Laser Ablation of Contaminants from Concrete and Metal Surfaces

**Topical Report
June - December 1994**

Joyce Freiwald
David A. Freiwald

December 1994

Work Performed Under Contract No.: DE-AR21-94MC30359

U.S. Department of Energy
Office of Environmental Management
Office of Technology Development
Washington, DC

For

U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
F2 Associates
Albuquerque, New Mexico

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December 1994

ABSTRACT

Tests have demonstrated that it is possible to clean coatings off surfaces using high-power, pulsed, high-repetition-rate lasers. The purpose of this contract is to demonstrate (1) that pulsed-repetition lasers can be used to remove paint from concrete and metal surfaces, including cleaning out the surface pores, (2) that the cleaning process will result in negligible release of contaminated ablated material to the environment, and (3) that the process generates negligible additional waste compared to competing technologies. This report covers technical progress during Phase I of the contract and makes recommendations for technology development in Phase II.

PREFACE

- The originals for some of the figures, such as the microphotographs, are in color, and show detail much better than black and white copies. They have been given to the METC COR.
- The thickness of coatings are normally discussed in terms of mil (0.001 inch) thickness and square feet of coverage. Filtration flows are normally discussed in terms of cubic feet per minute (cfm). English to metric conversion factors are given when first used in the text.

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Final Topical Report
TABLE OF CONTENTS

ABSTRACT	ii
PREFACE	III
ACKNOWLEDGMENTS	iv
TABLE OF CONTENTS	v
LIST OF FIGURES	viii
LIST OF TABLES	x
EXECUTIVE SUMMARY	xi
1.0 INTRODUCTION	1
1.1 Problem Overview: The Need for Coatings Removal	1
1.2 Coatings Removal Technologies	2
1.2.1 Mechanical Approaches	2
1.2.2 Chemical and Electrochemical Processes	3
1.2.3 Radiation Technologies	5
1.2.4 Incineration	5
1.3 Laser-Based Coating Removal Technology	5
2.0 PURPOSE	9
3.0 BACKGROUND	11
4.0 METHODOLOGY	15
4.1 Phase I Tests - Overview	15
4.2 Phase I Test Set-Up	16
4.3 Some Basic Parameters	20
4.4 Types of Coupon Tests	23

TABLE OF CONTENTS
(continued)

4.5	Single Pulse Tests	23
4.6	Repetition Rate Scan Tests	24
4.6.1	Microphotograph Data	24
4.6.2	Fully Instrumented Tests	31
4.7	Parallel Design Verification Tests (DVTs) for Components	31
5.0	RESULTS AND DISCUSSION	33
5.1	Task 1 - Site Visits	33
5.2	Task 3 - Phase I Test Results	34
5.2.1	Single-Pulse Tests	34
5.2.1.1	Red Lead Primer	34
5.2.1.2	Two-Part Epoxy	34
5.2.1.3	Scanning Rates	34
5.2.2	Repetition-Rate Scan Tests	36
5.2.2.1	Microphotograph Data	36
5.2.2.2	Fully Instrumented Tests	36
5.2.2.3	Gas / Vapor Samples	36
5.2.2.4	Particulate "Sniffers"	37
5.2.2.5	In-line Prefilters	37
5.3	Test Plans for Phase II	38
5.4	Task 4 - Integrated 6 kW System Design for Phase II	38
5.4.1	Background	38
5.4.2	Design Results	39
5.4.2.1	Laser, Articulating Optics, and Nozzle	39

TABLE OF CONTENTS (continued)

5.4.2.2 x,y scanner	39
5.4.2.3 Filtration system	39
5.4.2.4 Integrated system design for Phase II	44
5.4 Plans for Phase II	44
5.5 Interactions with Potential Users	47
6.0 CONCLUSIONS AND RECOMMENDATIONS	48
6.1 Conclusions	48
6.2 Recommendations	48
REFERENCES	50
LIST OF ACRONYMS, ABBREVIATIONS, AND DEFINITIONS	52

LIST OF FIGURES

Figure 1	Phase I Basic Test Set-Up With Low Power Laser	xiii
Figure 2	Levels of Dress for D&D Workers	4
Figure 3	Generic System Concept Sketch for Floor Cleaning	7
Figure 4	Depiction of Pulse-to-pulse Overlap and Raster Scan	13
Figure 5	Simplified Nozzle Sketch for Gas / Vapor and Particulate Capture	14
Figure 6	Photo of Phase I Lab Test Set-up with Laser / Nozzle Rolled Back Rightwards from Fume Hood	17
Figure 7	Photo of Phase I Nozzle with Pairs of Gas / Vapor and Particulate Sniffer Tubes Around Base of Nozzle and Scanner with Test Coupon	18
Figure 8	Commercial Particulate Sample Collectors	19
Figure 9	Plumbing Schematic for Gas / Vapor and Particulate Samplers	21
Figure 10	Drawing of In-line Filter Test Jig Used Between Nozzle and Nilfisk™ Vacuum Unit.	22
Figure 11A	Bare Aluminum and Cleaned Aluminum Coupons Before Painting	25
Figure 11B	Aluminum Coupons with Red-Lead Primer Paint	26
Figure 11C	Aluminum Coupons with Two-Part Epoxy Paint	27
Figure 12A	Concrete Reference Sample Before Applying Coatings	28
Figure 12B	Concrete Coupon Coated with Red-Lead Primer and Then Laser Ablated	29
Figure 12C	Concrete Coupon Coated with Two-Part Epoxy and Then Laser Ablated	30
Figure 13	Isometric Drawing of Phase II Transportable Laser Design and Articulating-Optics Beam Delivery System	40

LIST OF FIGURES
(continued)

Figure 14	Isometric Drawing of Phase II Transportable Floor Scanner and Nozzle, Plus PENTEK VAC-PAC Vacuum and Filtration Unit	41
Figure 15	Line Drawing of Transportable 6 kW Pulsed-Repetition CO₂ Laser System	42
Figure 16	Isometric Drawing of Small x,y Scanner	43
Figure 17	Sketch of Large Scanner Fitted to PENTEK MOOSE Robot for Floor Cleaning	45
Figure 18	Sketch of Large Scanner Fitted to CMU / RedZone ROSIE Robot for Wall Cleaning	46

LIST OF TABLES

Table	I	Relative Comparison of Technologies for Removal of Contaminated Paint from Surfaces	8
Table	II	Single-Pulse Test Data	35

EXECUTIVE SUMMARY

High-power pulsed high-repetition-rate lasers have recently become available, as discussed in more detail under Section 3.0, Background. Tests have demonstrated that such lasers can clean coatings off surfaces in a one-step process, where the coating material is ablated (vaporized) and promptly captured in a suction nozzle and vacuum filtration system. With proper operating parameters, there is also no damage to the substrate.

The purpose of this contract is to demonstrate the following in laboratory tests:

- That pulsed-repetition lasers can be used to remove lead-based paint and other DOE-specified paints such as two-part epoxy, from concrete and metal surfaces, including cleaning out the surface pores.
- That the cleaning process will result in negligible release of contaminated ablated material to the environment.
- That the process generates negligible additional waste compared to competing technologies. All processes have filtration waste.

This project is divided into two Phases. Phase I included design of integrated system and some testing using a lower powered laser. During Phase II, the integrated system would be built and tested. This Topical Report only covers Phase I. The original proposal used a time frame of three months for Phase I, but that was lengthened in the final contract to six months. The specific tasks for Phase I were:

- Task 1: Site visits to assess the surface cleaning issues, and obtain information on operations and logistics as input for Task 4.
- Task 2: Phase I test plan for Task 3.
- Task 3: Laboratory tests using a low-power laser (600 W, run at <100 W). The Statement of Work requires stripping DOE-specified paint from coupons and using micro-photographs (photos taken through a microscope) to show that the process also cleans out the pores.
- Task 4: Design of an integrated system for Phase II that will use a 6 kW laser
- Task 5: Topical report

Accomplishments by task:

- Task 1: Site visits were made to RMI and Fernald, including tours of hot areas. These visits were very informative, and the hosts were extremely cooperative. Discussions also included consideration of an on-site cleaning demonstration as a possible later addition to Phase II or a Phase III. The issues regarding coatings, operations, and logistics were considered in engineering designs for Task 4.

Task 2 and 3: The test plan and lab work involved two types of tests (Figure 1):

- (1) A series of single pulse tests for red-lead primer and a series for two-part epoxy were done. Both test series were done on metal coupons. These tests were to determine the energy needed to ablate through the coatings to the metal substrate. Microphotos were taken after each test. For a square laser spot size of 5 mm by 6 mm, it was found that the energy needed was 60 J for 4 mil thick red-lead primer, and 150 J for 10 mil thick two-part epoxy (1 mil = 0.001 inches = 0.00254 cm). The laser energy per pulse, the thickness of paint from microphotos, and the number of pulses to ablate through the paint can be used to determine other data, such as the average number of pulses to ablate through a given thickness of the type of paint. This is needed for setting baseline scan rates for repetition-rate tests. These Phase I results were then transformed through scaling laws based on theory and earlier experimental data. These results still project removal rates of 100 square feet per hour for ~20-mil thick paint. Microphotographs showed thorough cleaning, including cleaning out the surface pores, for both red lead primer and two-part epoxy on aluminum.
- (2) Rep-rate stripping tests on concrete and metal coupons, some painted with red-lead primer, some with two-part epoxy, and some with Krylon. Full instrumentation was used for the red-lead primer tests on concrete. The instrumentation included eight sampling points, with both gas / vapor sniffers and particulate samplers at each point, plus filter-paper samples in the vacuum-filtration system. Four of the sample points were around the base of the gas / vapor and debris capture suction nozzle, one each before and after the pre-filters, one after the final exit High Efficiency Particulate Air (HEPA) filter, and one room-reference sample. Microphotographs were also take before and after stripping.

Analysis of test data showed:

- Gas / vapor measurements: The Phase I tests used a lower energy laser with low repetition rates. These factors combined with the vacuum pump speed resulted in high dilution ratios of the debris cloud with ambient air. Analysis of the samples taken in Phase I showed no noticeable levels of carbon monoxide (CO), carbon dioxide (CO₂), hydrocarbons, or water vapor over background for the detection levels of the Hauser Labs instruments (1% for CO and 0.05% for CO₂). This should not be a problem in Phase II since the laser power will be >100 times greater, and the repetition rate will be 50 times greater, than those used in Phase I. These will result in high generation rates of material.
- Particulates: Particulates were mainly lead and chromium. Analysis showed that the vast majority of particulates (>99%) were under 5 μ in size, with ~90% being less than 1 μ in size. This is considerably smaller than the expected 10 μ average size, and the 5 - 30 μ particulates seen by others who used lower laser power densities on target.¹ Data also indicated that traces of particulates escaped out under the edge of the nozzle, with deposits showing on the test coupons at the nozzle edge. These particulates represented

Fig. 1 - Phase-I test set-up with low power laser.

about ~0.4% lead compared to that captured in the identical sniffers in the main filtration system, and more of the lighter chromium. The particulates escaped from under the edge of the nozzle because of the insufficient vacuum pump rate of ~87 cubic feet per minute (cfm; 1 cfm = 0.472 liters / second). This will be corrected in Phase II by using a much more powerful vacuum pump. Nozzle edge leakage is also sensitive to the stand-off distance (the gap width between the under edge of the nozzle and the surface being scanned). Larger stand-off distances result in more leakage. This is because of less inward ambient-air speed and thus less flow momentum to intercept and entrain ablated material. A solution option is to include increasing the flow speed and reducing the gap width to create near-sonic flow. Another solution option is to use a disposable skirt around the base of the nozzle. These will be investigated in detail in Phase II.

