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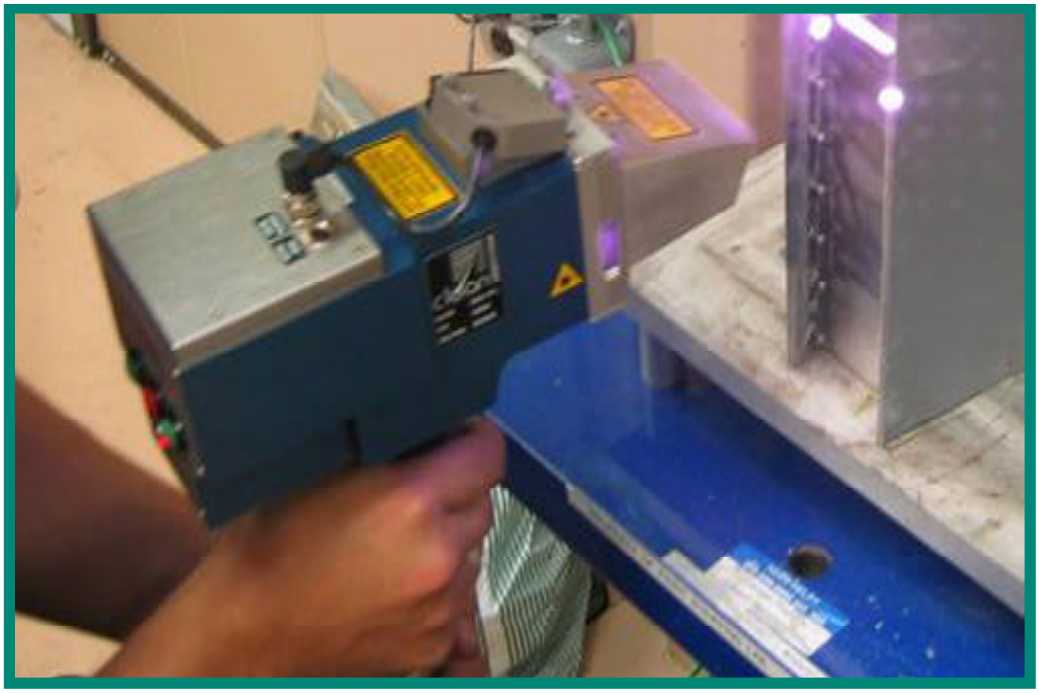
Cost and Performance Report

(WP-0027)



Portable Handheld Laser Small Area Supplemental Coatings Removal System

May 2006

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

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TABLE OF CONTENTS

Page

1.0 EXECUTIVE SUMMARY ES-1

2.0 TECHNOLOGY DESCRIPTION 1
- 2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION 1
- 2.2 PROCESS DESCRIPTION 1
  - 2.2.1 Description of Lasers 1
  - 2.2.2 Description of Portable Handheld Laser Systems 4
  - 2.2.3 Ease of Operation 6
  - 2.2.4 Health and Safety Requirements 6
- 2.3 PREVIOUS TESTING OF THE TECHNOLOGY 7
  - 2.3.1 Dwell Time of Laser Energy and Thermal Conductivity 7
  - 2.3.2 Pulse Duration Effects on Coating Removal Methods 7
  - 2.3.3 Coating Characteristics and Removal Efficiency 7
  - 2.3.4 Laser Characteristics and Removal Efficiency 8
  - 2.3.5 Penn State Comparisons 9
- 2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY 9

3.0 DEMONSTRATION DESIGN 11
- 3.1 PERFORMANCE OBJECTIVES 11
- 3.2 SELECTING TEST PLATFORM/FACILITY 11
- 3.3 TEST PLATFORMS/FACILITY HISTORY/CHARACTERISTICS 12
- 3.4 PHYSICAL SETUP 12
- 3.5 CURRENT OPERATIONS 13
- 3.6 SAMPLING/MONITORING PROCEDURES 14
- 3.7 ANALYTICAL PROCEDURES 14

4.0 PERFORMANCE ASSESSMENT 17
- 4.1 PERFORMANCE DATA 17
- 4.2 PERFORMANCE CRITERIA 21
- 4.3 DATA EVALUATION 21
- 4.4 TECHNOLOGY COMPARISON 24

