Thermal Spray Removal of Lead-Based Paint From the Viaduct Bridge at Rock Island Arsenal, IL

by

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Foreword

This study was conducted for the Environmental Security Technology Certification Program (ESTCP) under Project 9607 "Thermal Spray Removal of Lead-Based Paint." The technical monitor was Dr. Jeffrey Marqusee.

The work was performed by the Materials Science and Technology Division (FL-M) of the Facilities Technology Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (CERL). The CERL Principal Investigator was Dr. Ashok Kumar. Dr. Jeffrey H. Boy is at CERL under a postgraduate research participation program through the Oak Ridge Institute for Science and Education, Oak Ridge, TN. The field demonstration was conducted at the Rock Island Arsenal, Rock Island, IL. Contributions to the field demonstrations of the U.S. Army Rock Island Arsenal, the U.S. Army Corps of Engineers Rock Island District, and the U.S. Army Corps of Engineers Louisville District, Rock Island Field Office are gratefully acknowledged. Dr. Ilker R. Adiguzel is Acting Chief, CECER-FL-M, and L. Michael Golish is Acting Operations Chief, CECER-FL. The CERL technical editor was Gordon L. Cohen, Technical Information Team.

COL James A. Walter is Commander of CERL and Dr. Michael J. O'Connor is Director.

Table of Contents

List of Figures and Tables

Figures

Tables

1. Introduction

1.1 Background

Red lead primer has been used on many steel structures to control corrosion. Commonly used structures in the Department of Defense (DoD) that may contain lead-based paint include bridges, catwalks, towers, water storage tanks, petroleum storage tanks, piping, steel doors, fire hydrants, trusses, exterior railings, steel posts, poles, stairways, handrails, cranes, pontoons, and boiler plant structural members. In addition to the DoD facilities infrastructure, ship structures and bilges have been painted with lead-pigmented coatings. When lead-based paint shows evidence of peeling, it must be removed because peeling paint cannot be overcoated. During the removal process, a tight containment structure is required to keep the lead dust from contaminating the air, soil, or water. Inside such containment structures, increased worker protection is required due to the higher dust concentrations. These protective measures are time-consuming and cumbersome to use, which drives up costs by reducing worker productivity.

The project documented in this report demonstrated and validated the thermal spray vitrification (TSV) process to safely and effectively remove lead-based paint from DoD steel structures such as a section of a steel bridge at the Rock Island Arsenal. In the TSV process (Ref. 1) specially formulated molten glass is applied to a painted steel substrate using a conventional thermal spray application system. The molten glass reacts with the paint, and the lead from the paint adheres to the glass surface. Due to thermal stresses, the glass readily cracks and falls off the substrate, removing the lead-based paint. After remelting in the field, the glass waste product encapsulates the lead and the material is classified as nonhazardous. The principal advantage of the process is that airborne lead dust and vapors are not produced. As a result, the TSV process reduces the cost of environmental compliance and worker health protection associated with lead-based paint removal from DoD structures (Ref. 1-3).

The cost of removal and disposal of lead-based paint from flat surfaces on steel structures is estimated to be $5 to $18/sq ft using abrasive blasting in a tight containment structure. This cost can rise as high as $100/sq ft depending on the area, surface complexity, and other requirements such as working over water or in the presence of machinery. The disposal cost alone for the resulting hazardous waste is about $4/sq ft. By comparison, the cost of using the TSV process to remove lead-based paint from steel structures is estimated to be about $5/sq ft. Furthermore, the disposal cost of the resulting waste, after it is remelted in an onsite furnace, amounts to only a small fraction of the disposal cost for hazardous waste. The environmentally inert glass residue of the TSV process is classified as a standard construction waste that may be disposed of for only $45/cu yd, which converts to an area cost of about $0.31/sq ft.

1.2 DoD Requirements

1.2.1 Official DoD Requirement Statement. The work in this project addresses requirements documented in DoD Compliance Category 8, "Decontamination of Structural Facilities"; and Army-Wide Prioritized Requirement Statements (1998) 2.3.k, "Cost-Effective Technologies to Remove, Characterize, and Dispose or Reuse Sources of Lead Hazards," Ranking 1.

1.2.2 How Requirement(s) Were Addressed. The project addresses these requirements by demonstrating and validating an innovative process to remove lead-based paint from steel structures. The thermal spray vitrification (TSV) process of lead-based paint removal is projected to be less expensive than current removal processes and yields a vitrified waste that does not leach lead and is nonhazardous.

1.3 Objectives of the Demonstration

The objectives are to demonstrate and validate the environmental advantages of the TSV process for the removal of lead-based paint from steel structures. The main environmental and technology issues to be documented in the study are: (1) the number of passes required to remove the lead from the steel structure, (2) the production rate under field conditions, (3) air emission levels, (4) verification that the glass can be classified as a nonhazardous waste after being remelted, and (5) the projected cost of implementation. This demonstration was conducted on the Viaduct Bridge at the Rock Island Arsenal, IL.

1.4 Regulatory Issues

The principal regulatory issues involve the protection of the environment and the worker during lead-based paint removal. The principal regulatory drivers to protect the environment are: (1) Clean Air Act (CAA) and the 1990 CAA Amendments, including the National Emission Standards for Hazardous Air Pollutants (NESHAPS), (2) Clean Water Act (CWA) of 1977 as amended with the National Pollutant Discharge Elimination System Permit Requirements, and (3) Resource Conservation and Recovery Act (RCRA).

The principal regulatory drivers to protect workers during lead-based paint abatement are: (1) Title 29, Code of Federal Regulations (CFR) Part 1910, Occupational Safety and Health Administration, "Occupational Safety and Health Standards," and (2) 29 CFR Part 1926, Occupational Safety and Health Administration, "Safety and Health Regulations for Construction."

The Illinois Environmental Protection Agency (IL EPA) was contacted by the U.S. Army Corps of Engineers Rock Island District about the onsite remelting of the vitrified waste during the demonstration. Rock Island District informed IL EPA about the scope and purpose of the TSV demonstration project as well as about previous laboratory and field test results. The contract called for the onsite remelting of the glass in order to make the waste nonhazardous and permit disposal as a standard construction waste. The IL EPA Division of Air Pollution Control decided to classify the glass remelting stage as a repair/construction activity and to regulate it as a lead-based paint cleaning operation. IL EPA does not require air quality permits for paint cleaning activities. IL EPA determined that, based on the type and amount of work, this demonstration would not require a permit. Letters were sent by Rock Island District to the IL EPA Division of Air Pollution Control and Bureau of Land stating that permits are not required.

It is noted that other states are not bound by the Illinois decision; the environmental regulators in other states will make their own decisions on permit requirements as it becomes necessary.

1.5 Previous Testing of TSV Technology

A proof-of-principle field test of the TSV technology was conducted in June 1996 at the Triborough Bridge in New York City by the Thermal Spray Laboratory of the State University of New York at Stony Brook (SUNY). During the field test, lead-based paint was successfully removed and the required surface preparation for recoating was accomplished for a 5 ft by 10 ft area of the Triborough Bridge. The resulting surface was recoated with a surface-tolerant coating system (i.e., one that does not require perfect surface preparation to adhere well). The Army Center for Health Promotion and Preventive Medicine (CHPPM) conducted an industrial hygiene study of the workers during the field test of the technology. Researchers concluded that in this field test, operator exposure in the worker’s breathing zone did not exceed any applicable airborne exposure standard, including exposure to lead and other metals (Ref. 4).

2. Technology Overview

2.1 Description

The technology in this project uses molten glass to remove and vitrify lead-based paint. It was patented in 1996 by the U.S. Army (U.S. Patent No. 5,292,3758, A. Kumar and J. Petreanu) and is described in detail in references 1, 2, and 3. The designer iron silicate glass composition was developed by the U.S. Army Construction Engineering Research Laboratories (CERL) in conjunction with the Department of Energy Savannah River Technology Center (Ref. 5). This glass composition is a durable waste form that can load and immobilize up to 25 percent of its own weight in lead oxide without leaching more than 5 parts per million (ppm) of lead, as determined using the Toxicity Characteristic Leaching Procedure (TCLP). Crucible tests in the laboratory have shown that this glass composition can immobilize chromium, cadmium, and copper as well (Ref. 2).

The principal equipment for the TSV process consists of a commercially available thermal spray torch, powder feeder, gas manifold, flow controllers, as well as compressed air, fuel gas and oxygen sources. These are connected with a series of gas and powder feed lines. A schematic of the thermal spray system is shown in Figure C.1. The pressure of the oxygen and acetylene is controlled by the manifold and flow controllers. These are connected by separate gas feed lines to the thermal spray gun, where they are combined. The glass powder is mixed with compressed air in the powder feeder, and the air moves the glass powder to the thermal spray gun. The oxygen and acetylene are ignited in the torch and the powder is introduced into this flame. The flame melts the glass powder and propels the molten droplets onto the target surface. The temperature of the flame from the thermal spray torch is about 2000 °C (3600 °F), which is sufficient to melt the glass powder. As the glass is propelled toward the substrate, it cools in the air and sticks to the substrate at a temperature of about 475 °C (800 °F).

The glass strikes the substrate and solidifies within a few seconds. The glass is immediately reheated with the thermal spray torch two or three times, and remains molten for a total of about 30 seconds. This timing allows the lead ions to diffuse into the glass network and become trapped in the silica tetrahedra of the glass structure, achieving partial vitrification. The difference in the thermal expansion coefficient between the sprayed glass layer and the metal substrate causes the glass to crack and spall from the surface as it cools. The paint is vitrified at the surface of the glass and additional layers of the paint are attached to this vitrified layer. The crumbled glass fragments can be easily removed from the steel substrate, removing the lead-based paint. However, 2 or 3 applications of the vitrification process are required to obtain a surface suitable for repainting with a surface-tolerant coating system.

The small pieces of glass (on average less than 2 to 3 in.) fall into the catch basin of a collector unit. A vacuum-equipped needle gun with a high-efficiency particulate air (HEPA) filter is used in the current demonstration for spot removal of glass in crevices. The catch basin is sloped such that the glass slides into a storage container or directly into the glass remelter unit. The glass fragments are remelted to ensure that the vitrification process is driven to completion. The remelting of the glass immobilizes the lead inside the glass network, thereby preventing leaching. The concentration of lead in the leachate for the remelted glass, as determined by TCLP analysis, was below 5 ppm – the regulatory limit for classification as a hazardous waste.

The TSV process has been tested on carbon steel panels coated with a red lead primer (Federal Specification TT-P-86H) and both phenolic (Federal Specification TT-P-36) and alkyd topcoats. These are the most common topcoat systems used on Federal highway and Army bridges. The TSV process was successful in removing lead-based paint regardless of which topcoat system was used.

The molten glass is very corrosive and acts like a cleaning agent, restoring the surface to a dull finish with the profile it had before it was painted. For atmospheric exposure, the surface finish before recoating is not as critical as for immersion coatings. The surface finish produced by the TSV process requires a surface-tolerant coating that can provide 25-year performance for atmospheric exposure. After application of the TSV process the steel surface has a dusting of loosely adhered powdery residue that must be removed before repainting. The resultant surface needs to be free of all loose mill scale, loose paint, and other loose detrimental foreign matter. This may be accomplished as needed using vacuum-equipped power tools equipped with a HEPA filter in accordance with the Steel Structures Painting Council (SSPC) specification SSPC 3, "Power Tool Cleaning." The corrosive molten glass will remove and incorporate rust (iron oxide) into the glass structure.

A waste-collection hopper is used to collect the pieces of vitrified glass that spall off the surface. A high-temperature furnace is used to remelt the glass. The glass melter unit is cylindrical in form, measuring 32 in. tall and 17 in. diameter at the base of the legs. The typical weight of glass melted per cycle is approximately 10 lb.

The glass remelting procedure established in earlier tests was as follows:

- The vitrified glass is slowly added to the steel pot in the furnace until the pot is full.
- The iron pot is heated to at least 800 °C.
- After full melting, the molten glass is stirred occasionally using an appropriate tool – preferably steel with a handle made of wood, ceramic, or heat-resistant cloth. (The glass should fill only one-third of the pot when fully melted, helping to ensure a safe distance between the worker's hands and the molten glass.)

- Any glass that sticks to the stirrer is considered untreated and is added to other glass awaiting treatment when it cools and spalls off.
- The glass is kept in a molten state for 1 hour.
- The furnace is shut off.
- The steel pot is removed using tongs.
- The molten glass is rapidly cooled by pouring into a container of water.
- When the danger of scalding has passed, as much glass as possible is removed using a stirring tool designated for use only in this stage of the process (to avoid contaminating the treated waste with partially treated waste). The remelted glass waste, now cooled, is placed in an appropriate container for proper disposal according to the results of TCLP testing.

2.2 Strengths, Advantages, and Weaknesses

Currently used lead-based paint removal technologies include chemical strippers, abrasive blasting inside containment, closed-cycle ultra-high pressure water, and wet abrasive blasting with a chemical stabilizer (e.g., Blastox®). The TSV process has certain advantages over these methods.

A major advantage of the TSV process is that there is no need to build and use a containment structure when employing this technology. Monitoring data collected during the demonstration verify that the potential is small to generate airborne lead concentrations in excess of regulatory limits when the plume is uninhibited (as was found during the proof-of-principle field test at the Triborough Bridge). However, when TSV technology is used in areas where the plume is inhibited, such as semi-enclosed areas under a bridge, appropriate respirators should be used to prevent excessive worker exposure to airborne contaminants such as lead dust, additive effects of CO and NO, and NO_2. Based on initial monitoring of the workers at one particular job site, enhanced respiration protection – such as the use of pressure-demand or positive-pressure supplied-air respirator – or the reduction of operating hours may be required. These measures would eliminate the need for a tight containment structure and may actually reduce the degree of worker protection that would be needed inside a tight containment structure of the type required for abrasive blasting.

