370	0.000347	<0.2	<0.0002	0.440	0.000413	<1	<0.0009	<0.2	<0.0002	<0.2	<0.0002
FGNIMN191	23-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	6.76	0.00913	<0.2	<0.0003	0.27	0.00036	31.3	0.0423	<0.2	<0.0003	6.91	0.00933
FGNIMF192	23-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	2.49	0.00315	<0.2	<0.0003	<0.2	<0.0003	8.28	0.0105	<0.2	<0.0003	4.06	0.00513
FGNGRN196	23-Aug-11	GMAW UF	<0.2	<0.0020	<0.2	<0.0020	6.70	0.0686	<0.2	<0.0020	0.29	0.0030	19.0	0.194	<0.2	<0.0020	14.2	0.145
FGNELN197A	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	0.93	0.00104	<0.2	<0.0002	<0.2	<0.0002	2.6	0.00287	<0.2	<0.0002	1.61	0.00179
FGNELN197B	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	5.10	0.00568	<0.2	<0.0002	0.21	0.0002	12.4	0.0138	<0.2	<0.0002	10.4	0.0115
FGNELN197C	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	13.80	0.0154	<0.2	<0.0002	0.4	0.0004	33.1	0.0369	<0.2	<0.0002	28.4	0.0316
FGNELN197D	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	7.22	0.00804	<0.2	<0.0002	0.21	0.0002	20.3	0.0226	<0.2	<0.0002	15.1	0.0168
FGNELN197E	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	7.36	0.0082	<0.2	<0.0002	0.21	0.0002	24.7	0.0275	<0.2	<0.0002	15.7	0.0175
FGNELN197F	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	2.81	0.00313	<0.2	<0.0002	<0.2	<0.0002	11.0	0.0123	<0.2	<0.0002	6.54	0.00729
FGNELN197G	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	1.94	0.00216	<0.2	<0.0002	<0.2	<0.0002	7.2	0.00802	<0.2	<0.0002	4.64	0.00517
FGNELN197H	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	1.05	0.00117	<0.2	<0.0002	<0.2	<0.0002	4.9	0.00549	<0.2	<0.0002	1.93	0.00215
FGNELN197I	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	0.85	0.00095	<0.2	<0.0002	<0.2	<0.0002	3.2	0.00354	<0.2	<0.0002	1.46	0.00163
FGNELN197J	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	0.56	0.00062	<0.2	<0.0002	<0.2	<0.0002	2.9	0.00325	<0.2	<0.0002	0.72	0.0008
FGNELN197K	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	0.32	0.00036	<0.2	<0.0002	<0.2	<0.0002	1.5	0.00166	<0.2	<0.0002	0.25	0.00028

FGNELN197L	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	0.49	0.00055	<0.2	<0.0002	<0.2	<0.0002	2.0	0.00227	<0.2	<0.0002	0.42	0.00047
FGNELN197M	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	0.38	0.00042	<0.2	<0.0002	<0.2	<0.0002	1.3	0.00139	<0.2	<0.0002	<0.2	<0.0002
FGNGRN198	23-Aug-11	GMAW UF	<0.2	<0.0017	<0.2	<0.0017	7.74	0.0668	<0.2	<0.0017	0.33	0.0028	26.4	0.228	<0.2	<0.0017	21.8	0.188
FGNELN199A	23-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	0.76	0.00097	<0.2	<0.0003	<0.2	<0.0003	2.02	0.00258	<0.2	<0.0003	1.24	0.00158
FGNELN199B	23-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	10.7	0.0136	<0.2	<0.0003	0.41	0.00052	32	0.0409	<0.2	<0.0003	28.3	0.0361
FGNELN199C	23-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	2.27	0.0029	<0.2	<0.0003	<0.2	<0.0003	6.58	0.0084	<0.2	<0.0003	5.75	0.00734
FGNELN199D	23-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	2.02	0.00258	<0.2	<0.0003	<0.2	<0.0003	9.9	0.0126	<0.2	<0.0003	6.67	0.00852
FGNELN199E	23-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	1.78	0.00227	<0.2	<0.0003	<0.2	<0.0003	6.55	0.00836	<0.2	<0.0003	4.33	0.00553
FGNELN199F	23-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	2.7	0.00345	<0.2	<0.0003	<0.2	<0.0003	11.8	0.0151	<0.2	<0.0003	7.16	0.00914
FGNELN199G	23-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	1.62	0.00207	<0.2	<0.0003	<0.2	<0.0003	6.3	0.00804	<0.2	<0.0003	4.18	0.00534
FGNELN199H	23-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	0.54	0.00069	<0.2	<0.0003	<0.2	<0.0003	2.4	0.00306	<0.2	<0.0003	0.88	0.00112
FGNELN199I	23-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	0.78	0.001	<0.2	<0.0003	<0.2	<0.0003	3.29	0.0042	<0.2	<0.0003	1.42	0.00181
FGNELN199J	23-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	0.43	0.00055	<0.2	<0.0003	<0.2	<0.0003	1.6	0.00204	<0.2	<0.0003	0.37	0.00047
FGNELN199K	23-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	0.56	0.00072	<0.2	<0.0003	<0.2	<0.0003	2.55	0.00326	<0.2	<0.0003	0.91	0.00116
FGNELN199L	23-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	0.4	0.00051	<0.2	<0.0003	<0.2	<0.0003	1.68	0.00215	<0.2	<0.0003	0.47	0.0006
FGNELN199M	23-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	0.42	0.00054	<0.2	<0.0003	0.3	0.00038	1.28	0.00163	<0.2	<0.0003	<0.2	<0.0003
FGNIMN203	24-Aug-11	GMAW UF	<0.2	<0.0008	<0.2	<0.0008	1.02	0.00419	<0.2	<0.0008	<0.2	<0.0008	10.7	0.0440	<0.2	<0.0008	1.03	0.00424
FGNIMF204	24-Aug-	GMAW UF	<0.2	<0.0008	<0.2	<0.0008	0.580	0.00218	<0.2	<0.0008	<0.2	<0.0008	3.87	0.0146	<0.2	<0.0008	0.61	0.00229