5.0 COST ASSESSMENT 29
- 5.1 COST REPORTING 29
- 5.2 COST ANALYSIS 29
  - 5.2.1 Cost Drivers 29
  - 5.2.2 Cost Basis 29
  - 5.2.3 Cost Comparison 31

TABLE OF CONTENTS (continued)

Page

5.2.4 Life-Cycle Cost Analysis 32

6.0 IMPLEMENTATION ISSUES 35
6.1 COST OBSERVATIONS 35
6.2 PERFORMANCE OBSERVATIONS 35
6.3 SCALE-UP 35
6.4 LESSONS LEARNED 36
6.5 END-USER/ORIGINAL EQUIPMENT MANUFACTURER (OEM) ISSUES 36
6.6 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE 36

7.0 REFERENCES 37

APPENDIX A POINTS OF CONTACT A-1

LIST OF FIGURES

Page

Figure 1. Light Amplification by Stimulated Emission of Radiation (LASER). 2
Figure 2. Laser Ablation Mechanism. 3
Figure 3. Laser Thermal Decomposition Mechanism. 3
Figure 4. 250 W Portable CO_2 Laser System. 4
Figure 5. 40 W Portable Nd:YAG System with End Effector. 5
Figure 6. 120 W Portable Nd:YAG System with End Effector. 5
Figure 7. 250 W Diode Laser System. 6
Figure 8. Dedicated Test Area..... 13
Figure 9. Representative Chemical Depainting Process for Aircraft Parts. 14
Figure 10. Representative Chemical Depainting Process for Aircraft Parts. 29

LIST OF TABLES

Page

Table 1. Performance Objectives. 11
Table 2. Portable Handheld Laser Coating Removal Systems. 12
Table 3. Common and Extended Engineering and Test Requirements. 15
Table 4. Optimized CO_2 Laser Settings. 17
Table 5. Optimized 40 W Nd:YAG Laser Settings. 18
Table 6. Optimized 120 W Nd:YAG Laser Settings. 19
Table 7. Performance Test Results. 19
Table 8. Performance Criteria. 21
Table 9. Expected Performance and Performance Confirmation Methods. 22
Table 10. Matrix for Composite Flexural Data. 25
Table 11. Metallic Matrix for Paint Removal Methods. 26
Table 12. Annual Usage for the Baseline Chemical Depainting Operation. 30
Table 13. Comparison of Process Costs. 31
Table 14. Life-Cycle Cost Analysis. 33
Table 15. ECAM Economic Analysis Results. 33
Table 16. Summary of Investment Criteria. 33

ACRONYMS AND ABBREVIATIONS

µs	Microseconds
AFMC	Air Force Materiel Command
AFRL	Air Force Research Laboratory
ASTM	American Society for Testing and Materials
BTU	British Thermal Units
CAA	Clean Air Act
CBA	cost benefit analysis
CCAD	Corpus Christi Army Depot
CI	confidence interval
CO_2	carbon dioxide
COTS	commercial-off-the-shelf
CTIO	Coatings Technology Integration Office
CWA	Clean Water Act
D	Diameter
DMB	dry media blasting
DoD	Department of Defense
ECAM	Environmental Cost Analysis Methodology℠
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
ft^2	Square feet
HAP	Hazardous Air Pollutants
HQ AFMC/LFPE	Headquarters Air Force Materiel Command
Hz	Hertz
IRR	Internal Rate Of Return
J	Joules
JG-PP	Joint Group on Pollution Prevention
JTP	Joint Test Protocol
LASER	Light Amplification By Stimulated Emission of Radiation
LHMEL	Laser Hardened Materials Evaluation Laboratory
mJ	Millijoules
mm	Millimeters
MW	Milliwatts

NASA	National Aeronautics and Space Administration
Nd:YAG	neodymium:yttrium-aluminum-garnet
nm	Nanometer
NPV	Net Present Value
ns	Nanoseconds
OC-ALC	Oklahoma City Air Logistic Center
OD	optical density
OEM	original equipment manufacturer
OO-ALC	Ogden Air Logistic Center
OSHA	Occupational Safety and Health Administration
PAR	Potential Alternatives Report
Pi	power input
PLCRS	Portable Handheld Laser Small Area Supplemental Coating Removal System
PMB	plastic media blasting
P_o	power output
PPE	personal protective equipment
PRF	pulse repetition frequency
R&D	Research and Development
RCRA	Resource Conservation and Recovery Act
SAS	Statistical Analysis Software®
SLCR	Selective Laser Coating Removal (Lasertechnik GmbH)
SP	scan speed
SW	scan width
TEA	Transversely Excited at Atmospheric Pressure
TRI	Toxics Release Inventory
UDRI	University of Dayton Research Institute
VOC	volatile organic compounds
W	Watts
WPAFB	Wright-Patterson Air Force Base

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Technical material contained in this report has been approved for public release.