- Microphotographs showed thorough cleaning, including cleaning out the surface pores, for red lead primer and two-part epoxy on concrete.

A version of these tests will be repeated again in Phase II with the 6 kW high-power laser.

Task 4: A design package for the high-power system was completed. Given input from Tasks 1 and 3, design efforts were made to:

- A. Minimize contact of cleaning hardware with contaminated surfaces.
- B. Make any hardware, like nozzle cavity and filtration-system plumbing, either easy to clean, inexpensive, or disposable (and small volume). An example would be using slip liners in the nozzle.
- C. Whenever possible, design in engineering controls rather than operator controls. This would enhance safety and allow for remote operations.
- D. Interface with other existing hardware to enable faster and less expensive demonstrations later. Possibilities include the ROSIE robot developed by Carnegie Mellon University and Redzone Robotics, and the VAC-PAC filtration system and the MOOSE robot manufactured by PENTEK.
- E. Interface with other existing hardware (see under D. above) to maximize leverage on other DOE investments.

Designs include:

- The Tetra 6 kW transportable laser, located remotely from the surface being cleaned.
- Articulating optics, 14 ft (4.26 m), connecting the laser to the cleaning-head unit.
- Debris capture suction nozzle in the cleaning head unit.

- Two sizes of x,y scanners; 3-inch by 3-inch (7.5 cm x 7.5 cm) and 1-foot by 3-feet (30 cm x 90 cm), for test cleaning horizontal surfaces in the laboratory during Phase II. The nozzle mounts into the scanner. The larger scanner was also designed to interface with the Pentek MOOSE robot for floor cleaning, and later (for wall cleaning) with the ROSIE robot developed by Carnegie-Mellon University and RedZone Robotics.
- Filtration system. DOE METC suggested that F2 could avoid spending excessive time on filter development by working with robot and filter firms to design a compact filtration system that would be "on-board" with the scanner on a robot. The design resulted in a slightly modified Pentek VAC-PAC electric-powered filtration system using a new, recleanable Pall filter design as influenced by Task 4 test data.

Component design verification tests (DVTs) were also identified for Phase II work.

The conclusions based on the low-power Phase I tests are:

- Laser-based technology will ablate and capture contaminated paint and other contaminants from concrete and metal surfaces, while releasing negligible quantities of ablated contaminants to the environment. The current nozzle design needs fine tuning in Phase II, and filtration-system pump rates need to be increased to assure full capture of hazardous ablated material.
- Laser-based technology is effective in removing contaminants from surface pores of concrete. The surfaces and surface pores of metal and concrete can be fully cleaned.
- Laser-based technology will generate negligible amounts of additional waste compared to competing technologies. The higher-power and longer run Phase II tests are needed to obtain gas / vapor data and more complete particulate data for mass-balance calculations and filtration-system performance data.
- All the Phase I Statement Of Work objectives have been achieved. The Phase I tasks are completed and the Phase I deliverables have been submitted on schedule. The designs are complete for building the integrated laser-ablation system. The data collected in Phase I supports a positive results from the Phase II testing.

The recommendations are:

- Proceed immediately with Phase II.
- Acquire the Pentek VAC-PAC and set up and test an instrumented nozzle / hose / filter flow system including a ~10.0 μ recleanable filter early in Phase II to facilitate design verification testing.
- Acquire an on-line laser particulate counter, Residual Gas Analyzer, and the larger scanner rather than the small scanner originally proposed.

- Begin efforts to plan and coordinate a demonstration at RMI in Ashtabula, OH, and at FERMCO in Fernald, OH. This demonstration could be scheduled shortly after a successful testing and laboratory demonstration using lead based paint. The intense interest from the DOE facilities can be of benefit to the METC program.
- The need for parts cleaning, both in-situ parts such as grid work, and from scrap piles, is large, and can be investigated in Phase II or a parallel effort. An enhanced Phase II program could be initiated to explore laser ablation for parts cleaning.

Laser surface cleaning has the potential to work for many D&D applications. The technology offers a quantum leap in D&D technology with significant benefits in terms of worker safety, waste volume reduction, and the potential for recycling buildings and materials. It would be very advantageous to develop the technology as soon as possible.

1.0 INTRODUCTION

1.1 Problem Overview: The Need for Coatings Removal

There is a wide variety of coatings that need to be removed. The U.S. Department of Energy (DOE) has close to 4,000 contaminated sites. These DOE sites include hundreds of acres of square feet of buildings and other materials with surface contamination. For example, the Y-12 Plant at Oak Ridge, TN, has 160 acres of floor space.² The old gaseous diffusion plant (K-25) at Oak Ridge has 139 acres of floor space.³ It is the largest contaminated building in the world. Dr. Clyde Frank, the Deputy Assistant for the Office of Technology Development in DOE's Office of Environmental Restoration, estimates that "... there is enough concrete in that building to lay a roadbed from coast to coast."³ This concrete is primarily surface contaminated. In addition to the radioactive contamination, there are hazardous contaminants such as mercury, lead, chromates, asbestos, and polychlorobiphenyls (PCBs).⁴

Over the years as building and equipment surfaces became contaminated with "dust" or "spills" from uranium and other radioactive materials, or became contaminated with hazardous materials like PCBs, the surface contamination was stabilized in-situ by applying coats of paint, and in some cases strippable coatings. Most of the earlier paint used was lead-based. More recently, hydrocarbon-based and latex paints have been used. Repainting over the years has often resulted in several coats. Not only does the thickness vary, but the various types of coatings vary from site to site. For facility D&D, it is desirable to remove these coatings rather than having to remove walls, floors, and ceilings. Chemical paint strippers are messy, become contaminated, and result in an increased bulk of mixed hazardous waste. Sand, walnut-shell, water, or plastic-pellet blasting also adds to the bulk of contaminated waste. Carbon dioxide (CO₂) pellet blasting or liquid nitrogen cryofracture does not add to the bulk, but workers must wear air-breathing apparatus, operator control is not high, and the process is expensive. None of these processes cleans out the surface pores of the substrate being de-coated. The microwave technique developed at Oak Ridge National Laboratory does ablate the surface layer of concrete, but cannot be used for metals, nor for other substrates where substrate heating cannot be tolerated.

In addition, the DOE has between 1 and 2 million tons of contaminated scrap metal that includes nickel, copper, steel, and aluminum.^{5,6} For example, \$400M of surface-contaminated nickel must be disposed of unless the nickel can be decontaminated.⁵ Additional radioactively contaminated scrap metal is generated by the U.S. weapons facilities and nuclear power plants. The international inventory of radioactively contaminated scrap metal is estimated to be over seven million metric tons. The disposal cost would be about \$3 billion. If this inventory was decontaminated, it would have a scrap value of almost \$3 billion. To produce this same amount of metals from ores would cost \$4 billion. Therefore, if this metal was decontaminated and recycled, it would have a deferred value of \$10 billion. In addition, recent studies have concluded that there is a significant decrease in health and environmental risks if the scrap metal is decontaminated and recycled.⁷

The DOE has two choices: either to remove the contaminated coating (whence the buildings and materials can be re-used), or to dismantle the structures, package the debris into 55-gallon drums, and haul the huge mass-volume to a disposal site.

Disposal of radioactive waste is very expensive and is expected to rise dramatically. For example, it costs \$10,000 per metric ton to dispose of depleted uranium, which is a low-level radioactive waste.¹ It costs \$7 to \$400 per cubic foot to dispose of packaged contaminated concrete or scrap metal wastes. Most waste is packaged into 55 gallon drums, which hold approximately seven cubic feet and cost between \$600 and \$1,500 to dispose.^{7,8,9,10,11} These drums may not be efficiently packed. For buildings demolition debris, the packing density can be less than 50%. It is estimated that the DOE will spend \$400 billion on environmental clean-up over the next two decades, of which a significant fraction will be for buildings and other materials with surface contamination.

According to Pat Whitfield at the DOE, the DOE expenditures for cleaning up contaminated buildings is growing and will "break the bank" unless more cost effective methods are developed than those currently used.¹²

In addition, there are other government and commercial nuclear facilities worldwide that need decontamination. For example, just in the U.S. there are numerous other government and commercial facilities with radioactive contamination: There are 74 research reactors, 112 power reactors, 14 nuclear fuel fabrication facilities, and 2 uranium hexafluoride facilities.

Removal of lead-contaminated paint from government and private facilities is required under environmental protection regulations. Aircraft, ships, and bridges need to have paint and other coatings removed periodically. Nearly every product designed to withstand environmental exposure has some type of protective coating which must be regularly maintained. This involves the periodic removal and replacement of the protective coating and any accumulated deposits.

1.2 Coatings Removal Technologies

There are numerous approaches to coatings removal. Most of the approaches are two-step processes: In the first step the material is removed, and in the second step, the material must be collected and containerized. Coatings removal technologies fall into four major groups:

1. Mechanical approaches.
2. Chemical processes.
3. Radiation technologies.
4. Incineration.

1.2.1 Mechanical approaches to coatings removal include various types of surface blasting and scabblers. Surface blasting generally uses solid abrasives such as steel shot, sand, glass beads, walnut shells, or plastic pellets. Other mechanical decontamination processes use soda, dry grit, wet grit, high pressure water, dry ice, or liquid nitrogen. Surface blasting processes generally remove surface material along with the contaminants. Nearly all solid-abrasive approaches are messy. Since the beaters, sand, and beads become contaminated, the volume of hazardous waste is significantly increased, and thus the storage and disposal costs are also significantly increased.

Metal shot blasting uses various sizes of shot made of steel or other metals. This process cleans about 750 square feet per hour. For every hour of use, about two pounds of metal shot has to be replaced and disposed of. The process easily removes epoxy paints, but cannot clean corners or cracks. Tents or respirators are not required, but side shield safety glasses are required. The equipment costs between \$12,000 - \$27,000 per unit.¹³ It costs between \$1,500 and \$3,500 per ton to clean scrap metals with metal shot.¹⁰ The process generates a large amount of airborne contaminants.

Soda blasting uses crystalline bicarbonate to clean concrete and steel. This process requires a blasting enclosure, but doesn't disturb the underlying surfaces.¹⁴ Information about the economics was not available.

Wet and dry grit processes are messy and generate large amounts of waste.