Containment structures are needed for abrasive blasting, but they are expensive and cumbersome to prepare. The cost of building a small containment structure (e.g., to prepare a few square feet of steel surface area) is about $1000 to $2500. After abrasive blasting is completed, the cost of disposing of the waste abrasive is $4 to $5 per square foot of surface area treated, and there is an added liability risk if this material is not disposed of properly.

Chemical strippers are slow, and the resulting liquid waste – including the rinse water – is generally hazardous and requires appropriate disposal. By contrast, the TSV process chemically binds lead and chromium, and also minimizes the liability risk of heavy metals leaching into the environment.

The TSV process is limited to the removal of lead-based paint from steel structures. It is not applicable to removing lead-based paint from wood, concrete, or masonry structures.

2.3 Factors Influencing Cost and Performance

One factor that influences the cost and performance of the TSV process is the condition of the existing coating systems, particularly the thickness of the coating. Thicker paint may require an additional TSV application. The thickness of the substrate also affects costs because thicker substrates or larger structures may require additional preheating before the application of the molten glass. The preheating can be accomplished using either the thermal spray torch without powder flow or a separate torch. Proof-of-principle testing of the TSV process has shown successful removal of lead-based paint from a large steel structure such as a highway bridge. The removal rate in the proof-of-principle demonstration — one operator using one torch to make two applications of the TSV process — was found to be 30 sq ft/h. It is expected that with additional experience the workers could improve their productivity, and be able to complete three applications of the TSV process at rate of 30 sq ft/h. The complexity of the structure also influences the productivity rate and the resulting cost of the TSV process. Structures with excessive bends, corners, crevices, and recessed areas are more difficult to access and may require additional time for final cleanup before repainting.

3. Site/Facility Description

3.1 Background

Site selection for the demonstration of the TSV process was based on the following factors: (1) presence of a steel structure with lead-based paint, (2) structure design typical of those found on other DoD installations, (3) paint system similar to that used at other DoD installations, and (4) site willing to actively participate and assist in the demonstration.

Sampling and analysis found that the Viaduct Bridge at the Rock Island Arsenal is coated with a lead-based primer and alkyd topcoats. This paint system is commonly used by DoD and the Department of Transportation (DOT) for steel structures in atmospheric exposure. The bridge design is typical of Federal highway and Army bridges. The Rock Island Army Engineer District, on behalf of the Rock Island Arsenal, administered the contract for the demonstration. This included preparing the Contract Solicitation and Specification document as well as conducting an environmental and safety review of the contract, the bid solicitation, contractor selection, and contract award. The Rock Island District also assisted CERL in obtaining regulatory acceptance of the TSV process from IL EPA.

3.2 Site/Facility Characteristics

The Viaduct Bridge connects the Rock Island Arsenal and the City of Rock Island and has two lanes for vehicle traffic. The TSV process was demonstrated on a section of a horizontal steel beam below the traffic deck of the bridge.

The following site and facility maps and photographs are shown in Appendix C:

Figure C.1. Schematic of the thermal spray system.
Figure C.2. TSV technology in use to remove lead-based paint from the Viaduct Bridge at the Rock Island Arsenal.
Figure C.3. Location plan of Rock Island Arsenal.
Figure C.4. Detailed location plan of the Viaduct Bridge.
Figure C.5. Upstream elevation drawing of the Viaduct Bridge.
Figure C.6. Containment structure built for the demonstration.
Figure C.7. The Viaduct Bridge after completion of TSV demonstration.

4. Demonstration Approach

4.1 Performance Objectives

As stated in the demonstration plan, the main performance objectives were to demonstrate and validate that the TSV process can (1) remove lead-based paint in the field from a steel structure, (2) meet all applicable environmental standards, (3) meet all applicable worker health and occupational safety standards, (4) leave the bare steel substrate in suitable shape for recoating with a surface-tolerant coating system, and (5) provide data for calculating a valid general estimate of production costs.

4.2 Physical Setup and Operation

The demonstration required the construction of a temporary scaffold to permit worker access to the underside of the bridge. The contract specification also called for a containment structure in compliance with the requirements of SSPC 6, Class 3C (see Table 1). Instead of the containment required by the specification, the contractor provided full containment in accordance with the more stringent requirements of SSPC 6, Class 1C (see Table 1 and Figure C.6).

Electrical power was supplied by a portable gasoline-powered generator. Electrical power was used for the task lighting and for the PM 10 air monitors. Compressed air was provided for the powder feeder, the HEPA-equipped power tools, and for the paint spray gun.

Table 1. Containment and ventilation system components (Source: SSPC 6).

	Class 1C Containment System	**Class 3C Containment System**
Containment Materials	Rigid or Flexible	Rigid or Flexible
Penetrability	Air Impermeable or Chemical Resistant	Chemical Resistant
Support Structure	Rigid or Flexible	Minimal
Joints	Full Seams	Partial Seal
Entryway	Overlap	Open Seam
Air Makeup	Open	Open
Forced or Natural	Forced or Natural	Natural
Air Pressure	Not Required	Not Required
Air Movement	Not Specified	Not Specified
Exhaust Dust Filtration	Filtration	Not Required

The location of the demonstration site is shown in Figures C.3 and C.4. The demonstration was conducted on the first three panels of the easternmost bridge girder on the north (river) side of Pier 8 (see Figure C.5). Scaffolding was constructed to provide access to the girder. A ramp provided access to the scaffolding from the levy that abuts Pier 8. Bottles of oxygen and acetylene used in the thermal spray process were stored in a secure fenced area on the opposite side of Pier 8. The air compressor, electrical generator, and air filtration unit were deployed on top of the levy near the bridge, approximately 20 to 30 ft from the scaffolding. The powder feeder was placed on the scaffolding during the thermal spray process. Storage sheds were also placed on the levy near the work site. The principal equipment used by the contractor is listed in Table 2.

Table 2. Equipment used by the contractor.

	Model and Capacity	**Performance**
Personal pumps	Gilair 5	Used to monitor worker exposure
Pump calibration units	Gilian	Used to calibrate personal pumps
Geo tarp	Sized to fit containment	Used in the containment structure
Thermal blankets	Tillman 1000 °F blankets	Used in the containment structure
Geo booms	4 in. diameter	Can be deployed on land or water in compliance with emergency contingency plan
PM10 monitors	Gaseby Anderson GMH model	Used to monitor particulate matter smaller than 10 microns
TSP monitors	Gaseby Anderson GMH model	Used to monitor total suspended particles
HEPA VAC	HEPA filters	Used to clean up containment and is used in conjunction with needle guns for power tool cleaning.
Air compressor	185 CFM Ingersol Rand	Used to power needle guns and job air
Needle guns	Air powered	Used to dislodge trapped glass in crevices
2 Stage filtration	15 gal per minute	Used to filter wash water
Dust collector	ARS rated at 40,000 CFM	Used for filtration of containment air
Steel tower scaffold	5 ft X 6 ft, 6 in.	
Flame spray gun	Metco Model 6P	Used to apply the molten glass powder
Powder feeder	Miller Thermal Model	Supply the glass powder to the gun
Glass waste collection hopper	Supplied by USACERL	Used to collect spalled glass
Remelt pot furnaces	Supplied by USACERL	Used to remelt the glass

4.3 Sampling Procedures

As stated in the demonstration plan, paint evaluation and testing were conducted by personnel from the CERL Paint Technology Center. Worker health monitoring was conducted by personnel from the U.S. Army Center for Health Promotion and Preventive Medicine (CHPPM), Aberdeen, MD.

Evaluations of the existing paint system, the surface after the application of the TSV process, and the newly painted surface were conducted. Evaluation of the existing paint system included dry film thickness measurement using American Society for Testing and Materials (ASTM) D 1186, "Standard Test Method for Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to a Ferrous Base." The Positector Model 5002-F thickness gauge was used to measure the film thickness. The adhesion of the existing paint system was determined using ASTM D 3359, "Standard Test Method for Measuring Adhesion by Tape Method." The 150 sq ft of surface was subdivided into a grid containing 15 sections each with a surface area of approximately 10 sq ft. Thickness and adhesion measurements were conducted within each grid area. The sampling requirements for each of the ASTM standard test methods – ASTM D 1186 and ASTM D 3359 – were utilized. Personnel from CHPPM sampled the existing paint system and performed total metal and TCLP analysis.

Following the TSV application but before repainting, the surface profile was compared to visual standards from SSPC-VIS-1-89, "Visual Standards for Abrasive Blast Cleaned Steel (Standard Reference Photographs)." The profile was also evaluated using ASTM D 4417, "Standard Test Method for Field Measurement of Surface Profile of Blast Cleaned Steel. Following repainting, the paint was inspected in accordance with the requirements for Paint System No. 16 in the Corps of Engineers Guide Specification CEGS 09940, "Painting: Hydraulic Structures."

Personnel from the CHPPM Industrial Hygiene Field Services Program (IHFSP) conducted the sampling for worker health monitoring. Air samples were analyzed for metals, dust, crystalline silica, and combustion products. A combination of direct reading and indirect reading methods (i.e., requiring laboratory analysis) was used. The upwind air samples were used to assess the background chemical concentrations. The personal air samples were used to assess actual exposures, and this information was compared to occupational airborne exposure limits. The downwind air samples were used to assess diluted chemical concentrations downwind from the plume, and this information was used to determine potential exposures to others in close proximity. The source air samples were used to capture the rising plume, where emission concentrations would be at the highest, and this information was used to assess potential worst-case exposures and to ascertain the amount of dilution occurring at other sampling sites.

Occupational chemical exposures were compared to the Occupational Safety and Health Administration (OSHA) permissible exposure limits (PELs) and American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit values (TLVs). Metal leachate from the solid vitrified paint remelt samples were compared to Environmental Protection Agency (EPA) TCLP regulatory levels, i.e., Title 40, Part 261.24, Toxicity Characteristic, Table 1 - Maximum Concentration of Contaminants for the Toxicity Characteristics.

4.4 Analytical Procedures

Analysis was performed by a qualified laboratory selected by CHPPM personnel in accordance with analytical methods referenced in the demonstration plan.

5. Performance Assessment

5.1 Performance Data

5.1.1. Paint Inspection, Removal, and Repainting. Evaluation of the existing paint system was conducted by personnel from the CERL Paint Technology Center. This included dry film thickness and adhesion measurement. The results are contained in Figures D.1 and D.2. The measured thickness of the existing paint on the flat vertical web of the bridge girder ranged from 3.3 to 5.9 mils. The existing paint was thicker on the vertical ribs and the lower horizontal flange, ranging up to 17.8 mils. The existing paint was well adhered to the substrate. Personnel from CHPPM sampled the existing paint system and found lead content to range from 155,000 to 495,000 mg/kg. The lead content vitrified glass waste (first removal stage, before remelt) ranged from 48,200 to 106,000 mg/kg.

During the initial TSV application it was noted by the operator that the vertical web of the beam was warping. The TSV process was immediately stopped; the degree of warping was measured and found to range up to 3/8 in. A structural engineer from the Corps of Engineers Rock Island District inspected the beam and concluded that the warping did not adversely affect the structural integrity of the beam or the bridge. The warping was due to excess heat applied to the vertical web during preheating of the substrate. The steel temperature on the back of a vertical web of the bridge was measured with a thermocouple during TSV application to the front side of the vertical web, and is shown in Figures D.3 and D.4. The maximum temperature recorded was 273 °C (523 °F) and 322 °C (611 °F). Temperature control is only an issue with thin cross-section substrates that are less than 0.200 in. thick. The vertical webs are relatively thin – less than 0.5 in. thick – and are fastened into place by rivets at the vertical supports between panels. When the web was heated with the preheat torch, the resulting thermal expansion of the web – which is constrained by the fasteners – could not be relieved except by warping.

The TSV procedure was modified to eliminate the use of a separate torch to preheat the substrate. The thermal spray torch was used in a more controlled manner to preheat the substrate, and the amount of warping was minimized. The temperature for these substrates can also be controlled by the use of forced air or wet forced air from the onsite compressors. There is a minor cost associated with this temperature control method. For each 100 sq ft, the time to set up a forced air cooling system is less than 15 minutes. At $24/hr for labor, the cost is $6.00 per 100 sq ft or $0.06/sq ft. This is included in the revised labor cost for application of the TSV process (Section 6.1).

During the previous proof-of-principle field test of TSV at the Triborough Bridge in New York City, there was no warping of the beams. The beams on the Triborough Bridge differed from the Rock Island Bridge in that they were a one-piece design and, therefore, did not have separate constrained vertical web panels. The steel on the Triborough Bridge was also thicker, more than 0.75 in., and required a separate preheat torch to supply enough heat to the substrate so the glass would stick to the substrate and react with the lead-based paint. The use of a water misting spray is being considered to further reduce the maximum steel temperature in future applications of TSV on thin-section material.

The TSV process met the principal performance criterion of providing surface preparation for repainting. Following application of the TSV process, the surface was inspected by CERL personnel and was found to meet the requirements of SSPC SP1 and SP3 required in the contract specification, and it also was suitable for repainting with a surface-tolerant coating system. The surface profile was measured using ASTM D 4417 and found to range from 2.0 to 3.0 mils (Figure D.5 and D.6).

The first paint coat was a Sherwin-Williams industrial coating, SSPC 25 red primer. The topcoat was a Sherwin-Williams VOC* -compliant industrial enamel, No. 2.16. This is a medium oil, alkyd, all-purpose enamel designed for new construction and maintenance work and provides performance comparable to products formulated to Federal Specification TT-E-489. Temperature and relative humidity were measured before painting. The temperature of the substrate was more than 5 °F higher than the dew point, and the relative humidity was less than 80 percent before painting commenced. The contract specification required a spread rate of 500 sq ft per gal. One gal of primer and 1.5 gal of paint were used to apply one coat of the primer and two topcoats over the 180 sq ft area of the demonstration. The measured thickness of the dried primer ranged from 1.7 to 3.4 mils, and was on average 3.0 mils (Figures D.7 and D.8). The measured thickness of the completed coating system (primer plus topcoats ranged from 5.4 to 8.4 mils, and was on average 6.9 mils (Figures D.9 and D.10).