	11																0	
FGNIMB205	24-Aug-11	Blank	<0.2*	-	<0.2*	-	0.270*	-	<0.2*	-	<0.2*	-	<1*	-	<0.2*	-	<0.2*	-
FGNGRB206	24-Aug-11	Blank	<0.2*	-	<0.2*	-	0.220*	-	<0.2*	-	<0.2*	-	4.20*	-	<0.2*	-	<0.2*	-
FGNGRN210	24-Aug-11	GMAW UF	<0.2	<0.0019	<0.2	<0.0019	16.9	0.162	<0.2	<0.0019	0.65	0.0062	60.8	0.584	<0.2	<0.0019	41.9	0.402
FGNELN211A	24-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	1.95	0.00277	<0.2	<0.0003	<0.2	<0.0003	6.32	0.00898	<0.2	<0.0003	4.76	0.00676
FGNELN211B	24-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	9.06	0.0129	<0.2	<0.0003	0.4	0.00057	28.7	0.0408	<0.2	<0.0003	23.7	0.0337
FGNELN211C	24-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	2.88	0.00409	<0.2	<0.0003	<0.2	<0.0003	9.93	0.0141	<0.2	<0.0003	7.43	0.0106
FGNELN211D	24-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	7.75	0.011	<0.2	<0.0003	0.29	0.00041	29.5	0.0419	<0.2	<0.0003	20.8	0.0295
FGNELN211E	24-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	6.33	0.00899	<0.2	<0.0003	0.21	0.0003	26.2	0.0372	<0.2	<0.0003	15.4	0.0218
FGNELN211F	24-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	1.92	0.00273	<0.2	<0.0003	<0.2	<0.0003	7.00	0.00994	<0.2	<0.0003	3.62	0.00514
FGNELN211G	24-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	1.81	0.00257	<0.2	<0.0003	<0.2	<0.0003	9.29	0.0132	<0.2	<0.0003	6.21	0.00882
FGNELN211H	24-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	1.27	0.0018	<0.2	<0.0003	<0.2	<0.0003	5.45	0.00774	<0.2	<0.0003	3.18	0.00452
FGNELN211I	24-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	0.96	0.00136	<0.2	<0.0003	<0.2	<0.0003	3.93	0.00558	<0.2	<0.0003	1.84	0.00261
FGNELN211J	24-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	0.58	0.00082	<0.2	<0.0003	<0.2	<0.0003	2.94	0.00418	<0.2	<0.0003	0.9	0.00128
FGNELN211K	24-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	0.65	0.00092	<0.2	<0.0003	<0.2	<0.0003	3.25	0.00462	<0.2	<0.0003	0.75	0.00107
FGNELN211L	24-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	0.38	0.00054	<0.2	<0.0003	<0.2	<0.0003	1.38	0.00196	<0.2	<0.0003	0.23	0.00033
FGNELN211M	24-Aug-11	GMAW UF	<0.2	<0.0003	<0.2	<0.0003	0.3	0.00043	<0.2	<0.0003	<0.2	<0.0003	1.45	0.00206	<0.2	<0.0003	<0.2	<0.0003
BGNIMN214	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	6.42	0.00751	<0.2	<0.0002	0.37	0.00043	39.4	0.0461	<0.2	<0.0002	4.79	0.00560

BGNIMF215	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	0.700	0.000762	<0.2	<0.0002	<0.2	<0.0002	4.93	0.00537	<0.2	<0.0002	0.670	0.00073
BGNELN217A-M	24-Aug-11	GMAW Baseline UF	<0.2	<0.0001	<0.2	<0.0001	32.8	0.0234	<0.2	<0.0001	1.9	0.0013	77.4	0.0553	<0.2	<0.0001	70.2	0.0501
BGNGRN218	24-Aug-11	GMAW Baseline UF	<0.2	<0.0010	<0.2	<0.0010	9.73	0.0470	<0.2	<0.0010	1.2	0.0056	27.8	0.134	<0.2	<0.0010	30.4	0.147
BGNELN221A	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	0.63	0.0007	<0.2	<0.0002	<0.2	<0.0002	1.8	0.00186	<0.2	<0.0002	0.84	0.00087
BGNELN221B	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	4.33	0.0045	<0.2	<0.0002	0.26	0.00027	8.84	0.00913	<0.2	<0.0002	9.05	0.00935
BGNELN221C	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	8.57	0.0089	<0.2	<0.0002	0.49	0.00051	17.4	0.018	<0.2	<0.0002	20.1	0.0208
BGNELN221D	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	10.8	0.0112	<0.2	<0.0002	0.54	0.00056	22.1	0.0229	<0.2	<0.0002	25.7	0.0265
BGNELN221E	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	10.9	0.0113	<0.2	<0.0002	0.51	0.00053	26.9	0.0278	<0.2	<0.0002	27.9	0.0288
BGNELN221F	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	4.87	0.0050	<0.2	<0.0002	0.26	0.00027	12.4	0.0128	<0.2	<0.0002	12.6	0.013
BGNELN221G	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	3.04	0.0031	<0.2	<0.0002	<0.2	<0.0002	8.32	0.0086	<0.2	<0.0002	8.7	0.00899
BGNELN221H	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	1.01	0.0010	<0.2	<0.0002	<0.2	<0.0002	2.18	0.00225	<0.2	<0.0002	2.03	0.0021
BGNELN221I	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	0.66	0.0007	<0.2	<0.0002	<0.2	<0.0002	1.74	0.0018	<0.2	<0.0002	1.48	0.00153
BGNELN221J	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	0.51	0.0005	<0.2	<0.0002	<0.2	<0.0002	1.59	0.00164	<0.2	<0.0002	0.84	0.00087
BGNELN221K	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	0.41	0.0004	<0.2	<0.0002	<0.2	<0.0002	<1	<0.0010	<0.2	<0.0002	0.44	0.00046
BGNELN221L	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	0.37	0.0004	<0.2	<0.0002	<0.2	<0.0002	<1	<0.0010	<0.2	<0.0002	0.37	0.00038
BGNELN221M	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	0.27	0.0003	<0.2	<0.0002	0.27	0.00028	<1	<0.0010	<0.2	<0.0002	<0.2	<0.0002
BGNGRN222	24-Aug-11	GMAW Baseline UF	<0.2	<0.0014	<0.2	<0.0014	12.3	0.0849	<0.2	<0.0014	0.48	0.0033	20.0	0.139	<0.2	<0.0014	23.2	0.161
BGNIMN225	24-Aug-	GMAW Baseline	<0.2	<0.0005	<0.2	<0.0005	1.35	0.00369	<0.2	<0.0005	<0.2	<0.0005	4.18	0.0114	<0.2	<0.0005	1.34	0.00367