Water jet blasting uses high pressure water. It is a messy process that requires lots of water. Depending on the original contamination, water jet blasting can generate a large volume of waste liquid needing subsequent treatment. This waste liquid will often be classified as a mixed waste, containing radioactive contaminants and RCRA (Resource Conservation and Recovery Act) materials (such as lead).

The dry ice process use carbon dioxide pellets that vaporize upon impact. The operators must wear "space suits" to avoid suffocation (Figure 2). The carbon dioxide pellet process is expensive.

Cryo-blasting uses liquefied, cryogenic nitrogen. The operators must wear "space suits". The process is moderately messy and very expensive.

Scabblers use mechanical beaters. This process also removes surface material along with the contaminants. Contaminants can be driven into the underlying material by the process, rather than being removed. Scabbling generates lots of airborne contaminants. The Dustless Decontamination System (DDS) is a scabbling approach that was developed at Rocky Flats and uses either a piston device or a needle gun and a vacuum system. Operators wear respirators although theoretically they are not necessary. It removes paint and a layer of concrete 3/16" deep.

1.2.2 Chemical and electrochemical processes generally involve liquids, are messy, and use paint strippers containing hazardous chemicals. Different chemicals are required for different surfaces. Stripper solvents can add hazardous materials to the waste stream, are labor intensive and discouraged under Resource Conservation and Recovery Act (RCRA) regulations. Chemical storage, collecting equipment, and drainage control must be constructed for large jobs. Water or chemical paint strippers become contaminated, and the paint stripping chemicals are themselves toxic. Most chemical decontamination processes are not effective on porous surfaces (such as concrete), and can result in corrosion and safety problems when misapplied. These approaches generate large heterogeneous mixed waste volume with free liquids, that is waste that is classified as a mixed waste because it contains radioactive contaminants and RCRA materials (such as lead). It costs between \$4,400 and \$6,000 per ton to clean scrap metals with chemical decontamination processes.¹⁰

Level A
 Positive pressure SCBA
 Chem-resistant encap. suit
 Inner & outer gloves
 2-way radio

Level B
 Positive pressure SCBA
 Hooded disposable coveralls
 Rubber boots & Gloves
 Radio

Level C
 Facepiece respirator
 Splash suit
 Rubber boots
 Gloves & goggles

Level D
 Splash suit
 Gloves & goggles
 Rubber boots

Fig. 2 - Levels of dress for D&D workers.

Electrokinetic migration slowly draws out contaminants into a strippable coating. This approach is under development. It does not appear to be useful for large structures or large equipment.

1.2.3 Radiation technologies include ultraviolet lamps, microwaves, incineration, and lasers. Ultraviolet lamps are often used with other processes. Xenon flash lamps are sometimes used in conjunction with carbon dioxide pellets. Microwaves, such as the experiments at Oak Ridge National Laboratory, cannot be used on metal surfaces, and the in-depth heating will damage plastic and laminate substrates. At present, it is also a two-step process.

1.2.4 Incineration has problems such as stack gas clean-up and contamination of the incinerator. It can't be used for in-situ cleaning of floors and walls of structures. Autoclave incineration is not useful for large structures or large equipment.

The technologies currently used for coatings removal are generally messy, expensive, hazardous, and create large amounts of hazardous wastes. None of the above processes gets contaminants out of the pores of the material being cleaned. These technologies frequently damage the surface, especially plastic or laminate surfaces. It is very desirable to have one technology that can remove all coatings from all surfaces.

1.3 Laser-Based Coating Removal Technology

F2 Associates Inc. recognized that recent advances in the appropriate type of lasers for surface cleaning could result in real contributions towards environmental restoration. Laser coatings removal is a new initiative of high interest for several reasons.

- Only the laser process gets material out of the pores of the surfaces.
- Laboratory test data indicates that the intense laser pulses break down the paint into fundamental atoms, most of which recombine into gases commonly found in nature such as water vapor and carbon dioxide which can be released. Thus, unlike the competing technologies, the laser process results in a significant reduction of contaminated material that must be captured, packaged, transported, and stored in a repository. This is very important because volume is the cost driver for packaging, transportation, and long-term storage costs (Ranging between \$7 to \$400 per cubic foot).
- The laser process is a "one step" process. The laser ablates the coating material and the nozzle and vacuum system promptly capture the vapors and debris. This is a significant advantage compared to most other processes where the coating material is removed and then vacuumed off the floor. In many other processes, workers have to wear expensive Level A or B protective clothing as shown in Figure 2. This protective clothing reduces effective work time, further increasing costs.
- The laser process can clean coatings from various surfaces, such as concrete, metal, laminates, and wood. This technology can remove coatings such as paint, grease, and oil. These coatings could have various contaminants, such as

radioactivity, lead, or PCBs. This technology is unique in its ability to strip and collect assorted coatings in a manner which dramatically reduces the environmental impact and the associated costs.

Early in 1993 the DOE issued a Research Opportunity Announcement solicitation. F2 Associates Inc. responded with a proposal, which led to this contract. This project investigates the use of a pulsed high-energy laser system that delivers a beam through optics and a material-capture suction nozzle to a concrete or metal surface, such that the intense laser pulses ablate contaminated coatings such as paint from the surface and out of the pores. Ablated material comes off as gases, vapors, and particulates. The ablated material is sucked into a filtration system where harmful gases, vapors, and particulates are captured (Figure 3). This technology has already been demonstrated for non-contaminated coatings.

Given that lasers do clean material out of the surface pores, and given the potential advantages compared to other technologies (Table I), it is clear that R&D into cleaning contaminated coatings from concrete and metals using laser-based technology could have a high payoff for the DOE. This project is intended to demonstrate the cost, environmental, and safety benefits of the technology.

Fig.3 - Generic system-concept sketch for floor cleaning.

Table I

Relative Comparison of Technologies for Removal of Contaminated Paint from Surfaces

Characteristic Technology	LOGISTICS NEEDED TO BRING CLEANING MEANS TO TARGET SURFACE	ADDS MASS THAT BECOMES CONTAM. OR MUST BE TREATED AS SUCH	OPERATOR ABILITY TO CONTROL PROCESS	ADDS HAZARDOUS MATERIALS	CLEAN VS MESSY	OTHER COMMENTS
LASER-VAC: LASER ABLATION & DEBRIS VACUUM	Negligible: Laser Beam Pipe / Mirrors	Negligible	High	No	Clean	In RDT&E
BLAST-VAC: METAL BB BLAST & VACUUM	Constant Stream of BB's, etc.	Yes (High)	Modest to Low	No	Moderately Messy	Generates Lots of Airborne Contaminants
CO ₂ ICE PELLET BLAST & VACUUM W/ OR W/O XENON FLASH LAMPS	Constant Stream of CO ₂ pellets	Adds Evap CO ₂ (gas) to Area	Modest	No	Clean to Moderate	Expensive
PAINT STRIP CHEMICAL W/ PAPER OVERLAY	Chemicals & Paper	Yes (High)	High	Yes	Messy	Large Volume of Mixed Waste* with Free Liquids
WATER JET BLAST	<u>Lots</u> of Water	Yes (High)	Modest to Low	No	Messy	Large Volume of Mixed Waste* Water Needing Subsequent Treatment
SCABBLING W/ METAL BEATERS & VACUUM	Negligible	Yes - Beater Heads	Modest to High	No	Moderate to Low	Generates Some Airborne Contaminants
REMOVE ENTIRE ITEM (e.g. WALL)	Jack Hammer & Heavy Equipment	Yes (Very High)	Modest to High	No	Moderate	Generates Very large Waste Volume
SUPERCRITICAL FLUID - LN ₂	Constant Supply of LN ₂	Adds Evap LN ₂ (N ₂ gas) to Area	Low	No	Moderately Messy	Expensive

* Mixed waste contains both radioactive and RCRA hazardous materials.

2.0 PURPOSE

The purpose of this contract is to build a fully integrated and instrumented laboratory system to demonstrate that contaminated coatings on concrete can be removed (including the material in the pores), confined, and captured in a one-step process. It has already been demonstrated that lasers can be used to strip non-contaminated paint from metal, concrete, laminates, etc. This project is designed to demonstrate that lasers can be used to strip radioactive-contaminated coatings from various surfaces.

This project consists of two phases. The original proposal used a time frame of three months for Phase I, but that was lengthened in the final contract to six months. The main objective for both phases is to develop and test a laser-based technology for removing contaminated paint and other contaminants from concrete and metal surfaces. Other objectives in support of the main objective include:

- Demonstrate that laser-based technology will ablate and capture contaminated paint and other contaminants from concrete and metal surfaces, while releasing negligible quantities of ablated contaminants to the environment.
- Demonstrate the effectiveness of the laser-based technology in removing contaminants from surface pores of concrete.
- Demonstrate that the laser-based technology will generate negligible amounts of additional waste compared to competing technologies, such as chemical paint stripping, cryogenic cracking, and pellet, sand, or water blasting.

In Phase I, an existing laser system was used to strip paint or other coatings from concrete coupons covered with paint / coating. The coupons were analyzed with a microscope before and after stripping to verify that the laser system will remove the paint from the surface and pores. In addition, a fully-integrated laser-based system was designed. The system includes an enclosed beam transport from the laser head to the work surface; a contaminant suction nozzle; a vacuum and filter system to collect ablated debris; and system control and monitoring instrumentation.

In Phase II, F2 Associates Inc. will build a fully-integrated transportable, 6 kW laser-based system based on Tetra Corporation's existing 6 kW laser and capture nozzle, plus a filtration system and scanner designed by F2 Associates. F2 will conduct tests to remove paint / coating from concrete coupons. The coupons will be covered with red-lead primer paint. Laser-based system performance will be evaluated during these tests.

This Topical Report covers the work done during Phase I. The two main goals for Phase I were:

1. Assess the performance of the technology with regard to the three main objectives described above for this project.
2. Design the fully-integrated laser-based system.

Phase I was divided into five tasks:

1. **Assess Concrete and Metal Decontamination Issues:** The goal of Task 1 was to refine our understanding of the concrete and metal decontamination issues. This understanding was to support the design efforts in Task 4 and the assessment of the technology in Task 5.
2. **Test Plan:** The goals of Task 2 were to prepare a detailed test plan for conducting the laboratory tests and to receive DOE approval for that Test Plan.
3. **Laboratory Tests / Data Analysis:** The goal of Task 3 was to provide experimental data and design verification tests to support the design efforts in Task 4. This data was also used to verify that the laser system will remove paint / coating from the surface and pores.
4. **Design of Integrated 6 kW Laser-Ablation System:** The goal of Task 4 was to design an integrated laser-ablation system for removal of paint, coatings, and contaminants from concrete and metal surfaces. The design was for a high-power laser system based on modifying and adding onto Tetra Corporation's 6 kW laser design. This integrated design was submitted to METC for review. The system designed in this Task will be built and tested in Phase II.
5. **Topical Report:** The goal of Task 5 is to prepare and submit a topical report that covers efforts under Tasks 1 through 4. The topical report shall include an assessment of the performance of the technology based on data generated during Task 3. This assessment will focus on the three main objectives for this project described above. The topical report shall also include conclusions and recommendations for Phase II.