X-ray fluorescence analysis found that the lead concentration in areas adjacent to the demonstration with original coating intact ranged from 4.7 to 5.8 mg/sq in. (Figure D.11). In areas on which TSV was demonstrated, the measured lead concentration was found to range from 1.0 to 2.1 mg/sq in. (Figures D.12 and D.13). As with most other paint removal processes, such as chemical removal, some residual lead was present on the surface. The retention of lead on the steel surface is a function of the experience of the TSV applicator, the original amount of lead present, and the number of TSV applications used. In this demonstration, two applications were used. Additional applications of the process would be expected to further reduce the residual lead concentration. Also, it is reasonable to expect that lead removal will be more complete as operators gain experience with the technology. The workers in the current test had less than 2

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* VOC: volatile organic compound.

days of experience by the end of the test. With a week of on-the-job experience, the amount of residual lead should be reduced as the applicators become more proficient. Surface lead retention does not appear, with the data in hand, to be a function of the lead paint type or age. During any future paint removal from the treated area, proper protection and testing of the workers would be required to verify that worker exposure to any residual lead on the surface was below the regulatory levels applicable at that time.

Previous laboratory testing found that the TSV process was successful in removing the Navy paint system, Mil P 24441 epoxy-polyamide paint, from the ship structure plates (Ref. 6). The resulting surface was suitable for repainting using a surface-tolerant coating system that would be suitable for non-immersion applications.

There was concern that the presence of residual lead on the surface may contaminate the abrasive blast media used to prepare the surface for a coating suitable for immersion applications. The initial concentration of lead on the painted steel, measured using an X-ray fluorescence analyzer, was 12.54 mg/cm^2. After three passes of the TSV process in which the lead-based paint was removed to a level at which there was no visual evidence of paint remaining on substrate, the measured lead concentrations remaining on the steel were lower than 1 mg/cm^2 (see Appendix D, Tables D.7 and D.8). Laboratory testing found that 5 lb of mineral abrasives were required to treat each square foot of TSV-treated surface. After abrasive blasting of the TSV-treated steel specimen, TCLP analysis of the used blast media found it to leach less lead than the regulatory limit of 5 mg/L. Therefore, the TSV process followed by abrasive blasting can be used to prepare steel surfaces with a profile suitable for painting with a full range of paint systems, including those for underwater exposures. Any residual lead picked up by the blast media will accumulate only in trace concentrations low enough to satisfy environmental requirements for standard construction waste.

5.1.2 Worker Monitoring. Analysis of the air in the worker breathing zone was conducted by CHPPM during the demonstration. Monitoring for metals, dust, and silica included the following: aluminum, antimony, arsenic, barium, chromium, cadmium, calcium, cobalt, copper, respirable dust, iron, lead, magnesium, mercury, molybdenum, nickel, crystalline silica, tin, titanium, vanadium, zinc, and zirconium. The results of 493 samples of metals, dust, and silica were reported by CHPPM. Monitoring for combustion products included the following compounds: benzene, carbon monoxide, nitric oxide, nitrogen dioxide, oxides of nitrogen, oxygen, ozone, and sulfur dioxide. The results of 55 air samples for combustion products were reported. The results are presented in a separate report prepared by CHPPM entitled “Phase 2, Industrial Hygiene Study, No. 55-ML-5090-98 Lead Paint Vitrification Research Demonstration Project, Rock Island Arsenal, Rock Island, Illinois, 2-4 September 1997” (Ref. 7).

CHPPM concluded that the potential to exceed current airborne occupational health standards for some chemicals (Pb, respirable and total dust, additive effects of CO + NO, and NO_2) is high when vitrification is used in areas where the plume is inhibited. Such areas would include enclosed spaces and containment structures (such as at the Rock Island bridge demonstration) and areas such as under a bridge or where there is a low ceiling above the plume. This hazard can be reduced when TSV is used in areas where the plume is uninhibited or a heat shield is used. The hazard will be lowest where the plume is uninhibited and a heat shield is not used (e.g., on the outside of a bridge, as in the field test at the Triborough Bridge). The Pb concentrations were much higher in the demonstration on the Rock Island Arsenal bridge as compared to the proof-of-principle field test at the Triborough Bridge, primarily because TSV was applied in an enclosed area (although ventilated at a high exchange rate), the plume was inhibited, and the Pb concentration in the paint was about three times greater. At the Rock Island demonstration, the contractor provided full containment in accordance with SSPC 6, Class 1C (see Figure C.6). The total containment was found to inhibit the plume and create dead air space that allowed airborne materials to concentrate. Even though there was positive pressure air flow through the containment structure, there were spaces that collected airborne contaminants because the flow did not sweep these areas out.

CHPPM also concluded that there is the potential to exceed current airborne occupational health standards for Pb and possibly CO when working around the glass remelter. Installing local exhaust ventilation such as a chimney at the glass remelter would help capture metal fumes and combustion gases and reduce worker exposure – perhaps reducing the level of respiratory protection required or eliminating the need altogether.

Based on these conclusions, CHPPM recommended respirator protection for workers during the application of the TSV process in each of the following conditions:

(a) Enclosed containment structures or where the plume is inhibited by an overhead ceiling or roof. As a minimum, workers should wear National Institute for Occupational Safety and Health (NIOSH) certified pressure-demand or positive-pressure supplied-air respirator equipment with either a half-face or full-face piece when the process is either enclosed in a containment structure or where the plume is inhibited. Note that these recommendations apply to all cases where the plume is inhibited, even when the process itself is not enclosed. When the plume is not able to escape freely it will return into the face of the worker in concentrations that require a higher level of worker protection than paragraphs (b) and (c) below.

(b) Well ventilated outdoor areas where plume dissipation is uninhibited and heat shield is not used. As a minimum, workers should wear a NIOSH-certified full-face air-purifying respirator equipped with HEPA filters in well ventilated outdoor areas where plume dissipation is uninhibited and a heat shield is *not* used. Nitric oxide, NO_2, and CO should be monitored closely,

and the level of respiratory protection increased to that described in paragraph 5.1.2.a if exposures exceed the TLV or PEL.

(c) Well ventilated outdoor areas where plume dissipation is uninhibited and a heat shield is used. As a minimum, workers should wear a NIOSH-certified half-face air-purifying respirator equipped with HEPA filters when in well ventilated outdoor areas where plume dissipation is uninhibited and a heat shield is used.

(d) During remelting of the glass. As a minimum, workers should wear a NIOSH-certified half-face air-purifying respirator equipped with HEPA filters when conducting remelt operations in well ventilated outdoor areas where plume dissipation is uninhibited. If the glass remelter is equipped with adequate local exhaust ventilation, the level of respiratory protection required may possibly be reduced depending on air monitoring results.

5.1.3 Waste Characterization. The remelted waste met EPA regulatory guidelines for leachate (using TCLP), but it required a total remelt time of 5 hours. The initial remelt was performed for 1 hour (according to the routine procedure) and resulted in a heterogeneous mixture. Some of the samples from the initial 1-hour remelt met EPA regulatory guidelines whereas other samples did not (Table 3).

To fully commercialize the process, scale-up of the glass remelting process would be required. This would include the use of a larger glass melter so the vitrified glass from a day's paint removal could be remelted in one operation. The larger melter would also permit measurement and control of the melt temperature, and could provide for stirring of the molten glass. Such a melter may require mounting on a truck or a trailer to be deployable in the field.

An alternative to waste disposal may to recycle the vitrified glass for use in new glass or ceramic products. According to the RCRA recycling exemption, the vitrified product would not be classified as solid waste if it were used or reused as an ingredient in an industrial process to make a product (Ref. 8). Potential uses currently under investigation by Seiler Pollution Controls, Inc., Dublin, OH, include abrasive grit blasting media for blasting, buffing, and polishing applications as well as roofing tile granules and architectural materials (Ref. 9). Seiler is also investigating reuse of the vitrified TSV waste product in new feedstock for the TSV process. Seiler has received approval from the California Department of Toxic Substance Control (DTSC) for production of recyclable materials from three different waste feedstocks, including abrasive blast media (Ref. 10).

Table 3. Characterization of the remelted waste.

Sample Collected By	Total Remelt Time	TCLP Result for Pb (ppm)	TCLP Limit for Pb (ppm)	Comment
CHPPM	1 hr	2.9	5.0	Pass
CHPPM	1 hr	12.0	5.0	Fail
USACERL	1 hr	2.3	5.0	Pass
Contractor	1 hr	320	5.0	Fail
Contractor	1 hr	360	5.0	Fail
USACERL	2 hr	58	5.0	Fail
USACERL	2 hr	57	5.0	Fail
USACERL	5 hr	2.0	5.0	Pass
USACERL	5 hr	2.4	5.0	Pass

5.2 Data Assessment

The data collected allow a realistic assessment of the demonstration's objectives. No significant data gaps or missing values exist. The data quality permits an accurate evaluation of the technology.

5.3 Technology Comparison

The major advantage of the TSV process is that it does not generate hazardous lead dust. This eliminates the need for a containment structure such as that required for abrasive blasting. It also decreases the level for worker protection that would be needed if the paint-removal process were executed inside a containment structure. Power tools such as sanders cannot remove coatings in crevices and tight corners. Chemical strippers are slow and the resulting liquid waste, including the rinse water, is generally hazardous and requires special disposal. Containment structures are needed for abrasive blasting, but they are expensive and cumbersome to prepare. The cost of building a small containment structure (e.g., to prepare a few square feet of steel surface area) is about $1000 to $2500. Remelting the glass shed from the substrate in the TSV process produces a nonhazardous waste which reduces waste disposal costs compared to standard LBP-removal techniques.

The molten glass applied during TSV acts like a cleaning agent, restoring the substrate surface to a dull finish with the profile that it had before it was painted. The surface finish produced by the TSV process can be painted with a standard surface-tolerant coating that can provide 25-year performance in atmospheric exposure. For more demanding applications, however, TSV followed by abrasive blasting can provide a white metal finish that accepts a full range of coating systems suitable for use both in atmospheric and immersion applications.

6. Cost Assessment

6.1 Cost Performance

Based on the demonstration, the expected operational costs of the TSV process for a 1000 sq ft area of a bridge are shown in Table 4.

Table 4. Estimated operation cost for the TSV process (1000 sq ft).

Startup		**Operation and Maintenance (Surface Preparation and Repainting)**		**Demobilization**	
Activity	***$ [h]***	***Activity***	***$ [h]***	***Activity***	***$ [h]***
Rate (Carpenter)	27.43	Rate (Painter)	24.62	Rate (Laborer)	22.73
Hours (Carpenter)	[8]	Hours (Painter)	[33]	Hours	[8]
Rate (Foreman)	24.62	Rate (Laborer for remelt)	22.73	Rate (Foreman)	27.43
Hours (Foreman)	[8]	Hours (Laborer for remelt)	[8]	Hours (Foreman)	[8]
		Rate (Foreman)	24.62		
		Hours (Foreman)	[40]		
Labor Subtotal	***415***	***Labor Subtotal***	***1979***	***Labor Subtotal***	***401***
Materials for scaffolding and containment	100	Glass powder	500		
		Utilities (including, compressed gases, fuel for remelt, air compressor and power generators)	200		
		Misc. Materials	100		
Materials Subtotal	***100***	***Materials Subtotal***	***800***		
		Equipment	350		
		Worker protection and health monitoring	250		
		Environmental monitoring	150		
		Waste transportation	100		
		Waste disposal (nonhazardous)	25		
		Waste disposal (hazardous)	100		
Overhead/Profit	60	Overhead/Profit	200	Overhead/Profit	40
Category Total	***576***		***3954***		***441***
TOTAL					**4971**
Cost per sq ft					$4.96

The labor rates used in Table 4 were the prevailing wage rates determined by the U.S.

Department of Labor for Rock Island County, IL, that were included in the Construction Solicitation and Specification. The prevailing hourly wage rates, including salary and fringe benefits, were: carpenter $27.43, painter $24.62, and laborer $22.73. For the Rock Island demonstration, the site foreman and thermal spray applicators were painters, paid at a wage rate of $24.62. Production rates observed during the demonstration were 30 sq ft per hour for two applications by workers with no previous TSV experience. It is expected that with additional experience, the workers should be able to apply three cycles of the TSV process at the same rate of 30 sq ft per hour, which would further reduce concentrations of residual lead on the steel surface. For a 1000 sq ft area, the labor required for the TSV process was estimated at 24 hours by an applicator and 40 hours by a foreman, including the labor associated with any use of a water mist needed to reduce the temperature of the steel during the TSV process. The labor required to remelt the glass is estimated to be 8 hours using a larger-capacity glass furnace of the type that is available off-the-shelf from the current furnace supplier.

During the demonstration on a 180 sq ft area, approximately 90 lb of glass powder was used, or 0.5 lb per sq ft. With additional applications of the TSV process required to reduce residual lead, it is conservatively estimated that 1 lb of glass powder would be required per sq ft. Seiler Pollution Controls, Inc., has estimated that new glass powder could be produced by recycling the glass from the TSV process with other waste glass at a cost of $0.50/lb (as compared to the current price of $3.00/lb for virgin feedstock). Therefore, the total cost of the (recycled) glass powder would be $500 per 1000 sq ft. Utility costs such as compressed gases, fuel for the remelter, air compressor and power generators are estimated at $200 per 1000 sq ft. Including miscellaneous materials, the total material costs are estimated at $800 per 1000 sq ft. The cost of the worker health monitoring is estimated at $250, including the cost associated with initial monitoring of the workers at a new job site. The cost of environmental monitoring is estimated at $150 per 1000 sq ft. Waste transportation costs are estimated at $100. Disposal costs are estimated at $25 for nonhazardous glass generated in the remelter, and $100 for a very small quantity of hazardous waste (i.e., oily rags and a very small amount of paint waste from the power tool cleaning).

