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Lead-Based Paint Hazard-Mitigation Technologies: Final Report

David Booth, Richard Hollinger, L. D. Stephenson, and Ashok Kumar

Lead-based paints (LBP) and primers have been used in the past by the Department of Defense (DoD) to protect steel structures from corrosion. DoD owns about 200 million sq ft of steel structures with lead-based paint (such as bridges, aircraft hangars, water tanks, etc.). The DoD also owns about 2 billion sq ft of pre-1978 buildings with some lead-based paint. Cost-effective procedures for risk assessment, interim controls, and abatement need to be provided to DoD users for a lead hazard free environment.

The U.S. Army Construction Engineering Research Laboratory (CERL) has developed and demonstrated cost-effective environmentally compliant technologies for management and safe removal of LBP hazards from steel and wood. These include (1) thermal spray vitrification technology, which can be used safely and effectively for removal and immobilization of paints containing heavy metals; (2) an integrated "Lead Hazard Mitigation and Management System" (Painter-L); (3) emerging environmentally acceptable technologies for LBP removal; and (4) a microwave-assisted system for removal of LBP from wooden substrates.

This report summarizes the results of these four work tasks, which were supported wholly or in part by the multiagency Strategic Environmental Research and Development Program (SERDP).

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The work was performed by the Materials and Structures Branch (CF-M) of the Facilities Division (CF), U.S. Army Construction Engineering Research Laboratory (CERL). The CERL Principal Investigator was Dr. Ashok Kumar. Richard Hollinger is with HVS Technologies, Inc. A portion of this work was supported by an appointment to the Research Participation Program at CERL administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the Department of Energy and CERL. Dr. Ilker Adiguzel is the Chief, CF-M, and L. Michael Golish is Facilities Division Chief, CF. The CERL technical editor was Gordon L. Cohen, Information Technology Laboratory.

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Introduction

Problem Statement

The DoD has used lead-based paint in the past for steel structures and for buildings. The removal of this paint creates hazardous dust and waste. The DoD owns about 2 billion sq ft of buildings coated with some lead-based paint and about 200 million sq ft of steel structures coated with lead-based paint, such as aircraft hangars. In addition, Navy ships have lead, chromium, and copper in some coatings.

The Army owns 95,400 target facilities in the United States and 26,200 in foreign countries. The average age of these facilities is 36 years; 90,000 were built before 1978 and probably contain lead-based paint. Furthermore, about 2600 of these facilities are on or eligible for the National Register of Historic Places, and require special procedures for preservation. The goal of Army policy in this connection is to provide safe and healthful living and working environments. Lead-contaminated paint and dust can cause hazards in and near Army residential properties, child-occupied facilities, and nonresidential buildings constructed before 1978. Cost-effective procedures for risk assessment, interim controls, and abatement are needed by Army users to help ensure a lead-hazard-free environment. The Army's approach is to organize lead-hazard teams, conduct targeted blood screening, identify lead hazards, establish a lead-hazard management plan, implement interim controls, and develop plans to conduct cost effective abatement.

Three important Federally driven programs related to this requirement are:

- prevention of childhood lead poisoning
- prevention of overexposure of workers to lead
- characterization and proper disposal of lead-contaminated debris.

Existing technologies for routine maintenance, interim control, and abatement of lead hazards are often inefficient and costly. In addition, they may actually expose children and workers to lead hazards and contaminate the environment through improper controls during abatement and disposal.

Numerous steel structures such as water tanks, bridges, aircraft hangars, antennas, ladders, poles, railings, catwalks, fire hydrants, fuel storage tanks, and metal buildings were constructed or installed with lead-based coatings. The removal of lead-based paint from steel structures is currently accomplished through a variety of methods, the most common being abrasive blasting. Prior to recoating steel structures, abrasive blasting is required in order to remove the old lead-based paint and to provide adequate surface profile for bonding the new paint to the substrate. During abrasive blasting, a tight containment structure is required to prevent lead dust from contaminating air, soil, or water. Inside such containment structures, increased worker protection is required due to high lead dust concentrations. The large, concentrated volume of waste generated by abrasive blasting is hazardous and requires additional stabilization treatment prior to disposal.

The most common method for removal of lead-based paint from nonsteel buildings is chemical stripping. The waste generated by these operations is often hazardous due to the toxicity and leachability of lead. In addition, chemical strippers also introduce substances such as trichloroethylene, phenol, xylene, methylene chloride, and methyl ethyl ketone that are considered hazardous wastes under the Resource Conservation and Recovery Act (RCRA).

The total cost of Army-wide lead abatement would be prohibitive using conventional methods, especially considering the large stock of older Army facilities. Cost-effective technologies are needed by Army property owners to control and abate sources of lead hazards exposure and contamination as well as to safely remove, characterize, handle, store, transport, and dispose of lead-contaminated debris.

Innovative lead-abatement technologies and management systems, such as thermal spray vitrification, the Lead-Based Paint Hazard Management System (Painter-L), new environmentally acceptable chemical strippers and alternative blast media, and microwave-assisted paint removal have potential to reduce the cost of lead hazard control and abatement for DoD.

Objectives

The overall objective of this work unit was to develop and test cost-effective technologies for management and removal of lead-based paint (LBP) hazards from steel and wooden substrates. The specific technical objectives of this project were addressed under four tasks:

1. to develop novel vitrification technology for lead-based paint removal that can be used effectively for immobilization of heavy metal hazardous waste
2. to develop and demonstrate an integrated "Lead Hazard Mitigation and Management System" (Painter-L)
3. to evaluate the use of emerging environmentally acceptable technologies for removal of lead-based paint
4. to develop a microwave-assisted system for removal of lead-based paint from wooden substrates.

Task 1 will minimize the amount of hazardous waste produced during LBP removal from steel substrates. Task 2 will assist installations in developing the most cost-effective LBP hazard mitigation strategy. Tasks 3 and 4 focus on environmental compliance and improving worker and public safety.

Approach

The thermal spray vitrification (TSV) process to remove hazardous LBP was developed and patented. In the TSV process, thermal spray technology is used to apply molten glass onto a surface from which deteriorated LBP is to be removed. Laboratory experiments were performed using a specially formulated glass powder feedstock melted in the high-temperature flame of a thermal spray torch. When the molten glass is forced by carrier gas through the applicator onto the painted surface, it reacts with the paint, pyrolizing the organic components of the paint while trapping the lead ions within the silicate tetrahedra network of the glass. The leaded glass and carbon then vitrifies, immobilizing the lead ions within the glass network to prevent leaching. The difference in coefficient of thermal expansion between the glass and the substrate and the quenching stresses in the glass cause the glass to crack and spall off the substrate. Remelting the residue produces a nonhazardous waste in which the lead oxide is immobilized in a glassy iron silicate matrix. Laboratory and field demonstrations were conducted and documented.

Painter-L, a lead hazard mitigation management system, was developed to help engineers develop the best LBP abatement strategy for a specific installation. The system provides assistance with (1) installation-wide prioritization of abatement projects and (2) selection of the best abatement method for a given situation. User inputs to Painter-L include (1) a structure inventory that catalogs background information such as substrate type, building use, and age, and (2) field test information such as identification of potential lead-based paint hazards, lead testing results, and coating condition index. The knowledge base was designed to be updateable as new hazard assessment and abatement technolo-

gies emerge or as regulations change. The technical approach includes development of information and procedures required for decisionmaking; development of a coating condition index; development of knowledge bases; and development of methodologies and decision trees for prioritization and alternative selection of appropriate methodologies.

Emerging technologies for the removal of lead-based paint from nonsteel substrates were demonstrated at eight family housing units at Buffalo, New York, in June and July of 1996. Each technology was evaluated two or three times during a one-week period. X-ray fluorescence (XRF) spectroscopy was used to measure lead levels on substrates before and after treatment. Inductively coupled plasma atomic emission spectroscopy (ICP-AES) was used to quantify the change in lead levels of airborne particulate and settled dust wipe samples before and after removal.

Microwave-assisted paint removal laboratory experiments were conducted in order to ascertain the relevant parameters for controlling the heating of the LBP so that it will soften sufficiently such that it can be scraped easily, and yet be rendered nonleachable as determined by the Toxicity Characteristic Leaching Procedure (TCLP). Many tests were conducted to evaluate susceptor materials, chemical stabilizers, and removal procedures. A field demonstration of the microwave-assisted LBP technique was also conducted.

Scope

This research addresses *Department of Defense (DoD) Compliance Category 8*, "Decontamination of Structural Facilities," and *Army Environmental Quality Requirement Statements: Compliance A* (2.3.k), "Cost-Effective Technologies to Remove, Characterize, and Dispose or Reuse Sources of Lead Hazards," Ranking 1.

Mode of Technology Transfer

Technology transfer is being accomplished by presentation of papers at conferences, publication of results in conference proceedings, peer-reviewed journal articles, and an invited book chapter.

Field tests and demonstrations of the LBP removal and management technologies have been conducted at DoD installations. Painter-L has been beta-tested at Fort Belvoir, VA, to provide hazard assessment and an optimized mitigation

strategy. In order to transfer the methods and technologies developed in this program, an intensive documentation effort was conducted and full coordination was achieved through the DoD Interagency Lead-Based Paint Task Force. Draft Tri-Services guidance documents, including guide specifications and user guides have been prepared for the use of DoD installations. The TSV process has been tested and validated for application to DoD steel structures such as ships, bridges, and hangars. The Army patents on TSV and microwave-assisted LBP removal technology will be licensed and commercialized.

The technologies developed and demonstrated under this SERDP project have dual-use applications in the Department of Housing and Urban Development (HUD) for housing and Department of Transportation (DOT) for bridges.

Further transfer of the technologies developed under SERDP funding has been proposed for demonstration/validation through Army technology demonstration funding (6.3) starting in Fiscal Year (FY) 00 and continuing through FY03. Funds ($2.8 million) have been transferred from the Operations and Maintenance, Army (OMA) account to the Assistant Secretary of the Army for Research, Development, and Acquisition (SARDA) for this purpose.

1 Thermal Spray Vitrification for LBP Removal From Steel Substrates (Task 1)

Lead-based paints and primers were once used commonly throughout the Army and DoD for corrosion protection of steel structures, including bridges, catwalks, towers, water storage tanks, oil tanks, piping, steel doors, hangar doors, trusses, exterior railings, steel posts, poles, stairways, handrails, cranes, pontoons, and boiler plant structural members. In addition to DoD fixed infrastructure, ships and submarines also have been coated with lead-pigmented coatings. Until recently, red lead oxide was considered an excellent corrosion-inhibiting primer for steel and an alternative primer with equal performance has not yet been developed.

Paint removal is required before new coatings can be applied, especially if the old paint is peeling. Lead exposure can result from the ingestion of paint chips or dust from deteriorating paints, or from improper paint removal. Young children are at greatest risk from this exposure. Abrasive blasting is currently used to remove old lead-based paint. During abrasive blasting, a tight containment structure is required to keep the lead dust from contaminating air, soil, or water. Inside the tight containment structure increased worker protection is required due to higher lead dust concentrations, reducing worker productivity. Furthermore, the large volume of concentrated waste generated by abrasive blasting is hazardous and requires additional stabilization treatment before disposal.

Despite the large number of different systems available for treatment of hazardous waste, vitrification technology has proven to provide superior resistance to waste leaching as compared to other forms of waste treatment. Because of the environmental stability of glass-based waste forms, vitrification has been determined to be the Best Demonstrated Available Technology (BDAT) for hazardous waste by the Environmental Protection Agency (Marra, Andrews, and Schumacher 1995).

The TSV process to remove hazardous lead-based paint was developed and patented by CERL (U.S. Patent No. 5,292,375). The TSV process consists of thermal spray application of molten glass onto a surface from which the deteriorating paint is to be removed. Specially formulated glass powder feedstock is melted in

the high-temperature flame of the thermal spray torch. When the molten glass strikes the substrate it reacts with the paint to pyrolize the organic components of the paint while trapping the lead ions within a silicate tetrahedra network of glass. The molten leaded glass vitrifies on the substrate, but differences in the coefficient of thermal expansion between the glass and substrate, and the quenching stresses in the glass, cause vitrified material to crack and spall off. Remelting this spalled-off residue produces a nonhazardous waste, with the lead oxide immobilized in the glassy iron silicate matrix (Covey, Petreanu, and Kumar 1996).

The TSV process is well suited to remove LBP from steel substrates and offers several advantages over conventional LBP-removal techniques:

- The process produces no lead dust, eliminating the time and effort required to construct a tight containment structure around the work area.
- The elimination of tight containment also eliminates the need for heavy worker protection and environmental monitoring, saving costs, and improving worker productivity.
- The lead-containing waste is completely encapsulated in a chemically inert, nonleachable material that may be handled and disposed of as a nonhazardous waste, saving on associated costs and protecting the environment from lead contamination.

A special glass composition developed by the Savannah River Laboratory for the encapsulation of nuclear waste was modified to serve as the glass waste feedstock for the vitrification of lead, chromium, and cadmium. This glass composition was considered because of its ability to accommodate a wide variety of hazardous species, its outstanding long-term chemical durability, and its corrosion-resistance to a wide range of environmental conditions (Covey, Lattimore, and Kumar 1995).

To determine the stabilization mechanism of the iron silicate glass, specimens were melted in crucibles with 0, 5, 10, 20, 30, and 40 percent PbO (by weight). The results showed that this glass composition can successfully immobilize up to 25 weight percent (wt %) PbO as determined using the Environmental Protection Agency (EPA) Toxic Characteristic Leaching Procedure (TCLP).

The glass fragments after thermal spraying were collected from the multiple applications and remelted. The resulting glass was found to be nonhazardous as determined by TCLP. The disposal costs for nonhazardous waste are greatly reduced as compared to hazardous waste.

Surface lead concentration was shown to steeply decrease as a function of the number of sprayed layers applied. Test results showed that thermal spray vitrification can remove lead from the substrate to levels below the required 1.0 mg/cm^2 in three passes or less. Thick paint and topcoats provided a greater challenge than uncovered lead primer, but the method was effective for both applications.