1.0 EXECUTIVE SUMMARY

The traditional coating removal methods employed throughout the Department of Defense (DoD) involve hazardous chemical or abrasive blast media. These conventional methods result in major waste streams consisting of toxic chemicals and spent blast materials. The chemicals typically used in this process are high in volatile organic compounds (VOC) and hazardous air pollutants (HAP), both of which are targeted for reduction/elimination by environmental regulations. Coatings removal operations that use abrasive blast media instead of chemical methods result in large quantities of solid hazardous waste, which is subject to high disposal costs and scrutiny under environmental regulations.

Coatings removal activities are impacted by many regulations, including portions of the Clean Water Act (CWA), the Clean Air Act (CAA), the Resource Conservation and Recovery Act (RCRA), and the Environmental Protection Agency's (EPA) Toxics Release Inventory (TRI) Report. Washing surfaces following depainting operations can generate quantities of wastewater contaminated with methylene chloride or media and paint residue. Discharging wastewater with traces of hazardous waste can result in a direct violation of the CWA. The most common regulation associated with depainting activities is the CAA, including the recent efforts to minimize the use of HAPs such as methylene chloride. The RCRA directly regulates disposal of wastes generated by depainting activities. RCRA regulations include how and where depainting waste can be disposed and transported, as well as any future liabilities resulting from environmental damage. Chemical and mechanical coatings removal operations also require consideration for worker protection and training under the Occupational Safety and Health Administration (OSHA).

Because of these environmental concerns, all branches of DoD involved in coatings removal operations are concerned with identifying alternative methodologies focused primarily towards the elimination or reduction of chemical paint strippers (such as methylene chloride and methyl ethyl ketone), dry media blasting (using either plastic media or wheat starch), and hand sanding.

As a result, portable hand held laser systems have been identified as a technology with the potential to supplement existing coating removal operations. Laser coating removal is a non-intrusive, non-kinetic energy process that can be applied to a variety of substrates, including composites, glass, metal, and plastics. High-level absorption of energy occurs at the surface of a coating material resulting in the decomposition and removal of the coating. The applied energy is mostly absorbed and utilized in coating decomposition (i.e., instant evaporation, which carries away most of the radiation energy); therefore, the substrate experiences only a minimal increase in temperature. The only waste generated is the removed coating. The use of laser energy to strip coatings is a relatively new technology developed primarily for use in the aerospace industry.

If proven viable, laser coating removal systems could provide DoD depots with an environmentally friendly alternative to chemical, media blast, and hand sanding coating removal operations. The use of laser coating removal systems would be applicable to depainting activities on aircraft components, aviation support equipment, ground support equipment, and weapons systems for the Air Force, Army, Navy, Marine Corps, and National Aeronautics and Space Administration (NASA).

In this Environmental Security Technology Certification Program (ESTCP) project, Portable Handheld Laser Small Area Supplemental Coating Removal System (PLCRS), several portable handheld laser systems were demonstrated using test panels constructed of aluminum, steel, and composite materials. The objective of this demonstration was to verify the ability of candidate laser systems to effectively remove coatings that are commonly used throughout the DoD without causing physical damage to the substrate. The demonstration was performed in the Laser Hardened Materials Evaluation Laboratory (LHMEL) at Wright-Patterson Air Force Base (WPAFB) in Dayton, Ohio. Results of this testing will assist stakeholders in implementing laser paint stripping operations at their facilities.

The testing included evaluating the effects of the laser on the material properties of aerospace substrates as well as evaluating safety aspects of the systems themselves. These test results show that the portable handheld neodymium:yttrium-aluminum-garnet (Nd:YAG) laser systems evaluated do not significantly affect the substrate materials and are an effective, versatile tool for coating removal applications.

A cost-benefit analysis was performed to estimate the impact of installing a portable handheld laser system for supplemental depainting on aircraft parts at an Air Force depot. During this economic analysis the process specifically targeted for replacement with a handheld laser system was the chemical nitpicking step that is part of the chemical depainting of off-aircraft parts (i.e., nose domes, cowlings, spoilers, etc.).