	11	UF																
BGNIMF226	24-Aug-11	GMAW Baseline UF	<0.2	<0.0005	<0.2	<0.0005	0.460	0.00119	<0.2	<0.0005	<0.2	<0.0005	1.21	0.00313	<0.2	<0.0005	0.220	0.000569
BGNGRN230	25-Aug-11	GMAW Baseline UF	<0.2	<0.0037	<0.2	<0.0037	23.0	0.421	<0.2	<0.0037	1.0	0.019	41.5	0.760	<0.2	<0.0037	49.2	0.901
BGNELN231A	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	<0.2	<0.0005	0.72	0.0020	<0.2	<0.0005	<0.2	<0.0005	1.55	0.00419	<0.2	<0.0005	1.10	0.00298
BGNELN231B	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	<0.2	<0.0005	6.01	0.0163	<0.2	<0.0005	0.33	0.00089	10.6	0.0288	<0.2	<0.0005	12.5	0.0337
BGNELN231C	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	<0.2	<0.0005	18.8	0.0509	<0.2	<0.0005	0.96	0.0026	32.5	0.088	<0.2	<0.0005	41.7	0.113
BGNELN231D	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	<0.2	<0.0005	17.8	0.0483	<0.2	<0.0005	0.93	0.00252	39.5	0.107	<0.2	<0.0005	46.8	0.127
BGNELN231E	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	<0.2	<0.0005	9.96	0.0269	<0.2	<0.0005	0.47	0.00127	24.2	0.0654	<0.2	<0.0005	26.9	0.0727
BGNELN231F	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	<0.2	<0.0005	5.74	0.0155	<0.2	<0.0005	0.28	0.00076	14.9	0.0404	<0.2	<0.0005	16.5	0.0446
BGNELN231G	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	<0.2	<0.0005	1.45	0.0039	<0.2	<0.0005	<0.2	<0.0005	3.44	0.00931	<0.2	<0.0005	3.63	0.00982
BGNELN231H	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	<0.2	<0.0005	1.31	0.0035	<0.2	<0.0005	<0.2	<0.0005	3.94	0.0107	<0.2	<0.0005	2.71	0.00733
BGNELN231I	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	<0.2	<0.0005	1.23	0.0033	<0.2	<0.0005	<0.2	<0.0005	2.38	0.00644	<0.2	<0.0005	2.34	0.00633
BGNELN231J	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	<0.2	<0.0005	0.82	0.0022	<0.2	<0.0005	<0.2	<0.0005	1.44	0.0039	<0.2	<0.0005	1.39	0.00376
BGNELN231K	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	<0.2	<0.0005	0.59	0.0016	<0.2	<0.0005	<0.2	<0.0005	10.1	0.0272	<0.2	<0.0005	0.68	0.00184
BGNELN231L	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	<0.2	<0.0005	0.35	0.0009	<0.2	<0.0005	<0.2	<0.0005	<1	<0.0027	<1	<0.0027	0.27	0.00073
BGNELN231M	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	<0.2	<0.0005	0.37	0.0010	<0.2	<0.0005	<0.2	<0.0005	<1	<0.0027	<1	<0.0027	0.25	0.00068
MCEBL_232	25-Aug-11	Blank	<0.2 *	-	<0.2 *	-	0.510 *	-	<0.2 *	-	1.56 *	-	1.48 *	-	<0.2 *	-	<0.2 *	-
ELPI-234	25-Aug-11	Blank	<0.2 *	-	<0.2 *	-	0.260 *	-	<0.2 *	-	<0.2 *	-	<1*	-	<0.2 *	-	<0.2 *	-

BGNELN236A	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	<0.2	<0.0006	2.52	0.0082	<0.2	<0.0006	<0.2	<0.0006	4.98	0.0162	<0.2	<0.0006	5.44	0.0177
BGNELN236B	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	<0.2	<0.0006	2.59	0.0084	<0.2	<0.0006	<0.2	<0.0006	5.98	0.0194	<0.2	<0.0006	5.77	0.0187
BGNELN236C	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	<0.2	<0.0006	19.5	0.0633	<0.2	<0.0006	1.18	0.00383	40.2	0.131	<0.2	<0.0006	49.5	0.161
BGNELN236D	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	<0.2	<0.0006	15	0.0487	<0.2	<0.0006	0.83	0.00269	34	0.111	<0.2	<0.0006	40.7	0.132
BGNELN236E	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	<0.2	<0.0006	2.51	0.0082	<0.2	<0.0006	<0.2	<0.0006	5.73	0.0186	<0.2	<0.0006	5.77	0.0187
BGNELN236F	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	<0.2	<0.0006	5.99	0.0194	<0.2	<0.0006	0.33	0.00107	14.4	0.0469	<0.2	<0.0006	16.3	0.0529
BGNELN236G	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	<0.2	<0.0006	1.1	0.0036	<0.2	<0.0006	<0.2	<0.0006	2.7	0.00877	<0.2	<0.0006	2.92	0.00948
BGNELN236H	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	<0.2	<0.0006	1.56	0.0051	<0.2	<0.0006	0.21	0.00068	3.73	0.0121	<0.2	<0.0006	3.29	0.0106
BGNELN236I	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	<0.2	<0.0006	6.85	0.0222	<0.2	<0.0006	0.36	0.00117	19.4	0.0629	<0.2	<0.0006	19.8	0.0644
BGNELN236J	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	<0.2	<0.0006	0.79	0.0026	<0.2	<0.0006	<0.2	<0.0006	1.88	0.0061	<0.2	<0.0006	0.99	0.00321
BGNELN236K	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	<0.2	<0.0006	0.55	0.0018	<0.2	<0.0006	<0.2	<0.0006	1.15	0.00373	<0.2	<0.0006	0.65	0.00211
BGNELN236L	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	<0.2	<0.0006	0.4	0.0013	<0.2	<0.0006	<0.2	<0.0006	<1	<0.0032	<0.2	<0.0006	0.44	0.00143
BGNELN236M	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	<0.2	<0.0006	0.39	0.0013	<0.2	<0.0006	<0.2	<0.0006	1.98	0.00643	<0.2	<0.0006	0.28	0.00091

Table G3 Field test data for metals (Part II)