During laboratory testing, the certified results of daily airborne lead emissions ranged from below the detection limit of 0.92 $\mu g/m^3$ to 2.6 $\mu g/m^3$. These results were below the EPA National Ambient Air Quality Standard (NAAQS) limit of 1.5 $\mu g/m^3$ (90 days average), with an Adjusted Daily Allowance of 27 $\mu g/m^3$ (40 CFR 50). The certified results of personal lead exposure monitoring during laboratory testing were lower than the Occupational Safety and Health Administration (OSHA) Action Limit of 30 $\mu g/m^3$ (8 hour exposure).

A field demonstration successfully removed lead-based paint from the Viaduct Bridge at Rock Island, Illinois, in September 1997 (Boy, Weber, and Kumar 1998). The thermal spray process was able to provide sufficient heat to overcome thermal losses to the large heat sink effect created by the steel bridge. The lead-free surface was thermal sprayed with a nonhazardous plastic coating system. Additional demonstrations are scheduled (or have already been completed by press time) to remove LBP from an aircraft hangar door and a Navy ship. These demonstrations will be documented in separate technical reports at the earliest feasible date.

Over the course of this project, this work has been documented in the following publications and patents:

Publications and Presentations

Boy. J., and A. Kumar, "Lead-Based Paint Hazard Mitigation" in *The Encyclopedia of Environmental Analysis and Remediation,* Robert A. Meyers, ed. (John Wiley and Sons, Inc., 1998), pp 2501-2516.

Covey, S., J. Petreanu, and A. Kumar, "Vitrification of Lead Contained in Lead-Based Organic Coatings Using Thermal Spray Technology" in ASTM Special Technical Publication (STP) 1240, *Stabilization and Solidification of Hazardous, Radioactive, and Mixed Waste* (October 1996).

Boy, J., R. Weber, and A. Kumar, *Thermal Spray Removal of Lead-Based Paint from the Viaduct Bridge at Rock Island Arsenal, IL,* CERL Technical Report 98/119, ADA353950 (June 1998).

Kumar, A., and J. Boy, "Thermal Spray Vitrification for Removal of Lead-Based Paint from Steel Structures" in *Proceedings, Army Science Conference* (1997).

Kumar, A., and J. Boy, "Thermal Spray Removal of Lead-Based Paint from Steel Structures" in *Proceedings of the Tri-Service Environmental Conference,* (St. Louis, MO, May 1997).

Kumar, A., "Thermal Spray Vitrification for Lead-Based Paint Removal from Steel Structures," presented at the Advanced Techniques for Painting and Depainting DoD Weapon Systems Conference (Johnstown, PA, 9 September 1997).

Covey, S.W., J.L. Lattimore, A. Kumar, and J.H. Boy, "Vitrification of Lead-Based Paint Using Thermal Spray" in *Ceramics Transactions Vol. 72: Environmental Issues and Waste Management Technologies in the Ceramic and Nuclear Industry*, V. Jain and D. Peeler, eds. (Am. Ceramic Society, Westerville, OH, 1997), pp 145-155.

Marra, J.C., A. Kumar, and J. Boy, "Glass Composition Development for a Thermal Spray Vitrification Process" in *Ceramics Transactions Vol. 72: Environmental Issues and Waste Management Technologies in the Ceramic and Nuclear Industry,* V. Jain and D. Peeler, eds. (Am. Ceramic Society, Westerville, OH, 1997) pp 419-442.

Covey, S., L. Lattimore, and A. Kumar, "In Situ Vitrification and Removal of Lead-Based Paint for Steel Structures," *1995 Advances in Thermal Spray Science & Technology*, C.C. Berndt and S. Sampath, eds. (American Society for Metals [ASM] International, Materials Park, OH, 1995), p 605.

Petreanu, John P., and Ashok Kumar, "Vitrification of Lead Contained in Lead-Based Organic Coatings Using Thermal Spray Technology," *1994 Advances in Thermal Spray Science & Technology*, C.C. Berndt and S. Sampath, eds. (ASM International, Materials Park, OH, 1994).

Patents Awarded

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

Patents Filed

"Vitrification and Removal of Coatings Containing Hazardous Materials," A. Kumar and S. Covey, April 1996.

2 The Painter-L Lead Hazard Mitigation Management System (Task 2)

Before the dangers of lead in the environment were known, it was common to use lead-based paint to protect and decorate wood surfaces. Now that the dangers are recognized, the Army finds itself with many structures having lead-contaminated coatings and insufficient funds to remove it all. Family housing is a particular problem since young children are more sensitive to lead poisoning than adults. Identification of lead hazards in paint, dust, and soil is required by the EPA and the Department of Housing and Urban Development (HUD). When lead hazards are found, action must be taken to manage or remove them.

The Residential Lead-Based Paint Hazard Reduction Act of 1992, which is often referred to as Title X (read as "Title Ten"), requires disclosure of known lead hazards in housing built before 1978. Section 1017 of Title X required HUD to develop guidelines for lead hazard identification and control (U.S. Public Law 102-550, 1992). HUD published "Guidelines for the Evaluation and Control of Lead-Based Paint Hazards in Housing" (1995) to meet this requirement. This document replaced the 1990 publication "Lead-Based Paint: Interim Guidelines for Hazard Identification and Abatement in Public and Indian Housing."

The U.S. Army Center for Public Works has published Public Works Technical Bulletin 420-70-2, "Installation Lead Hazard Management," to provide technical guidance to personnel who operate and maintain Army facilities. This document assists in identifying and controlling hazards from lead-contaminated paint, dust, and soil, and from other sources in facilities constructed before 1978. It also stresses a program of risk assessment, on-going monitoring, interim controls, and abatement.

For a person responsible for a large number of housing units, the task of keeping track of all the details on lead testing data collected and remedial actions is formidable. Even for small numbers of housing units, a facility-management staff would have many other responsibilities beside the monitoring of lead hazards, and it might miss following up on required actions.

A computer-based lead hazard management system, Painter-L, has been developed jointly by the Army and Navy. The Painter-L system assists Army personnel in performing lead hazard inspections or risk assessments. Painter-L uses current applicable regulations to interpret risk assessment inspection data in order to manage family housing and other structures that have lead hazards associated with them. The program serves to standardize:

- collection and analysis of risk assessment data
- development of installation lead hazard management plans
- establishment of interim and long term lead hazard control strategies.

Painter-L facilitates management of hazards found and the remedial actions taken by taking as input the lead hazard risk assessment data and giving as output the required disclosure documents and a lead hazard management plan customized for the user's installation. The program also enables the collection of ancillary data useful for addressing worker protection issues.

Painter-L accomplishes its objectives by providing on-screen forms to facilitate entry of lead hazard information, generating a comprehensive database, and outputting a lead hazard management plan incorporating the analyzed data. In addition, Painter-L can output a disclosure document with all the lead hazards found and any remedial actions taken. The program uses database tables to contain all the necessary information and uses Microsoft FoxPro® to link and relate them as necessary. While the program is designed for risk assessment data, paint inspection information can be stored and analyzed as well. The Painter-L program is designed to run on personal computers running the Windows 95 operating system. The program requires at least a Pentium-class computer with 16 megabytes (Mb) of memory, at least 10 Mb of available hard disk space, and a display resolution of 800 x 600 pixels. To generate the lead hazard management plan, Microsoft Word® version 7 is required.

The Painter-L helps installations collect and analyze lead hazard data in a consistent manner. It uses current applicable regulations to interpret the data in order to manage family housing and other child-occupied facilities that present lead hazards. The lead hazard management plan generated by Painter-L presents a priority table indicating where remedial actions are needed. In addition, the program can print the required Disclosure of Information document (Public Law 102-550, sec 1018) as new tenants move in, stating the extent of any known lead hazard problems and what actions have been taken to alleviate the problems.

Technologies such as Painter-L will help to reduce the cost of lead hazard control in DoD family housing and child-occupied facilities. Qualitative benefits include improved health, welfare, and quality of life for the soldiers and their families, which will enhance military readiness and mission focus. Other important benefits will include decreased liability for childhood blood lead poisoning and easier compliance with lead disclosure regulations.

Painter-L is documented in a draft CERL technical report that is currently being prepared for publication:

"Lead-Based Paint Hazard Management System (Painter-L), Implementation Guide and User's Manual," by Aaron J. Averbuch, James J. Long, and Ashok Kumar.

This work is also cited in the following reference:

Boy, J., and A. Kumar, "Lead-Based Paint Hazard Mitigation" in *The Encyclopedia of Environmental Analysis and Remediation*, Robert A. Meyers, ed. (John Wiley and Sons, Inc., 1998), pp 2501-2516.

3 Emerging Technologies for LBP Removal Paint From Nonsteel Substrates (Task 3)

CERL has evaluated environmentally acceptable chemical strippers and alternative blast media technologies for the removal of lead-based paint from DoD buildings and structures. The technologies evaluated include cryogenic blasting, laser paint removal, chemical stabilizers, alternative chemical strippers, and confined hydraulic blasting. A sponge media blasting technique appeared to be particularly promising for LBP removal from surfaces of buildings. Soft sponge media abrasive products have been developed to address issues of worker and public safety, hazardous waste minimization, and pollution prevention. The sponge medium consists of a matrix of water-based urethane foam within which abrasive particles are dispersed. The medium can be wet with water or chemical solutions to increase productivity. The aggressiveness of sponge media can be tailored for the specific application by changing the characteristics of the abrasive particles inside the urethane foam. However, during field testing, it was determined that sponge blasting caused unacceptable damage to historical wooden structures.

Granulated carbon dioxide (CO_2) blasting and pelletized CO_2 blasting have been evaluated for removing LBP from interior architectural wood components (Kominsky, Hock, and Daniels 1997). The CO_2 blast medium is a soft abrasive that removes the LBP by mechanical impact and thermal expansion mechanisms. The spent media evaporates directly to a gaseous state and dissipates, leaving only paint solids as waste. However, it was found that both the granulated and pelletized CO_2 proved ineffective in removal of the LBP from interior wooden components without severe damage to the underlying substrate. Also, residual lead levels of 6 mg/cm^2, as determined by an XRF spectrum analyzer, exceeded the HUD guideline of 1 mg/cm^2 (U.S. Public Law 102-550, 1992).

The Torbo® wet abrasive blasting system, manufactured by Keizer Technologies America, Inc., uses conventional blast abrasives (such as coal slag or silica sand) mixed with water (80 percent abrasive to 20 percent water). The abrasive-water slurry mixture is fed through a blast nozzle system designed, in principle, to encase every particle of the abrasive in a thin layer of water. Water pressure forces

the slurry into a compressor-generated airstream where it is accelerated to the blast nozzle. The LBP is removed by the kinetic energy and mechanical abrasion of the blast media striking the paint. Blastox®, a chemical stabilizer, was added to the slurry mixture prior to blasting in order to create an "engineered abrasive," that would react with the lead in the paint chemically in order to stabilize the leachable lead as lead silicate, with stabilization mechanisms similar to those of portland cement. The wet abrasive blasting technology used with the engineered abrasive efficiently removed LBP from exterior architectural wood components to bare substrate with no apparent damage, and yielded a substrate ready for repainting (Kominsky, Hock, and Daniels 1997). Overall, the residual lead levels as determined by XRF were 0.93 mg/cm^2, which is below the HUD guideline.

Encapsulant paint removal technology effectively employs a two-part liquid system consisting of potassium hydroxide and a proprietary polymer, which are sprayed with an applicator gun that uses an external mixing technique. The dwell time is dependent on time and number of layers of paint, temperature, and other environmental factors. After the paint is absorbed into the remover matrix, the resulting residue is removed as a semi-solid material using a putty knife. Encapsulant paint removal technology has been used to remove LBP from interior architectural wood components to bare substrate with no apparent damage. The residual lead levels as determined by XRF were found to be 0.8 mg/cm^2 (Kominsky, Hock, and Daniels 1997).

Reduced-toxicity chemical strippers are sometimes referred to as "environmentally acceptable (EA)" strippers. These chemicals are of interest because of their low volatility and low toxicity. They are noncorrosive and not caustic to humans. Typical EA strippers are based on ingredients that have low environmental impact, such as citric acid and N-methyl pyrrolidone (NMP). Where they can be used effectively, these products eliminate the need for sodium hydroxide and methylene chloride strippers. However, these new formulations require long dwell periods; consequently, in exterior applications, their performance is vulnerable to degradation by rain, wind, and low temperatures. Of the six EA strippers investigated in the laboratory, only NMP-based strippers performed comparably to conventional solvents and caustic strippers (Drozdz and Engelage 1996).

Laser paint removal systems have been designed and built for use on fragile historic wood structures. These systems contain a CO_2 pulse laser and beam delivery system. Evaluation of the paint removal system by CERL showed potential as a paint removal technology for use on historic wood structures. Advantages include no containment costs, no requirements for worker protection, and reduc-

tion of hazardous waste compared to chemical paint strippers. However, further engineering enhancement will be necessary to make the process cost-effective.

Emerging technologies evaluated under this project have been documented in the following publications:

Boy, J., and A. Kumar, "Lead-Based Paint Hazard Mitigation" in *The Encyclopedia of Environmental Analysis and Remediation*, Robert A. Meyers, ed. (John Wiley and Sons, Inc., 1998) pp 2501-2516.

Drozdz, Susan A., and Jennifer D. Engelage, *Evaluation of Reduced-Toxicity Chemical Paint Strippers*, UR 96/111 (CERL, September 1996).

Kominsky, J., V. Hock, and A. Daniels, *Field Demonstration of Clean Technologies for the Removal of Lead-Based Paint from Residential Housing in Buffalo, New York*, draft report (U.S. Environmental Protection Agency, March 1997).

Hock, V.F., C.M. Gustafson, D.M. Cropek, and S.A. Drozdz, *Demonstration of Lead-Based Paint Removal and Stabilization Using Blastox,* FEAP TR 96/20 (CERL, October 1996).