The final operational costs for the TSV process were projected to be $4.93/sq ft, based on an area of 1000 sq ft to be deleaded. When the TSV process is used in conjunction with other maintenance and repair activities, the costs associated with construction of a temporary scaffolding and demobilization would be shared as a part of other onsite activities. Additional cost saving would also be expected to result from sharing of utilities and bulk purchases of gases and fuels. Therefore, the projected costs for the deleading could be reduced to as low as $3.50/sq ft. Depending on the complexity of the structure (truss bridges are more expensive that girder bridges, for example) and the location of the job site (over water), the cost may be higher than average. The average cost of the TSV process is estimated at $5.00/sq ft, with a range from $3.50 to $10.00/sq ft.

Seiler Pollution Controls, Inc. (Dublin, OH) is commercializing a high-temperature vitrification system that converts hazardous waste into a nonhazardous glass-ceramic material, metal oxides, and salts. The system uses the waste feedstock to produce commercial glass-ceramic products such as abrasives, construction materials (concrete mix aggregate), or refractory insulating materials. Seiler has expressed an interest in recycling the glass slag from the TSV process to produce new powder suitable for the TSV process or other value-added glass-ceramic products, reducing or eliminating waste disposal costs. This would make the TSV process more competitive by reducing powder feed cost, reducing paperwork related to waste disposal, and generating income from the sale of value-added products made from the recycled waste.

If it is assumed that 10 percent of the painted steel structures at Army facilities have lead-based paint that needs to be removed, and if the TSV process can be used on half of them, the process would be applicable to 5.9 million sq ft of steel. Based on an average cost saving of $3.00/sq ft, the estimated savings to the Army would be $17.7 million. DoD-wide, the potential cost benefit would be estimated at $30 million over the next 10 years for the 200 million sq ft of steel structures coated with lead-based paint. The section that follows includes an application-specific estimate of cost performance as compared to current methods of deleading.

6.2 Cost Comparisons With Other Available Technologies

The Federal Highway Administration conducted a study on the cost of removing lead-based paint from highway structures (Ref. 11). The costs of various paint-removal technologies are shown in Table 5. The projected cost for the TSV process ranges from $3.50 to $12.00/sq ft, with an average cost projected at less than $5.00/sq ft. This is lower than the costs of other technologies, which ranged from $7.00 to $13.00/sq ft. Based on discussions with the Army Corps of Engineers district engineers, the cost of lead paint removal using existing technologies was more than $20/sq ft for Lock and Dam No. 13 on the Mississippi River.

The demonstrated TSV process also would appear to be appropriate for removal of lead-based paint during spot removal or zone painting. In zone painting, the most corrosion-prone areas on a structure are given a higher degree of protection. Typically for a bridge, these areas are the bearings, sections adjacent to the joints below the deck, and the lower 6 – 10 ft above the deck on the truss. In zone painting, the remainder of the bridge is either not painted at all or given a light cleaning and then topcoated.

Another example of a TSV deleading application would be the removal of lead-based paint from fire hydrants. Tyndall Air Force Base (AFB), FL, has a total of the 320 fire hydrants. Inspection of a representative sample (10 percent) was conducted in 1998, and all of the inspected hydrants were found to be coated with lead-based paint. Current processes for lead paint removal would require the hydrants be disassembled and taken to a location where the lead paint would be removed by abrasive blasting or chemical stripping. The TSV process could be used to remove lead-based paint from the hydrants in-place without requiring disassembly, transportation, and handling.

A demonstration of the TSV process was conducted on two hydrants at Tyndall AFB. Site preparation required 30 – 40 minutes. The TSV process took 90 – 105 minutes. Cleanup and preparation for painting took 20 – 30 minutes. It was estimated that 4 –5 hydrants could be processed at a cost of $200 – $250 each. Using conventional processes, it would require 90 minutes to remove the hydrant and transport it to a workshop, 30 minutes to grit-blast the hydrant clean, and 90 minutes to transport and reinstall the hydrant. Considering also that the waste from grit blasting would have to be disposed of as a hazardous waste, the cost savings for deleading a single fire hydrant with TSV technology would be about $75. Therefore, the estimated cost saving to Tyndall AFB for deleading 300 hydrants would be $22,500. Assuming that there are 300 major DoD installations each with 300 hydrants, the total cost saving to DoD for this one application would be estimated at $6.75 million.

Table 5. Costs for lead-based paint removal.

Technology	Range $/sq ft	Average $/sq ft
Thermal Spray Vitrification (Projected)	3.50 - 12.00	5.00
Abrasive Blasting	5.00 - 18.00	8.00
Wet Abrasive Blasting	5.00 - 20.00	12.00
Vacuum Blasting	4.00 - 20.00	10.00
Water Blasting	4.00 - 20.00	13.00
Water Blasting with Abrasive Injection	4.00 - 19.00	9.00
Power Tool Cleaning To Bare Metal	5.00 - 15.00	7.00

7. Regulatory Issues

7.1 Approach to Regulatory Compliance and Acceptance

Personnel from Rock Island District contacted IL EPA about regulatory requirements related to the onsite remelting of vitrified waste during the Rock Island TSV demonstration. Corps personnel briefed IL EPA on the scope and purpose of the TSV demonstration and about previous laboratory and field test results. As a result of this discussion the IL EPA Division of Air Pollution Control classified the TSV process, including the glass remelting, as a repair/construction activity to be regulated as a standard lead-based paint cleaning operation. IL EPA does not require air quality permits for paint cleaning activities, and the IL EPA representative stated that, based on the type and amount of work to be done, the demonstration did not require a permit. A record of the telephone conference between Rock Island and IL EPA on this subject is attached in Appendix E.

The job contract called for the onsite remelting of the glass in order to make the waste nonhazardous and to permit disposal in a construction landfill. Remelting the glass for a minimum of 5 hours produced a nonhazardous waste, as determined by TCLP analysis, so the requirements of the job contract were satisfied.

For immersion applications discussed in Appendix F, additional surface preparation (at an additional cost) is required after application of the TSV process. Laboratory testing found that the residual lead on the surface after application of the TSV process did not contaminate the abrasive blast media and cause it to be classified as a hazardous waste. This waste, along with any remelted glass not recycled, could be disposed as a nonhazardous or special waste in an industrial landfill.

8. Technology Implementation

8.1 DoD Need

The estimated surface area of steel structures at Army facilities such as water tanks, bridges, aircraft hangars, antennas, ladders, poles, railings, catwalks, metal buildings, etc., is about 118 million sq ft. The total surface area of steel structures in the DoD is estimated at 200 million sq ft. The U.S. Army Corps of Engineers also has 275 navigation locks and dams and 383 other dams on lakes and reservoirs, which total an additional estimated 100 million sq ft of steel. Most of this steel is coated with red lead oxide primer to protect it from corrosion. Over the next 20 years this steel will have to be repainted. Based on data collected during the demonstration, the estimated cost of the TSV process to range from $3.50 to $12.00/sq ft with an average cost of about $5.00/sq ft. This is $3.00/sq ft less expensive than currently used abrasive blasting techniques, which average $8.00/sq ft. If it is assumed that 20 percent of DoD painted steel structures can be treated with the TSV process, the process is applicable to 60 million sq ft of steel. Based on a benefit of $3/sq ft, the estimated savings over the next 20 years to the DoD are $180 million.

8.2 Transition

8.2.1 Next step for this technology. The next demonstration of the technology is planned for Fiscal Year (FY) 98 on an aircraft hangar at the Marine Corps Base Hawaii, Kaneohe Bay, HI. The State of Hawaii does not have a hazardous waste landfill, so all hazardous waste must be shipped off the island, which significantly increases the cost of disposal. The TSV process yields a nonhazardous waste as determined by TCLP testing, and it would result in cost savings compared to existing technologies. An additional demonstration is scheduled in FY99 on a ship structure at the Puget Sound Naval Shipyard, Bremerton, WA.

8.2.2 How will the deficiencies identified above be addressed? By Whom? When? The TSV process will be modified by CERL before any future demonstrations to correct problems related to warping of thin substrate sections and the possibility of incomplete immobilization of the lead upon remelting. Warping of the substrate will be minimized by carefully regulating the amount of heat applied during the preheating stage of the TSV process. The temperature of these substrates can also be controlled by the use of forced air or wet forced air from the onsite compressors. Remelting of the vitrified waste will be conducted for a minimum of 5 hours to obtain full homogenization of the glass melt and complete the immobilization of the lead.

8.2.3 Recommendations for the best implementation pathway. The technology will be implemented by transferring it through a commercial firm that does lead paint removal, such as the one retained for this demonstration. Its economic viability will be determined through its success in competitively bidding paint removal projects. The Construction Solicitation and

Specification prepared for the Rock Island Bridge demonstration can be used as guidance for future lead paint removal projects.

8.2.4 Was industry involved during the demonstration? Will industry be interested in the technology if the demonstration is successful? The contractor who performed the demonstration was obtained through a competitive bid process. The contractor, Midwest Foundation, Tremont, IL, expressed interest in bidding on future paint removal contracts using the TSV process. Zatorski Coatings Co., East Hampton, CT, – a small business that was contracted to conduct the training for the demonstration – as well as other companies have also expressed interested in commercialization of the TSV process. A presentation will be made on the results of the demonstration to the DOT, Federal Highway Administration, Fairbanks Research Center as well as to the New York State DOT and other state DOTs.

8.2.5 Who will be responsible for the necessary actions, and when? Future actions will be the responsibility of the Principal Investigator, Dr. Ashok Kumar, U.S. Army Construction Engineering Research Laboratories (CERL). The second demonstration is scheduled for FY98 on an aircraft hangar at the Marine Corps Base Hawaii.

9. Lessons Learned

- The demonstration of the TSV process was successful in meeting all of the objectives: (1) removed lead-based paint in the field from a steel structure, (2) met all applicable environmental standards, (3) met all applicable worker health and occupational safety standards, (4) enabled recoating of the substrate using a surface-tolerant coating system, and (5) collected data and estimated production rates.

- When the TSV process is used in an enclosed containment structure or where the plume is inhibited by an overhead ceiling, as a minimum, workers should wear a NIOSH-certified pressure-demand or positive-pressure supplied-air respirator equipped with either a half-face or full-face piece. Note that these recommendations apply to all cases where the plume is inhibited, even when the process is not enclosed. When the plume is not able to escape freely it will return into the face of the worker in concentrations that require a higher level of worker protection than when the plume dissipation is uninhibited.

- When the TSV process is used in a well ventilated outdoor area where plume dissipation is uninhibited and heat shield is NOT used (i.e., the plume is not channeled away from the face of the workers), as a minimum, workers should wear a NIOSH-certified full-face air-purifying respirator equipped with HEPA filters. In addition, nitric oxide, NO_2, and CO should be monitored closely, and the level of respiratory protection should be increased if exposures exceed the threshold limit values or personal exposure limits.

- When the TSV process is used in a well ventilated outdoor area where plume dissipation is uninhibited and a heat shield is used (i.e., the plume is channeled away from the face of the workers), as a minimum, workers should wear a NIOSH-certified half-face air-purifying respirator equipped with HEPA filters.

- During onsite remelting of the cooled glass, as a minimum, workers should wear a NIOSH-certified half-face air-purifying respirator equipped with HEPA filters.

- Onsite remelting of the waste requires a minimum of 5 hours to ensure the homogenization of the glass and full immobilization of the hazardous species in order to render the waste nonhazardous as determined by RCRA.

- In future depainting of the treated surfaces of the demonstration structure, proper protection and testing of the workers would be required to verify that worker exposure to any residual lead on the surface was below the regulatory requirement.

- The amount of heat applied to the substrate during the preheat stage must be carefully monitored and controlled to avoid warping of the substrate.

- The production rate of the TSV process was estimated at 30 sq ft per hour, and the cost was estimated to range from $3.50 to $12.00/sq ft, with an average cost of $5.00/sq ft.

- The glass from the TSV process can be recycled using commercial processes that convert the waste into nonhazardous value-added glass or ceramic products such as abrasives, construction material, refractory insulating materials, or new glass powder for the TSV process. This recycling could reduce or eliminate the disposal of the glass waste from the TSV process, consequently reducing the associated costs.

- It is expected that the market for the TSV process would be a niche market including surface preparation for zone painting on a large structure, such as a bridge, or for small fixed structures such as fire hydrants, posts, railings, fence posts, flag poles, towers, etc.

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John Blazis
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Springfield, IL 62794-9276
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Appendix B: Data Archiving and Demonstration Plan(s)

Two copies of all electronic files relevant to the demonstration have been stored on diskettes or other permanent storage media. All electronic files and documents, including field notebooks, are stored at the U.S. Army Construction Engineering Research Laboratories, Champaign, IL. Copies of the approved demonstration plan can be obtained from the Principal Investigator, Dr. Ashok Kumar, U.S. Army Construction Engineering Research Laboratories, P.O. Box 9005, Champaign, IL 61826, 217-373-7235.

Appendix C: Figures

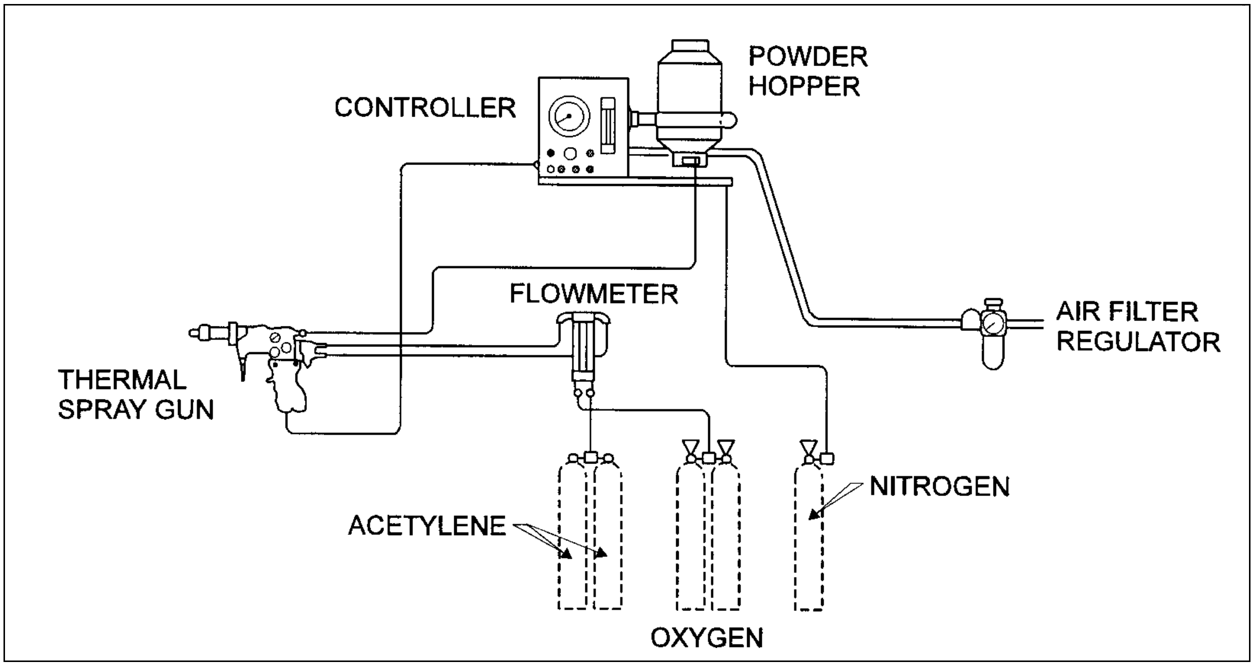

Figure C.1. Schematic of the thermal spray system.