Sample ID	Date of Sample Collection	Sample Event	Results											
			Molybdenum		Nickel		Strontium		Vanadium		Zinc		Ruthenium	
			(µg)	(mg/m3)	(µg)	(mg/m3)	(µg)	(mg/m3)	(µg)	(mg/m3)	(µg)	(mg/m3)	(µg)	(mg/m3)
BGEIMB045	11-Aug-11	GMAW Baseline UF	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
BGEIMN046	11-Aug-11	GMAW Baseline UF	<0.2	<0.0003	2.3	0.0031	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BGEIMF047	11-Aug-11	GMAW Baseline UF	<0.2	<0.0003	0.61	0.0008	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BGEELN051A-M	11-Aug-11	GMAW Baseline UF	<0.2	<0.0058	<0.2	<0.0058	<0.2	<0.0058	<0.2	<0.0058	0.29	0.0085	<0.2	<0.0058
BGEELN052A-M	11-Aug-11	GMAW Baseline UF	<0.2	<0.0039	0.63	0.012	<0.2	<0.0039	<0.2	<0.0039	0.68	0.013	<0.2	<0.0039
BGEELN053A-M	11-Aug-11	GMAW Baseline UF	<0.2	<0.0078	0.31	0.012	<0.2	<0.0078	<0.2	<0.0078	0.52	0.020	<0.2	<0.0078
BGEELN054A-M	11-Aug-11	GMAW Baseline UF	<0.2	<0.0058	0.21	0.0061	<0.2	<0.0058	<0.2	<0.0058	0.35	0.010	<0.2	<0.0058
BGEGRN055	11-Aug-11	GMAW Baseline UF	<0.2	<0.0083	<0.2	<0.0083	<0.2	<0.0083	<0.2	<0.0083	<0.2	<0.0083	<0.2	<0.0083
BGNIMN058	11-Aug-11	GMAW Baseline UF	<0.2	<0.0004	0.76	0.0014	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNIMF059	11-Aug-11	GMAW Baseline UF	<0.2	<0.0004	0.25	0.00046	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
BGNELN062A-M	11-Aug-11	GMAW Baseline UF	<0.2	<0.0078	0.28	0.011	<0.2	<0.0078	<0.2	<0.0078	1.4	0.055	<0.2	<0.0078
BGNELN063A-M	11-Aug-11	GMAW Baseline UF	<0.2	<0.0078	<0.2	<0.0078	<0.2	<0.0078	<0.2	<0.0078	0.49	0.019	<0.2	<0.0078
BGNELN064A-M	11-Aug-11	GMAW Baseline UF	<0.2	<0.0078	0.41	0.016	<0.2	<0.0078	<0.2	<0.0078	<0.2	<0.0078	<0.2	<0.0078
BGNELN065A-M	11-Aug-11	GMAW Baseline UF	<0.2	<0.0078	<0.2	<0.0078	<0.2	<0.0078	<0.2	<0.0078	<0.2	<0.0078	<0.2	<0.0078
BGNGRN066	11-Aug-11	GMAW Baseline UF	<0.2	<0.0093	0.27	0.012	<0.2	<0.0093	<0.2	<0.0093	0.23	0.011	<0.2	<0.0093
FGNIMN180	23-Aug-11	GMAW UF	<0.2	<0.0004	3.82	0.00743	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
FGNIMF181	23-Aug-11	GMAW UF	<0.2	<0.0004	1.23	0.00229	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004	<0.2	<0.0004
FGNIMB182	23-Aug-11	Blank	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
FGNGRB183	23-Aug-11	Blank	<0.2*	-	0.340*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
FGNGRB185	23-Aug-11	GMAW UF	<0.2	<0.0013	10.8	0.0702	<0.2	<0.0013	<0.2	<0.0013	0.63	0.0041	<0.2	<0.0013

FGNELN186A	23-Aug-11	GMAW UF	<0.2	<0.0002	1.36	0.00128	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN186B	23-Aug-11	GMAW UF	<0.2	<0.0002	5.29	0.00497	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN186C	23-Aug-11	GMAW UF	<0.2	<0.0002	7.11	0.00668	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN186D	23-Aug-11	GMAW UF	<0.2	<0.0002	9.44	0.00887	<0.2	<0.0002	<0.2	<0.0002	0.62	0.00058	<0.2	<0.0002
FGNELN186E	23-Aug-11	GMAW UF	<0.2	<0.0002	6.21	0.00583	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN186F	23-Aug-11	GMAW UF	<0.2	<0.0002	4.74	0.00445	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN186G	23-Aug-11	GMAW UF	<0.2	<0.0002	2.23	0.22209	<0.2	<0.0002	<0.2	<0.0002	0.27	0.00025	<0.2	<0.0002
FGNELN186H	23-Aug-11	GMAW UF	<0.2	<0.0002	1.09	0.00102	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN186I	23-Aug-11	GMAW UF	<0.2	<0.0002	1.06	0.000995	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN186J	23-Aug-11	GMAW UF	<0.2	<0.0002	0.74	0.000695	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN186K	23-Aug-11	GMAW UF	<0.2	<0.0002	1.09	0.00102	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN186L	23-Aug-11	GMAW UF	<0.2	<0.0002	0.57	0.000535	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN186M	23-Aug-11	GMAW UF	<0.2	<0.0002	2.4	0.00225	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNIMN191	23-Aug-11	GMAW UF	<0.2	<0.0003	5.66	0.00764	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNIMF192	23-Aug-11	GMAW UF	<0.2	<0.0003	1.92	0.00243	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNGRN196	23-Aug-11	GMAW UF	<0.2	<0.0020	5.17	0.0530	<0.2	<0.0020	<0.2	<0.0020	<0.2	<0.0020	<0.2	<0.0020
FGNELN197A	23-Aug-11	GMAW UF	<0.2	<0.0002	0.61	0.0007	<0.2	<0.0002	<0.2	<0.0002	0.24	0.00027	<0.2	<0.0002
FGNELN197B	23-Aug-11	GMAW UF	<0.2	<0.0002	3.46	0.0039	<0.2	<0.0002	<0.2	<0.0002	0.35	0.00039	<0.2	<0.0002
FGNELN197C	23-Aug-11	GMAW UF	<0.2	<0.0002	9.19	0.0102	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN197D	23-Aug-11	GMAW UF	<0.2	<0.0002	5.32	0.0059	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN197E	23-Aug-11	GMAW UF	<0.2	<0.0002	6.51	0.0073	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN197F	23-Aug-11	GMAW UF	<0.2	<0.0002	2.58	0.0029	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN197G	23-Aug-11	GMAW UF	<0.2	<0.0002	2.00	0.0022	<0.2	<0.0002	<0.2	<0.0002	0.32	0.00036	<0.2	<0.0002
FGNELN197H	23-Aug-11	GMAW UF	<0.2	<0.0002	0.72	0.0008	<0.2	<0.0002	<0.2	<0.0002	0.23	0.00026	<0.2	<0.0002
FGNELN197I	23-Aug-11	GMAW UF	<0.2	<0.0002	0.68	0.0008	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN197J	23-Aug-11	GMAW UF	<0.2	<0.0002	0.52	0.0006	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN197K	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN197L	23-Aug-11	GMAW UF	<0.2	<0.0002	0.33	0.0004	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNELN197M	23-Aug-11	GMAW UF	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
FGNGRN198	23-Aug-11	GMAW UF	<0.2	<0.0017	7.08	0.0611	<0.2	<0.0017	<0.2	<0.0017	<0.2	<0.0017	<0.2	<0.0017