4 Microwave-Assisted Paint Removal (Task 4)

Overview

The microwave-assisted process for removing lead-based paint from wood and composites was developed and patented by A. Kumar and has been assigned to the U.S. Army (U.S. Patent No. 5,268,548, 1993). In the microwave-assisted paint removal process, microwave coupling compounds called *susceptors* are applied as a waterborne slurry or as a polymer binder paste to the painted surface. Microwaves have the unique ability to rapidly and selectively heat the coated surface. Compounds such as graphite or iron oxide can reach temperatures up to 1000 °C in less than a minute when exposed to microwaves (800 watts). The susceptor material increases both the efficiency of the system as well as the uniformity of the heating process. The microwave applicator uses the same standard 2.45 gigahertz magnetron tubes that are used in household microwave ovens. The applicator horn is designed to focus microwave energy onto a coupling material (the susceptor), where it is used effectively. The paint is debonded from the substrate by heat and is removed easily by scraping. A microwave shield is provided for worker protection. Since the airborne lead levels from this process are below the EPA and OSHA threshold requirements, containment structures, environmental monitoring, and worker health monitoring are not required. The microwave-assisted LBP removal system can make the worksite safer and reduce negative environmental impacts.

Two prototypes of the microwave device were tested: a CERL-developed unit designed to apply 300 W of energy over an area of 15 x 15 cm, and a unit developed by HVS Technologies (under contract to CERL) designed to apply 1000 W over an area of 2.54 x 2.54 cm. These design differences have implications for dwell time, surface temperature, ease of application, and overall paint-removal time.

Development of CERL Microwave Applicator and Paint-Removal Process

A number of laboratory experiments were necessary in order to develop the microwave-assisted paint removal equipment and procedure. Initial testing of the

procedure was conducted on painted wood substrates in a conventional microwave oven. This initial testing later gave way to the development of a custom-designed microwave applicator system for removing paint from the surface of a wall. Various parameters such as microwave power, exposure time, and susceptor material were important factors in the development of the custom-designed applicator and procedure.

Experiment 1: Microwave Generator Power Output Capabilities

Purpose

The purpose was to determine the fixed distance from a microwave waveguide output that would provide maximum energy output. A custom-built Micro Dry variable-power microwave oven was used for the experiment, with a consumer-grade Sharp microwave used for purposes of comparison to determine the approximate amount of energy being absorbed at the hot spot by a specified amount of water.

Setup

Figure 1 illustrates the physical layout of the experiment.

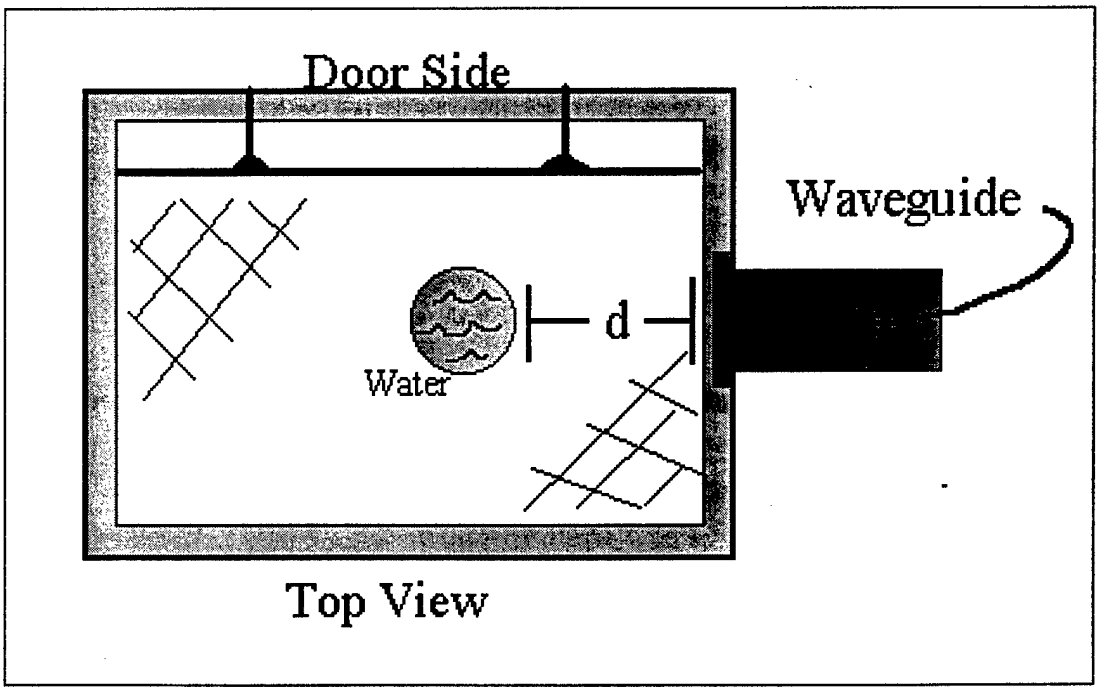

Figure 1. Experimental setup within the custom-built, variable-power microwave oven.

Procedure

The following is a copy of the instructions for the experimental procedure:

Part A: Identify the Hot Spot in Custom-Built Oven

1. Set oven power level. Start with moderate power of 600 W; test series will be repeated at 900 W and 1200W.
2. Fill paper cups with 275 ml tap water.
3. Place cup at measured distance from waveguide opening, heat for 1 minute, record temperature using standard lab-grade pyrometer.
4. Repeat Step 3 at a different distance from the waveguide opening with another water sample; record temperature.

Part B: Measure Maximum Energy Absorbed at the Hot Spot

1. Heat water in consumer-grade microwave unit for 1 minute; record temperature.
2. Heat water in the hot spot of the custom-built microwave unit set at 1000 W for 1 minute; record temperature.

Data

Table 1 presents the data recorded for Part A of this experiment.

Table 1. Temperatures recorded at different distances from waveguide opening in custom-built variable-power microwave oven.

Distance (cm)	Temp (°C at 600 W)	Temp (°C at 900 W)	Temp (°C at 1200 W)
4	34	40	42
8	28	29	30
12	28	29	30
16	26	26	28
20	25	27	26
24	24	26	25
28	24	25	25
32	24	25	25

The data for Part B of this experiment are summarized below:

Temperature after 1 min. in Sharp oven from 24 °C: 77 °C

Temperature after 1 min. in MicroDry oven from 24 °C: 75 °C

Power calculations for Sharp oven:

$$\frac{4.2159\ \mathrm{J}}{\cancel{\mathrm{g}}\cancel{\mathrm{K}}} \bullet \frac{.9584\cancel{\mathrm{g}}}{\cancel{\mathrm{cm}}^3} \bullet 275\ \cancel{\mathrm{mL}} \bullet 53\cancel{\mathrm{K}} \bullet \frac{1}{60\ \mathrm{sec}}$$

$$= 982\ \mathrm{W}$$

Power calculations for MicroDry oven:

$$\frac{4.2159\ \mathrm{J}}{\cancel{\mathrm{g}}\cancel{\mathrm{K}}} \bullet \frac{.9584\cancel{\mathrm{g}}}{\cancel{\mathrm{cm}}^3} \bullet 275\ \cancel{\mathrm{mL}} \bullet 51\cancel{\mathrm{K}} \bullet \frac{1}{60\ \mathrm{sec}}$$

$$= 944\ \mathrm{W}$$

Power calculation notes: specific heat of water = 4.2159 J/gK at ~50 °C; density of water found to be 0.9584 g/cm^3.

Results for Experiment 1

Experiment 1 indicated that there is a great deal of dispersion a short distance from the waveguide opening. With a calculated wavelength of approximately 15 cm, there were no noticeable high or low points that a standing wave would be expected to demonstrate at distances of twice its wavelength. At the 1000 W setting with the cup of water less than 1 cm from the waveguide, the MicroDry unit was able to heat the water almost as well as the conventional Sharp oven, and high power (around 944 W) is attained, but only near the waveguide's opening.

Experiment 2: Effect of Resistance Levels on Heating Time

Purpose

The purpose of Experiment 2 was to determine what effect the resistance of the susceptor material has on heating characteristics, including time and burning point.

Setup

A 20 dB gain horn antenna was fitted over the opening of the waveguide for this and later experiments. Figures 2 and 3 illustrate the physical setup.

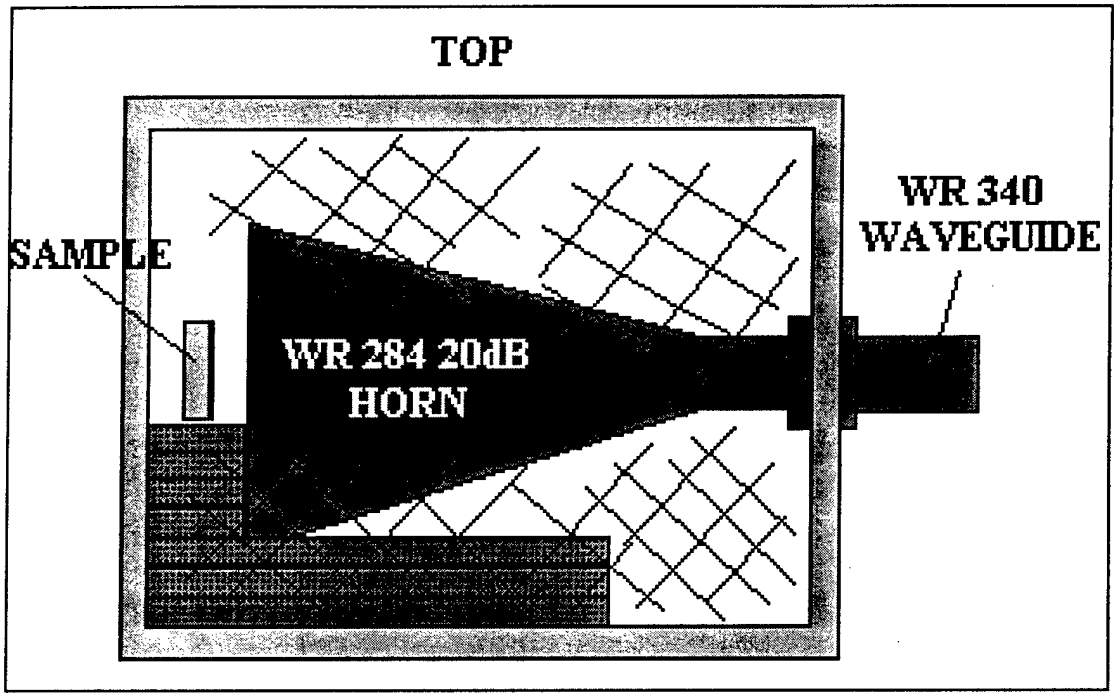

Figure 2. Laboratory test setup for testing effects of susceptor resistances on heating time.

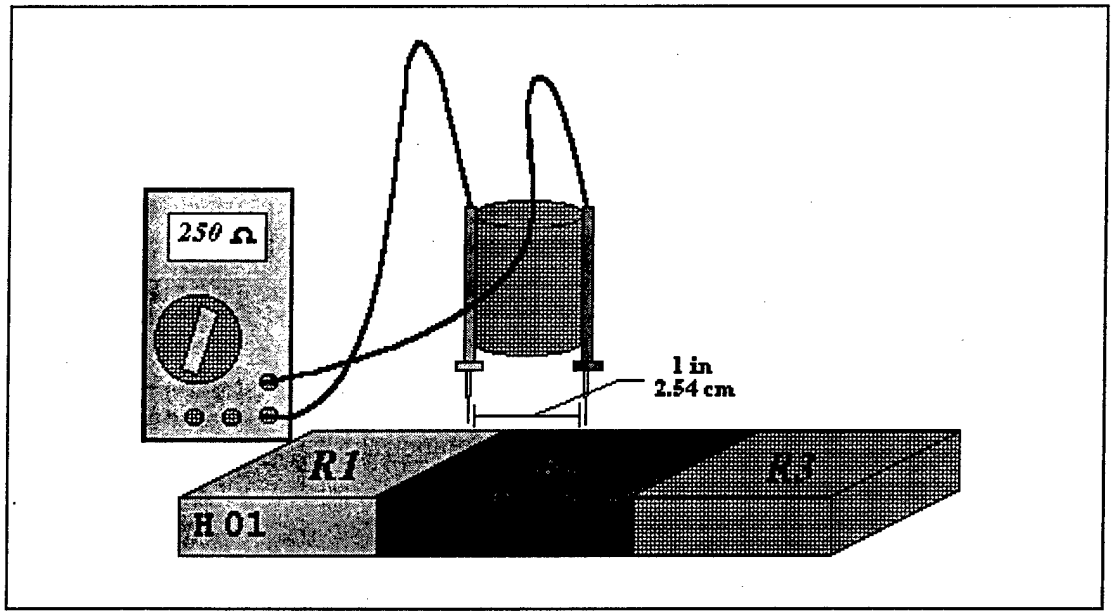

Figure 3. Resistance measurement setup.

Procedure

The following is a copy of the instructions for the experimental procedure:

1. Measure and record resistivities of all susceptor samples, taking three measurements in each of the three regions, and then taking an average.
2. Determine a good array of highest, lowest, and intermediate resistance levels.

3. Heat each susceptor sample at full power until smoke is produced. Record exposure time and temperature in each of the three regions.

Data

Tables 2 and 3 present the data recorded for Experiment 2.

Table 2. Resistance measurements.