Figure C.2. TSV technology in use to remove lead-based paint from the Viaduct Bridge at Rock Island Arsenal.

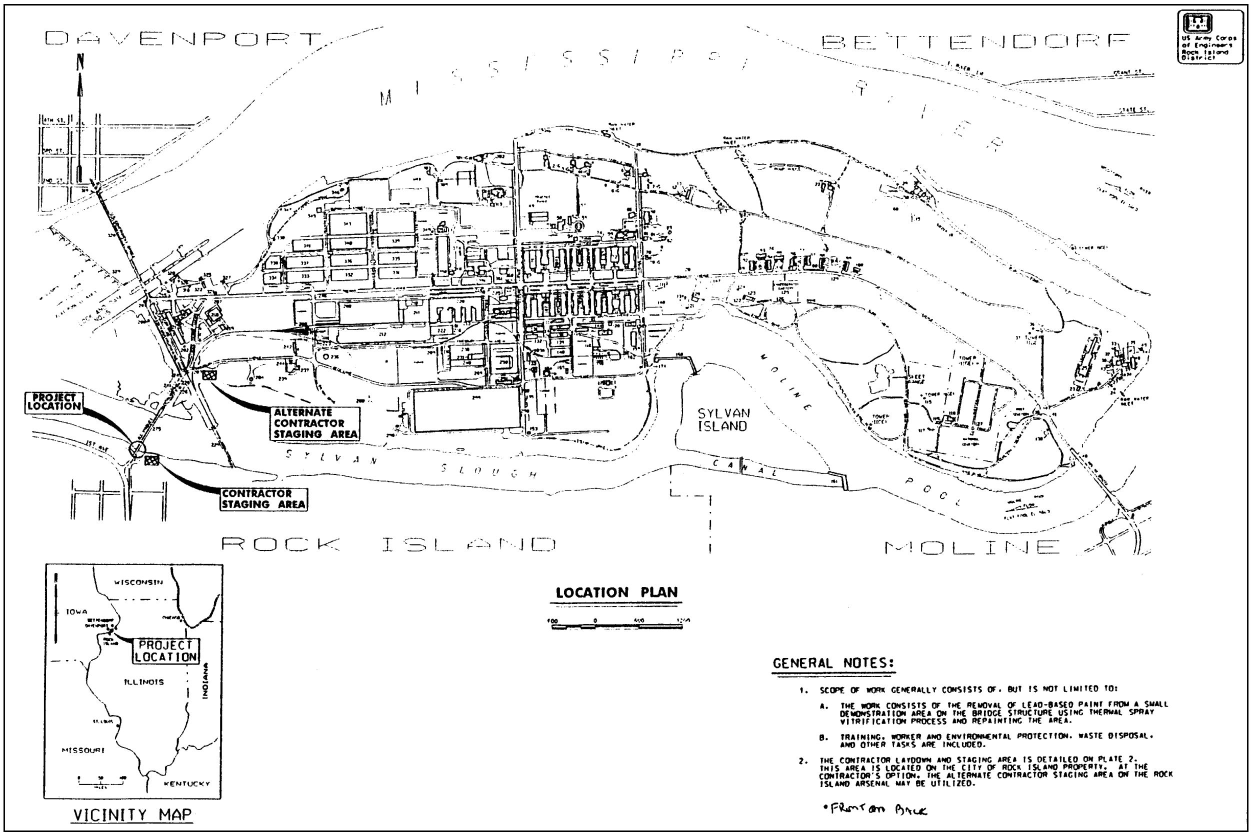

Figure C.3. Location plan of the Rock Island Arsenal.

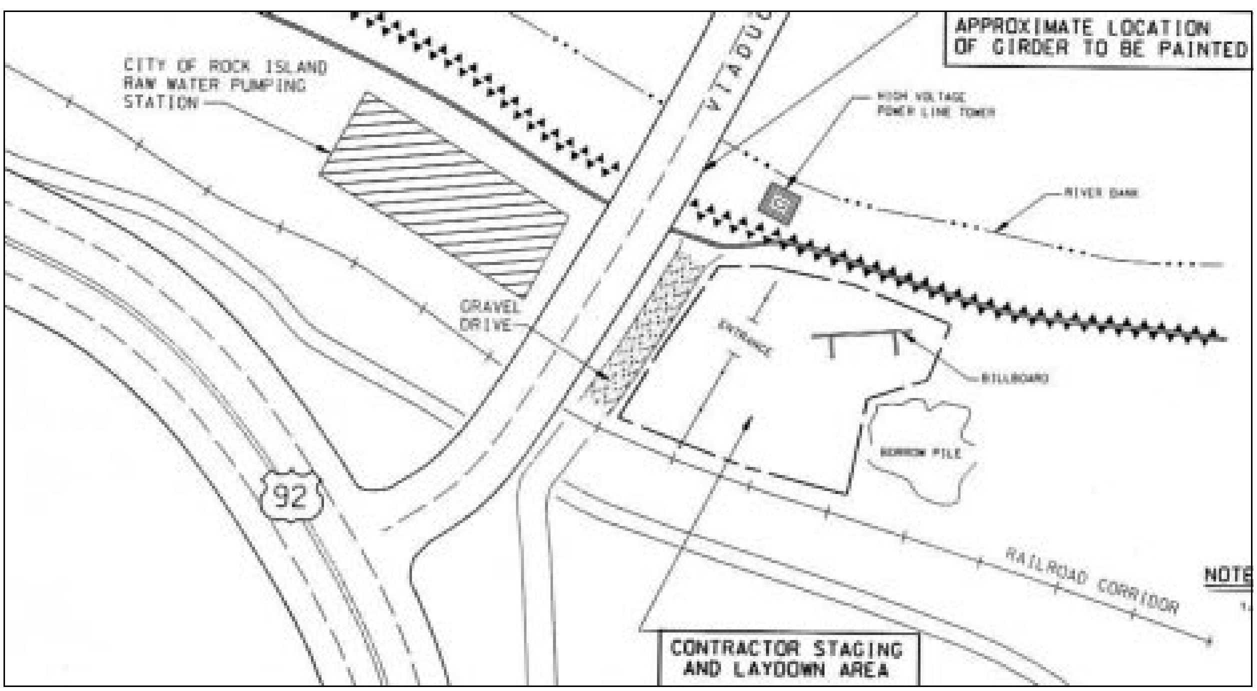

Figure C.4. Detailed location plan of the Viaduct Bridge.

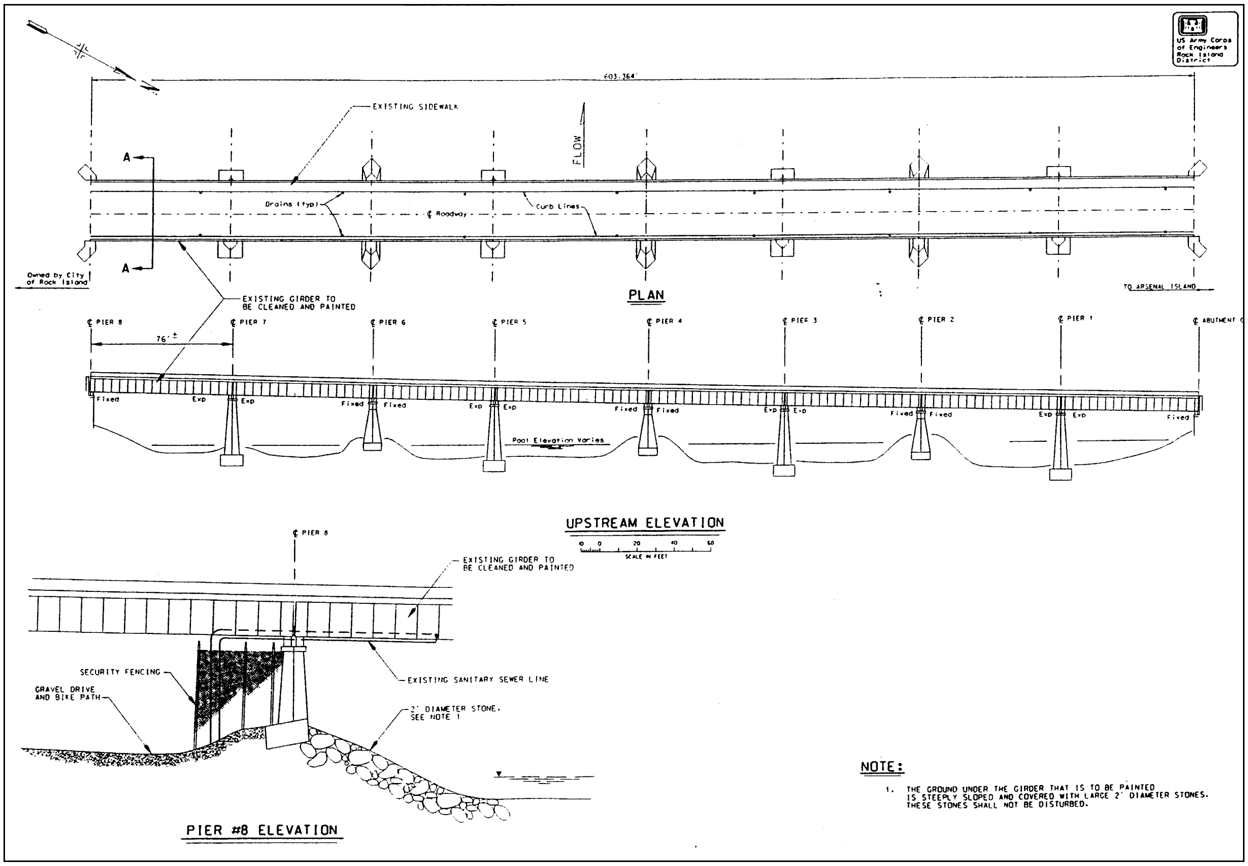

Figure C.5. Upstream elevation drawing of the Viaduct Bridge.

Figure C.6. Containment structure built for the demonstration.

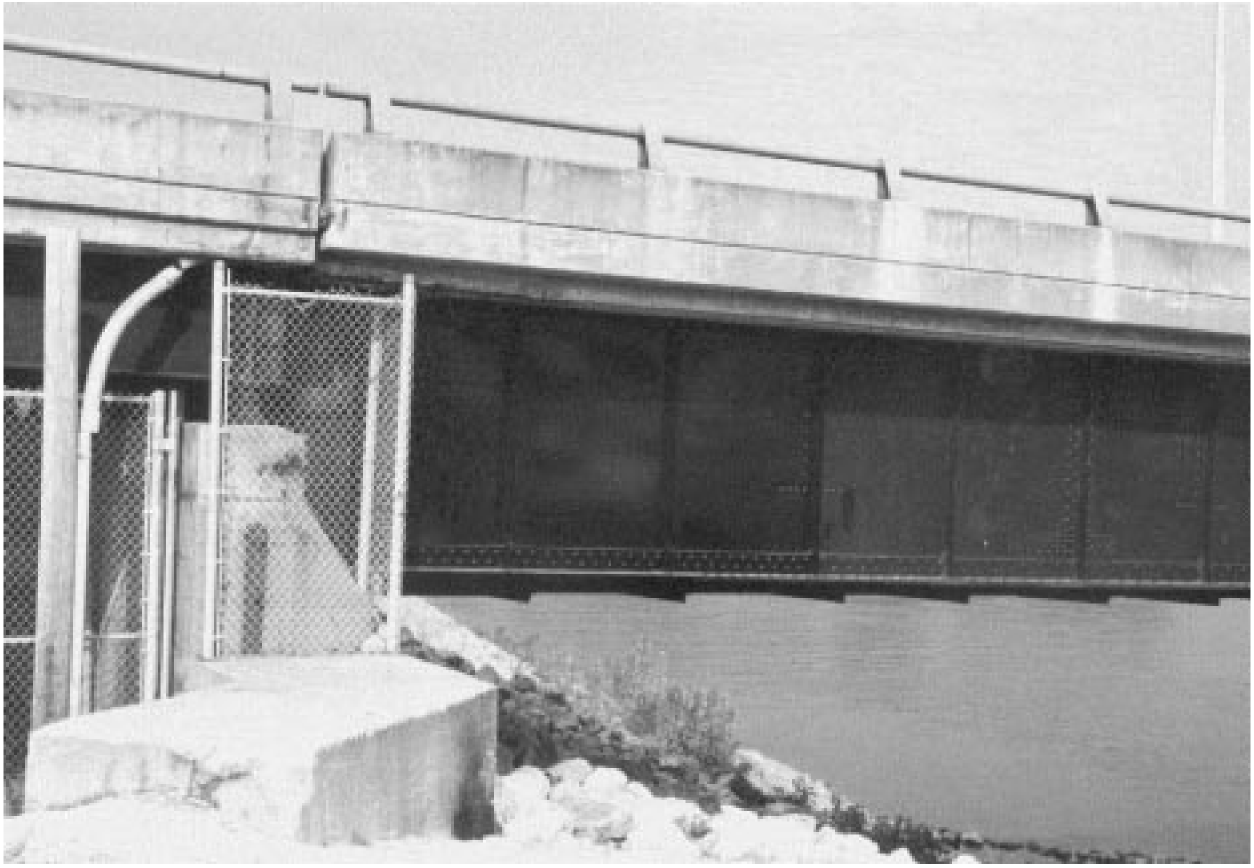

Figure C.7. The Viaduct Bridge after completion of TSV demonstration.