FGNELN199A	23-Aug-11	GMAW UF	<0.2	<0.0003	0.43	0.000549	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN199B	23-Aug-11	GMAW UF	<0.2	<0.0003	8.47	0.0108	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN199C	23-Aug-11	GMAW UF	<0.2	<0.0003	1.77	0.00226	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN199D	23-Aug-11	GMAW UF	<0.2	<0.0003	2.09	0.00267	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN199E	23-Aug-11	GMAW UF	<0.2	<0.0003	1.47	0.00188	<0.2	<0.0003	<0.2	<0.0003	0.34	0.00043	<0.2	<0.0003
FGNELN199F	23-Aug-11	GMAW UF	<0.2	<0.0003	3.78	0.00483	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN199G	23-Aug-11	GMAW UF	<0.2	<0.0003	1.51	0.00193	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN199H	23-Aug-11	GMAW UF	<0.2	<0.0003	0.38	0.000485	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN199I	23-Aug-11	GMAW UF	<0.2	<0.0003	0.72	0.000919	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN199J	23-Aug-11	GMAW UF	<0.2	<0.0003	0.23	0.000294	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN199K	23-Aug-11	GMAW UF	<0.2	<0.0003	0.55	0.000702	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN199L	23-Aug-11	GMAW UF	<0.2	<0.0003	0.26	0.000332	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN199M	23-Aug-11	GMAW UF	<0.2	<0.0003	2.39	0.00305	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNIMN203	24-Aug-11	GMAW UF	<0.2	<0.0008	1.02	0.00419	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0008
FGNIMF204	24-Aug-11	GMAW UF	<0.2	<0.0008	0.410	0.00154	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0008	<0.2	<0.0008
FGNIMB205	24-Aug-11	Blank	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
FGNGRB206	24-Aug-11	Blank	<0.2*	-	0.300*	-	<0.2*	-	<0.2*	-	0.25*	-	<0.2*	-
FGNGRN210	24-Aug-11	GMAW UF	<0.2	<0.0019	16.1	0.154	<0.2	<0.0019	<0.2	<0.0019	0.27	0.0026	<0.2	<0.0019
FGNELN211A	24-Aug-11	GMAW UF	<0.2	<0.0003	1.64	0.00233	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN211B	24-Aug-11	GMAW UF	<0.2	<0.0003	7.9	0.0112	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN211C	24-Aug-11	GMAW UF	<0.2	<0.0003	2.46	0.00349	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN211D	24-Aug-11	GMAW UF	<0.2	<0.0003	7.99	0.0113	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN211E	24-Aug-11	GMAW UF	<0.2	<0.0003	6.74	0.00957	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN211F	24-Aug-11	GMAW UF	<0.2	<0.0003	1.62	0.0023	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN211G	24-Aug-11	GMAW UF	<0.2	<0.0003	2.23	0.00317	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN211H	24-Aug-11	GMAW UF	<0.2	<0.0003	1.29	0.00183	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN211I	24-Aug-11	GMAW UF	<0.2	<0.0003	0.94	0.00134	<0.2	<0.0003	<0.2	<0.0003	0.39	0.00055	<0.2	<0.0003
FGNELN211J	24-Aug-11	GMAW UF	<0.2	<0.0003	0.71	0.00101	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN211K	24-Aug-11	GMAW UF	<0.2	<0.0003	0.88	0.00125	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
FGNELN211L	24-Aug-11	GMAW UF	<0.2	<0.0003	0.4	0.000568	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003

FGNELN211M	24-Aug-11	GMAW UF	<0.2	<0.0003	0.78	0.00111	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003	<0.2	<0.0003
BGNIMN214	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	6.85	0.00801	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
BGNIMF215	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	0.460	0.000501	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
BGNELN217A-M	24-Aug-11	GMAW Baseline UF	0.21	0.00015	22.59	0.01614	<0.2	<0.0001	<0.2	<0.0001	0.61	0.00044	<0.2	<0.0001
BGNGRN218	24-Aug-11	GMAW Baseline UF	<0.2	<0.0010	8.03	0.0388	<0.2	<0.0010	<0.2	<0.0010	0.62	0.0030	<0.2	<0.0010
BGNELN221A	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	0.27	0.000279	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
BGNELN221B	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	2.31	0.00239	<0.2	<0.0002	<0.2	<0.0002	0.21	0.0002	<0.2	<0.0002
BGNELN221C	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	4.56	0.00471	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
BGNELN221D	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	5.79	0.00598	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
BGNELN221E	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	6.19	0.00639	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
BGNELN221F	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	2.74	0.00283	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
BGNELN221G	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	1.85	0.00191	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
BGNELN221H	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	0.49	0.000506	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
BGNELN221I	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	0.4	0.000413	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
BGNELN221J	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	0.28	0.000289	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
BGNELN221K	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
BGNELN221L	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002
BGNELN221M	24-Aug-11	GMAW Baseline UF	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	<0.2	<0.0002	0.26	0.0003	<0.2	<0.0002
BGNGRN222	24-Aug-11	GMAW Baseline UF	<0.2	<0.0014	5.31	0.0368	<0.2	<0.0014	<0.2	<0.0014	<0.2	<0.0014	<0.2	<0.0014
BGNIMN225	24-Aug-11	GMAW Baseline UF	<0.2	<0.0005	1.00	0.00274	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
BGNIMF226	24-Aug-11	GMAW Baseline UF	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
BGNGRN230	25-Aug-11	GMAW Baseline UF	<0.2	<0.0037	11.6	0.213	<0.2	<0.0037	<0.2	<0.0037	<0.2	<0.0037	<0.2	<0.0037
BGNELN231A	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	0.29	0.000785	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
BGNELN231B	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	3.29	0.0089	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
BGNELN231C	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	9.46	0.0256	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
BGNELN231D	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	10.2	0.0277	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
BGNELN231E	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	6.2	0.0168	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
BGNELN231F	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	3.69	0.00998	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
BGNELN231G	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	0.8	0.00216	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
BGNELN231H	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	0.67	0.00181	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005

BGNELN231I	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	0.6	0.00162	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
BGNELN231J	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	0.34	0.00092	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
BGNELN231K	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	0.22	0.000595	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
BGNELN231L	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
BGNELN231M	25-Aug-11	GMAW Baseline UF	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005	<0.2	<0.0005
MCEBL_232	25-Aug-11	Blank	<0.2*	-	18.3*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
ELPI-234	25-Aug-11	Blank	<0.2*	-	0.310*	-	<0.2*	-	<0.2*	-	<0.2*	-	<0.2*	-
BGNELN236A	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	1.39	0.00451	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006
BGNELN236B	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	1.42	0.00461	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006
BGNELN236C	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	10.6	0.0343	<0.2	<0.0006	<0.2	<0.0006	0.21	0.0007	<0.2	<0.0006
BGNELN236D	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	8.53	0.0277	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006
BGNELN236E	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	1.49	0.00484	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006
BGNELN236F	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	4.01	0.013	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006
BGNELN236G	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	0.6	0.00195	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006
BGNELN236H	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	1.37	0.00445	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006
BGNELN236I	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	4.37	0.0142	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006
BGNELN236J	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	0.33	0.00107	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006
BGNELN236K	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	0.36	0.00117	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006
BGNELN236L	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	0.23	0.000747	<0.2	<0.0006	<0.2	<0.0006	0.21	0.0007	<0.2	<0.0006
BGNELN236M	25-Aug-11	GMAW Baseline UF	<0.2	<0.0006	0.21	0.000682	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006	<0.2	<0.0006