Sample	R1 (ohms)	R2 (ohms)	R3 (ohms)	R avg. (ohms)	Sample	R1 (ohms)	R2 (ohms)	R3 (ohms)	R avg. (ohms)
H 01	160	100	200	153	H 15	145	130	200	158
H 02	160	100	200	153	H 16	190	85	115	130
H 03	160	100	230	163	H 17	115	85	125	108
H 04	230	90	200	173	H 18	125	80	110	105
H 05	195	85	160	146	H 19	160	85	135	127
H 06	115	85	125	108	H 20	145	100	155	133
H 07	240	85	120	148	H 21	170	120	185	158
H 08	270	105	220	198	H 22	145	145	210	166
H 09	160	75	115	116	H 23	215	85	105	135
H 10	130	80	135	115	H 24	125	90	270	161
H 11	280	90	105	158	H 25	110	75	250	145
H 12	170	120	160	150	H 26	95	80	275	150
H 13	125	90	130	115	H 27	80	75	230	128
H 14	115	105	150	123					

Table 3. Temperature measurements by sample number.

Sample	T1 ©	T2 ©	T3 ©	T avg ©	Time (s)
H 08	51	56	47	51.3	3
H 04	75	68	37	60.0	3
H 22	53	59	35	49.0	4
H 01	47	38	35	40.0	3
H 25	68	56	38	54.0	5
H 23	89	76	45	70.0	3
H 19	52	56	36	48.0	3
H 13	60	52	36	49.3	5
H 18	68	60	37	55.0	3

Results for Experiment 2

This experiment revealed very little correlation between the two parameters. It is possible that the temperature range into which all the samples fall in the wider spectrum is negligible, so resistance may be of little importance for this investigation. There was also a problem in taking the measurements, as R1 was measured first, then R2, then R3. The cooling of the samples was extremely rapid, and although the whole data collection procedure took only a few seconds, the sample may cool substantially in even less time than that.

Experiment 3: Uniformity of E-field within Horn Antenna

Purpose

The purpose of Experiment 3 was to determine how uniformly the E-field is transmitted at the opening of the 20 dB gain horn to determine where the most energy is applied to the test sample.

Setup

Figure 4 illustrates the layout of wooden substrate samples used in this experiment.

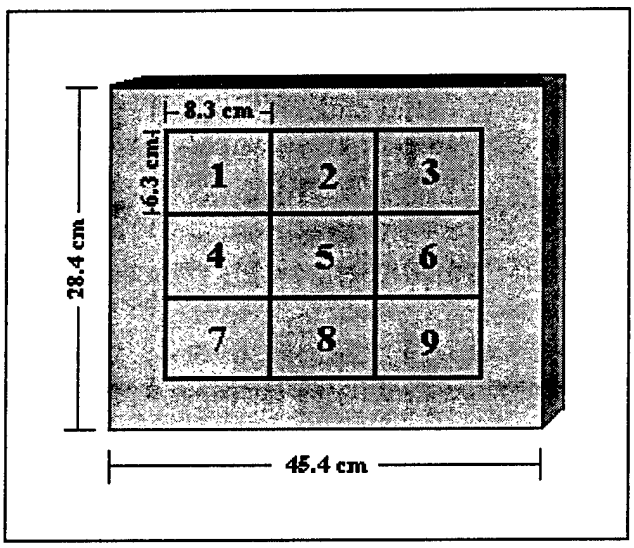

Figure 4. Temperature measurement positions on wooden substrate samples.

Procedure

The following is a copy of the instructions for the experimental procedure:

1. Using the same horn and cage setup used in Experiment 2, place an untreated piece of wood in front of the horn and trace the outline of its opening on the board.
2. Heat on maximum power until smoke or other signs of sufficient heat appear.
3. Measure each box evenly, record, then measure and record again.
4. Repeat for different temperatures.

Data

Table 4 summarizes the data collected in this experiment.

Table 4. Temperature measurement data for wooden substrates.

	TRIAL					
Position	T1 ©	T2 ©	T avg ©	T1 ©	T2 ©	T avg ©
1	37	35	36	35	34	34.5
2	66	64	65	56	55	55.5
3	35	34	34.5	33	34	33.5
4	66	60	58	38	38	38
5	89	87	88	77	75	76
6	53	46	49.5	37	35	36
7	56	50	53	40	40	40
8	74	71	72.5	65	65	65
9	40	40	40	38	39	38.5

Results for Experiment 3

Figure 5 shows a plot of data from the experiment to help visualize the output energy within the horn antenna.

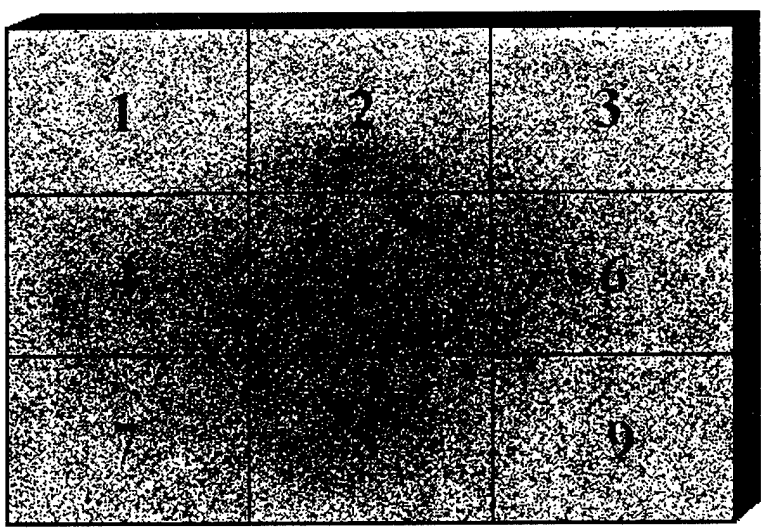

Figure 5. Energy output to test sample through 20 dB gain horn antenna.

The measurements collected in Experiment 3 indicate that the samples received the most energy in the center while output to the corners dropped off substantially — to as little as 40 percent of the energy being produced in the center. This finding is important for developing a hand-held horn applicator, because a device with these characteristics is ideal for sweeping a large surface.

Experiment 4: Modified Horn Configuration

Purpose

The purpose of Experiment 4 was to modify the horn antenna for operation outside of the steel cage and test it to simulate the eventual application on a veritable paint/susceptor-covered wall.

Setup

The setup for this experiment is illustrated in Figure 6.

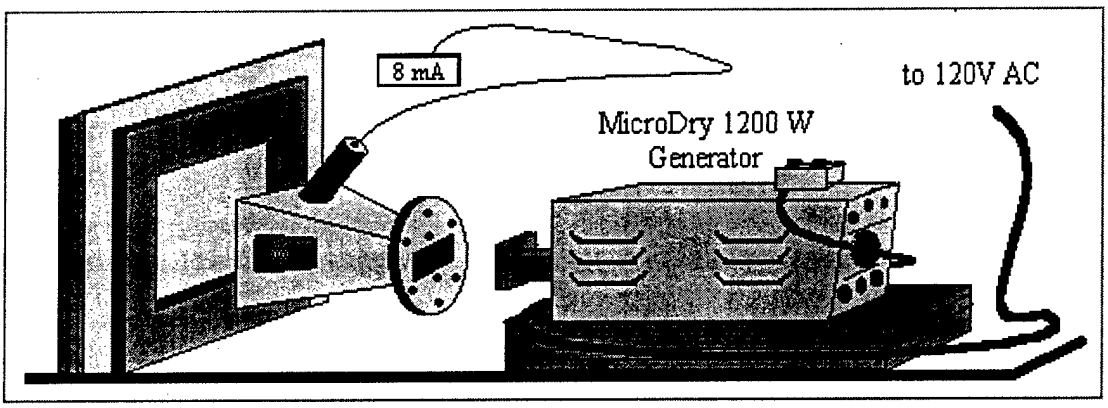

Figure 6. Modified horn microwave system.

Procedure

The following is a copy of the procedure followed for Experiment 4:

1. Place sample in frame and fix edges of horn flush with surface.
2. At 300 W, vary cycling times and repetitions, recording temperatures after each cycle and time per cycle, as well as observations.
3. Repeat at 450 W and 600 W.

Data

The data gathered from these tests are presented in Table 5.

Table 5. Data from modified horn experiments simulating paint removal process.

Sample	Power (W)	Cycles	Max Temp (degrees C)	Scraping Time (s)	Observations
A17	300	4, 4s	114	7	Scraped fair, did not burn
H11	300	4, 5s	131	9	Scraped well, bubbled but no burn
H20	300	3, 10s	112	7	Difficult to scrape, bubbles but no burn
H21	300	3, 12s	121	12	Scraped well, bubbled and no burn
H27	300	5, 4s	136	14	Scraped very well, some bubble, no burn
H09	450	2, 15s	140	15	Scraped well, but smoked and burnt
H10	450	4, 10s	153	10	Scraped well, but smoked and burnt
H17	450	4, 5s	130	14	Scraped well, a little smoke but no marks
A22	600	1, 12s	112	6	Did not scrape, burnt and smoked
H24	600	3, 4s	135	15	Scraped well, a little smoke and bubbles
H26	600	4, 3s	130	17	Scraped very well, no marks, bubbled well, a little smoke

*Data in the CYCLES column is presented in the following format: number of cycles separated by a 2-second delay, exposure time of each cycle.

Results of Experiment 4

The results of this experiment indicated that higher powers drastically increase the chances of damaging the substrate by burning even though they reduce the time required for paint removal. However, the most important result is that removal of paint is possible using such a device at 300 W, 450 W, and 600 W output.

Experiment 5: Graphite Susceptor Testing

Purpose

This experiment was intended to determine the effects of microwave exposure on samples coated with a graphite susceptor.

Part A Procedure

The following steps were used:

1. Coat samples with Slip Plate No. 3, a dry film graphite-based lubricant, and allow to dry (several hours).
2. Measure initial temperature of sample, T_i.
3. Heat in microwave oven on high power for indicated time; measure final temperature, T_f.
4. Immediately scrape sample.

Part A Data

Sample 65A
Exposure: 3 sec
T_i: 20 °C
T_f: 20 °C

Comments: No effects were observed and the sample was not scraped.

Sample 63A
Exposure: 6 sec
T_i: 20 °C
T_f: 88 °C

Comments: A thin wisp of smoke was observed. The surface of the sample bubbled in a region approximately 1 inch in diameter. The paint was very difficult to remove; only a tiny area could be removed using the corner of the scraper. The sample appeared to cool rapidly.

Sample 62A
Exposure: 9 sec
T_i: 20 °C
T_f: 174 °C

Comments: A large flame was observed during microwave exposure. The surface was bubbled and blistered with slight discoloration. Paint was removed from about 50 percent of the sample. The paint was soft but still very difficult to remove. A white residue remained on the wood even after scraping. In the areas where the wood was charred, no residue remained.

Sample 65A
Exposure: 12 sec
T_i: 20 °C
T_f: 130 °C

Comments: No fire was observed. Small uniform bubbling was evident across the surface of the sample. A large area of paint was removed (about 60 percent). The paint scrapings were removed in large pieces. A white residue remained but there was no damage to the wood.

Part B Procedure

The following steps were used:

1. Coat samples with Slip Plate No. 3 using an airless power sprayer and allow to dry.
2. Measure initial temperature, T_i, and three resistance values, R.
3. Heat in microwave oven on high power for indicated time; measure final temperature, T_f.
4. Immediately scrape sample.

Part B Data

Sample 62A R1: ~520Ω R2: ~340Ω R3: ~303Ω
Exposure: 3 sec, R avg.: 388Ω
T_i: 20 °C
T_f: 20 °C

Comments: No observable surface changes were noted.

Sample 69A R1: ~425Ω R2: ~490Ω R3: ~430Ω
Exposure: 6 sec, R avg: ~448Ω
T_i: 20 °C
T_f: 150 °C

Comments: Sample smoked, but did not burn. Surface bubbled. Bubbles concentrated on 2/3 of sample with one large blister at the end of the sample at R3. It was observed that the bubbles consisted of graphite only; the paint did not bubble up. The paint was soft but difficult to remove. About 15 percent of the sample was scraped to the bare wood. Most of the paint was removed from areas that had a high degree of bubbling. Some of the graphite was removed from other areas. No white residue was left, but the wood was gouged by the scraper.

Sample 57A R1: ~330Ω R2: ~400Ω R3: ~455Ω
Exposure: 9 sec, R avg: ~395Ω
T_i: 20 °C
T_f: 109 °C

Comments: Smoke was observed during microwave exposure; a small spot fire occurred at the very end of exposure between R2 and R3. The graphite was discolored in the location of the fire. The surface was uniformly bubbled. The graphite was removed in small areas over 50 percent of the sample. The paint

was difficult to remove. The paint was stripped to the wood in two thin stripes below the burned area. The wood was charred.

Sample 55A R1: ~305Ω R2: ~385Ω R3: ~350Ω
Exposure: 12 sec, R avg: 347Ω
T_i: 20 °C
T_f: 118 °C

Comments: A large fire engulfed the sample after 10 seconds, and the microwave device was turned off. Microwave restarted, but it is likely that no more power was absorbed due to a 2-second delay in microwave generation. The surface had numerous small bubbles and one large blister. Once again, the blister was graphite only; the paint was softened but did not bubble. The paint was difficult to remove. About 15 percent of paint was removed. A yellow-white residue was left behind. Some fire damage was revealed at the corner and one end of the sample.

Results for Experiment 5

The results for this experiment are included and interpreted with the results for Experiment 6 (next section).

Experiment 6: Optimization of Hand-Held Horn Generator System

Purpose

The purpose of this experiment was to find an optimal method of applying microwave power to graphite-coated painted wood surfaces using the prototype equipment.

Setup

Figure 7 shows a diagram of the prototype portable paint-removal system.