Appendix D: Field Data

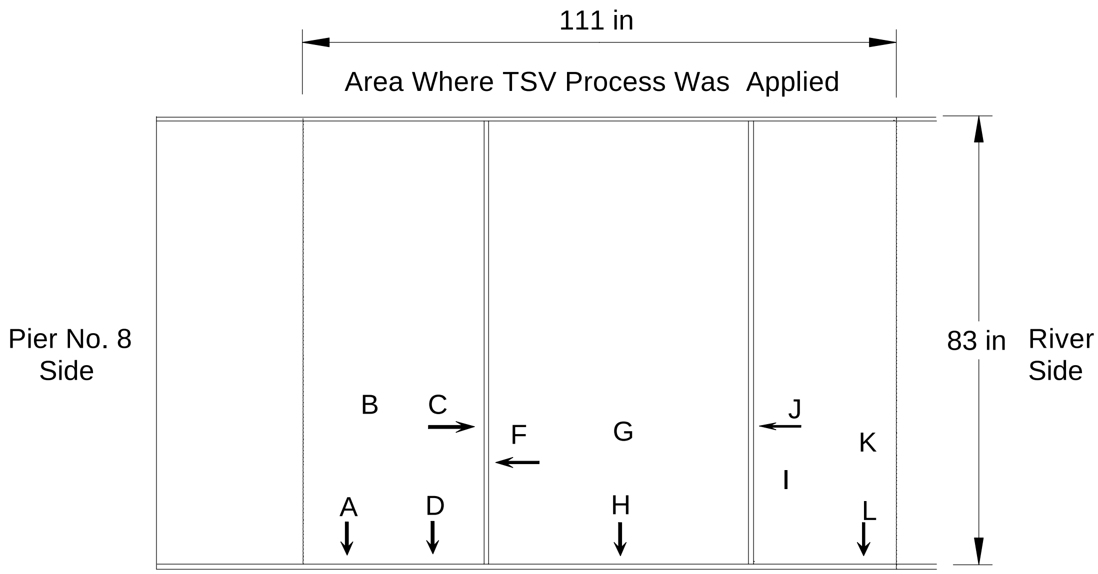

Figure D.1. Location of thickness measurements of existing paint system before application of TSV process (east side).

Table D.1. Thickness of existing paint system before application of TSV process (east side).

Location	Sample 1 (mils)	Sample 2 (mils)	Sample 3 (mils)	Average Thickness
A	11.8	10.4	9.5	10.6
B	4.7	4.3	4.4	4.5
C	6.7	7.1	7.3	7.0
D	5.0	5.5	6.3	5.6
E	3.5	3.2	3.1	3.3
F	2.3	2.2	2.6	2.4
G	5.5	6.7	5.4	5.9
H	18.1	19.6	15.7	17.8
I	7.1	6.0	6.4	6.5
j	6.3	8.3	7.6	7.4
K	9.8	9.0	7.6	8.8

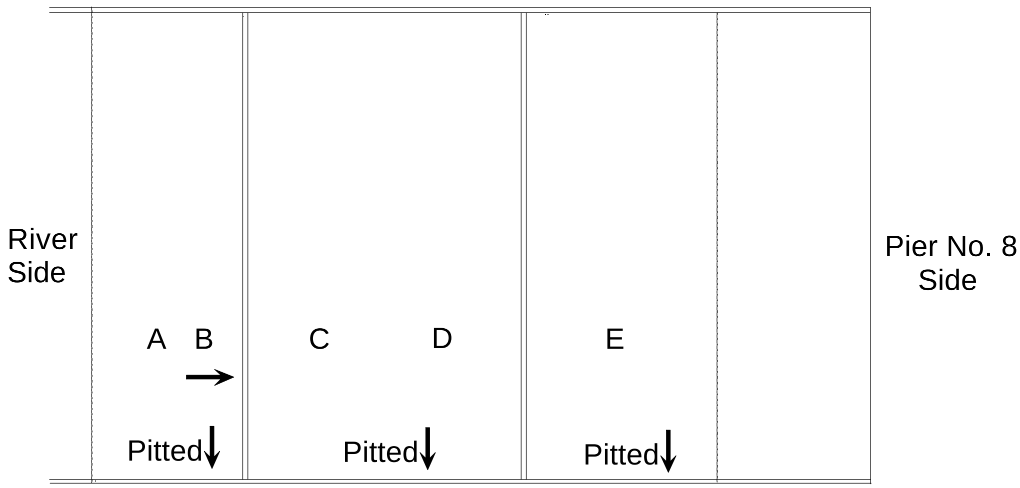

Figure D.2. Location of thickness measurements of existing paint system before application of TSV process (west side).

Table D.2. Thickness of existing paint system before application of TSV process (west side).

Location	Sample 1 (mils)	Sample 2 (mils)	Sample 3 (mils)	Average Thickness
A	3.4	3.1	3.5	3.3
B	7.2	6.4	4.6	6.1
C	4.3	4.4	4.1	4.2
D	3.5	3.1	3.2	3.3
E	3.1	3.3	3.5	3.3

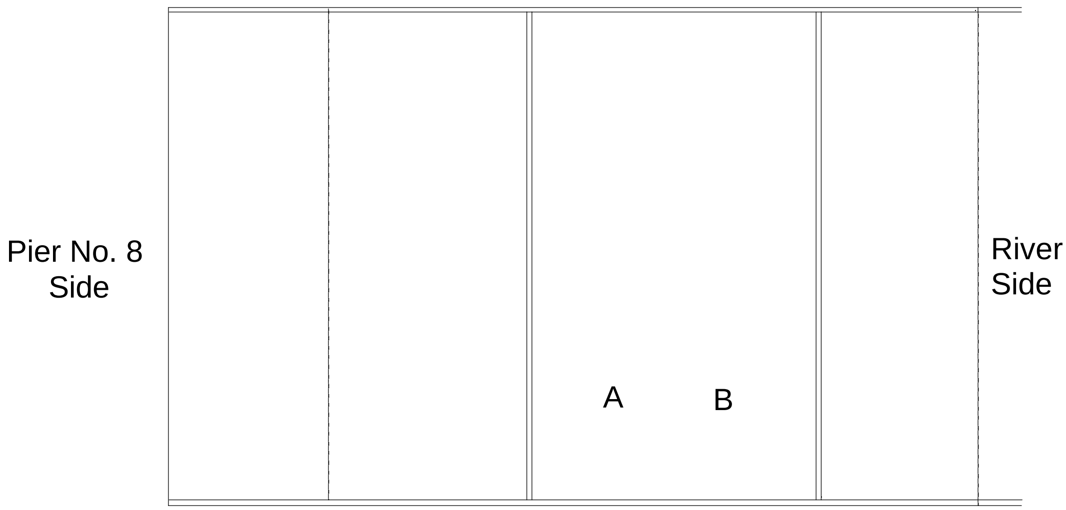

Figure D.3. Location of steel temperature measurements during application of TSV process.

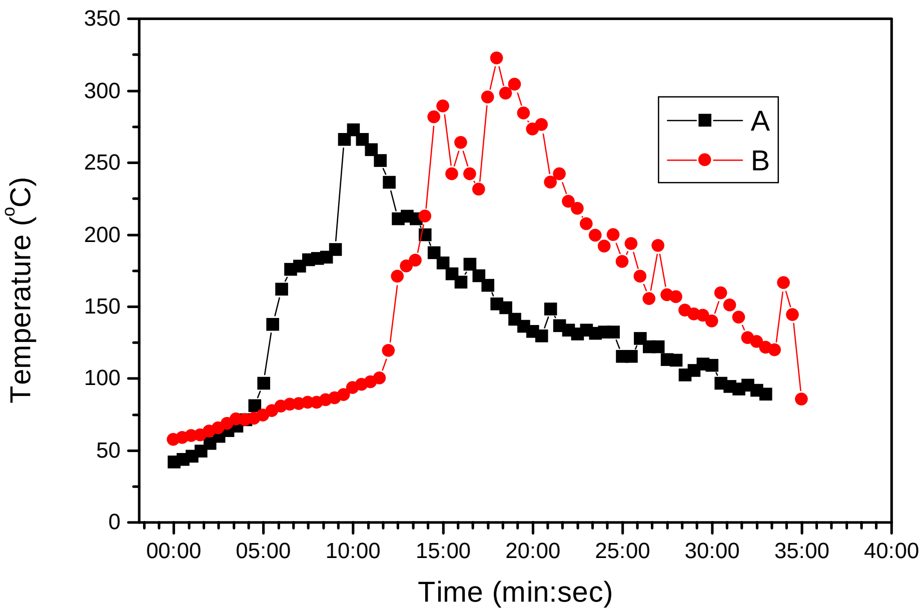

Figure D.4. Steel temperature measurements during application of TSV process.

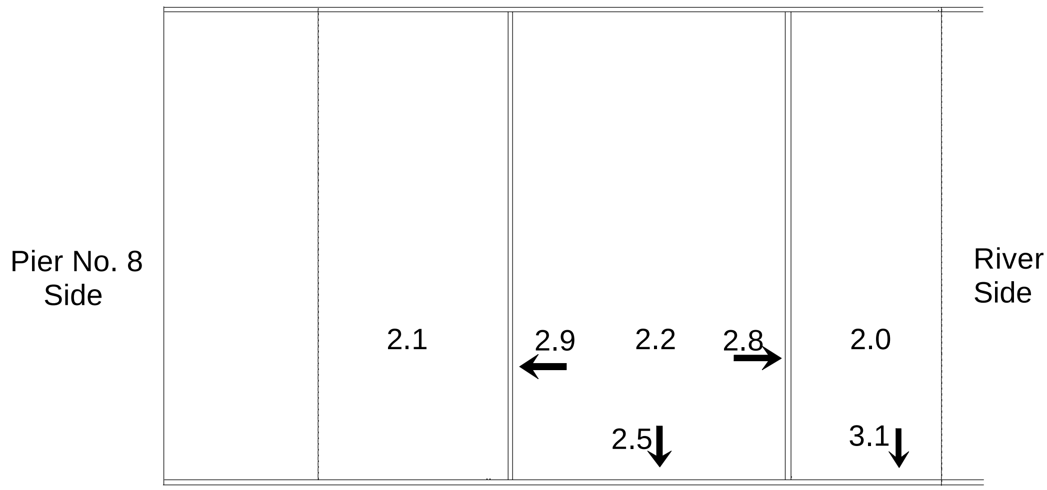

Figure D.5. Surface profile after application of TSV process in mils (east side).

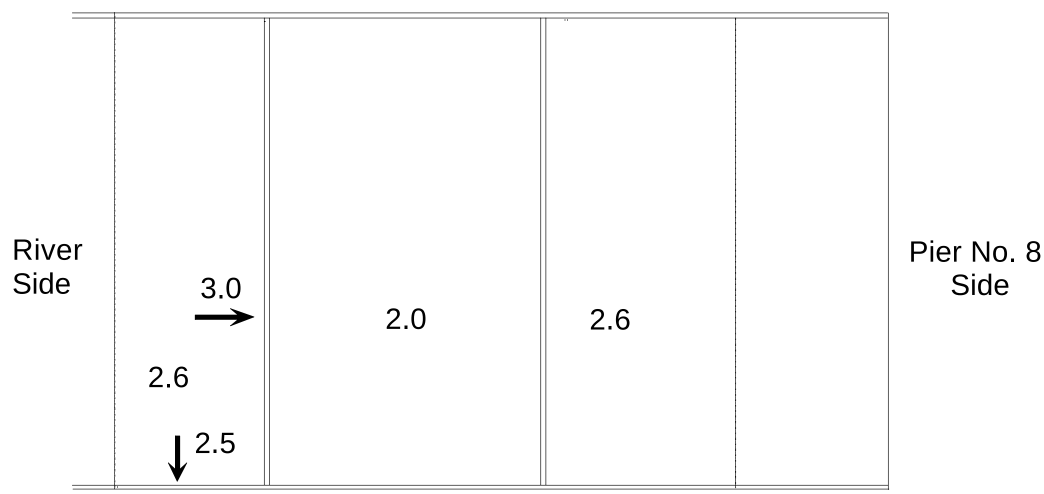

Figure D.6. Surface profile after application of TSV process in mils (west side).

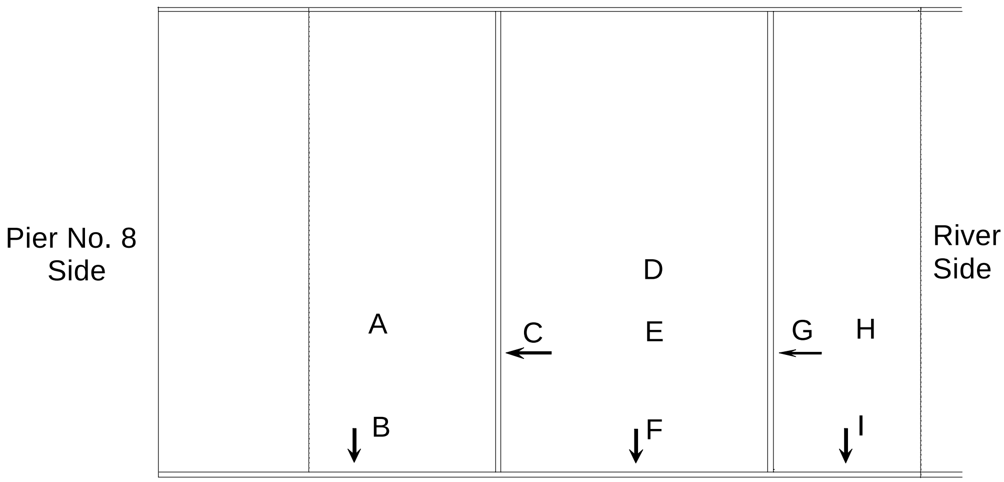

Figure D.7. Location of thickness measurements of the primer after application of TSV process (east side).