The cost-benefit analysis showed an annual environmental cost savings of approximately $83,140 and an annual total cost avoidance of approximately $99,140. A life-cycle cost analysis demonstrated that implementing and using either of the hand held Nd:YAG lasers for this nitpicking step would result in life-cycle cost savings greater than $1.2 million. These cost savings translate into a payback period for the implementation of either of the portable Nd:YAG laser systems of under 3 years.

It is estimated that other Air Force depot facilities, as well as other DoD facilities, that perform chemical depainting of parts will also realize similar cost savings. For example, if similar cost savings were assumed at all three major Air Force depots that perform chemical depainting operations on aircraft parts, the combined cost estimates would result in environmental savings of approximately $249,500 and a total annual cost avoidance of approximately $297,500 in cost savings.

Additionally, after the portable Nd:YAG laser systems are implemented into depot operations, there is a high probability that a labor savings will be achieved compared to the current chemical depainting process. This labor savings will result from the increased stripping rates over the chemical process as well as savings in preparation and cleanup time. These labor savings were not quantified during this program due to the large variance in geometries of the parts that are actually processed at DoD facilities. These varying geometries make extrapolation of the stripping rates achieved on flat panels difficult. Tracking of the actual labor savings will be performed during depot implementation of these systems.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

This Portable Handheld Laser Small Area Supplemental Coating Removal System (PLCRS) project, led by Headquarters Air Force Materiel Command (HQ AFMC/LGPE) and Air Force Research Laboratory (AFRL/MLSC) and supported by the Environmental Security Technology Certification Program (ESTCP) and the Joint Group on Pollution Prevention (JG-PP), investigated the use of portable handheld laser systems to supplement existing methods used for removal of coatings from weapon system components.

The PLCRS project first surveyed the laser industry and identified portable handheld laser commercial-off-the-shelf (COTS) systems that could be used for coatings removal from weapon system components. Due to this requirement for COTS systems all Research and development (R&D) or made-to-order portable laser systems were eliminated from consideration. Three types of portable handheld laser systems were identified for further investigation and testing: carbon dioxide (CO_2), neodymium:yttrium-aluminum-garnet (Nd:YAG), and diode. These identified laser systems met the COTS designation as well as the criteria that were established for cost, logistics footprint, reliability, and maintainability. This investigation and its results are documented in the Potential Alternatives Report (PAR), *Potential Alternatives Report for the Portable Handheld Laser Small Area Supplemental Coating Removal System* (SAIC, 2001a).

The PLCRS project then developed the *Joint Test Protocol (JTP) for Validation of a Portable LASER System for Coating Removal* (SAIC, 2001b). This JTP contained the critical requirements and tests necessary to qualify the portable handheld laser coating removal systems for use on metallic and nonmetallic substrates. Tests included in the JTP were derived from engineering, performance, and operational impact requirements.

These documents formed the basis for the technology demonstration that is detailed in this Cost and Performance Report.

2.2 PROCESS DESCRIPTION

2.2.1 Description of Lasers

LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. The laser beam is generated by an energy source that excites atoms of a lasing medium to emit photons in an optical resonator. The coherent radiation (laser beam) is then discharged through one of the reflectors (Figure 1). The laser beam may be a continuous wave or a pulsed beam, depending on how the reflectors are controlled.

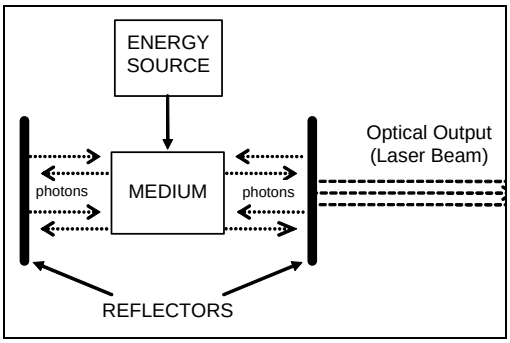


Figure 1. Light Amplification by Stimulated Emission of Radiation (LASER).

The energy source is typically an electrical discharge, flashlamp, or diode laser. Lasers can provide either a continuous wave beam or a pulsed beam. The wavelength of the light emitted is determined by the lasing medium used to generate the beam, which may be solid-state, gas, excimer, dye, or semiconductor. The lasing mediums most commonly used for coating removal are solid-state, gas, or semiconductor.