Table G4 Field test data for amorphous silica

Sample ID	**Date of Sample Collection**	**Sample Event**	**Results**					
			Dust (mg)	**Volume (L)**	**Dust Conc. (mg/m^3)**	**Amorphous Silica (mg)**	**Amorphous Silica (%)**	**Amorphous Silica (mg/m^3)**
BGNISB001	9-Aug-11	Baseline	<0.01	0	N/A	N/A	N/A	N/A
BGNISN002	9-Aug-11	Baseline	0.08	243	0.33	BLD	BLD	BLD

BGNISF003	9-Aug-11	Baseline	0.02	248	0.081	BLD	BLD	BLD
BGNISB025	10-Aug-11	Baseline	<0.01	0	N/A	N/A	N/A	N/A
BGNISN026	10-Aug-11	Baseline	0.11	410	0.268	BLD	BLD	BLD
BGNISF027	10-Aug-11	Baseline	0.04	426	0.094	BLD	BLD	BLD
BGEISN035	10-Aug-11	Baseline	0.25	426	0.587	BLD	BLD	BLD
BGEISF036	10-Aug-11	Baseline	0.05	440	0.114	BLD	BLD	BLD
BGEISB042	11-Aug-11	Baseline	<0.01	0	N/A	N/A	N/A	N/A
BGEISN043	11-Aug-11	Baseline	0.08	442	0.181	BLD	BLD	BLD
BGEISF044	11-Aug-11	Baseline	0.03	449	0.067	BLD	BLD	BLD
BGNISN056	11-Aug-11	Baseline	0.06	317	0.189	BLD	BLD	BLD
BGNISF057	11-Aug-11	Baseline	0.03	318	0.094	BLD	BLD	BLD
FGNISN187	23-Aug-11	UF	0.08	310	0.258	BLD	BLD	BLD
FGNISF188	23-Aug-11	UF	0.08	308	0.26	BLD	BLD	BLD
FGNISN194	23-Aug-11	UF	0.18	443	0.407	BLD	BLD	BLD
FGNISF195	23-Aug-11	UF	0.08	449	0.178	BLD	BLD	BLD
FGNISN208	24-Aug-11	UF	0.03	383	0.183	BLD	BLD	BLD
FGNISF209	24-Aug-11	UF	0.05	388	0.129	BLD	BLD	BLD
BGNISN219	24-Aug-11	Baseline	0.15	383	0.391	BLD	BLD	BLD
BGNISF220	24-Aug-11	Baseline	0.03	388	0.077	BLD	BLD	BLD
BGNISN227	25-Aug-11	Baseline	0.05	219	0.229	BLD	BLD	BLD
BGNISF228	25-Aug-11	Baseline	0.06	217	0.276	BLD	BLD	BLD

Appendix G: MSDS for Tetramethylsilane (TMS)

Health	2
Fire	4
Reactivity	0
Personal Protection	J

Material Safety Data Sheet
Tetramethylsilane MSDS

Section 1: Chemical Product and Company Identification

Product Name: Tetramethylsilane

Catalog Codes: SLT3877

CAS#: 75-76-3

RTECS: VV5705400

TSCA: TSCA 8(b) inventory: Tetramethylsilane

CI#: Not available.

Synonym:

Chemical Formula: C4H12Si

Contact Information:

Sciencelab.com, Inc.
14025 Smith Rd.
Houston, Texas 77396

US Sales: **1-800-901-7247**
International Sales: **1-281-441-4400**

Order Online: ScienceLab.com

CHEMTREC (24HR Emergency Telephone), call: 1-800-424-9300

International CHEMTREC, call: 1-703-527-3887

For non-emergency assistance, call: 1-281-441-4400

Section 2: Composition and Information on Ingredients

Composition:

Name	CAS #	% by Weight
Tetramethylsilane	75-76-3	100

Toxicological Data on Ingredients: Tetramethylsilane LD50: Not available. LC50: Not available.

Section 3: Hazards Identification

Potential Acute Health Effects:
Very hazardous in case of eye contact (irritant), of inhalation. Inflammation of the eye is characterized by redness, watering, and itching.

Potential Chronic Health Effects:
Very hazardous in case of eye contact (irritant), of inhalation. CARCINOGENIC EFFECTS: Not available. MUTAGENIC EFFECTS: Not available. TERATOGENIC EFFECTS: Not available. DEVELOPMENTAL TOXICITY: Not available. The substance is toxic to lungs, mucous membranes. Repeated or prolonged exposure to the substance can produce target organs damage.

Section 4: First Aid Measures

Eye Contact: Check for and remove any contact lenses. Do not use an eye ointment. Seek medical attention.

p. 1

Skin Contact: No known effect on skin contact, rinse with water for a few minutes.

Serious Skin Contact: Not available.

Inhalation: Allow the victim to rest in a well ventilated area. Seek immediate medical attention.

Serious Inhalation:
Evacuate the victim to a safe area as soon as possible. Loosen tight clothing such as a collar, tie, belt or waistband. If breathing is difficult, administer oxygen. If the victim is not breathing, perform mouth-to-mouth resuscitation. Seek medical attention.

Ingestion:
Do not induce vomiting. Loosen tight clothing such as a collar, tie, belt or waistband. If the victim is not breathing, perform mouth-to-mouth resuscitation. Seek immediate medical attention.

Serious Ingestion: Not available.

Section 5: Fire and Explosion Data

Flammability of the Product: Flammable.

Auto-Ignition Temperature: Not available.

Flash Points: CLOSED CUP: -27°C (-16.6°F).

Flammable Limits: LOWER: 1.5%

Products of Combustion: These products are carbon oxides (CO, CO2).

Fire Hazards in Presence of Various Substances: Flammable in presence of open flames and sparks.

Explosion Hazards in Presence of Various Substances:
Risks of explosion of the product in presence of mechanical impact: Not available. Risks of explosion of the product in presence of static discharge: Not available.

Fire Fighting Media and Instructions:
Flammable liquid, insoluble in water. SMALL FIRE: Use DRY chemical powder. LARGE FIRE: Use water spray or fog. Cool containing vessels with water jet in order to prevent pressure build-up, autoignition or explosion.