Table D.3. Thickness of primer after application of TSV process (east side).

Location	**Sample 1 (mils)**	**Sample 2 (mil)**	**Sample 3 (mils)**	**Average**
A	2.4	2.2	1.9	2.2
B	4.3	4.4	4.7	4.4
C	2.6	2.5	2.0	2.4
D	1.5	1.8	1.8	1.7
E	2.5	2.4	2.7	2.5
F	4.3	3.6	2.4	3.4
G	3.3	3.2	3.9	3.4
H	2.5	2.1	2.8	2.5
I	1.7	1.8	2.1	1.9

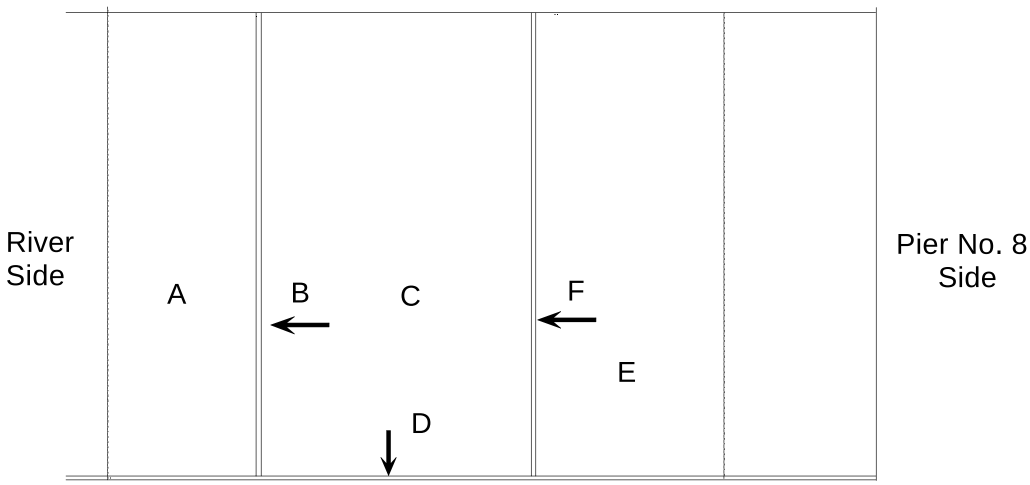

Figure D.8. Location of thickness measurements of the primer after application of TSV process (west side).

Table D.4. Thickness of primer after application of TSV process (west side).

Location	Sample 1 (mils)	Sample 2	Sample 3 (mils)	Average
A	2.6	2.3	2.2	2.4
B	3.0	2.7	2.2	2.6
C	2.8	2.8	3.0	2.9
D	6.0	8.8	6.6	7.1
E	1.7	2.8	2.6	2.4
F	2.3	2.5	2.0	2.3

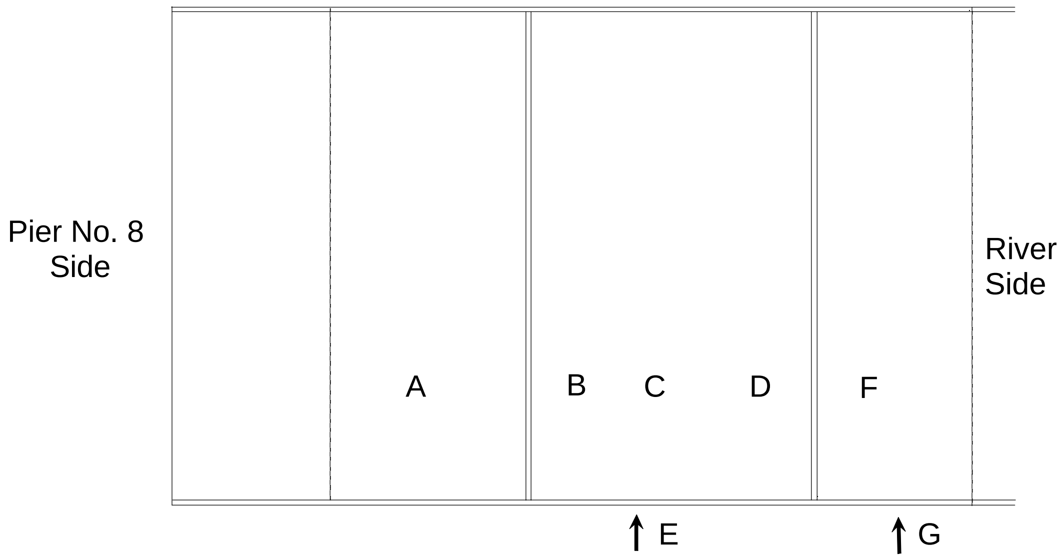

Figure D.9. Location of thickness measurement of primer plus topcoats after application of TSV process (east side).

Table D.5. Thickness of primer plus topcoats after application of TSV process (east side).

Location	**Sample 1 (mils)**	**Sample 2 (mil)**	**Sample 3 (mils)**	**Average**
A	8.2	8.4	7.4	8.0
B	6.4	6.4	6.6	6.4
C	6.6	6.4	7.7	6.9
D	7.1	8.3	7.4	7.6
E	6.6	7.6	6.2	6.8
F	6.3	6.1	6.0	6.1
G	8.3	8.4	8.5	8.4

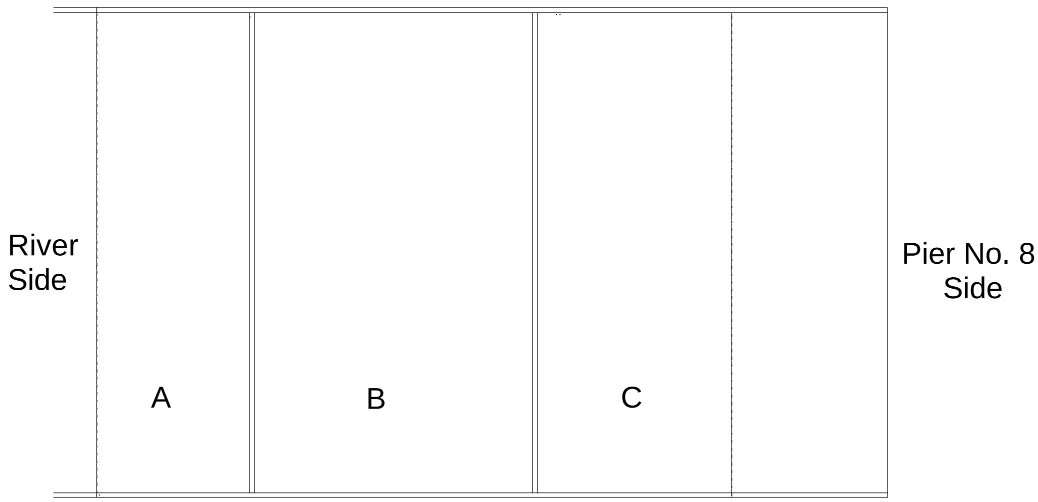

Figure D.10. Location of the thickness measurements of primer plus topcoat after application of TSV process (west side).

Table D.6. Thickness of primer plus topcoats after application of TSV process (west side).

Location	Thickness (mils)	Thickness (mil)	Thickness (mils)	Average Thickness (mils)
A	5.0	6.0	5.3.	5.4
B	6.4	6.0	7.6	6.7
C	5.6	7.7	8.3	7.2

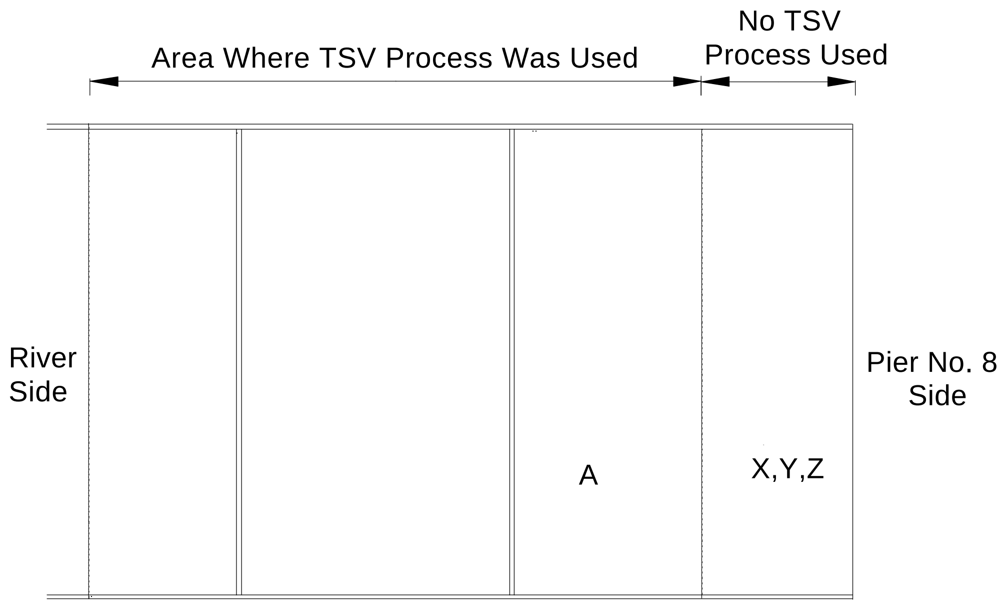

Figure D.11. Location of measurements for lead concentration using x-ray fluorescence spectroscopy with and without application of the TSV process (west side).

Table D.7. Lead concentration using x-ray fluorescence spectroscopy after application of TSV process (west side).

Location	**Instrument Sample No.**	**TSV Process Used**	**Lead Conc. mg/cm2**
A	107.6	Yes	2.12
X	107.7	No	4.70
Y	107.8	No	4.71
Z	107.9	No	5.84

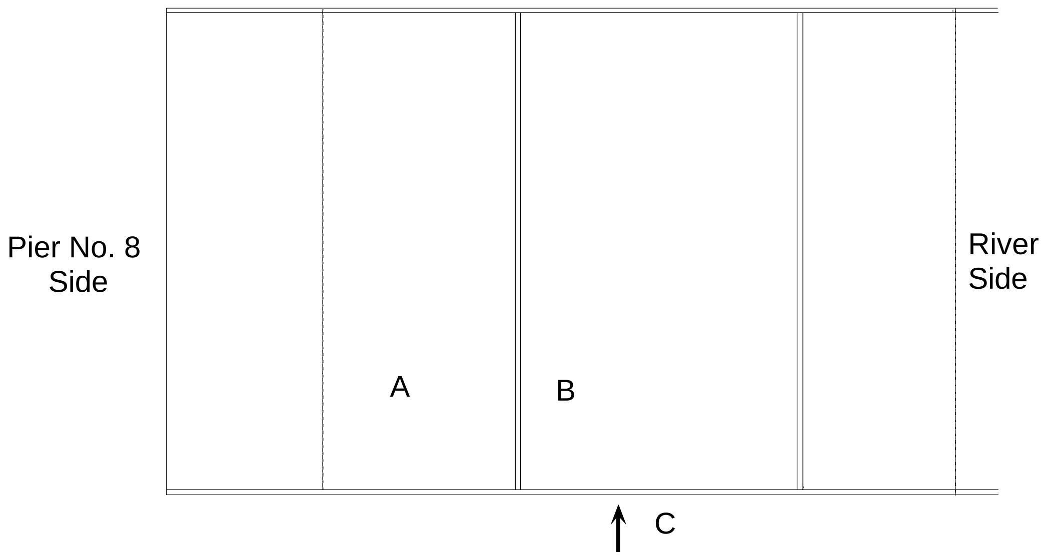

Figure D.12. Location of measurements for lead concentration after application of the TSV process.

Table D.8. Lead concentration using x-ray fluorescence spectroscopy after application of the TSV process (east side).

Location	Instrument Sample No.	Lead Concentration. (mg/cm^2)
A	107.2	1.03
B	107.3	2.32
C	107.5	1.46

Appendix E: Memorandum on the IL EPA

CONVERSATION RECORD	TIME 1035	DATE 21 May 1997		
TYPE ☐ VISIT ☐ CONFERENCE [X] TELEPHONE ☐ INCOMING [X] OUTGOING Location of Visit/Conference:			ROUTING NAME/ SYMBOL	INI
NAME OF PERSON(S) CONTACTED OR IN CONTACT WITH YOU Mr. John Blazis	ORGANIZATION (Office, dept., bureau, etc.) ILEPA, Division of Air Pollution Control	TELEPHONE NO: (217) 782-2113		
SUBJECT CERL VITRIFICATION DEMONSTRATION PROJECT - AIR PERMIT				

SUMMARY

I informed Mr. Blazis about the scope and purpose of the thermal spray vitrification demonstration project (the extent of the work (150 SF), the previous tests that were performed during laboratory and field work, etc.). After his asking a lot of questions about the process and how we planned to address air emissions control, he stated that the Division of Air Pollution Control would treat our glass remelter as a repair/construction activity and regulate it as they would a lead-based paint cleaning operation. ILEPA does not require air permits for paint cleaning activities (such as the upcoming water tower project on RIA). Mr. Blazis stated that our work would also not require an air permit, based on the type and amount of work.

Note: Earlier discussions with ILEPA, Division of Air Pollution Control, did not result in any type of decision being given regarding the need to acquire a permit. Previously, I was cut short and asked to submit two separate permit applications and all of the background information in writing and then the ILEPA would review the remelting process.