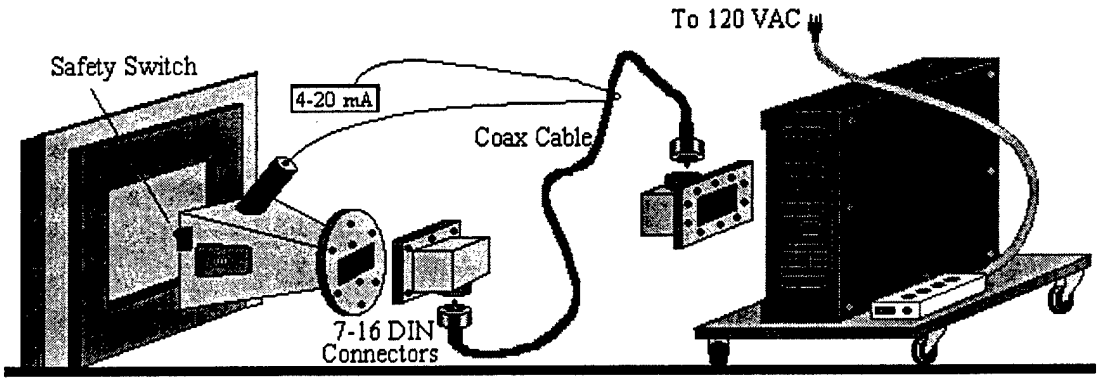

Figure 7. CERL portable microwave paint removal system.

Procedure

The following text is a copy of the procedure followed.

1. Coat the large painted samples (28.5 cm X 35 cm) with the graphite susceptor material (see Figure 8).
2. Test different methods and time exposures of application.
3. Record the method used, the duration of exposure, and the results (including final temperature and ease of paint removal).

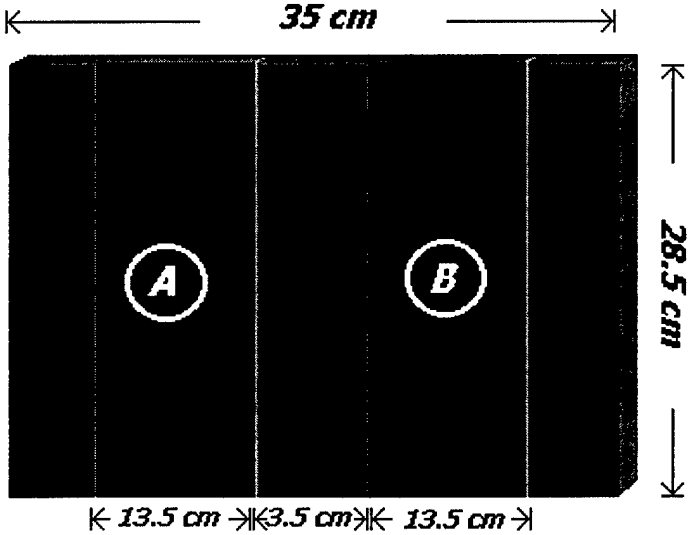

Figure 8. Wood substrate painted with lead-based paint and coated with susceptor.

Data

Table 6 presents the measurements and data collected for Experiment 6.

Table 6. Data from optimization experiment.

Sample	Method	Result
L01A	60 sec continuous motion, then 20 sec static in each 1/3, scraping after each 20 sec period.	2 small burns on an overlap, temperatures to 130 °C. Scraped very well.
L01B	30 sec static in each 1/3, two times through scraping after entire process.	No burns, but spots between overlaps did not get hot enough to scrape. Not a good system.
L02A	60 sec continuous motion, scraping large surface after exposure.	Poor scraping, minimal part of center heated sufficiently. Not a good method.
L02B	45 sec continuous, then 20 sec static on each 1/3, scraping after each 20 sec period.	More wood than paint came up, very difficult to scrape. Not a good method.
L03A	30 static seconds in each 1/3 of sample, scraping after each 1/3 exposed.	Good scraping, small burns on overlaps. Scraped easily and completely.
L03B	20 static seconds in each 1/3 of sample, scraping after each 1/3 exposed.	Not enough exposure. Overlaps scraped well, but other parts did not scrape.
L04A	60 sec continuous motion, then 15 static seconds in each 1/3, scraping after each 15 sec period.	Did not remove exceptionally easily, but removed completely. Burns on overlaps.
L04B	20 sec on, 5 sec off, 20 sec on to each 1/3, scraping after process completed to 1/3.	After the second heating, small portions were removed, while overlaps again burned.
L05A	Heat gun for 6 minutes.	Very long, high temperatures, but still poor scraping.
L05B	60 sec continuous motion, then 30 sec on top 1/3, 30 sec on remaining 2/3 (motion), scrape after each 1/3.	Complete removal, good temperatures, difficult scraping, burn on overlap.
L06A	120 sec continuous motion over entire sample, scraping entirety after exposure.	Scraped easily and completely, but not enough room to test applicator maneuverability. No burning.
L06B	90 sec continuous motion over entire sample, scraping entirety after exposure.	Not quite as high temperatures, but easily scrapable. Again, need more painted surface to truly test system.
L07A	120 second continuous motion, scraping after entire 2 minutes.	Exceptional removal. No discoloration, no burning, easy scraping, came off in large pieces.
L07B	150 second continuous motion, scraping after entire exposure.	Even better. No discoloration, burns, very easy scraping, large pieces.
L08A	135 second continuous motion, scraping after entire exposure.	A little more difficult to scrape, but still easy. Total removal, no discoloration, no burns, large pieces.
L08B	120 seconds continuous motion, scraping after entire exposure.	This seems to be the target time. Again, very easy scraping, no burns, no discoloration, large pieces.
L09A	105 seconds continuous motion, scraping after entire exposure.	Possibly a little too short. Although total removal, no burns or discoloration, scraping more difficult.
L09B	105 seconds continuous motion, scraping after entire exposure.	Better than L09A, but still more difficult than full 2 minute exposure time.
L10A	120 seconds continuous motion, scraping after entire exposure.	Again, the best method found with these samples and the working setup.
L10B	120 seconds continuous motion, scraping after entire exposure.	Complete removal, no burns, no discoloration, large pieces, ideal temperatures.

Results for Experiments 5 and 6

The results of Experiments 5 and 6 indicate that graphite-based susceptors are suitable for coupling microwave energy to underlying paint. These experiments also indicate that the most consistent, complete, and best method of applying the microwave power is using 2 minutes of continuous motion, moving back and forth across approximately a 1 foot by 5 inch section and scraping after the full exposure. Average temperatures reached about 120 °C consistently, with temperatures as high as 138 °C and as low as 98 °C on the samples tested with this method. These experiments were quite successful in finding a way to remove paint completely and evenly without burning or discoloring the substrate.

Experiment 7: Minimum Scraping Temperature

Purpose

The purpose of Experiment 7 was to determine the minimum temperature that the paint must reach in order to be scraped from a wooden substrate.

Setup

Because temperature was the only variable being tested in this experiment, a standard lab-grade convection oven was used for optimal temperature uniformity and control within the test environment. All temperatures were measured with a standard lab-grade pyrometer.

Procedure

The steps presented below were followed:

1. Heat oven to 100 °C, then place three painted samples (no susceptor) in it.
2. Allow to cook until temperature of wood is equal to the temperature of the oven (100 °C).
3. Remove samples and attempt to scrape; record data.
4. If scrapable, repeat procedure at a temperature 5 °C below the previous recorded data until scraping is not possible.

Data

Table 7 presents the data recorded for this experiment.

Table 7. Data for determining minimum scraping temperature.

Sample #	Temperature (°C)	Observations
U01	100	Scraping was very easy; similar to the best microwaved samples. The paint came off cleanly and in large portions. Good scrapability at this temperature.
U02	100	
U03	100	
U04	90	Scraping again was extremely easy. The paint was removed with little difficulty leaving a very thin coating of primer and came off in large pieces again.
U05	90	
U06	90	
U07	80	Scraping was possible, but not as easy as the previous two temperatures. The paint did not come off in as large of pieces, but still scraped clean.
U08	80	
U09	80	
U10	70	Scraping not feasible at this temperature. Difficult and did not come off evenly or completely. Scraping possible, but not easy. Completion achieved.
U11	70	
U12	75	

Results for Experiment 7

The results for this experiment are included and interpreted with the results for Experiment 8 (next section).

Experiment 8: Further Experimentation With Fully Coated Samples

Purpose

The purpose of this experiment was to use the system as developed thus far to remove paint from the larger samples fully coated with paint and graphite susceptor.

Setup

Figure 9 illustrates the frame setup used to hold the horn in Experiment 8.

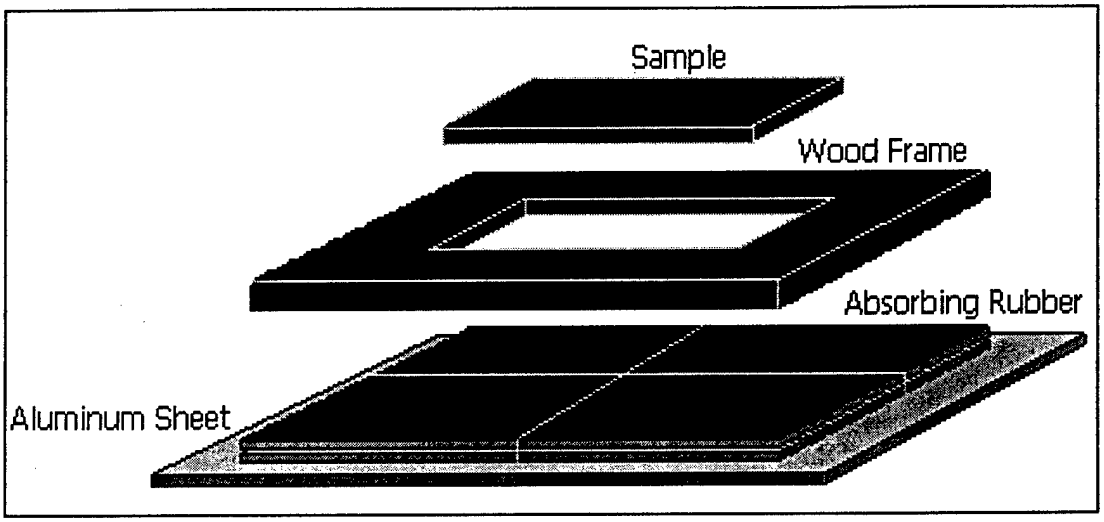

Figure 9. Sample holding frame for laboratory testing of microwave applicator.

Procedure

The steps followed in this experiment were as follows:

1. Using the large, fully coated samples (28.5 cm x 35 cm), place a full sample in the frame and reflector/absorber setup.
2. Use different methods and exposure durations.
3. Record method, time, and observations.

Data

Table 8 presents the data collected for Experiment 8.

Table 8. Data for fully coated samples.

Sample	Method	Result
F01	3 minutes continuous motion over entire surface.	Approximately 2/3 paint removed, some wood with it. No burns, clean.
F02	2 minutes over top ½, scrape, then 2 minutes over bottom ½, scrape again.	100% Removal. No burns, clean removal, large pieces. Very good.
F03	4 minutes continuous motion over entire surface.	90% Removal. Difficult to scrape, some wood with it. No burns, clean.
F04	1½ minutes over top ½, scrape, then 1½ minutes bottom, scrape.	100% Removal with a very small portion of wood. No burns, good.
F05	1:45 over top ½, scrape, 1:45 over bottom ½, scrape again.	100% Removal, no burns, discoloration, large pieces, very good.

Results for Experiments 7 and 8

The results of Experiments 7 and 8 indicate that 75 °C is the absolute minimum temperature at which the paint can be removed, but ideally a temperature of 80

°C should be attained. These temperatures are helpful in determining when to pull the applicator off of the paint and when to begin scraping. Furthermore, the experiments reveal that 1 sq ft of susceptor-coated paint can be removed in approximately 2½ to 3 minutes. The paint is removed easily in large pieces with a hand-held scraper.

Laboratory experiments using the microwave oven revealed that the amount of paint removed increases with increasing microwave exposure time. However, increased microwave exposure time, in general, increases the chances of a spot fire and damage to the substrate. It was found that paint can be removed more easily and in larger quantities by maintaining the sample at a relatively high temperature while avoiding the peak temperatures that resulted in combustion. This result can be accomplished by cycling the power on and off.

Experiment 9: Leakage from CERL Microwave Applicator

Purpose

The purpose of this experiment was to determine the levels of microwave leakage to which the user may be exposed to while using the CERL system.

Setup

A rubber shielding skirt, designed by HVS Technologies, Inc., was installed on the applicator, as shown in Figure 10. The figure also illustrates where leakage measurements were taken on the microwave applicator device. The measurements were made with a Simpson 380-2 Microwave Leakage Detector.

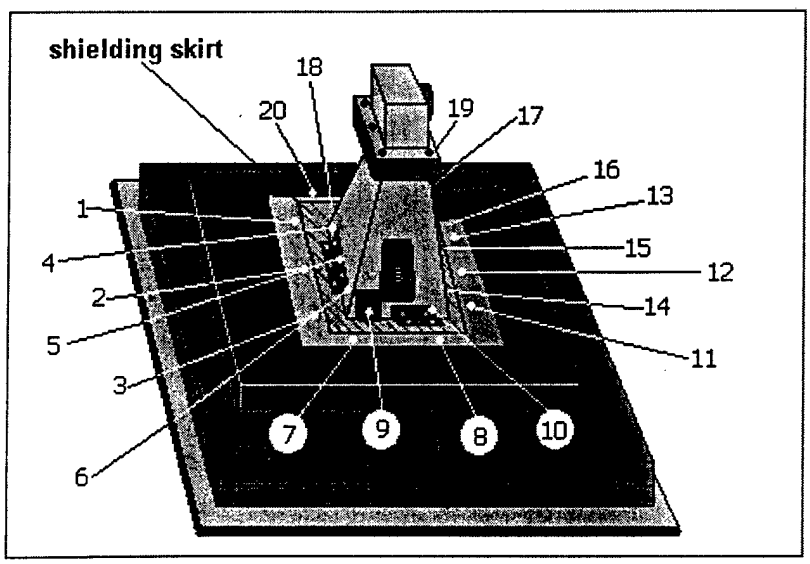

Figure 10. Diagram of shielding skirt and microwave energy leakage measurement positions.

Procedure

The following procedure was followed for Experiment 9:

1. Set applicator down on setup used in previous experiment (see Figure 9), but use an uncoated sample.
2. Start the system at a time sufficient to take measurements at strategic locations using the leakage detector.
3. Record results.