Special Remarks on Fire Hazards: Catches fire if exposed to air.

Special Remarks on Explosion Hazards: Not available.

Section 6: Accidental Release Measures

Small Spill: Absorb with an inert material and put the spilled material in an appropriate waste disposal.

Large Spill:
Flammable liquid, insoluble in water. Keep away from heat. Keep away from sources of ignition. Stop leak if without risk. Absorb with DRY earth, sand or other non-combustible material. Do not get water inside container. Do not touch spilled material. Prevent entry into sewers, basements or confined areas; dike if needed. Eliminate all ignition sources. Call for assistance on disposal.

Section 7: Handling and Storage

Precautions:
Keep away from heat. Keep away from sources of ignition. Ground all equipment containing material. Do not breathe gas/ fumes/ vapour/spray. Avoid contact with eyes In case of insufficient ventilation, wear suitable respiratory equipment If you feel unwell, seek medical attention and show the label when possible.

Storage:

Flammable materials should be stored in a separate safety storage cabinet or room. Keep away from heat. Keep away from sources of ignition. Keep container tightly closed. Keep in a cool, well-ventilated place. Ground all equipment containing material. A refrigerated room would be preferable for materials with a flash point lower than 37.8°C (100°F).

Section 8: Exposure Controls/Personal Protection

Engineering Controls:
Provide exhaust ventilation or other engineering controls to keep the airborne concentrations of vapors below their respective threshold limit value. Ensure that eyewash stations and safety showers are proximal to the work-station location.

Personal Protection: Splash goggles. Lab coat. Vapor respirator. Be sure to use an approved/certified respirator or equivalent.

Personal Protection in Case of a Large Spill:
Splash goggles. Full suit. Vapor respirator. Boots. Gloves. A self contained breathing apparatus should be used to avoid inhalation of the product. Suggested protective clothing might not be sufficient; consult a specialist BEFORE handling this product.

Exposure Limits: Not available.

Section 9: Physical and Chemical Properties

Physical state and appearance: Liquid.

Odor: Not available.

Taste: Not available.

Molecular Weight: 88.22 g/mole

Color: Colorless.

pH (1% soln/water): Not applicable.

Boiling Point: 26.5°C (79.7°F)

Melting Point: -99°C (-146.2°F)

Critical Temperature: Not available.

Specific Gravity: 0.65 (Water = 1)

Vapor Pressure: Not available.

Vapor Density: Not available.

Volatility: Not available.

Odor Threshold: Not available.

Water/Oil Dist. Coeff.: Not available.

Ionicity (in Water): Not available.

Dispersion Properties: See solubility in water, methanol, diethyl ether.

Solubility:
Soluble in methanol, diethyl ether. Insoluble in cold water.

Section 10: Stability and Reactivity Data

Stability: The product is stable.

Instability Temperature: Not available.

Conditions of Instability: Not available.

Incompatibility with various substances: Not available.

Corrosivity: Non-corrosive in presence of glass.

Special Remarks on Reactivity: Not available.

Special Remarks on Corrosivity: Not available.

Polymerization: No.

Section 11: Toxicological Information

Routes of Entry: Eye contact. Inhalation.

Toxicity to Animals:
LD50: Not available. LC50: Not available.

Chronic Effects on Humans: The substance is toxic to lungs, mucous membranes.

Other Toxic Effects on Humans: Very hazardous in case of inhalation.

Special Remarks on Toxicity to Animals: Not available.

Special Remarks on Chronic Effects on Humans: Not available.

Special Remarks on other Toxic Effects on Humans: Not available.

Section 12: Ecological Information

Ecotoxicity: Not available.

BOD5 and COD: Not available.

Products of Biodegradation:
Possibly hazardous short term degradation products are not likely. However, long term degradation products may arise.

Toxicity of the Products of Biodegradation: The products of degradation are more toxic.

Special Remarks on the Products of Biodegradation: Not available.

Section 13: Disposal Considerations

Waste Disposal:

Section 14: Transport Information

DOT Classification: Class 3: Flammable liquid.

Identification: : Tetramethylsilane : UN2749 PG: I

Special Provisions for Transport: Not available.

Section 15: Other Regulatory Information

Federal and State Regulations: TSCA 8(b) inventory: Tetramethylsilane

Other Regulations: OSHA: Hazardous by definition of Hazard Communication Standard (29 CFR 1910.1200).

Other Classifications:

WHMIS (Canada):
CLASS B-2: Flammable liquid with a flash point lower than 37.8°C (100°F). CLASS D-2A: Material causing other toxic effects (VERY TOXIC).

DSCL (EEC):
R12- Extremely flammable. R41- Risk of serious damage to eyes.

HMIS (U.S.A.):

Health Hazard: 2

Fire Hazard: 4

Reactivity: 0

Personal Protection: j

National Fire Protection Association (U.S.A.):

Health: 2

Flammability: 4

Reactivity: 0

Specific hazard:

Protective Equipment:
Not applicable. Lab coat. Vapor respirator. Be sure to use an approved/certified respirator or equivalent. Wear appropriate respirator when ventilation is inadequate. Splash goggles.

Section 16: Other Information

References: Not available.

Other Special Considerations: Not available.

Created: 10/10/2005 12:03 AM

Last Updated: 11/01/2010 12:00 PM

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Appendix H: Quote for TMS premixed cylinder gas

To: **University of Florida**

Gainesville, Florida

Ph:

Fx:

Attn: **Jun Wang**

Date: **July 22,2011**

RE: **Gas Quote** Quote: **UF J Wang 7-11** Valid: 30 days

Qty	Part Number	Product Description	Unit of Measure	Unit Price	Extended Price
1	X02 AR95C2000002	Certified Gas Mixture 5 % Tetra Methyl Silane Bal Argon Size 200	Cyl	$1,214.00	$1,214.00

NOTES:
1. Lead time 21 working days
2. FOB Pearland, TX

Appendix I: List of Publications and Presentations

The following publication and conference presentations were derived from the project, and listed the project as a major funding source in the acknowledgement section.