- **Solid-state** lasers have a solid matrix lasing material such as a ruby or Nd:YAG laser. The Nd:YAG laser, which was investigated in the PLCRS project, emits infrared light at 1,064 nanometers (nm) and can be delivered via fiber optical cable.

- **Gas** lasers commonly use helium, helium-neon, argon, or CO_2 as the lasing medium and have an output of visible red light. A CO_2 laser, which was investigated in the PLCRS project, emits energy in the far-infrared spectrum (10,600 nm), and has been used frequently in the metal fabrication industry for cutting hard materials. CO_2 lasers can be pulsed using a transverse excitation at atmospheric pressure (TEA) method. To date, the laser beams of handheld TEA-CO_2 lasers can only been delivered using mirrors (articulated arm).

- **Semiconductor** lasers are commonly called diode lasers and are not solid-state lasers. These lasers are usually very compact and very efficient. Diode lasers have been used in larger arrays such as laser printers or compact disc players. The diode lasers used for de-painting operations can be delivered via fiber optic cables at a wavelength of 808 or 940 nm.

For coating removal, the mechanism varies depending on the laser beam characteristics and laser delivery method. However, there are two basic laser coating removal mechanisms: (1) ablation and (2) thermal decomposition.

Ablation. Laser ablation can be achieved with pulsed lasers, which create bursts of high intensity energy. One advantage when compared to the continuous wave laser paint stripping process is that the depainting can occur at lower average temperatures. The ablation process is a mechanical process where a thin layer of coating is vaporized and converted into plasma creating a shock wave. This shock wave removes the coating and creates a crack network in the remaining coating. There are different variations of the ablation mechanisms that can be

observed depending on the laser beam characteristics, which include power, wavelength, pulse width, pulse frequency, beam profile, and operating parameters. The key to efficient and clean ablation of coatings is to employ beam irradiance levels (power per unit area) at the work surface that are large enough that the organic material pyrolizes rapidly without producing char on the surface. This is typically done in two ways. If the laser is a pulsed device, a spot size is selected such that the irradiance is greater than about 10^5 W/cm^2 and the irradiance multiplied by the pulse width produces a fluence (energy per unit area) in the range of 2 to 10 J/cm^2. Under these conditions, organic materials are rapidly ablated and the effluent is ejected from the surface at high velocity. The ejected material consists of pyrolysis gases and inorganic materials that typically clear the beam path between pulses and are swept away to an effluent evacuation system. Figure 2 is a graphical representation of this mechanism.

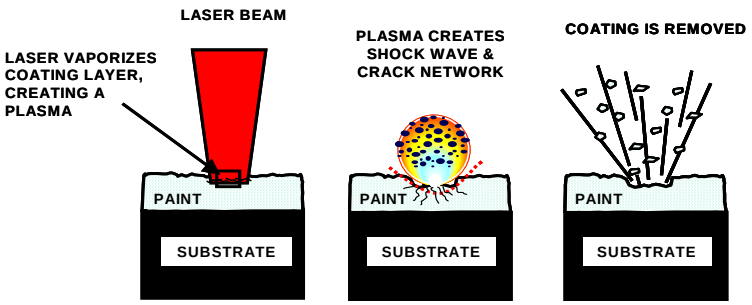


Figure 2. Laser Ablation Mechanism.

Thermal Decomposition. Continuous wave lasers vaporize thin layers of the coating system. This process uses thermal energy to remove layers of paint from the substrate surface. Continuous wave lasers apply energy for a long period of time, heat up the material, and burn it off. Since it is easy to damage the substrate, these continuous wave lasers require extensive training, controls, and diagnostics to safely remove paint. The continuous laser beam must be swept at high velocity such that the effective pulse width on the surface (spot diameter divided by scan velocity) is sufficiently short that the local fluence received on the surface after passage of the beam is again in the 2 to 10 J/cm^2 range. An additional requirement for a continuous laser beam is an air jet to continuously blow the effluent out of the beam path. A representation of this mechanism is provided in Figure 3.