Data

Table 9 lists the results of the microwave leakage tests with the shielding skirt in place.

Table 9. Results of microwave leakage measurements.

Location #	Leakage (mW/cm³)	Location #	Leakage (mW/cm³)	Location #	Leakage (mW/cm³)	Location #	Leakage (mW/cm³)
1	<1	*6*	1	*11*	<1	*16*	<1
2	<1	*7*	1	*12*	<1	*17*	<1
3	1	*8*	<1	*13*	<1	*18*	4
4	<1	*9*	1	*14*	<1	*19*	<1
5	<1	*10*	<1	*15*	<1	*20*	2

Results for Experiment 9

This experiment revealed that the leakage from the portable microwave applicator with shielding skirt falls within safe exposure levels as specified in IEEE C95.1 (5 mW/cm^3 at a range of 5 cm). The final CERL prototype device further protects the user from microwave exposure by incorporating safety switches that prevent the unit from operating unless it is held steadily and in full contact with the substrate.

Optimization of Susceptor Materials

Electrical Properties of Susceptor Materials

The ability of a material to absorb microwave energy is related to the electrical conductivity (σ) through the loss tangent, $\tan \delta = \sigma/(\omega\varepsilon)$, where ω is the frequency and ε is the permittivity or dielectric constant. Using the loss tangent, the microwave power absorption can be calculated for a given electrical conductivity or resistivity. Table 10 lists the dielectric properties of the experimental

susceptor materials. Initial work used graphite and graphite-based compounds as the susceptor material.

Table 11 lists the electrical resistivity of the selected graphite susceptors.

Table 10. Dielectric properties of susceptors.

Substrate	Dielectric Constant	Loss Tangent	Conductivity (S/cm)	Frequency (GHz)
SiC	107	0.686	0.041	1.0
Carborundum	60	0.580	0.058	3.9
Graphite		5×10^7	7.0 x 104	2.45

Table 11. Properties of selected graphite materials.

Coating	Vehicle	Consistency	Texture	Resistivity (ohm-cm)	Sq. R (ohm/sq.)
Slip plate No. 4*	Water	Medium	Even	0.4709	43
GW 220†	Water	Watery	Flaky	66.2	9.33
GW 330†	Water	Medium	Even	0.641	157.67
GW 430†	Water	Thick	Brush Strokes	0.89	113.167
Slip Plate No. 3*	Oil	Medium	Even	1.150	491.167
Slip Plate No. 1*	Oil	Thick	Brush Strokes	4.572	864.33
Slip Plate Spray*	Oil	Spray	Even	5.802	518.33

* Superior Graphite Co.

† Dixon Ticondaroga Co.

Arcing Issues

The graphite susceptor only arcs after it has been heated to a high temperature. One reason for this is that under a strong electric field, as a material gets hotter it will begin to boil off electrons. These electrons, under this strong electric field, can then initiate an arc across the material's surface. Hot spots of a very small size may contribute greatly to this undesirable effect. Hot spots can be caused by minuscule inhomogeneities in the susceptor or by field concentrations at the applicator-susceptor interface.

Some methods for reducing the occurrence of arcing include (1) increasing the work function of the surface and (2) reducing the field strength. Reducing the field strength can be accomplished a number of ways:

- The power of the magnetron can be reduced (but only at the expense of reducing the overall rate of paint stripping).
- The power density can be reduced by increasing the size of the aperture and heating a larger area.

- The time-average power density can be lowered by repeatedly scanning a small aperture over a larger area until the whole area is hot enough to scrape away the paint.

These three methods for lowering the effective power field strength while preheating the substrate were investigated.

Another way to possibly address this issue would be to slightly modify the applicator to prevent field concentrations that may initiate hot spots or small arcs that lead to larger burning arcs. This line of investigation was not pursued in the current study, however.

Polyaniline

Due to arcing and burning of some samples using the graphite susceptor, the use of a self-regulating susceptor material was investigated. Such a material would absorb energy well within the desired temperature range but would become less absorbing at higher temperatures, thus preventing burns. Polyaniline is a conducting polymer that exhibits this behavior within approximately the desired temperature range. It can be used to produce a susceptor coating with a direct current (DC) resistivity in the range 50 to 500 Ω. Its resistivity increases with temperature, and becomes virtually insulating at 180 °C. To measure this property, polyaniline was coated onto glass with two electrodes positioned 1 inch apart. These leads were connected to an ohm meter, and the specimen was placed in a lab-grade convection oven. Figure 11 and 12 show the measured resistance-versus-temperature curves. This behavior is irreversible in that the polyaniline loses its conductivity permanently when heated to the applicable temperatures.

After the polyaniline is applied to the substrate it must be "activated" by rinsing with ethanol before microwave energy is applied. This activation rinse raises the DC conductivity into a functional range for energy absorption. The mechanism by which this activation step works is not fully understood. It appears that rinsing with ethanol removes a top insulating layer from the material, but this does not really account for the activation phenomenon. It was considered that the underlying polyaniline might be conductive before activation but that the top insulating layer prevented DC conductivity measurement. However, the microwave absorption of unactivated polyaniline was found to be negligible, indicating that the underlying polyaniline is nonconductive until activated with ethanol. To verify the irreversibility of the conductivity loss when the polyaniline was heated above 180 °C, the glass sample used in this experiment was again rinsed with

ethanol after heating, but no change in the resistivity of the sample was detected after rinsing.

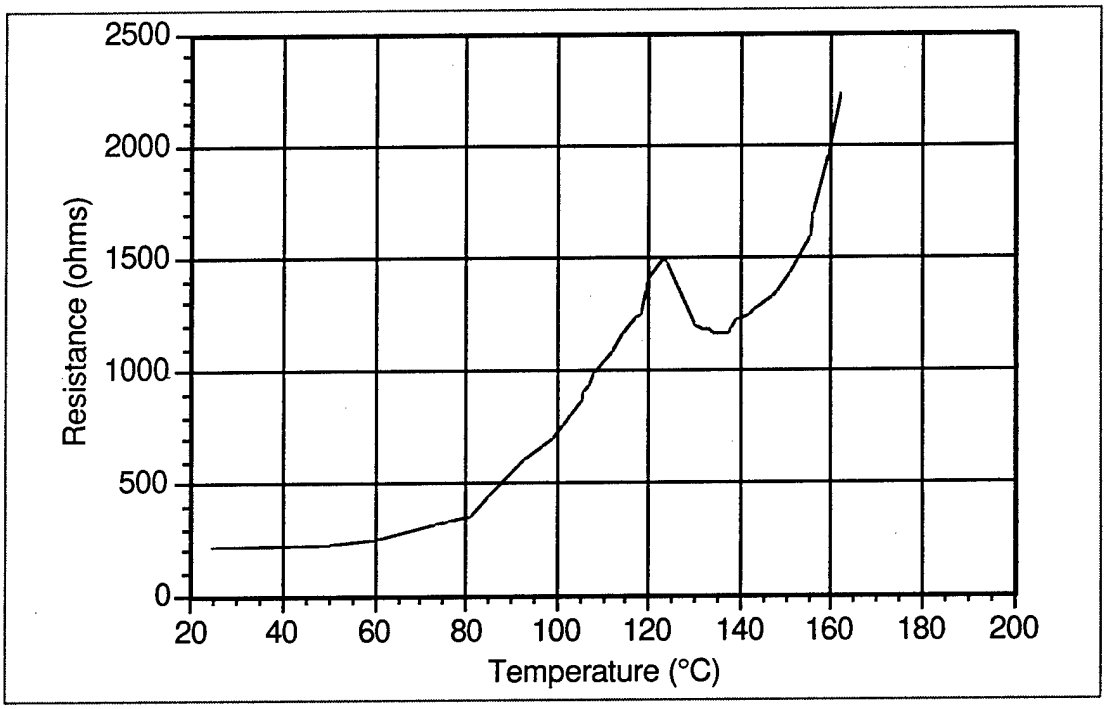

Figure 11. Resistance of a polyaniline film versus temperature.

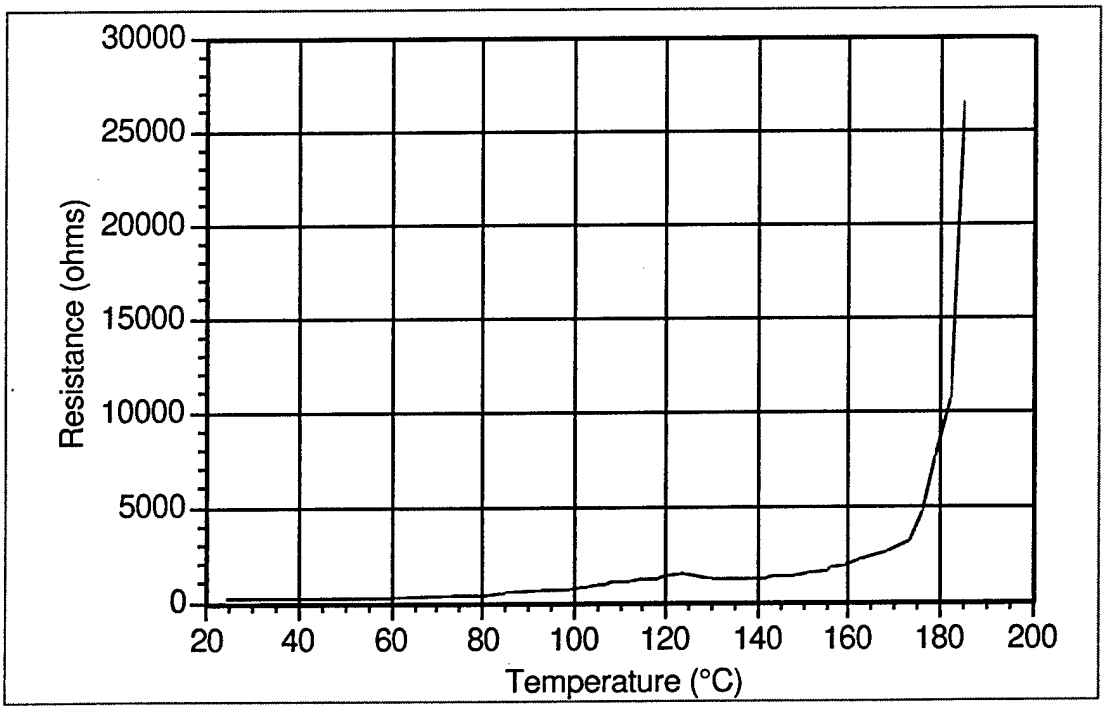

Figure 12. Resistance of a polyaniline film versus temperature showing rapid transition from conductor to insulator above 180 °C.

Experiments Using Chemical Stabilizers with Susceptor Materials

Further laboratory experiments were conducted in order to determine if chemical stabilizers applied in conjunction with susceptors would render nonhazardous paint scrapings without affecting the ease of removal. The susceptors tested were mixtures of graphite and glue, and mixtures of graphite and Slip Plate #3. The chemical stabilizers tested were Lead-X® and PreTox 2000®. Experiments were specifically designed to determine the optimum scheme for mixing or layering the susceptors with the stabilizers.

Initial screening of susceptor candidates was accomplished by measuring resistances of the applied susceptors after they were allowed to dry. The resistances of both brush-applied and spray-applied susceptors were determined in this manner. It was found that the spray-applied susceptors had resistances approximately one order of magnitude lower than the brush-applied susceptors. The graphite/glue mixtures had extremely high resistances, and thus did not yield suitable susceptors.

As in previous experiments, the susceptor/stabilizer combinations chosen from the initial screening were applied to samples of lead-based paint on glass substrates, which were subsequently heated in a microwave oven at 1000 watts for 3 minutes in cycles of 5 seconds on / 5 seconds off, and then removed and scraped. The on/off duty cycle simulates microwave heating that would be acheived using the CERL portable microwave applicator. These experiments were performed in order to ascertain the ability of the susceptor/stabilizer combination to yield nonhazardous waste when subjected to microwave heating. Glass substrates were chosen because the paint can be completely removed from the glass substrates very easily. The resulting paint waste scrapings were analyzed using the EPA toxicity characteristic leaching procedure (TCLP) in order to determine if the waste was nonhazardous. In order to be classified as nonhazardous, the waste must leach less than 5 ppm lead as determined by TCLP.

Experiment 10: Microwave Oven Test of Susceptors and Stabilizers

Specifications

1. Paint layer
- In-house lead-based paint.
2. Lead-abatement layer
- PreTox2000 (samples PT1-PT3)
- Slip Plate No. 3 (samples L1-L3)
- Slip Plate No. 3 and Lead-X (samples L4-L6).

3. Susceptor layer
- Slip Plate No. 3 graphite.

Procedure

1. Prepare lead abatement layer
- Prepare 15 percent by weight mixture of Slip Plate No. 3 and Lead-X.
2. Prepare samples
- Paint nine glass plates with lead-based paint.
- Spray three of the lead-painted panels Slip Plate No. 3.
- Spray three of the lead-painted panels with the Slip Plate No. 3 graphite and Lead-X mixture.
- Coat three of the lead-painted panels with PreTox2000 using a brush.
- Spray the three PreTox2000-coated panels with Slip Plate No. 3 graphite.
3. Heat samples and scrape
- Place a sample in a microwave oven.
- Heat the sample for 3 minutes in on/off cycles of 5 seconds.
- Scrape the paint from the panels (be sure to collect all the scrapings).
- Grind up the scrapings and send them out for TCLP testing.

Data

Tables 12 and 13 list parameters and data collected in Experiment 10.

Results

Several promising candidates for susceptor/stabilizer systems emerged from the microwave oven heating experiments. These susceptor/stabilizer systems were applied to lead-based paint samples on wooden substrates, and then heated using the CERL portable microwave applicator. After being heated with the microwave applicator, the samples were scraped as before, and the scrapings (lead-based paint, susceptor, and stabilizers) were analyzed in accordance with TCLP.

Table 12. Microwave-assisted paint removal laboratory experiments with PreTox2000 as the stabilizer and graphite as the susceptor using microwave oven and glass substrates.