3.0 BACKGROUND

There are various types of lasers, including electric gas lasers. Electric gas lasers use an electrical discharge through a chamber in which there is a special mixture of gas. There are two basic kinds of electrical gas lasers, which can use different gases depending on the color of output light desired.

- 1) Those that emit a continuous wave ("CW") beam of intense light, like a flashlight.
- 2) Those that emit a rapid series of light pulses, like from a machine gun. These are called pulsed, high-repetition rate lasers.

For efficient industrial-rate removal of paint and other contaminants off surfaces, a pulsed high-repetition, high energy laser is best. The laser must emit powerful, narrow spikes of laser-light. The laser operates at a high pulse-repetition rate, analogous to a machine gun firing laser bullets. A pulse from the remote laser is delivered, via mirrors and a focusing lens, to the surface to be cleaned. The laser pulse ablates off surface material via intense energy deposition into the material. Then there is a waiting period before the next pulse, with just the right time interval between pulses. If the time intervals are too short, the pulses will de-focus. The right time interval is also needed to capture and suck away ablated debris between pulses. If the time intervals between pulses are too long, the cleaning process is too slow. A pulsed-repetition unit is preferred over a CW (continuous-wave or continuous-on) system, because all of the vapor and debris can be captured before the next pulse. Removing the vapor and debris cloud prevents defocusing the laser beam.

Therefore the right laser system has a high energy per pulse, narrow pulses, and high pulse-repetition-rate with just the right time between pulses. It also ablates off thin layers per pulse, such that the material is ablated faster than heating of the material below can occur. The result is a cold surface after cleaning.

A generic sketch of the laser paint stripping system is shown in Figure 3. The system uses a unique, proprietary high-energy pulsed CO₂ (carbon dioxide) closed-cycle laser. The laser is operated remotely.

The laser beam is directed through articulating optics (enclosed beam tubes with swivel joints and turning mirrors), to and through a proprietary debris-capture nozzle, and onto the work surface. The vapor / debris capture suction nozzle includes a focusing lens. The beam spot size on the work surface is 0.35 cm² for the laser to be used in Phase I and ~4.2 cm² for the Phase II laser. The energy delivered is 5 Joules (J) per pulse, with pulses lasting a few μ sec (μ sec = microsecond). Since the speed of light is ~30 cm / ns (cm / ns = centimeters per nanosecond), a 1 μ sec pulse of light can be thought of as being 300 meters long.

The "on" time of a pulse is a few millionths of a second. During a pulse, surface material is vaporized. The laser pulse is tailored such that material is ablated faster than heat can propagate into the substrate, thus leaving a cold surface behind.

After each laser pulse, there is a brief waiting period of a tiny fraction of a second before the next laser pulse. During this time the ablated material is promptly sucked from the area through the debris / vapor capture / suction nozzle. The mixture of ablated material and room air is then drawn through a filtering system by vacuum pumps.

During the few thousandths of a second when laser is "off", the laser spot is moved sideways while the debris cloud from the proceeding pulse is cleared away. The system may be thought of as analogous to a milling machine, but with a laser-beam "machine gun" cutter instead of a metal cutting tool. For surface stripping, the laser spot is moved slightly, such that there is overlap with the last pulse spot, and the process described above is repeated. The surface coating is thus removed in strips in a series of overlapping pulses, as shown in Figure 4. The surface is scanned in a raster pattern. For thicker coatings, the surface can be re-scanned, or the scan rate can be slowed. However, for scanning concrete, too slow a scan rate will result in heat build up in the concrete and glassify the silica therein. If the silica is glassified, it will difficult to detect alpha emitters since the alpha particles can be absorbed by glass.

When the intense laser pulse interacts with the coating on the work surface, a complex process ensues. The outermost layer of coating material is vaporized into a plasma (ionized gas). The CO₂ laser wavelength of 10.6 μ breaks the hydrocarbon bonds. The resulting plasma rapidly expands away from the surface. The recoil impulse from this expansion sends a pressure wave inwards, fracturing some coating material below, which in debris form also expands outwards due to heating of the debris / gas-vapor mixture. As the debris and gas-vapor expand outwards, the latter part of the laser pulse further rapidly heats the mixture within the capture nozzle, breaking hydrocarbons into fundamental particles, most of which recombine into carbon dioxide (CO₂), carbon monoxide (CO), and water vapor. Then the pulse ends.

The hot mixture of ablated material (gases, vapor and debris) is mixed and highly diluted in the nozzle with cooler room air as shown in Figure 5. This mixture is sucked into the filtering system (Figure 3). Some of the room air is drawn in around the base of the nozzle, and additional air can, if needed, be drawn in through small ports in the nozzle housing.

In addition to the privately funded experiments, Ames Laboratory, Iowa, has been funded by the DOE to do bench-top experiments using an excimer laser.^{15,16} Experimental results show that most of the ablated material ends up as basic gases found in nature, such as water vapor, oxygen, nitrogen, and carbon dioxide. The resulting volume of solid waste is 10 - 50 % of the original paint volume. The total waste reduction is at least a factor of 200, compared to sand, pellet, and water blasting. Thus the process results in contaminated mass-volume REDUCTION in contrast to the other competing processes. Since storage / disposal costs per cubic foot can be high, volume reduction is very desirable.

In summary, our laser based system offers a clean one-step process that also cleans out the pores and gets into tight corners with no damage to the substrate and a very significant mass-volume reduction.

Fig. 4 - Depiction of pulse-to-pulse overlap & raster scan.

Fig. 5 - Simplified nozzle sketch for gas/vapor & particulate capture.

4.0 METHODOLOGY

4.1 Phase I Tests - Overview

The Phase I tests were all done at the Tetra Corporation facilities in Albuquerque, NM. More thorough and exhausting tests in Phase II will use a 6 kW laser run at >100 Hertz (Hz). The Phase I tests used an existing smaller, lower-powered 600 W laser run at 2 - 4 Hz and 10 - 20 W to strip lead-based and two-part epoxy paints from concrete and metal. The tests included preliminary tests on nozzle performance, filtration-system components, and gas / vapor and debris sampling. The purpose of the tests was defined in terms of the three main objectives for the project.

- Negligible release: Demonstrate that laser-based technology will ablate and capture contaminated paint and other contaminants from concrete and metal surfaces, while releasing negligible quantities of ablated contaminants to the environment.
- Surface and surface-pore cleaning: Demonstrate the effectiveness of the laser-based technology in removing contaminants from the surface and the surface pores of concrete. This was the main emphasis of the Phase I tests.
- Waste volume: Demonstrate that the laser-based technology will generate negligible amounts of additional waste compared to competing technologies, such as chemical paint stripping, cryogenic cracking, and pellet, sand, or water blasting.

1. Negligible release: *Demonstrate that laser-based technology will ablate and capture contaminated paint and other contaminants from concrete and metal surfaces, while releasing negligible quantities of ablated contaminants to the environment.*

The vacuum system between the suction nozzle and the release from the final HEPA filters (Figure 1) is designed to be air tight. Thus, the two possible release points during normal operation are: a) gas / vapor and particulates escaping from under the edge of the nozzle, and b) material exiting the final HEPA filters.

- a) Nozzle: Through instrumented tests, the capture performance of the nozzle was be measured.
- b) Filtration: Tests were conducted to define the nature of the debris cloud. The filtration system was optimized to reduce emissions to negligible levels.

2. Removing contaminants from surface pores. *Demonstrate the effectiveness of the laser-based technology in removing contaminants from the surface and the surface pores of concrete.*

This is a key element of laser ablation. Other processes such as sand, pellet, and water blasting, or cryo-cracking, do not effectively remove contaminated coatings from surface pores. Once cleaning media get into the pores, they further clog them. Concrete coupons painted with non-lead, uncontaminated paint have been laser stripped and sent to the DOE. Microphotographs of these coupons show the effectiveness of pore cleaning. Laser radiation has no mass to clog the pores. In this research, coupons

were painted with lead-based or two-part epoxy paint and laser stripped to demonstrate that all of the paint was removed from the surface and surface pores.

3. Negligible amounts of additional waste. *Demonstrate that the laser-based technology will generate negligible amounts of additional waste compared to competing technologies, such as chemical paint stripping, cryogenic cracking, and pellet, sand, or water blasting. All processes have filtration waste.*

This is also a key element of laser ablation. For processes that use abrasives like sand, plastic pellets, ground walnut shells, or water, the cleaning material itself becomes contaminated. Also the cleaning process can be difficult for operator control. For processes like carbon-dioxide ice pellets or liquefied-nitrogen cryofracture, where the cleaning material promptly evaporates, there is no cleaning mass that is added, but the operators must use breathing apparatus and operator control of the process is generally poor. In all of the above, it is difficult to get into corners and other nooks-and-crannies.

With laser ablation, the laser radiation, converted to heat, adds no mass in the cleaning process at the work surface. Data for non-contaminated laser stripping indicates that much of the hydrocarbon-based coating materials are converted to gases like carbon dioxide, carbon monoxide, and water vapor.

For the tests done for this contract, gas / vapor and particulate samples were taken at various places throughout the system (Figure 1), and numerous filter samples were also analyzed, to determine resultant constituents. This is to demonstrate that there was no new mass (except for filtering material, common to all processes) generated by the laser cleaning process, that secondary clean-up like vacuuming or washing laser-cleaned surfaces is eliminated, and that workers will need not dress in protective clothing to the extent that they must for most other coatings removal processes.

Part of the work is also to design and test an efficient filtration system that provides high throughput while minimizing filter-system mass in terms of filter housings. Furthermore, the Phase II work will provide strong indicators for system designs where much can be robotized, further reducing worker exposure, and increasing worker efficiency.

4.2 Phase I Test Set-Up

The basic test set-up for Phase I testing is shown in Figures 1, 6 and 7. The beam from the pulsed-repetition laser is directed through a beam pipe into the nozzle, and focused onto the work surface (i.e., the coated test coupon).

Small evacuated 150-cc gas / vapor sampling bottles were used to collect gas / vapor samples at four places around the outside edge of the nozzle at the work surface (Figure 7), in the filter system plumbing before and after the pre-filters, and at the exit of the final filter. Another room-reference sampler was also used, for a total of eight samplers.

Particulate samplers, like those used to certify a dusty work area for NIOSH (National Institute of Occupational Safety and Health), were also used. An example of a particulate sampler is shown in Figure 8. We gathered specifications from

Fig. 6 - Photo of Phase-I lab test set-up with laser/nozzle rolled back rightwards from fume hood.

Fig. 7 - Photo of Phase-I nozzle with pairs of gas/vapor & particulate sniffer tubes around base of nozzle, & scanner with test coupon.