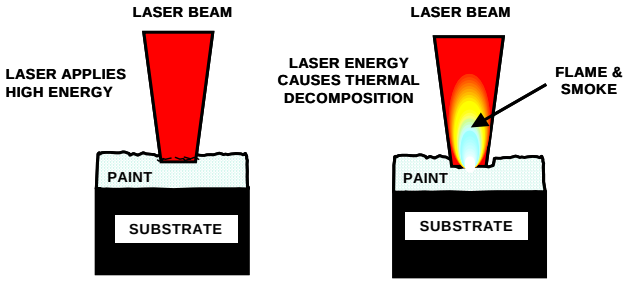


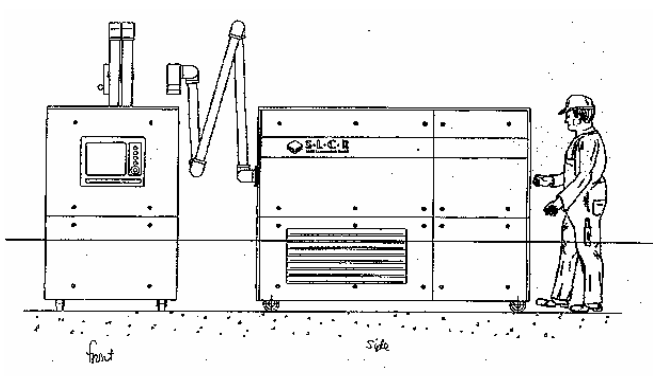
Figure 3. Laser Thermal Decomposition Mechanism.

2.2.2 Description of Portable Handheld Laser Systems

During this demonstration, three laser types were investigated: CO_2, Nd:YAG, and diode. These systems were selected based on their performance during screening testing at each manufacturer's facility and on the availability of a COTS cleaning/coatings removal system.

CO_2 Laser System. The CO_2 laser system, which operated in the pulsed mode using the TEA method, offered high power conversion efficiencies and economic operating costs but presented challenges in the areas of system size and beam delivery convenience. There are currently no fiber-optic or core fiber delivery systems available that will handle either the power or wavelength required of a CO_2 device. A CO_2 system must, therefore, rely on transmissive or reflective optics and enclosed beam ducts for beam delivery, adding a level of complexity to the concept of hand-directed operation. In Figure 4, picture #1 shows an artist rendered drawing of the CO_2 mobile unit, which includes a side view (right) and a front view (left), and picture #2 is a photo of the actual unit in use. The system, which includes the laser system and chiller, is quite large with a footprint of nearly 40 square feet (ft^2). The system has an average output power of 250 W with a maximum energy of 6.5 J per pulse, pulse repetition frequency (PRF) of 50 hertz (Hz), and pulse duration of about 2 microseconds (μs). The end effector produces a linear beam of approximately 3 millimeters (mm) in width and an adjustable length of 8-50 mm in length.

#1



FRONT VIEW SIDE VIEW

#2

Figure 4. 250 W Portable CO_2 Laser System.

Nd:YAG Laser Systems. The PLCRS project investigated both a 40 W and a 120 W Nd:YAG system. Both Nd:YAG lasers operated in the pulsed mode. The 40 W Nd:YAG laser system, shown in Figure 5, is a COTS hand-directed system with a fiber-optically delivered laser beam. This system, which includes the laser system and chiller, is much more compact than the CO_2 unit, requiring only ~20 ft^2 of floor space. The system also has a pencil-like end effector, shown in Figure 5, which may also be used for glove box applications as it offers a much smaller and more easily directed laser beam. The end effector was not equipped with any type of particle collection system; however, a Plexiglas attachment was designed to incorporate the particle collection system. The output beam is square and ranges in size from 3 mm x 3 mm to 5 mm x 5 mm, making it more effective on small or intricate components. The system has a maximum

average power of 40 W with a maximum energy of 333 millijoules (mJ) per pulse, PRF of 120 Hz, and pulse duration of 9 nanoseconds (ns).

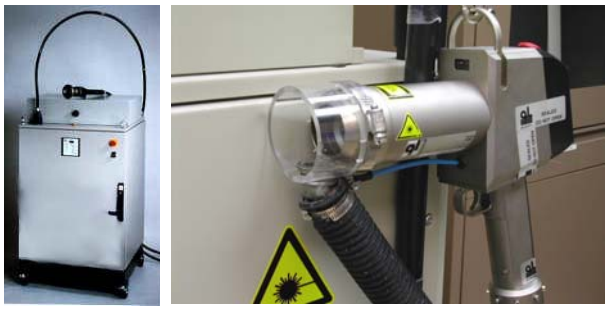


Figure 5. 40 W Portable Nd:YAG System with End Effector.