ACTION REQUIRED

Inform ED-DF, ED-DN, ED-DE, ED-C, and CERL of the fact that a permit is not required. Letters will be sent to ILEPA's Division of Air Pollution Control and Bureau of Land stating that permits are not required. Bureau of Land correspondence and guidance will be followed. Background information will be included.

NAME OF PERSON DOCUMENTING CONVERSATION	SIGNATURE	DATE
Kenneth G. Barnes		21 May 1997

ACTION TAKEN

SIGNATURE	TITLE	DATE

CONVERSATION RECORD **OPTIONAL FORM 271 (12-76)**
DEPARTMENT OF DEFENSE

Appendix F: Laboratory Testing of the Thermal Spray Vitrification of Epoxy-Polyamide Paints for Navy Ship Structures

by

Ashok Kumar and Jeffrey Boy

U.S. Army Construction Engineering Research Laboratories (CERL)

Champaign, IL

Stephen Hobaica

Naval Surface Warfare Center

Carderock Division

Bethseda, MD

F.1 Introduction

Red lead primer has been used on many steel structures, including ships, to control corrosion. When old paint starts to peel, removal of the paint may be required before repainting. The most common method of removing paint from Navy ship structures has been the use of a dense abrasive blast media. A collateral benefit of abrasive blasting is its tendency to roughen the surface, creating an anchor profile for repainting the structure. While the method is highly effective and the procedure itself is cost-effective, abrasive blasting creates large amounts of hazardous dust and waste material. The waste stream consists of small particles of paint and abrasive blast media that is partially fragmented and a significant portion of that paint and abrasive blast media becomes airborne dust. In removal of lead-based paint (LBP) systems, the presence of lead particles in the airborne dust and waste media creates an environmental risk that must be contained. The U.S. Environmental Protection Agency (EPA) requirements mandate the use of containment structures to prevent the contamination of air, soil, or water. Inside the containment structures, stringent requirements must be met to protect the workers from the high concentration of lead dust [1].

Regulations that require the monitoring of exposed workers and the release of hazardous materials have greatly increased the cost of lead-based paint removal. When EPA's Toxicity Characteristic Leaching Procedure (TCLP) reveals that concentrations of hazardous species in the leachate from lead-based paint removal wastes exceed the regulatory limits, a licensed special waste hauler must be employed to remove the material from the site and deliver it to a licensed hazardous material disposal site [2]. Even if the waste material ultimately is found to be nonhazardous, the administrative and testing requirements add substantial costs to the overall project. Furthermore, the costs of worker health and environmental monitoring also dramatically increases the cost of LBP removal, sometimes exceeding the cost of disposal by a factor of five [3]. Innovative technologies that could effectively remove LBP from ship structures while rendering the wastes nonhazardous would be highly beneficial. One excellent candidate technology is thermal spray vitrification (TSV) [4]. This process was patented by Kumar and Patreanu and assigned to the U.S. Army [5].

The nonhazardous vitrified product may have potential use as feedstock in other glass/ceramic products. According to the recycling exemption of the Resource Conservation and Recovery Act, the vitrified product would not be classified as solid waste if it is used or reused as an ingredient in an industrial process to make a product. Recycled products currently under investigation by Seiler Pollution Control System, Inc., Dublin, OH, include abrasive grit blasting media and architectural materials [6]. The reuse of the vitrified product as feed material for the TSV process is also under investigation.

Until recently, testing of lead-based paint by CERL has been restricted to a system of aluminum phenolic topcoat (TT-P-38E) and red lead alkyd primer (TT-P-86H). In response to U.S. Navy interest in removal of lead-based paint from ships, lead containing epoxy-polyamide paints were tested to ensure that no significant differences in performance and safety procedures existed compared to alkyd paint systems. This included laboratory samples and a section of a painted steel structure cut from a Navy ship at the Puget Sound Naval Shipyard, Bremerton, WA.

F.2 Experimental Procedure

F.2.1 Laboratory Samples Sample plates (4 x 6 x 1 in.) were painted with a minimum of 12 mils of a lead containing epoxy paint (MIL-P-24441). The TSV process was used to remove paint as described below. Air sampling was conducted throughout these tests. The air monitor was a Mine Health and Safety Administration (MHSA) approved Sensidyne Model 44 air sampling pump, fitted with collection cartridges supplied by Kemper Laboratory (NATLSCO). The collection cartridge was placed in the exhaust stream of the hood where work was performed. The equipment used was a Praxair (Miller) Thermal mechanical powder feeder Model 1264, modified to accept a Sulzer Metco 6P-II-H spray gun with a P7C-K nozzle. The powder feeder contained borosilicate glass powder (Table E.1), with -230 to +100 mesh particle size (nominal 0.1 mm).

The substrate was preheated with an acetylene-rich (reducing) flame until a black coating appeared over the whole sample using the processing conditions listed in Table E.2. Using a normal flame, preheating continued until the temperature reached approximately 200 °C at which point the actual vitrification process was begun. The powder feeder was activated and molten glass laid down. The glass was allowed to slough off and showed a tendency to do so. Glass application continued until glass adhered to the substrate. Then the sample was allowed to cool enough for glass to spall. If the spalling process left an area of glass adhered to substrate, a scraper was used to release it. The preheat/glass application was repeated a second time. The glass and paint were collected for remelt using the furnace. TCLP analysis was conducted on the remelted glass and the remaining remelted glass was properly disposed.

F.2.2. Ship Structure Plates The Puget Sound Naval Shipyard, Bremerton, WA, cut painted steel plates from a Navy ship. The procedure described above for the thermal spray vitrification process was used to remove the paint from the ship structure plate. The steel plate from the Navy ship structure was 5/8 in. thick and was approximately 15 x 18 in. The thickness of the paint ranged from 10 to 40 mils.

Table F.1. Glass composition.

Species	**Wt. %**
SiO_2	54.1
B_2O_3	6.8
Al_2O_3	4.1
Na_2O	10.3
Li_2O	4.7
MnO_2	2.9
NiO	0.9
CaO	1.5
MgO	0.8
Fe_2O_3	12.3
ZrO_2	1.2

Table F.2. Gas pressures and flow rates to the spray gun.				
	Normal Flame		**Reducing Preheat Flame**	
Material	**Pressure (psi)**	**Flow Rate (%)**	**Pressure (psi)**	**Flow Rate (%)**
Oxygen	45	42	45	10
Acetylene	14	50	14	50
Compressed Air	5	N/A	5	N/A
Glass powder	N/A	89 g/min	N/A	N/A

The suitability of steel to be abrasively blasted after application of the TSV process was investigated in the laboratory. Lead-based-paint was removed using the TSV process from a steel specimen from a highway bridge coated with a red lead primer and alkyd topcoat. Although the surface was suitable for repainting with a surface tolerant system, there is the possibility that some residual lead may remain on the surface. Subsequent abrasive blasting may contaminate the blast media creating a waste that would be classified as hazardous. In the laboratory test, new abrasive blast media was used to clean the specimen after application of the TSV process. The mineral abrasive, Black Beauty (Reed Mineral Corp.), is used by the Navy for abrasive blasting of ships and was used in this test. TCLP analysis was then conducted on the blast media.

F.3 Results and Discussion

The TSV process was successful in removing the Navy paint system, Mil P 24441 epoxy polyamide paint containing lead pigments, from laboratory samples. The surface quality was suitable for repainting with a surface-tolerant system after cleaning described in Steel Structures Painting Council (SSPC) SP-3 [7]. It is noteworthy that much relatively loose debris remained on the plate after the glass spalled. The amount of glass used in the TSV process for the removal of epoxy-polyamide paint was similar to that previously found to be necessary for the removal of phenolic and alkyd paints, which is about 1/2 lb of glass per sq ft. Results of the air monitoring showed that the TSV process did not exceed the regulatory standards for airborne lead. Airborne lead concentrations were less than 10 $\mu g/m^3$ (Table E.3). TCLP analysis showed that the concentration of lead in the leachate was less than 1.5 mg/L for the remelted glass, below the EPA regulatory standard of 5 mg/L. This is consistent with previous results of TCLP analysis of remelted glass obtained by the TSV process for removal of phenolic and alkyd paint systems.

The TSV process was also successful in removing the Navy paint system, Mil P 24441 epoxy-polyamide paint, from the ship structure plates. The resulting surface was suitable for repainting using a surface tolerant coating system which would be suitable for non-immersion applications.

Table F.3. Results of environment monitoring.		
Test	**Results**	**Regulatory Standard**
TCLP analysis of remelted glass	1.5 mg/L	5.0 mg/L
Airborne lead concentration	Less than 10 $\mu g/m^3$	50 $\mu g/m^3$

For immersion applications, more durable paint systems that are not surface tolerant must be used. These paint systems require the steel surface be abrasively blasted after application of the TSV process. The possible presence of residual lead on the surface may contaminate the abrasive blast media used to prepare the surface. The initial concentration of lead on the painted steel measured using an X-ray fluorescence analyzer was 12.54 mg/cm^2. Following the application of the TSV process, the concentration of lead on the steel was less than 1.0 mg/cm^2. Three passes of the TSV process was used to remove the lead-based paint such that there was no visual evidence of paint remaining on substrate. Laboratory testing found that 5 lb of Black Beauty mineral abrasive were required per sq ft of the surface that was abrasively blasted. After abrasive blasting of the steel specimen, TCLP analysis of the media found it to leach less than the regulatory limit of 5 mg/L Pb, Table E.4. Therefore, the TSV process followed by abrasive blasting can be used to prepare surfaces for the painting with a full range of paint systems. As previously indicated, the TSV process can be used to remove lead-based paint from ship structures that are repainted with a surface tolerant coating system. The TSV process is also suitable for ship structures that are going to be demolished without further repainting.

F.4 Comparison to Hydroblasting

A demonstration of the thermal spray vitrification process was provided on 23 September 1977 by USACERL for Mr. Stephen Hobaica of the Naval Surface Warfare Center and Mr. Ray Travis, Mr. Richard Olsen and Mr. Mel Herbstritt of the Puget Sound Navy Shipyard. The advantages and disadvantages of the thermal spray vitrification process were discussed in comparison with the hydroblasting process. Applications where the thermal spray vitrification process would address Navy needs were determined. The hydroblasting process uses high pressure water to remove lead-based paint and has been tested at the Puget Sound Naval Shipyard and is shown in Figure E-1. The hydroblasting process can be used only on the outside of the ship on the hulls, while the thermal spray vitrification process can be used both inside and outside of the ship hulls. Vitrification stabilizes the lead and other hazardous metals so that they can be disposed as nonhazardous waste. This is in contrast to the hydroblasting process which does not stabilize the hazardous metals and results in the entire volume of water used in the process being contaminated and classified as hazardous waste. The production rate for

Table F.4. TCLP of abrasive blast media used on TSV-cleaned steel specimens.		
	TCLP Analysis for Pb	**Regulatory Limit**
Sample A	0.20 mg/L	5.0 mg/L

vitrification is much slower (30 sq ft per hour) than for the hydroblasting process (200 sq ft per hour). Overall the two technologies are complimentary because the vitrification process can be used inside the ship and in tight spaces and the hydroblasting process can be used on large flat areas of the ship hull.

F.5 Conclusions

The TSV process was successful in removing lead-containing epoxy-polyamide paint from laboratory samples. The TSV process was also successful in removing epoxy-polyamide paint from Navy ship structure plates. The result of air monitoring during lead paint removal using the TSV process was 10 $\mu g/m^3$, below the regulatory standard of 50 $\mu g/m^3$. The result of TCLP analysis of the remelted glass was 1.5 mg/L, below the regulatory standard of 5.0 mg/L. The environmental advantages of the TSV process are similar for epoxy, phenolic, and alkyd paint systems. TCLP analysis of abrasive media used to clean the steel surface after application of the TSV process leached less than the regulatory limit of 5 mg/L Pb. The advantages of the TSV process compared to the hydroblasting process are that the TSV process can be used inside the ship and the resulting TSV waste is nonhazardous.

F.6 Recommendations

1. For immersion application on Navy ships, the TSV process can be used to remove lead-based paint followed by subsequent abrasive blasting to prepare the surface for painting.

2. For air exposure applications on Navy ships, the TSV process can be used to remove lead-based paint and followed by painting with a surface tolerant coating system.

3. For ship structures that are to be demolished and not repainted, the TSV process can be used to remove lead-based paint.

4. A full demonstration and validation of the TSV process for Navy ship structures should be conducted at the Puget Sound Naval Shipyard as scheduled in FY99.

F.7 References

1. S. Covey, L. Lattimore, and A. Kumar, "Vitrification and Removal of Lead-Based Paint for Steel Structures," Advances in Thermal Spray Science & Technology: Proc. 8th National Thermal Spray Conference, C.C. Brendt and S. Sampeth, eds, American Society for Metals (ASM) International, Materials Park, OH, 1995, pp 605-614.

2. Code of Federal Regulations (CFR), Title 40, Part 261, U.S. Environmental Protection Agency Method 1311, "Toxicity Characteristic Leaching Procedure."

3. L. Smith, G. Tinklenberg, and J. Peart, "The Cost of Lead-Based Paint: A Federal Highway Study," Journal of Protective Coatings and Linings, Steel Structures Painting Council, January 1996, pp 56-65.

4. J. Petreanu and A. Kumar, "Deleading Paint by Vitrification Using Thermal Spray Technology," Thermal Spray Coatings: Research, Design and Applications, C.C. Berndt and T.F. Bernecki, eds, ASM International, 1993, pp 629-634.

5. A. Kumar and J.P. Petreanu, "Removal of Lead-Based Coatings by Vitrification," U.S. Patent No. 5,292,375 (8 March 1994).

6. R.D. Blume, C.H. Drummond, and A. Sarko "High Grade Abrasive Product Development from Vitrified Industrial Waste," to be published in the Proceedings of the American Ceramic Society, International Symposium on Environmental Issues and Waste Management Technologies in Ceramic and Nuclear Industry, Indianapolis IN, April 1996.

7. "Systems and Specifications, Steel Structures Painting Manual, Vol. 2," Steel Structures Painting Council, Pittsburgh, PA (1985).

Figure F.1. Hydroblasting of a ship hull.

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