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Aluminum	Copper Fume	Picric Acid
Antimony	Cyanide	Platinum
Arsenic	Iron	Potassium Hydroxide
Barium	Iron Oxide Fume	Selenium
Cadmium	Lead	Sodium Hydroxide
Calcium	Magnesium	Tin
Chromium Acetate	Molybdenum	Zinc
Chromium Metal	Nickel	and others
Cobalt, Metal	Oil Mist (Mineral)	
Copper Dust	Oxalic Acid	

Fig. 8 - Commercial particulate-sample collectors. Eight of these were used with a common vacuum pump, and were fitted with the NIOSH/OSHA-compliant 0.8 μ filters.

manufacturers of particulate samplers. We built sampling tubes and a vacuum system (but used commercial filter pads and holders) for simultaneous collection of the samples. A schematic of the system used is shown in Figure 9. The particulate samplers were located side-by-side with the gas / vapor samplers.

The system of gas / vapor samplers and particulate samplers was engineered so that: a) all tubing lengths to the sampler were the same length, and b) samplers could be operated simultaneously via remote controlled solenoid valves. The locations where the gas / vapor and particulate samplers were located is shown in Figures 1 and 9.

In addition, one objective of the Phase I tests was to obtain data on the size distribution of ablated particulates. An in-line filter test jig was fabricated (Figure 10, also Figures 1 and 9) into which various kinds and meshes of filter material could be mounted.

For scanning the coated coupons for the Phase I tests, a fixed nozzle and moving sample was used. The nozzle was locked in position and the coated sample moved behind it using a small x,z-motion table (commercially available). The x,z-motion table was located in the fume hood, where z = vertical and x = horizontal (see Figure 1), transverse to the beam. The x motion was driven with a variable-speed stepper motor, and the z step was done manually. For Phase I testing, this was a bit less expensive, avoiding the cost of procuring an articulating-optics beam tube. It also enabled the pre-filter test jig, final filter, and nozzle-area sample-collection units to also be stationary.

In Figure 5, the offset distance between the nozzle and the sample is exaggerated, since for most tests the distance was only 1 to 3 mm (1.58 mm baseline).

4.3 Some Basic Parameters

The repetition-rate scan tests described above were done to see how well the system captured all ablated material. Ablated material will consist of gases, vapors, and particulates. Part of the Phase I tests were to determine what kinds of each, and how much of each are created. This section will provide some background information regarding ablated material. It is important to discuss ablated material in terms of the percentage by mass and the percentage by volume. In lead-based paint, the percentage of lead by mass is large, while the percentage of lead by volume is small. Thus, laser ablation can result in large percentage volume reduction, but a low percentage mass reduction. For paints with heavy metals, the filtration system will capture a heavy mass.

Tetra Corporation already had data indicating that the pulsed laser system removes aged and outside-weathered paint at a rate of 100 square feet per hour of 23 mil thick paint for a ~6 kW laser system (average power). The coating consisted of a red-lead primer paint (one coat at ~2.4 mils) and aluminum paint overcoat (2 coats at ~3.0 mils), or 44% primer and 56% topcoat. The removal rate translates to ~6,000 cm³ (375 in³) of material per hour. This can be compared to a gallon paint can that has a volume of ~250 in³. Of this, ~80% by **mass** ended up as non-combustible particulates (solids), of which ~37% (by mass) was lead oxide (Pb₃O₄, 90% lead by weight). Data also indicates that the removal rate for new lead-based paint is somewhat slower, but is noticeably faster for non-leaded paints such as hydrocarbon-based paints.

Fig. 9 - Plumbing schematic for gas / vapor and particulate samplers.

Fig. 10 - Drawing of in-line filter test jig used between nozzle and Nilfisk vacuum unit [includes charcoal and 0.3 μ HEPA filters.] Can be used in various configurations.

For non-lead-based, non-metallic paint containing hydrocarbons, data by others also indicates that ~90% (by **volume**) is converted to gases and vapors, and ~10% by volume ends up as solids (particulates) that must be collected. This is likely due to the efficient coupling of the CO₂ laser wavelength with hydrocarbon molecules (causing excitation / dissociation). This coupling efficiency is why CO₂ lasers are used for detection of pollutants and chemical-warfare agents.

According to information supplied by METC, over the years a variety of paints have been used, even in different layers on the same surface. Typically, the original coats were lead-based paint of 6 - 7 mil thick, with later overcoatings including oil-based paints, coal-tar-based paints, rubber-based paint in some instances, some strippable coatings, some epoxy-based paints, and more recently latex-based paints. Total thickness of the layers is typically 15 to 20 mils or more.

4.4 Types of Coupon Tests

There were two basic kinds of coupon tests, overlaid with DVTs (design verification tests) for primary-filter designs. There were two types of test coupons -- metal and concrete. The two basic types of coupon tests were:

- (1) A series of single-pulse tests on metal coupons to determine the amount of energy needed to ablate through a known thickness of DOE-specified paint.
- (2) A series of multi-pulse scans across concrete coupons, with the laser running at 2 - 10 Hz, to:
 - a. Assure that sufficient gas / vapor and debris is generated for sampling, such that the readings are over the background levels.
 - b. Assure that sufficient gas / vapor and debris is generated for filter design verification tests. For filter design, it is necessary to determine the constituents of the gas / vapor and the particulates, as well as the particulate sizes.
 - c. Obtain data on strip rates for the paint used.
 - d. Obtain coupons with swath stripping for micro-photograph analysis.

For Phase I, lead-based paint was used rather than radioactive-contaminated paint, since: a) lead is a heavy metal not far from uranium in the periodic table, and b) the major subcontractor already had some experience in removing lead-based paints and "ordinary" paints from metals and concrete. The same paints will be used in Phase II.

4.5 Single Pulse Tests

Several single-pulse tests were done on aluminum coupons. Tetra had already done such tests with steel coupons painted with red-lead primer and aluminized-paint overcoats, but these new tests were a calibration for the concrete and metal tests with

the same material coating. The metal coupons are thick enough, with thick-enough coatings such that the laser energy for each pulse manifests in coating removal versus metal heating.

- (1) The metal coupons were 3-inch by 3-inch by ~2 mm thick. The surfaces were sand blasted for better paint adhesion (Figure 11A). Some were painted with 4 mil thick "red-lead" primer (77% by weight Pb_3O_4 and 23% by weight linseed oil). Some were painted with 10-mil-thick two-part epoxy. Microphotos were taken (Figures 11B and 11C).
- (2) Each coupon was exposed to pulses of laser energy as follows. First, the coupon was subjected to a single pulse. Then, the coupon was moved sideways and exposed to two laser pulses, then moved again and exposed to three laser pulses, and so on, until the substrate was reached. The laser-beam spot size was focused to 5 mm by 7 mm on target. Each coupon could handle up to ten test spots (Figures 11B and 11C). Sample microphotos were taken of the "exposed" coupons to define the pulse area, geometric shape, and edge detail of the cleaned versus the uncleaned surface, uniformity and depth (Figures 11a, 11B, and 11C).
- (3) Intermixed before, during, and after coupon exposure tests were a number of tests where a calorimeter was used to measure the laser energy per pulse, to determine the statistical-average laser energy per pulse (4.9 J).
- (4) The above data was cross-correlated to determine the energy needed to ablate through 4 mils of red-lead paint and 10 mils of two-part epoxy for the spot size of 5 mm by 6 mm.

4.6 Repetition Rate Scan Tests

Repetition-rate scan tests were done on concrete coupons coated with lead-based paint and two-part epoxy paint. Some of these tests were to make microphotographs of the concrete coupons before and after coatings removal. The other tests were fully instrumented.

4.6.1 Microphotograph data only was taken on some of the concrete coupons. These tests used coupons that were either coated with red lead or two-part epoxy paint.

- (1) Concrete coupons 3 inch square by 1.5 inch thick were made from Redi-Crete (cement, sand, and gravel plus water). As a baseline, a laser scan was made across a strip of the concrete surface before painting. Microphotos were taken of the scanned and the unscanned surface before they were painted (Figure 12A).
- (2) The coupons were then painted with 4 mils of red lead primer or two-part epoxy paint, and again photographed (Figures 12 B and 12C).
- (3) The coupons were mounted into the x,z scanner (Figure 7).
- (4) Strip tests were done on each coupon to demonstrate surface and pore cleaning. Microphotos again taken after stripping (Figures 12B and 12C).

**RAW STOCK 6061T6
UNCLEANED BARE
ALUMINUM COUPON,
7.75 cm x 7.75 cm**

**SAND BLASTED
BARE ALUMINUM,
TO ENHANCE PAINT
ADHESION.**

ORIGINAL PHOTOS
IN CRISPER COLOR

RAW STOCK MICROPHOTO

**MICROPHOTO AFTER SAND BLASTING
LIGHT SPOTS = 'CRATERS'**

Fig. 11A - Bare aluminum & cleaned aluminum coupons before painting.

CLEANED ALUMINUM
PAINTED WITH 4 mils
of RED LEAD PRIMER.
10 LASER SPOTS/COUPON,
EACH ~5 mm X 6 mm.

EACH COUPON WAS USED
FOR 10 TESTS IN THE
"BURN THRU" SERIES
TO DETERMINE J/cm^2
FOR THE TYPE OF PAINT
AND THICKNESS.

ORIGINAL PHOTOS
IN CRISPER COLOR

MICROPHOTO AFTER PAINTING
BUT BEFORE LASER STRIPPING

MICROPHOTO AFTER LASER STRIPPING OF PAINT
TO BARE METAL. LIGHT SPOTS = 'CRATERS'

Fig. 11B - Aluminum coupons with red-lead primer paint.

**CLEANED ALUMINUM
PAINTED WITH 10 mils
of 2-PART EPOXY.
10 LASER SPOTS/COUPON,
EACH ~5 mm X 6 mm.**

**EACH COUPON WAS USED
FOR 10 TESTS IN THE
"BURN THRU" SERIES
TO DETERMINE J/cm²
FOR THE TYPE OF PAINT
AND THICKNESS.**

ORIGINAL PHOTOS
IN CRISPER COLOR

**MICROPHOTO AFTER PAINTING
BUT BEFORE LASER STRIPPING**

**MICROPHOTO AFTER LASER STRIPPING OF PAINT
TO BARE METAL. LIGHT SPOTS = 'CRATERS'**

HASH MARKS VIA CLEAR PLASTIC RULER OVER TOP EDGE OF COUPON

Fig. 11C - Aluminum coupons with 2-part epoxy paint.

REFERENCE

CONCRETE COUPON
7.75 cm x 7.75 cm x 3.8 cm thick
TROWELED SMOOTH SURFACE
(Typical of a concrete floor);
NO OTHER COATING.

NO ABLATED-MATERIAL
CAPTURE / SUCTION
NOZZLE USED

ORIGINAL PHOTOS
IN CRISPER COLOR

MICROPHOTO BEFORE REMOVING
TROWELED SURFACE

MICROPHOTO AFTER LASER ABLATION
OF TROWELED SURFACE

Fig. 12A - Concrete reference sample before applying coatings.