The 120 W Nd:YAG system, shown in Figure 6, is entirely self contained and requires only 6 ft^2 of floor space. The system has a self-contained water chiller system and a pulsed Q-switched laser that has an average power of 120 W with a pulse length ranging from 120 to 290 ns, PRF range of 8,000 to 35,000 Hz, and maximum pulse energy of 5 mJ per pulse. The unit is also equipped with an end effector with an integral particle collection system and interchangeable nose tips (i.e., "freehand" style nose tip and a wheeled tip designed to clean flat or slightly contoured surfaces—reducing operator fatigue and maintaining a constant working distance from final-optic to work surface thereby delivering a consistent energy to the surface). The end effector rasters the fiber-optically delivered beam to produce a 0.4 mm wide linear beam shape that can be adjusted from 1.3 to 50 mm in length. Raster speed can be varied from 40 to 100 Hz.

Figure 6. 120 W Portable Nd:YAG System with End Effector.

Diode Laser System. The diode laser system, shown in Figure 7, is a COTS laser system with power capabilities ranging up to 2,000 W in the continuous wave mode with a dual wavelength system producing 250 W of continuous wave power at either 808 or 940 nm wavelength. The system delivers a laser spot size of 0.4 mm diameter, which is rastered into a square pattern measuring 45 mm x 45 mm at speeds of 250 to 10,000 mm/sec.

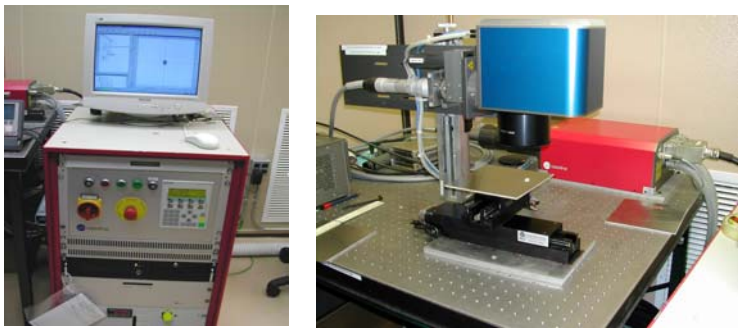


Figure 7. 250 W Diode Laser System.

While the laser system itself is COTS, it cannot be categorized as "handheld" according to its current configuration. The end effector, as currently designed, is large and mounted to an optical table. Likewise, the square beam delivery pattern described above is also stationary. In order to be usable as a coating removal system, an x-y translation stage would be needed to transport the sample rapidly under the existing end effector. Also, the system, as delivered, was not equipped with any particle collection system. A collector was later installed for testing.

As an emerging technology, there is very little information available on optimum laser parameters for coating removal. The diode laser system end effector, as currently designed, is hard mounted to an optical table, and, therefore, does not meet the "portable handheld" criteria for this demonstration. This system was, therefore, eliminated from the testing under this project and not used in this demonstration.

2.2.3 Ease of Operation

Operation of the handheld lasers requires only simple daily inspections of the electrical power cable condition, cooling water level, fiber-optic sheath condition (if fiber-optic delivery is used), end cleaning of the end effector protective window. After this daily maintenance, the operator can begin use of the laser.

Operation of these systems is accomplished by depressing a trigger on the end effector and moving the end effector across the work surface. Variations in the specific laser systems end effector designs determine how the operator maintains a specified standoff distance and moves the laser beam across the work surface. This program evaluated the operator's ease of use for each laser system, including the ergonomic design and the operational flexibility.

2.2.4 Health and Safety Requirements

The personal protective equipment (PPE) required for use with the laser systems include laser safety glasses/goggles and latex gloves. Ear plugs are required for use with the CO_2 and 40 W Nd:YAG systems, but may not be required when operating the 120 W Nd:YAG laser. The use of hearing protection needs to be assessed on a case-by-case basis based on the type of laser system being used and the location/environment in which it is used. All the laser systems considered for coating removal operations are Class 4 lasers, and, therefore, require laser safety

glasses/goggles specific for the wavelength of the laser being used. The laser systems used for this demonstration required laser safety glasses with an optical density (OD) of +7. All the laser systems should be connected to an air filtration system. A half-face respirator is required when replacing the air filtration system filter bags. For additional information on the safety analysis conducted for handheld lasers, refer to the AFMC *System Safety Engineering Analysis (SSEA) for Hand-Held Paint-Stripping Lasers* report, dated June 14, 2004, and the ESTCP *Portable Handheld Laser Small Area Supplemental Coating Removal System Final Report.*