Sample	Gl	Gl+Pb	Gl+Pb+PT2	Gl+Pb+PT2+Gr	TCLP Results
PT1	1011.86 g	1027.79 g	1035.40 g	1039.11 g	<0.06 PPM
PT2	1014.10 g	1028.72 g	1036.54 g	1040.31 g	<0.06 PPM
PT3	1016.53 g	1027.53 g	1068.55 g	1072.10 g	<0.06 PPM
Gl=glass	Pb=LBP		Gr=graphite	PT2=PreTox2000	

Table 13. Microwave-assisted paint removal laboratory experiments with Lead-X as the stabilizer and graphite as the susceptor using microwave oven and glass substrates.

Sample	Gl	Gl+Pb	Gl+Pb+Gr	Gl+Pb+Gr/Ldx	TCLP Results
L1	1011.12 g	1019.41 g	1021.85 g	NA	350 PPM
L2	1028.68 g	1038.04 g	1040.27 g	NA	260 PPM
L3	1006.95 g	1016.23 g	1018.84 g	NA	300 PPM
L4	1008.22 g	1017.31 g	NA	1010.27 g	300 PPM
L5	999.51 g	1008.55 g	NA	1011.53 g	320 PPM
L6	1017.16 g	1025.86 g	NA	1029.29 g	380 PPM
Gl=glass	Pb=LBP	Gr=graphite	Ldx=Lead-X		

Notes: Samples L1-L3 have a susceptor coating of approximately 2 mils. Samples L4-L6 have a susceptor coating of approximately 1 mil. The first four columns of each table reflect data taken to keep track of mass of coatings on glass panels.

Experiment 11: Test of CERL Microwave Applicator Using Both Susceptors and Stabilizers

Specifications

1. Paint layer
   - In-house lead-based paint
2. Lead-abatement layer
   - PreTox2000
3. Susceptor layer
   - Slip Plate No. 3 graphite and graphite powder

Procedure

The following procedure was followed in Experiment 11:

1. Prepare samples.
   - Paint four wooden panels with lead-based paint (brush on).
2. Prepare susceptor layer.
   - Find the mass of the volume of Slip Plate No. 3 to be used
   - Add graphite powder until the total mass of the mixture is 17.4 percent powder and 83.6 percent Slip Plate No. 3
3. Apply lead abatement layer (brush on).
4. Apply susceptor layer (airless sprayer).
5. Perform microwave-assisted paint removal process and send waste out for TCLP.

Data

Table 14 summarizes the data collected for Experiment 11.

Table 14. Microwave-assisted paint removal tests using PreTox2000 and Slip Plate No. 3/graphite powder on painted wood substrate.

Sample	Temp ©	Resistance (ohms)			
		Left	Center	Right	TCLP Results
F2A	90 – 128	300	210	260	<0.06 PPM
F2B	30 – 110	500	200	320	<0.06 PPM
F3A	70 – 150	390	550	320	0.08 PPM
F3B	60 – 120	400	320	400	0.08 PPM
F4A	35 – 210	350	235	320	<0.06 PPM
F4B	80 – 220	310	300	520	<0.06 PPM

Comments

F2A: Heated very evenly. Substrate was very warm, and initial scraping damaged it a little. Everything came off. There doesn't appear to be any lead paint remaining on the surface. Smoke appeared near the end of 2 minute application.

F2B: Heated fairly unevenly. Initially cooler side didn't scrape well, but eventually all scraped very well. Everything came off, but some residue of lead paint visible in board. Board heated also, and smoke appeared near end of 2 minutes.

F3A: Scraped well. Some discoloration in the center of board where it was hottest. Very little wood scraped up in an area with approximate dimensions of 1 in. by 0.5 in.

F3B: Scraped extremely well. Some discoloration in center of board where it was hottest.

F4B: Surface became extremely hot. Area where graphite bubbled was difficult to scrape. All paint scraped. The substrate suffered some heat damage. Scraping with the grain seems to work best.

F4A: Same as F4B, except it seemed that by first scraping against grain and then scraping with the grain, the results were achieved more quickly. Burn spots occurred in regions where the surface temperature was greater then 190 °C after heating.

Summary of Results

The combined results for Experiments 10 and 11 show that the optimal combination of easy removal and nonhazardous waste product was achieved when PreTox2000 was chosen as the stabilizer, and a mixture of Slip Plate No. 3 and graphite powder was chosen as the susceptor. Optimal conditions were achieved when:

- The PreTox was brush-applied directly over the lead-based paint and allowed to dry for 24 hours.
- Slip Plate No. 3 and graphite powder were mixed together in a weight ratio of 5 parts. Slip Plate No. 3 to 1 part graphite to form the susceptor, and then spray-applied as a separate layer over the PreTox as shown in Figure 13.
- The susceptor topcoat was allowed to dry for 24 hours.

Using this scheme, it was determined that 0.5 sq ft of lead-based paint could be removed in about 3 minutes. This estimate includes heating times of approximately 2 minutes using the applicator, required to obtain a surface temperature of about 100 °C, and a scraping time of approximately 1 minute.

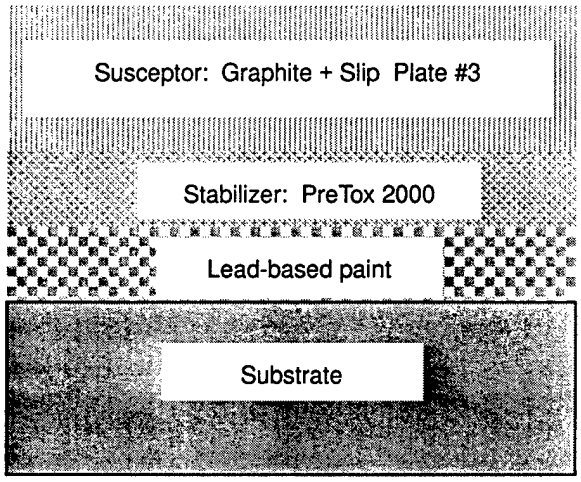

Figure 13. Optimal scheme for arrangement of susceptor and stabilizer over substrate coated with lead-based paint.

HVS Microwave Paint Removal System

A system developed by HVS Technologies, State College, PA, under contract to CERL, was designed to provide high power to a relatively small area with the goal of rapidly and uniformly heating that area (Hollinger, Varadan, and Varadan 1996). The HVS system (Figure 14) can provide up to 1000 watts of power. A low-loss coaxial cable connects the generator to a hand-held or robotically op-

Figure 14. HVS microwave paint removal system.

erated applicator. In the applicator, a stub tuner is used to match the impedance of the microwave to that of the susceptor applied over the painted substrate. In the HVS applicator, an aperture is used to focus the microwaves onto a small area (2.54 cm by 2.54 cm) of substrate. This aperture is a specially designed ceramic window that couples the microwave energy from the waveguide to the painted surface. The aperture window material was selected to have low dielectric loss, high temperature resistance, excellent thermal shock resistance, and good mechanical strength.

The applicator is equipped with four safety switches that are closed when the applicator is pressed against a flat surface. No microwave energy is produced unless all four safety switches and the activator switch are closed. The activator switch is located on the hand grip. Surrounding the applicator is an electromagnetic shielding skirt made of a conducting polymer. On the base of the applicator is an exhaust tube, which is connected to a vacuum system and a high-efficiency particle air (HEPA) filter. The front panel on the generator contains an indicator light, an on-off switch, a reflected power meter, and a forward power meter. The power delivered to the substrate is the difference between the forward and reflective power. The amount of reflected power can be minimized by impedance matching.

Investigations of susceptor/stabilizer combinations by HVS revealed that lower susceptor resistances could be obtained by mixing 28 wt percent Desulco Graphite Powder 9033 with 43.2 wt percent latex paint and 28.8 wt percent water to make a susceptor that can be brush-applied. When this susceptor was brush-applied over PreTox2000 (which itself was brush-applied over LBP), the average

resistance was 90.1 ohms. When the susceptor was brush-applied directly over the LBP, and the PreTox2000 was subsequently brush-applied over the susceptor, the average resistance was found to be 166.7 ohms. Neither of these systems has been subjected to TCLP testing, but because the graphite-based susceptor is similar to that used by CERL and the stabilizer (PreTox2000) is the same, there is good reason to expect that the HVS treatment will yield waste products with TCLP results similar to those obtained in the CERL experiments. Due to the lower surface resistances of the HVS susceptor/stabilizer systems, paint heating time might be reduced.

Field Demonstrations of Microwave-Assisted Paint Removal Technologies

Demonstrations of microwave-assisted paint-removal technology were performed on the abandoned lockmaster's house at the Army Corps of Engineers Lock and Dam #6, on the Kentucky River near Lexington. HVS was contracted to conduct the demonstration, so the company used its own system in this phase of the study. The onsite work was conducted on 10, 11, and 12 December 1997. Initially the area chosen to be stripped was the interior surface of an outer wall on the enclosed porch. The substrate appeared to be plywood.

Day 1

Ten square feet for field testing of the HVS applicator and about five square feet for the CERL microwave removal system were marked off, and susceptors were applied. HVS personnel used two different susceptors, covering 5 sq ft with each. The first was a latex-based graphite susceptor of a refined composition, developed by HVS. The second was an intrinsically conductive polymer (polyaniline) dissolved in the solvents cellosolve and xylene. Both susceptors were applied using paint brushes (although both are also sprayable). These were allowed to dry overnight.

Day 2

As explained previously, the polyaniline must be activated before it is conductive. To do this, chemical sorbent socks (3 in. diameter by 48 in. long) were placed on the floor against the wall on which polyaniline had been applied, and ethanol was spayed onto the polyaniline from a squirt bottle. The activation with ethanol causes the polyaniline to shrink slightly which results in 'mud cracking.' Resistivity measurements of the susceptors were taken as shown in Figure 15.

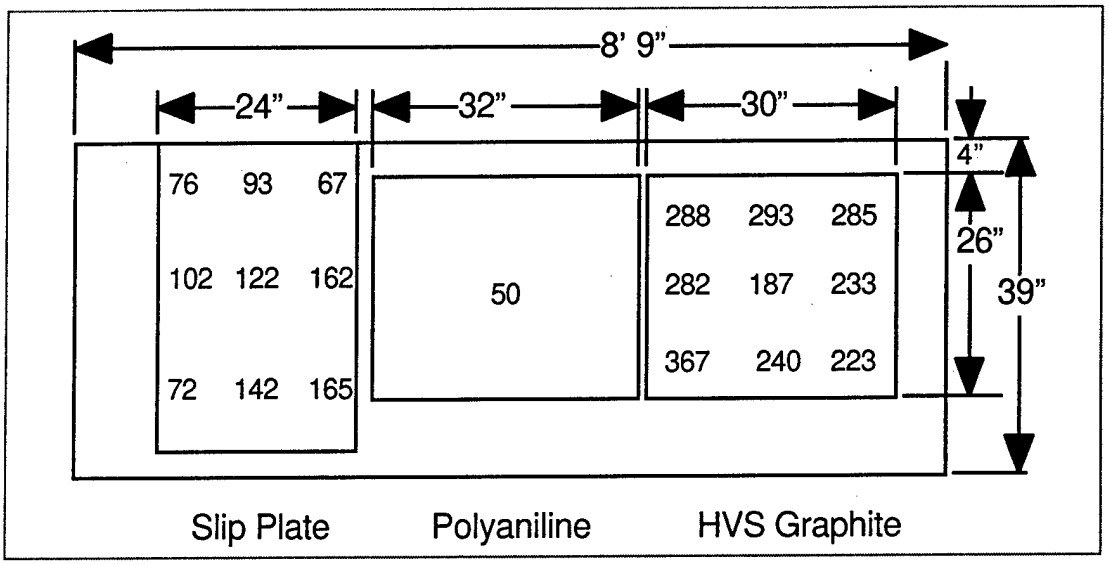

Figure 15. Resistivities (ohms) of the susceptors coated on the interior porch wall, measured using HVS probe.

The HVS microwave paint stripper was used first on the HVS graphite susceptor. However, when attempting to scrape off the paint after heating, the scraper dug into and tore up the substrate. It was discovered that the substrate in this area was not solid wood as expected, but was compressed paper board. Several attempts were made to scrape both the graphite and the polyaniline-treated areas with the same result. The decision was made to look for substrate specimens known to be solid wood. A wooden door and door frame (Figures 16 and 17) were chosen for HVS to strip. The CERL applicator was demonstrated on a window frame. Both susceptors (graphite and polyaniline) were applied and allowed to dry overnight.

Day 3

The graphite susceptor on the door had a higher resistance than it did on the porch wall (compare Figures 15 and 16). The overall average on the wall was 266 Ω while on the door it was more than double that (646 Ω). This was probably because the susceptor in the can had partially dried and formed a gel that was too thick to apply. Water was added, but this made it thinner than desirable. This overthinning apparently impaired the susceptor's conductivity, thus resulting in higher resistivity measurements. The gelling of the susceptor may have been caused by the cold ambient temperatures, which averaged from the mid 30s to low 40s (degrees Fahrenheit) during the test dates. Friday was the coldest day.