CONCRETE COUPON
 7.75 cm x 7.75 cm x 3.8 cm thick
 TROWELED SMOOTH SURFACE
 PLUS 4 mils OVERCOAT of
RED LEAD PRIMER

EDGE DEPOSITS
 DUE TO INSUFFICIENT
 PUMP SPEED FOR
 CAPTURE / SUCTION
 NOZZLE (to be corrected
 in Phase-II)

ORIGINAL PHOTOS
 IN CRISPER COLOR

**MICROPHOTO BEFORE REMOVING
 COATING & TROWELED SURFACE**

**MICROPHOTO AFTER LASER ABLATION
 OF COATING & TROWELED SURFACE**

Fig. 12B - Concrete coated with red lead primer & then laser ablated.

CONCRETE COUPON
 7.75 cm x 7.75 cm x 3.8 cm thick
 TROWELED SMOOTH SURFACE
 PLUS 10 mils WHITE
 (reflecting) OVERCOAT of
2-PART EPOXY

EDGE DEPOSITS
 DUE TO INSUFFICIENT
 PUMP SPEED FOR
 CAPTURE / SUCTION
 NOZZLE (to be corrected
 in Phase-II)

ORIGINAL PHOTOS
 IN CRISPER COLOR

**MICROPHOTO BEFORE REMOVING
 COATING & TROWELED SURFACE**

HASH MARKS VIA CLEAR PLASTIC RULER OVER TOP EDGE OF COUPON

**MICROPHOTO AFTER LASER ABLATION
 OF COATING & TROWELED SURFACE**

Fig.12C - Concrete coated with 2-part epoxy & then laser ablated.

4.6.2 Fully instrumented tests were performed while removing red lead paint from concrete coupons.

- (1) Concrete coupons 3 inch square by 1.5 inch thick were made from Redi-Crete (cement, sand, and gravel plus water). Microphotos were taken of the surface before they were painted.
- (2) The coupons were then painted with 4 mils of "red lead" primer, and again photographed.
- (3) The coupons were mounted into the x,z scanner (Figure 7).
- (4) Four strip tests were done on each coupon, with ~1.58 mm (1/16 inch) stand-off between the under-edge of the nozzle and the concrete surface (Figure 7). Between swipes the coupon was manually stepped in the z direction. For the z-steps, the steps were made large enough so that there was no edge overlap between x-direction swipes (Figure 7). For the first scan across a coupon, the full set of gas / vapor, particulate, and filter-paper pre-filter data were taken. For the next four scans, only pre-filter data was taken. Thus the prefilters accumulated material from four scans to assure enough captured material for analysis.
- (5) After each strip test, the bottle samples and filter material were sent to Hauser Labs in Boulder, CO, for detailed and certified analysis to determine types and percentages of constituents. In addition, microphotos were taken of the stripped surfaces to obtain additional data on surface and pore cleaning. All of the data from Hauser and the microphotos were cross-correlated.

Some "show and tell" coupons were made with four colors of paint over an aluminum substrate. Otherwise, no high-repetition-rate metal stripping tests were run. Tetra already had data, as indicated above, on stripping lead-based primer plus overcoat from metal.

4.7 Parallel Design Verification Tests (DVTs) for Components

There were two main parallel DVTs planned in conjunction with the tests described above:

- A. Nozzle-design fine tuning. The stand-off distance of the nozzle could affect the gas / vapor and debris samples taken around the base of the nozzle. This would indicate that detectable amounts of gas / vapor or debris were getting out from under the nozzle edge. In this situation, minor design modifications would have been made for the nozzle, such as adding a flex "skirt" like brush weather stripping (commercially available material), and tests would have been re-done. Nozzle DVTs were not proposed for the Phase I work, but will be done in Phase II where higher pump rates will also be used.
- B. Test jig to obtain data for optimizing long-run filter design of Task 4. To obtain data on the needed filter mesh sizes, types, and feed rates for the long-run filter design work (Task 4), an inexpensive test jig as shown in Figure 10 (see also Figure 1) was fabricated. It uses between two and four sheets of filtering material -- coarse,

medium, fine, and charcoal. The purpose of the charcoal filter was to filter the gas / vapor before it exited into the room air. The filters were stacked in pancake fashion, where the first three were particulate-filter test material, and the fourth was a charcoal filter, all commercially available and inexpensive. The design accommodates thin-film filtering material. Data analysis focused on determining the size distribution and loading of accumulated particulates.

This test jig enabled inexpensive testing of various filter materials, with analysis done by Hauser Labs, to determine the optimum combination for lead-based paint for Task 4. Another goal was to pre-filter as much as possible so that the final charcoal and HEPA filters can run longer between changes, while maintaining good air flow throughput rates with no excessive pressure drop across any given filter.

5.0 RESULTS AND DISCUSSION

Task 2 was the preparation and submittal of a Test Plan for DOE approval. The Test Plan was submitted to DOE METC for approval and after iteration was approved on schedule. Prior to the initiation of the contract, an Environmental Questionnaire for NEPA compliance was completed and submitted to DOE METC. A Categorical Exclusion Determination covering Phases I and II was made on 29 November 1993.

This section focuses on Task 1 (site visits), Task 3 (tests with lower-power system), and Task 4 (integrated 6 kW system design).

5.1 Task 1 - Site Visits

Per the recommendations of DOE METC, site visits were made to the RMI facility in Ashtabula, OH, and to the Fernald facility (FERMCO) near Cincinnati, OH. These visits were done sequentially on the same trip the week of 3 October 1994. The purposes of these visits were to:

1. See the facilities and discuss the contaminated coatings issues and types of coatings at each facility.
2. See the rooms in buildings that might be candidates for laser coatings removal after a successful Phase II.
3. To assess the logistics and ES&H issues for those rooms in terms of design considerations for the integrated systems design (Task 4) for Phase II work and a possible demonstration thereafter.

This task interfaced with Task 4 in the spirit of concurrent engineering and Total Quality Management early to avoid as much re-design as possible later. Relevant highlights of the trip report are as follows:

- Both RMI and FERMCO can provide full support for on-site testing. They were very cooperative and enthusiastic. They stated that they needed a quantum leap in D&D technology and that there were no other strong candidates.
- Candidate spots were identified for doing cleaning demonstrations.
- Equipment engineering must be done such that contact with contaminated surfaces is minimized, and such that equipment surfaces that do become contaminated can be easily cleaned. Otherwise our equipment will not be allowed to leave the site.

In general, the site visits did not change the basic hardware designs planned for Phase II laboratory tests and envisioned for room floor cleaning. However, certain specific items did surface:

- Pentek's MOOSE robot is commercially available. It might be modified to carry an x,y scanner for floor cleaning. The mechanical scabbler would be removed, and replaced with the laser x,y scanner. It has an on-board filtration system that is

driven by either high-power electric blowers or by compressed air with venturi suction. We plan to use their model with high-power electric blowers. The on-board filtration system might need slight modification (filters) for the products of laser ablation, but could lead to a lower-cost "buy-and-tie" demonstration after Phase II. "Buy-and-tie" means to acquire as many available existing components and subsystems as possible, and to do the systems and interface engineering to integrate them into a working system -- buy components and "tie" them together, rather than developing all custom made (more expensive) components.

- A simpler version of the ROSIE robot¹⁷ developed by Carnegie-Mellon University and RedZone Robotics might similarly be used for a wall cleaning demonstration. The 7-axis end effector is not needed, but on-board filtration will have to be added.

The need for parts cleaning, both in-situ parts such as grid work, and from scrap piles, is large, and can be investigated in Phase II or a parallel effort.

Our interactions with DOE sites was very encouraging. The personnel at the DOE sites made it clear that they need better D&D technologies. It is clear that laser coatings removal could work for many D&D applications. The sites are enthusiastic about the potential for laser surface cleaning and see the technology as offering significant benefits in terms of worker safety, waste volume reduction, and the potential for recycling buildings and materials. Although it needs to be analyzed, laser cleaning has the potential to be very cost effective. The site personnel were very anxious to schedule the demonstrations as soon as possible.

5.2 Task 3 – Phase I Test Results

5.2.1. Single-pulse tests data is summarized in Table II.

5.2.1.1 Red Lead Primer. Aluminum coupons painted with 4 mils of red-lead primer by a professional painting company (Figure 11B). The thickness was measured by a micrometer. Test results and analysis indicate that for the spot size used, it takes 60 J of energy to ablate through to the substrate. With an average of 5 J / pulse this amounts to 12 laser pulses. Test data is summarized in Table II. In comparing the microphotos in the lower right of Figures 11A and 11B, it can be seen that all paint was removed from the surface and surface pores to at least the 200 μ resolution.

5.2.1.2 Two-part Epoxy. Aluminum coupons were coated 10 mils thick with white, two-part epoxy paint (Figure 11C). Test results and analysis indicate that for the spot size used, it takes 150 J of energy to ablate through to the substrate. With an average of 5 J / pulse this amounts to 30 laser pulses. In comparing the microphotos in the lower right of Figures 11A and 11C, it can be seen that all paint was removed from the surface and surface pores to at least the 200 μ resolution.

5.2.1.3 Scanning Rates. It is interesting to note that the burn-through energy for red lead primer and two-part epoxy is essentially the same, namely ~50 J per mil per cm² of area. When translated through theoretical and experimental scaling data, this still projects a stripping rate of ~100 square feet per hour for 20-mil thick, aged (heavily oxidized) paint using a 6 kW, 200 Hz system. The stripping rate for newer

Table II
Single Pulse Test Data

General Information:

- The laser pulse energy is 5 joules and the laser pulse full width at half maximum intensity is 4 μ sec.
- Small aluminum coupons were previously used to determine mass removal rates because of their small size, whereas more detailed information can be obtained on the larger coupons.
- The coupons are made of 3 inch by 3 inch by 1/16 inch sandblasted aluminum plate.
- Ten test sites per coupon, starting with one laser pulse for the first site and incrementing by one for each successive site.
- One to 10 pulses on the first coupon, 11 to 20 pulses on the second coupon, and 21 to 30 pulses on the third coupon, etc., until the paint has been removed down to the bare metal.
- Micrometer measurements and microphotographs are taken for each site, yielding volumetric removal rates and energy required to remove all of the paint.

Test 1: Red-Lead Primer

- The paint was ~0.004" thick
- Cross sectional area of the laser spot is ~0.5 cm by 0.6 cm = 0.368 cm² (0.057 in²)
- Depth of paint removed per pulse averaged 3.5 E-4 inch
- Volume removed per pulse averaged 2.0 E-5 cubic inches
- Volume removed per joule averaged 4.0 E-6 cubic inches
- The laser energy density was 87.7 joule per square inch (13.6 j / cm²)
- ~12 pulses were required to remove all of the 0.004" thick red-lead paint
- This was the worst case: new, hard paint.