Peer-reviewed journal papers

1. Topham, N.; Kalivoda, M.; Hsu, Y.-M.; Wu, C.-Y.; Oh, S.; Cho, K., Reducing Cr^{6+} emissions from gas tungsten arc welding using a silica precursor. *Journal of Aerosol Science* 2010, **41(3)**, 326-330.
2. Yu, K.-M.; Topham, N.; Wang, J.; Kalivoda, M.; Tseng, Y.; Wu, C.-Y.; Lee, W.-J.; Cho, K., Decreasing biotoxicity of fume particles produced in welding process. *Journal of Hazardous Materials* 2011, **185(2–3)**, 1587-1591.
3. Topham, N.; Wang, J.; Kalivoda, M.; Huang, J.; Yu, K.-M.; Hsu, Y.-M.; Wu, C.-Y.; Oh, S.; Cho, K.; Paulson, K., Control of Cr^{6+} emissions from gas metal arc welding using a silica precursor as a shielding gas additive. *Annals of Occupational Hygiene* 2011, **56(2)**, 233-241
4. Paulson, K. M.; Wang, J.; Topham, N.; Wu, C.-Y.; Alexandrov, B. T.; Lippold, J. C.; Es-Said, O. S., Alternatives for Joining Stainless Steel to Reduce Cr(VI) Emissions and Occupational Exposures. *Journal of Ship Production and Design* 2011, **27(2)**, 91-97.
5. Wang, J.; Topham, N.; Wu, C.-Y., Determination of silica coating efficiency on metal particles using multiple digestion methods. *Talanta* 2011, **85(5)**, 2655-2661.
6. Wang, J.; Mark, K.; Guan, J.; Theodore, A.; Sharby, J.; Wu, C.-Y.; Paulson, K.; Es-Said, O., Double shroud delivery of silica precursor for reducing hexavalent chromium in welding fume. *Journal of Occupational and Environmental Hygiene* 2012, **9 (12)**, 733-742.
7. Wang, J.; Wu, C.-Y.; Frank, G., Effectiveness of Amorphous Silica Encapsulation Technology on Welding Fume Particles and Its Impact on Mechanical Properties of Welds, submitted to Aerosol Science & Technology.

Conference proceedings/presentations

1. Topham, N.; Kalivoda, M.; Wu, C.-Y.; Huang, J.; Tuchman, A.; Oh, S.; Cho, K.; Hsu, Y. M., Control of welding HAP emissions using silica precursors as shield gas additives, 102nd AWMA Annual Conference & Exhibition, Abstract No. 577, Detroit, MI, June 16-19, 2009.
2. Topham, N.; Kalivoda, M.; Oh, S.; Hsu, Y.-M.; Tuchman, A.; Huang, J.; Wu, C.-Y.; Cho, K., A novel technique for control of hazardous metal emissions from welding operations, 28th Annual Meeting of the American Association for Aerosol Research, Abstract No. 7D3, Minneapolis, MN, October 26-30, 2009.
3. Wu, C.-Y.; Topham, N.; Kalivoda, M.; Huang, J.; Oh, S.; Hsu, Y.-M.; Cho, K.; Paulson, K., Innovative welding technologies to control HAP emissions using silicon additives, SERDP-ESTCP Partners Symposium, Abstract No. 358, Washington, DC, December 1-3, 2009.
4. Wang, J.; Topham, N.; Huang, J.; Kalivoda, M.; Wu, C.-Y.; Paulson, K.; Cho, K.; Hsu, Y.-M. Application of silica precursor to reduce toxic metal emissions from stainless steel welding

process, Leapfrogging Opportunities for Air Quality Improvement", Abstract No. 169, Xi'an, China, May 10-14, 2010.

5. Wang, J.; Topham, N.; Kalivoda, M.; Wu, C.-Y.; Paulson, K.; Cho, K.; Hsu, Y.-M. Application of silica precursor to reduce toxic metal emissions from gas metal arc welding process, 103rd AWMA Annual Conference & Exhibition, Abstract No. 154, Calgary, Canada, June 22-25, 2010.
6. Topham, N.; Wang, J.; Kalivoda, M.; Huang, J.; Yu, K.-M.; Hsu Y.-M.; Wu, C.-Y.; Oh, S.; Cho, K.; Paulson, K., Control of Cr^{6+} from welding using silica precursors as shield gas additives, International Aerosol Conference, Abstract No. 782, Helsinki, Finland, August 29-September 3, 2010.
7. Yu, K.-M.; Topham, N.; Wang, J.; Kalivoda, M.; Wu, C.-Y.; Lee, W.-J.; Cho, K., Minimization of the biotoxicity of welding fume particles, 2010 International Aerosol Conference, Helsinki, Finland, August 29-September 3, 2010.
8. Wang, J.; Topham, N.; Kalivoda, M.; Wu, C.-Y.; Paulson, K.; Cho, K.; Hsu, Y.-M. Application of silica precursor to reduce toxic metal emissions from gas metal arc welding process, 47th Annual Florida A&WMA Conference, Crystal River, FL, October 10-12, 2010.
9. Wang, J.; Topham, N.; Kalivoda, M.; Wu, C.-Y.; Paulson, K.; Cho, K.; Hsu, Y.-M. In Application of silica precursor to reduce toxic metal emissions from stainless steel welding process, 29th Annual Meeting of the American Association for Aerosol Research, Abstract No. 3.D.6, Portland, OR, October 25-29, 2010.
10. Wang, J.; Topham, N.; Kalivoda, M.; Wu, C.-Y.; Paulson, K.; Hsu, Y.-M., Application of silica precursor to reduce hexavalent chromium emission from stainless steel welding process, SERDP-ESTCP Partners Symposium, Abstract No. P175, Washington, DC, December 1-3, 2010.
11. Wang, J.; Kalivoda, M.; Guan, J.; Theodore, A.; Sharby, J.; Wu, C.-Y.; Paulson, K., Application of silica precursor to reduce toxic metal emissions from stainless steel welding process, Fall 2011 Florida AIHA meeting, St. Augustine, FL, September 29-30, 2011.
12. Wang, J.; Kalivoda, M.; Guan, J.; Theodore, A.; Sharby, J.; Wu, C.-Y.; Paulson, K., Application of silica precursor to reduce toxic metal emissions from stainless steel welding process, 30th Annual Meeting of the American Association for Aerosol Research, Abstract No. 10.B.2, Orlando, FL, October 25-29, 2011.
13. Wang, J.; Topham, N.; Wu. C.-Y., Determination of Silica-coating Efficiency on Metal Particles by Using Different Digestion Methods, 30th Annual Meeting of the American Association for Aerosol Research, Abstract No. 8.A.4, Orlando, FL, October 25-29, 2011.
14. Wang, J.; Kalivoda, M.; Guan, J.; Theodore, A.; Sharby, J.; Wu, C.-Y.; Paulson, K., Development of Silica Precursor Technology on Reducing Welding Fume Toxicity, 105th AWMA Annual Conference & Exhibition, Abstract No. 41, San Antonio, TX, June 19-22, 2012.

15. Wang, J.; Kalivoda, M.; Guan, J.; Theodore, A.; Sharby, J.; Wu, C.-Y.; Paulson, K., Development of Silica Precursor Technology on Reducing Welding Fume Toxicity, American Industrial Hygiene Conference and Expo 2012, Indianapolis, IN, June 16-21, 2012.