Despite the high resistivities explained above, it was possible to strip the paint using the HVS microwave paint stripper. However, more time was needed to

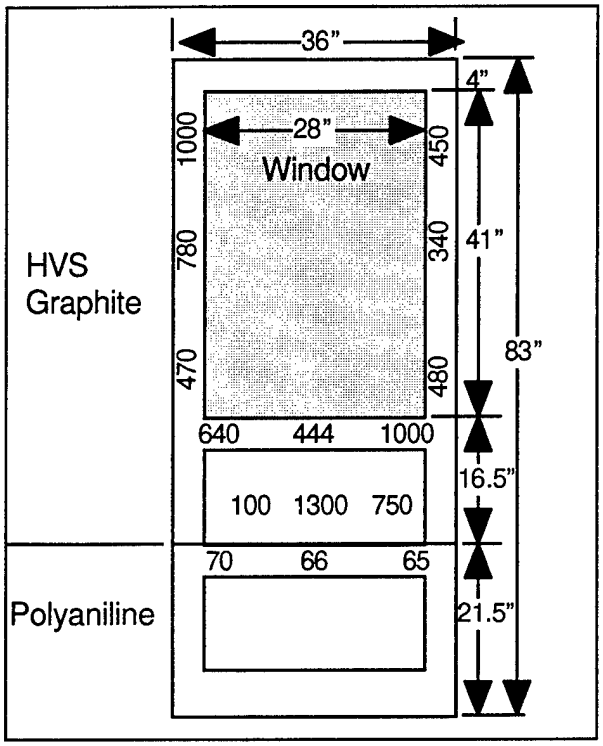

Figure 16. Diagram of door stripped by HVS, showing measured resistivities of the susceptors.

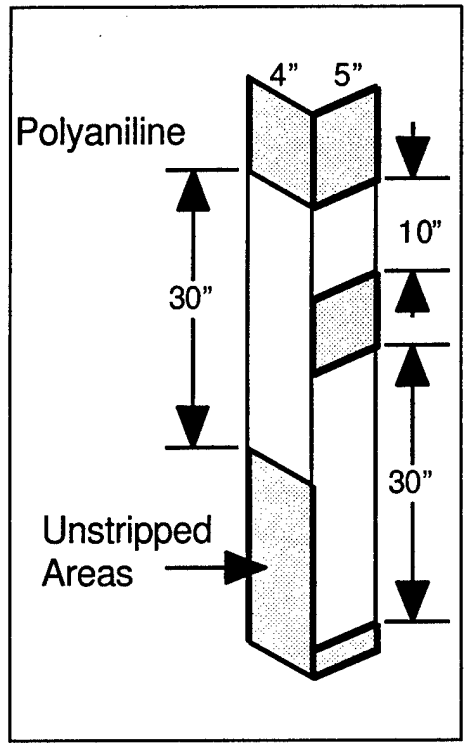

Figure 17. Detail of door frame stripped by HVS system.

heat the paint, and the period of time after heating during which it was possible to scrape the paint was very short — on the order of 5 seconds. The slow heating can be attributed both to the cold weather and to the high resistivity of the susceptor. The short period of time available to remove the heated paint was due solely to the cold weather. Typically an area 6 in. long by 1.5 to 1.75 in. wide was heated for about 30 seconds, then scraped immediately with a 1.25 in. wide putty knife. Both the multiple-scan method developed by CERL and the single-scan method were used. It was believed that the multiple scanning method might work better to gradually heat the substrate as well as the paint. However, the single-scan method seemed to work better and was certainly less tiring for the operator. Arcing of the graphite was not a problem with the N131C graphite, even during prolonged heating of the same spot. With prolonged heating the paint itself would melt enough to start absorbing microwave power and start smoking. In this condition the paint would almost fall off of the wood, but the time required to soften the paint this way was too long to be efficient.

The polyaniline susceptor exhibited low resistivities and worked well during microwave paint stripping, but as with the graphite-treated samples, the cold weather caused slow heating rates and very short paint scraping time limits. One drawback to the polyaniline susceptor is that it irreversibly loses its conductivity as it is heated. Therefore, once it is heated, if all of the heated paint is not scraped off, the remaining susceptor is very difficult to reheat. Even though the

microwave applicators produce a very uniform field, the energy output does taper off some at the outer edges. Furthermore, the paint near the edges of the heated spot cools more rapidly because it is adjacent to unheated paint and substrate, and these act as heat sinks. Another complicating factor is that during scraping, some of the susceptor is removed at the edges without removing all of the paint under it. Because of this phenomenon, an estimated 50 percent or more of the scraping time was of necessity dedicated to removing the paint adjacent to previously stripped areas. The center portion of the heated area came off in one scrape, but near the edges of the area the paint was not nearly as soft and required much more effort to remove (Figure 18).

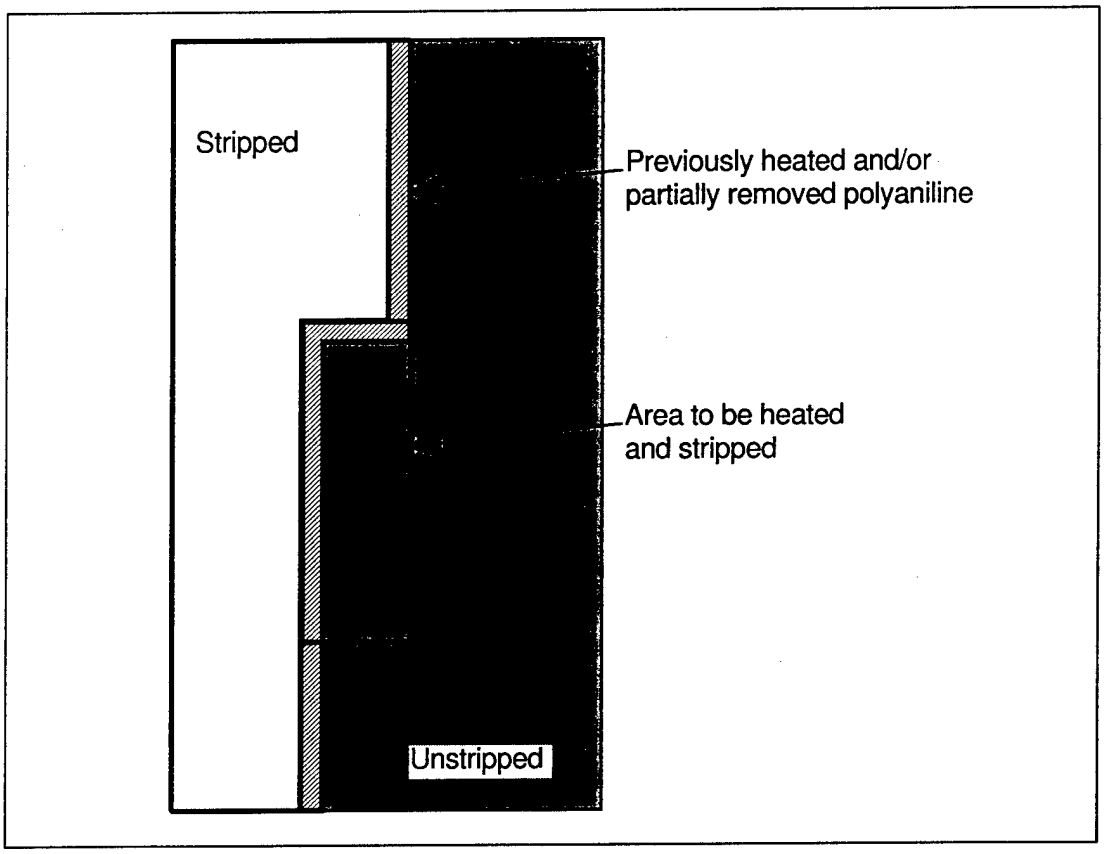

Figure 18. Illustration of the difficult-to-strip boundary between stripped and unstripped areas of polyaniline-treated areas.

A few cases of arcing and burning were noted. All such cases occurred with the graphite susceptor. In the laboratory experiments arcing was associated with low susceptor resistivities, but in this field test the graphite susceptor had a higher-than-desired resistivity due to the gelling and thinning problem noted previously. Therefore, it is likely that the arcing was caused by the presence of small nails or brads that were visually inconspicuous.

It is worth noting, however, that there were two burn marks in the graphite-treated area that did not appear to be caused by metal; both appeared to be related to discontinuities in the paint. In one case the paint had been chipped down to bare wood, and both the bare wood and the paint surrounding it were coated with susceptor. In the other case, there was significant burning right at the paint/no paint interface. In this case, the paint was cracked and the edges appeared to be curled up. Two possible explanations for this are as follows:

1. The paint on the door was quite thick, so in both cases a crevice existed that could have retained excess susceptor that initiated burning during the paint removal process.
2. The irregularity of the surface may have produced electric field concentrations that initiated arcing and burning.

It is interesting to note that no arcing or burning problems occurred with the polyaniline susceptor even though its resistivity in this test was only about 50 percent compared to the graphite-coated samples. It may be that the polyaniline coating was of very uniform resistivity, but a simpler explanation would be that the sample was free of nails or brads of the right size and orientation to cause arcing.

Figure 19 shows two views of the door, before and after LBP removal.

a b

Figure 19. Wooden door coated with LBP before (a) and after (b) microwave-assisted paint removal.

Field Demonstration Results

It is concluded that microwave-assisted removal of LBP from wood was successfully demonstrated in these tests. Lead levels on the wood were dramatically reduced on the areas stripped. The new type of susceptor — polyaniline — was used effectively to heat the paint without any arcing or burning. This is a promising material, but at a current cost of approximately $1500 per liter it is still too expensive for widespread use in routine LBP removal projects.

The graphite susceptor exhibited very little arcing and burning. Those few examples of this problem appear to have been caused by the presence of metal in the substrate and pre-existing physical damage to the paint that exposed the bare substrate to the susceptor. The time taken to strip the 10 sq ft was approximately 5 hours, or a rate of 2 sq ft per hour. The cold weather made it necessary to heat the samples longer than was necessary at ambient temperatures in the laboratory, but it also required the technician to scrape the softened paint more rapidly to prevent re-solidification before removal. Therefore, the overall time required for the process in the field was approximately the same as that achieved in the laboratory.

The paint at the field site seemed to be more tenacious than expected, but this may have been due to the cold temperatures and the resulting inability to reach the same paint temperatures that would be reached in a warmer environment.

This work has resulted in the following publications and patents:

Boy, J., and A. Kumar, "Lead-Based Paint Hazard Mitigation" in *The Encyclopedia of Environmental Analysis and Remediation*, Robert A. Meyers, ed. (John Wiley and Sons, Inc., 1998), pp 2501-2516.

Kumar, A., and J. Boy, "Microwave-Assisted Removal of Lead-Based Paint from Wooden Structures," Proceedings, Army Science Conference (1998).

U.S. Patent No. 5,268,548, "Microwave-Assisted Paint Stripping," Ashok Kumar (7 December 1993).

Summary

This report has documented several LBP-removal and management technologies funded entirely or in part through the multiagency Strategic Environmental Research and Development Program (SERDP). The following technologies were developed and demonstrated to reduce the cost of control and abatement of LBP on DoD steel and wooden structures:

Thermal Spray Vitrification. The removal of lead-based primers and paints from steel surfaces as been achieved through a thermal spray vitrification process that uses a glass compound designed for high lead solubility and resistance to chemical leaching. Oxyacetylene flame spray technology was used to apply the glass compound to steel samples containing a commonly used red lead primer. The resulting glass waste was collected and analyzed for lead content using the Toxicity Characteristic Leaching Procedure (TCLP). The results showed that the lead absorbed into the glass was partially vitrified during thermal spray processing, and vitrification was completed by remelting the deposit in a portable onsite furnace. During laboratory testing, lead emissions were determined to fall below the EPA National Ambient Air Quality Standard Limit as well as the OSHA Action Limit for personal exposure. The advantages of the thermal spray vitrification over conventional abrasive blast LBP removal are cost savings that result from the elimination of tight containment, worker health protection measures, and environmental monitoring. Waste disposal costs are also reduced because the vitrified residue from the process is nonhazardous.

Painter-L. This computer-based lead hazard management system provides for the collection and analysis of LBP risk-assessment data, the development of installation lead hazard management plans, and identification of interim and long-term lead hazard control strategies. It also facilitates the tracking of hazards found and remedial actions taken. Painter-L can print the mandatory Disclosure of Information document as new tenants move in, disclosing the extent of any known lead hazard problems and what actions were taken to alleviate the problems. It also enables the collection of ancillary data for worker protection issues.

Evaluation of Emerging Technologies. CERL evaluated emerging environmentally acceptable technologies for LBP removal from nonsteel DoD buildings and structures. During field testing, it was determined that sponge blasting caused unacceptable damage to historical wooden structures.

Blasting technologies based on granulated and pelletized CO_2 abrasives proved to be unacceptable for removing LBP from interior wooden components because they caused severe damage to the substrate. However, a wet abrasive blasting technology using an engineered abrasive that incorporates a chemical stabilizer efficiently removed LBP from exterior architectural wood components to bare substrate with no apparent damage, and yielded a surface suitable for repainting without further treatment. Also, encapsulant paint remover technology proved effective in removing LBP from interior wood components down to bare substrate. Six environmentally acceptable (EA) chemical strippers, containing ingredients such as citric acid and the noncaustic, toxicologically benign compound N-methyl pyrrolidone (NMP), were also evaluated, but only the NMP-based strippers performed comparably to traditional solvent-based and caustic strippers.

Microwave-Assisted Paint Removal. This process offers a technically viable solution to problems associated with lead-based paint removal and provides an alternative to currently used technologies that rely either on hazardous chemicals or produce airborne lead-bearing particulates. An extensive series of laboratory experiments was performed in order to investigate the parameters related to proper heating of the paint for easy removal. In particular, the parameters investigated included susceptor type, dwell time, scan rate, equipment safety factors, and the effectiveness of chemical stabilizers. Graphite and polyaniline susceptor materials, applied over the painted surface, were used successfully to absorb microwave energy and heat the paint. The heat softens the paint, which is easily scraped from the substrate. Two prototypes of the microwave paint stripping system have been developed: a high-power system that applies energy to a 2.54 cm square area, and a low-power system that applies energy over a 15 cm square area. Microwave-assisted LBP removal procedures were optimized in the laboratory and successfully demonstrated in the field. The lead levels on the stripped areas of the test substrates were dramatically reduced. When applied according to the optimized procedures and conditions documented here, the microwave-assisted LBP removal process is safe and effective in removing paint in large quantities without burning, discoloring, or otherwise damaging the substrate. It has also been demonstrated that select chemical stabilizers applied in conjunction with the susceptors can render the waste nonhazardous as verified by TCLP testing.

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