Test 2: Two-Part Epoxy

- The paint was ~0.010" thick
- Cross sectional area of the laser spot is ~0.5 cm by 0.6 cm = 0.368 cm² (0.057 in²)
- Depth of paint removed per pulse averaged 3.5 E-4 inch
- Volume removed per pulse averaged 2.0 E-5 cubic inches
- Volume removed per joule averaged 4.0 E-6 cubic inches
- The laser energy density was 87.7 joule per square inch (13.6 j / cm²)
- ~30 pulses were required to remove all of the 0.010" thick two-part epoxy paint

20-mil paint is about half that for aged paint or 50 square feet per hour. This is in line with the 60 square feet per hour per 20 mil thick paint predicted by Plasmatronics, Inc.,¹⁸ and the apparent average (new-old paint) of 75 square feet per hour of 20 mil thick paint predicted by INTA.¹

5.2.2. Repetition-rate scan tests were done on concrete coupons coated with lead-based paint and two-part epoxy paint. Some of these tests were to make microphotographs of the concrete coupons before and after coatings removal. The other tests were fully instrumented. The scan rate used was 0.68 cm / sec, for a total time of 11 seconds across a 7.5 cm coupon.

5.2.2.1 Microphotograph Data. Tests were done on concrete coupons painted with red-lead primer or two-part epoxy as described above. In comparing the microphotos in the lower right of Figures 12B and C to Figure 12A, it can be seen that all paint was removed from the surface and surface pores to at least the 200 μ resolution.

5.2.2.2 Fully Instrumented Tests. Tests were done on concrete coupons painted with 4 mil of red-lead primer (Figure 7). A total of four scans were made on each coupon. For the first scan, the entire set of gas / vapor, particulate, and pre-filter samples were taken. For the next three scans, only pre-filter samples were taken. Thus, the particulates from all four scans were accumulated onto the same pre-filter papers to collect enough particulates for analysis.

5.2.2.3 Gas / Vapor Samples. The sampling locations are shown in Figures 1 and 9. For all eight gas / vapor sampling locations, the same Tygon™ hose lengths were used between sample-point inlet and the gas bottle. The bottles were evacuated (Figure 9). During the middle of a scan, the samples were all taken simultaneously using electric solenoid valves to the bottles, with the pump line shut off. The fill time for the 150 cc bottles was ~4 seconds. This is the time it took the bottles to suck in gas / vapor until nearly up to atmospheric pressure. The mass flow rate into the bottles is exponentially decreasing with time, since the pressure differential drops and the flow rate drops accordingly as the bottles fill. Thus the bottles fill fast in the first second, and then slowly "top off" with decreasing speed thereafter. The tubing lengths between the sampler inputs and the bottles amounted to a volume of ~20% of the volume of the bottles themselves. This results in another 20% dilution in addition to the high dilution of the ablation flow / sampling dynamics. The bottles were sealed with a manual valve, and sent to Hauser Labs for content analysis. Residual gas analysis for the first two sets of tests showed no measurable CO, CO₂, other hydrocarbons or water over background. It was concluded that the lower-repetition-rate, lower-power laser used in these Phase I tests resulted in low material generation rates, coupled with high dilution ratios (ambient air mixed with ablated material gas / vapor), resulting in concentrations too low for Hauser to measure. Their levels of detection are: 1% CO, 0.05% CO₂, and 300 - 500 parts per million for other hydrocarbons. The decision was made to continue these tests in Phase II where material generation rates will be much higher, and also to use flow-through collection bottles in Phase II like those used for the particulate tests in Phase I.

5.2.2.4 Particulate "Sniffers" (Figures 8 and 9). As for the gas / vapor samples, the lengths of all tubing from sample-point inlets to the filter holders was the same. The filters and cartridges for collecting samples were pre-weighed by Hauser Labs. When a scan was started, the valve to the vacuum vessel (plenum tank, Figure 9) was opened. Air mixed with ablated material (gas / vapor and particulates) was constantly sucked from the sample-point inlets through the in-line filter pads to the tank and on into the vacuum pump. The 0.8 μ filter pads caught the particulates. Samples were taken for 10 seconds out of the 11 second scan time across the coupon. After a test, the sniffer cartridges were then sealed and sent to Hauser, who opened them, extracted the filter paper, and analyzed the contents against fresh (unused) filters. In the samples located before the in-line prefilter, mass levels were measured to be ~70.0 μ g of lead per sniffer filter pad, plus 0.87 μ g of chromium. In the samples located after the prefilters, the level was measured to be ~36.1 μ g of lead on the sniffer pads, plus 0.07 μ g of chromium. Although the in-line prefilters used were too coarse (see below), one purpose of these Phase I tests was to obtain such data for use in the filter designs for Phase II.

Particulate sniffers around the base of the nozzle also picked up traces of lead and chromium, at levels of ~0.1 μ g per sniffer, or ~700 times lower than in the filtration system before the in-line prefilter. This data, coupled with visual data showing some "soot" deposits on the coupons around the base of the nozzle, indicate that the filtration-system pump rate for Phase II will have to be substantially increased, to several hundred cubic feet per minute (cfm). A higher filtration-system pump rate will be used in Phase II. This also couples into nozzle designs. The baseline nozzle design will also be tested in DVTs in Phase II.

5.2.2.5 In-line Prefilters (Figures 1, 9, and 10). The inside diameter of the hose between the nozzle and prefilter was 2 inches, although the nozzle itself has an exit constriction of 1.5 inch. On the 170 μ and 14 μ prefilters used in early tests, the mass levels were measured to be 7,896 μ g and 2,503 μ g respectively from ~80 laser pulses. These filters were too coarse and not homogeneous enough. Analysis showed clumping of particulates in the denser regions of the fibers. As particulates built up, the filter became more efficient in collection. This is typical, where a slightly "dirty" filter works better than a new, clean one.

In subsequent tests, the filter size was reduced to 0.8 μ . Results showed that >99% of the particulates (lead and chromium) were less than 5 μ in size, with 90% of those being less than 1 μ in size. This was somewhat smaller than the 5 - 30 μ size range reported by others.¹ This is probably because the power density in these experiments were a few MW / cm² compared to several hundred kW / cm² used by others. In the Phase II tests with the 6 kW system, the power density will be the order of 1 MW / cm² because of slightly longer laser pulses. If, as suspected the lower power densities result in larger particulates, then a nominal particulate size of ~10 μ is predicted for Phase II.

5.3 Test Plans for Phase II

During Phase II, several component DVTs will be performed in parallel with final design and fabrication of the 6 kW system, such as:

- Laser: head flow, vibration and thermal analysis, preionizer lifetime, and output window heat transfer.
- Nozzle design upgrade and higher filtration system vacuum flowrate for ablation material capture for a 6 kW system. The upgrade will include a Pentek VAC-PAC pump and filter unit retrofitted with Pall Corporation recleanable ~10.0 μ filters plus a charcoal filter and a 0.3 μ exit HEPA filter.

The following system tests will be done:

- Repeat particulate sniffer tests as in Phase I.
- Repeat gas / vapor sampler tests as in Phase I, but use flow-through bottles. If necessary, use a Residual Gas Analyzer for on-line gas / vapor analysis.
- Use an on-line laser particulate size counter.
- Use a Pentek VAC-PAC filter with at least 400 cfm flowrate.
- Use more system differential pressure sensors and flowmeters.
- Use humidity sensors.

5.4 Task 4 – Integrated 6 kW System Design for Phase II

5.4.1 Background: Custom design was performed for the Tetra 6 kW transportable CO₂ laser system, articulating optics from the remote laser to a cleaning head nozzle, gas / vapor and particulate capture suction nozzle, the fixture to clamp the nozzle into a x,y scanner, and a filtration system that will capture the ablated material after it leaves the nozzle. The laser, optics, and nozzle are Tetra's responsibility. F2 is responsible for the scanner, filtration system, and overall system integration, operations, and ES&H issues. F2 did designs for a 3-inch by 3-inch scanner and for a 1-foot by 3-feet scanner.

DOE METC suggested that F2 work with filtration-system firms to see if there were "buy-and-tie" filter system possibilities for an early demonstration, rather than long-run filter R&D by F2, and also suggested the names of several prominent filtration-system firms. Though many firms have filtration expertise, it was found that few had specific experience in dealing with the products of *laser ablation*, and that data from Task 3 is important for them to make design decisions. To maximize use of Task 1 travel funds, while in the region, F2 also visited with PENTEK in Pittsburgh, PA, to discuss their filtration technology used in their scabbling system for lead-based paint. F2 has also been in active contact with Pall Corporation and 3M. F2 has negotiated Proprietary Information Non-disclosure Agreements with Pall, Carnegie Mellon University / Red-Zone Robotics, and PENTEK in order to share proprietary information and put the experts, Task 3 data, and F2 new concepts together in order to get the best designs possible for the DOE. Information from interactions with these firms has been folded into the design discussed below.

DOE METC put F2 in contact with various entities that do robotics work. Prior to the Task 1 site visits, F2 corresponded with The Robotics Institute of Carnegie Mellon University, RedZone Robotics, and PENTEK. To maximize use of Task 1 travel funds, F2 visited each of them as part of the Task 1 travel. These entities are all located in the Pittsburgh area. F2 wanted to learn about the PENTEK MOOSE robot to see if it might be modified for use in laser cleaning. The idea again was to look towards a possible demonstration after Phase II and to do concurrent engineering and TQM (Total Quality Management) early to avoid as much re-design as possible later.

5.4.2 Design Results: A scaled isometric drawing of the transportable, 6 kW Phase II laser is shown in Figure 13. A scaled isometric drawing of the design for a Phase II horizontal-surface demonstration-cleaning-system with the nozzle, 1-foot by 3-foot scanner, and vacuum / filter unit is shown in Figure 14. The end of the articulating optics beam-delivery pipe (right side of Figure 13) fastens vertically downwards into the nozzle (left side of Figure 14). These are the baseline for the discussions below.

5.4.2.1 Laser, articulating optics, and nozzle: Figure 15 shows a multi-view line drawing of the 6 kW laser, with dimensions. In finalizing this design, several DVTs were identified as listed in Section 5.3 above that would be desirable to help assure long mean time between failures. These DVTs are part of the Phase II work, and it would be highly desirable to accelerate work on them.

5.4.2.2 x,y Scanner: Figure 16 shows the 3-inch by 3-inch scanner design with the Tetra nozzle attached to it. This scanner uses commercially available slides and stepper motors and controls. Although this could be used for a stationary experiment to clean a small area of horizontal surface in Phase II, it is recommended that the 1-foot by 3-foot scanner (Figure 14) would not only provide for a more credible demonstration, but will also yield better Phase II test results with the longer run times available with a 3-foot scan.

Figure 14 shows a 1-foot by 3-foot scanner, with the same Tetra nozzle mounted to it. For a slight additional cost over the 3-inch by 3-inch scanner, this could be used to clean a much larger area. This design shows use in Phase II in a transportable mode, where the unit would manually be put into place to scan a horizontal surface at fixed scan rates and a fixed stand-off distance for laboratory demonstration purposes.

One useful addition to the scanner would be an on-line optical comparator. It would tell when the coatings have been removed to the base substrate. Signals from such a sensor could be used as part of a feedback and control system to adjust the scan speed in real time for cases where the paint thickness may vary. Information has been obtained on the BDM on-line optical comparator, but funding limits precluded design integration of this into the scanner during Phase I. It can be added later.

5.4.2.3 Filtration System (F2): As discussed earlier, DOE METC suggested that F2 work with existing filtration system firms versus getting into long-run filter R&D, and suggested several firms for F2's consideration. F2 has provided METC with two design concepts for long-run filters to handle materials such as uranium oxide paste.

Fig.13 - Isometric drawing (to scale) of Phase-II transportable laser design and articulating-optics beam delivery system.

Fig 14 - Isometric drawing (to scale) of transportable floor scanner & nozzle, plus Pentek VAC-PAC vacuum-&-filtration unit.

Fig. 15 - Line drawing (to scale) of transportable 6kW pulsed-rep CO₂ laser system.

Fig. 16 - Isometric drawing (to scale) of small x,y scanner.

F2 subsequently contacted all of those suggested, and the list has narrowed down to Pall Corporation and Pentek. The present baseline design for Phase II uses a modified version of the small Pentek VAC-PAC filter, such as the electric-powered unit on-board their MOOSE robot. It has a two-stage pre-filter and a final 0.3 μ HEPA filter. Pentek acquires the filter media from others. Pall Corporation has a design for a pre-filter based on Lawrence Livermore National Laboratory experience. Pentek has agreed to work with Pall to use a Pall pre-filter if necessary. The exact pre-filter design will be determined pending further analysis of data from Phase I tests, and may be iterated in Phase II for the much higher flow rates. It should be noted that the exact filter design used in a specific location may also be influenced by local conditions such as humidity.

We have found no data in the literature on particulate sizes and types for the products of laser ablation. This will depend on the laser wavelength and pulse parameters, and coating material. Under a small business technical assistance grant, Dr. Claude Phipps of Los Alamos National Laboratory (LANL), an expert in laser / surface and laser / plasma interactions, provided F2 with some general background literature.

5.4.2.4 Integrated System Design for Phase II: Using input and analysis from Task 1, F2 has also performed preliminary designs for attachment of the Phase II 1-foot by 3-foot scanner to both the MOOSE robot and the ROSIE robot. These are shown respectively in Figures 17 and 18. For the purposes of a demonstration, the Tetra 6 kW laser (Figure 15) would be remotely located, with articulating optics connecting the laser to the nozzle mounted in the scanner on the robots. The MOOSE robot could be used for a floor-cleaning demonstration, and the ROSIE robot (with on-board filtration added) for a wall-cleaning demonstration.

5.5 Plans for Phase II

The Phase II tests will involve using a more powerful 6 kW laser system, with all equipment scaled up from Phase I. These tests will be done with hardware that is transportable or can easily be made mobile. It will also involve a larger x,y scanner than in Phase I for cleaning horizontal surfaces. In this phase, the testing will directly address Objectives 1 and 3 in a high-power system where material is being removed at a rapid rate, and will address cleaning-rate issues for that system.

Note that in Phase II testing, there will be fixed samples and a moving nozzle. In Phase II, articulating-beam-tube optics will be used between the remote laser and nozzle. The nozzle will be attached to the x,z scanner, and the beam will scan fixed surfaces. Tetra has already demonstrated that articulating optics can be used with a hand-held moving nozzle in a lower-power system. A system that includes a high-powered laser, articulating-beam-tube optics, a moving nozzle, and an automated scanner was designed during Task 4 of Phase I. This system will be built and tested during Phase II. In this option, the nozzle and some sample-collection units need to be moved (kept fixed relative to the moving nozzle), and flex hose would be used between the moving nozzle and stationary filters. The design details were defined as part of Task 4.

Fig. 17 - Sketch of large scanner (ref: Fig. 14) fitted to Pentek MOOSE robot for floor cleaning; includes on-board filtration system.

Fig. 18 - Sketch of large scanner (ref: Fig.14) fitted to CMU/Redzone ROSIE robot for wall cleaning, with on-board filtration system.

With successful results in Phase II, the next step would be to build a mobile system that can be taken to a DOE facility for a field test of removing radioactively-contaminated coatings. One possibility might be to take the system to the RMI Facility in Ashtabula, OH, or to FERNALD near Cincinnati, for field testing to remove paint from concrete or metal that is contaminated with depleted uranium. There are also other possibilities such as mobile units for cleaning metal parts, for which F2 has pre-designs.

5.6 Interactions With Potential Users

This project involves a multi-use technology with the following types of coating-removal applications:

1. Non-hazardous, non-radioactive.
2. Hazardous (e.g., lead-based paint), but non-radioactive.
3. Radioactive and mixed.

This project will help advance the engineering for mobile industrial systems for all three items above. Approaches for each are as follows:

Items (1) and (2): It has been demonstrated that a laser based system can effectively remove paint and other coatings from various surfaces. With funding from the U.S. Army Corps of Engineers, Tetra Corporation has done laboratory tests on stripping lead-based paints, and has completed designs of mobile systems to do so on bridges. They have received Navy funding to continue this work for cleaning inside submarine hulls. Phase I of this DOE project has furthered the state of the technology for removing non-hazardous and hazardous coatings. F2 Associates Inc. and its subcontractor Tetra Corporation may attend and present at the annual DoD Coatings Removal Conference as well as DOE-sponsored conferences.

Item (3): The purpose of this R&D is to demonstrate by using lead-based paint, that radioactive and mixed-waste coatings can be removed and captured. F2 will interface with potential users per guidance from the DOE, and will work with DOE sites for field tests like the RMI Facility in Ashtabula, OH, and the FERMCO facility near Cincinnati, OH. It is premature to advertise that this is an operational system ready for wide-scale use for stripping radioactive-contaminated coatings, but our efforts in Task 1 and Task 4 also involved looking to the future for integration of the system hardware into robots. There is also considerable interest in parts cleaning, and at the contract kick-off meeting on 24 August 1994, F2 Associates Inc. presented design concepts for mobile parts cleaning units and mobile lasers.

Our interactions with DOE sites has been very encouraging. The personnel at the DOE sites made it clear that they need better D&D technologies. It is clear that laser coatings removal could work for many D&D applications. The sites are enthusiastic about the potential for laser surface cleaning and see the technology as offering significant benefits in terms of worker safety, waste volume reduction, and the potential for recycling buildings and materials. Although it needs to be analyzed, laser cleaning has the potential to be very cost effective. The site personnel were very anxious to schedule the demonstrations as soon as possible.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The three goals specified by the DOE for the contract are:

- (1) Demonstrate that laser-based technology will ablate and capture contaminated paint and other contaminants from concrete and metal surfaces, while releasing negligible quantities of ablated contaminants to the environment.
- (2) Demonstrate the effectiveness of the laser-based technology in removing contaminants from surface pores of concrete.
- (3) Demonstrate that the laser-based technology will generate negligible amounts of additional waste compared to competing technologies.

For Phase I, low-power tests were done to obtain data vis-a-vis the goals, and design work was completed for a high-power system for Phase II to repeat the tests.

With regard to Goal #1, the conclusions based on the low-power Phase I tests are that all coatings material can be ablated, but that nozzle design needs fine tuning in Phase II, and filtration-system pump rates need to be increased to assure full capture of hazardous ablated material.

With regard to Goal #2, the conclusions based on the low-power Phase I tests are that surfaces and surface pores of metal and concrete can be fully cleaned.

With regard to Goal #3, the conclusions based on the low-power Phase I tests are that the higher-power and longer run Phase II tests are needed to obtain gas / vapor data and more complete particulate data for mass-balance calculations and filtration-system performance data.

All the Phase I Statement Of Work objectives have been achieved. The Phase I tasks are completed and the Phase I deliverables have been submitted on schedule. The designs are complete for building the integrated laser-ablation system. The data collected in Phase I supports a positive results from the Phase II testing.

6.2 Recommendations

- Proceed immediately with Phase II.
- Acquire the Pentek VAC-PAC early in Phase II to facilitate design verification testing.
- Acquire an on-line laser particulate counter and Residual Gas Analyzer to facilitate testing and data collection and analysis.
- Purchase the larger, 1 foot by 3 foot scanner rather than the small 3 inch by 3 inch scanner originally proposed.

- Set up and test an instrumented nozzle / hose / filter flow system early in Phase II to facilitate design verification testing.
- Add subcontracts with Pall and Pentek to support a retrofit with the ~10.0 μ recleanable filter, plus 0.3 μ HEPA exit filter.
- Begin efforts to plan and coordinate a demonstration at RMI in Ashtabula, OH, and at FERMCO in Fernald, OH. This demonstration could be scheduled shortly after a successful testing and laboratory demonstration using lead based paint. The intense interest from the DOE facilities can be of benefit to the METC program.
- The need for parts cleaning, both in-situ parts such as grid work, and from scrap piles, is large, and can be investigated in Phase II or a parallel effort. An enhanced Phase II program could be initiated to explore laser ablation for parts cleaning.

Laser surface cleaning has the potential to work for many D&D applications. The technology offers a quantum leap in D&D technology with significant benefits in terms of worker safety, waste volume reduction, and the potential for recycling buildings and materials. It would be very advantageous to develop the technology as soon as possible.

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LIST OF ACRONYMS, ABBREVIATIONS, AND DEFINITIONS

Ablated	See "laser ablation"
Buy-and-tie	To acquire as many available existing components and subsystems as possible, and to do the systems and interface engineering to integrate them into a working system -- buy components and "tie" them together, rather than developing all custom made (more expensive) components.
cfm	Cubic feet per minute
cm / ns	Centimeters per nanosecond
CO	Carbon monoxide
CO ₂	Carbon dioxide
CW	Continuous-wave or continuous-on
D&D	Decontamination and decommissioning
DDS	Dustless Decontamination System
DOE	U.S. Department of Energy
DVTs	Design verification tests
ES&H	Environmental Safety and Health
F2	F2 Associates Inc.
FERMCO	Fernald Environmental Restoration and Management Corporation, their facilities are located in Fernald, OH near Cincinnati
HEPA	High Efficiency Particulate Air
High power high-repetition-rate	See discussion under 3.0, Background on page 11
Hz	Hertz
J	Joules
kW	Kilowatts
Laser ablation	Removal by vaporizing; that is intense heating of solid material using laser energy such that the solid material goes directly to the gaseous state, resulting in a partially ionized gas (plasma)

LIST OF ACRONYMS, ABBREVIATIONS, AND DEFINITIONS (continued)

METC	Morgantown Energy Technology Center
μ sec	microsecond
NIOSH	National Institute of Occupational Safety and Health
Pb_3O_4	Lead oxide
PCBs	Polychlorobiphenyls
Pulsed-repetition	See discussion under 3.0, Background on page 11
RCRA	Resource Conservation and Recovery Act
TQM	Total Quality Management
W	Watts