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

2.3.1 Dwell Time of Laser Energy and Thermal Conductivity

Another set of property interactions is that between length of time the laser energy contacts the substrate and the substrate's ability to conduct that energy, i.e., thermal conductivity. University of Southern California (USC) reported results of a study comparing a continuous wave CO_2 and Q-switched pulsed Nd:YAG laser on various substrates (USC, 1995). The results indicated that a continuous wave CO_2 laser was not able to remove coatings as efficiently from substrates with a high thermal conductivity because the heat was lost to the substrate, thus heating it. The continuous wave CO_2 laser successfully removed coating systems from substrates with a low thermal conductivity because all the laser energy was used to remove the coating system and not absorbed into the substrate. When a Q-switched pulsed laser was tested, as long as the pulse duration was shorter than the time it took to transfer energy to the substrate, all the laser energy was used to remove the coating system. The pulse duration was optimized during this study for multiple substrates to be 8ns.

2.3.2 Pulse Duration Effects on Coating Removal Methods

This difference in response to thermal conductivity is due to the different methods by which coating systems are removed from a substrate by a laser. A continuous wave or long pulse laser heats the coating material to vaporization by way of thermal decomposition or burning, while the short pulsed or Q-switched laser will ablate the coating material. Ablation is a method where the top few microns of coating absorb enough laser energy to be converted into plasma. As the coating particles expand, they create a shock wave that removes the underlying coating layers from the substrate as solid flakes of coating. In this manner, the laser energy never touches the substrate, thus no heat transference or damage to heat-sensitive substrates occurs. In research conducted by Pennsylvania State University (Penn State) documented in a report entitled *An Investigation of Laser Based Coating Removal* it was determined that shorter pulses of laser energy, in the nanosecond range versus the millisecond range, will result in ablation of the coating system, while longer pulses will result in thermal decomposition or burning. Thermal decomposition of a coating can result in the generation of hazardous air emissions, while the by-products of ablation are primarily carbon dioxide, water, and coating flakes.

2.3.3 Coating Characteristics and Removal Efficiency

The age of the coating system was one property thought to affect the ability of the laser technology to remove the coating. In personal communications with JET Lasersysteme GmbH and Selective Laser Coating Removal (SLCR) Lasertechnik GmbH, each company indicated

that, in their experience with aerospace coatings, no difference was observed in the laser removal of artificially aged and freshly cured paint. One property of the coating system that can impact the ability of the laser technology to remove the coating is the pigments that add color to the coating system.

Research conducted by Penn State and documented in the report entitled *An Investigation of Laser Based Coating Removal*, indicates that the pigment in coating systems can significantly affect the performance of pulsed lasers due to the low peak irradiance and the pigment's ability to absorb it. However, the irradiance of the Q-switched pulsed laser is high enough that energy is absorbed into the coating regardless of color resulting in ablation of the coating. Similarly, USC investigated the effect of pigment wavelength on the efficiency of laser coating removal (USC, 1995) and concluded that laser energy removes a coating most efficiently when it is absorbed by the coating system. The wavelength of the pigments in the coating system can influence laser energy absorption. If the laser energy is the same wavelength as the pigment in the coating system, then the laser energy will be reflected, not absorbed. In light of this, the USC team recommends the use of a laser with a different wavelength than the pigment. Conversely, as the wavelength of the laser increases, the amount of energy that the coating system can absorb (absorption coefficient) decreases, indicating that a ceiling can be reached when adjusting a laser wavelength to enhance the rate of coating removal.

Research by USC also indicated a similar property of paint, threshold intensity, which is the amount of energy needed to remove the coating system (USC, 1995). The intensity of a laser is manipulated by changing the beam size, i.e., beam diameter. The intensity of the laser can be increased by decreasing the beam size (concentrating the energy on a smaller area); however, the efficiency of coating system removal also decreases. USC, 1995 also reported that the difference in threshold intensity among paints is small, indicating that the beam size, once optimized, can remain fairly constant when the laser system is transferred to different coating system removal applications.

2.3.4 Laser Characteristics and Removal Efficiency

Additional research findings by Penn State and USC into the removal efficiencies of continuous wave, pulsed, and Q-switched lasers have put forth diagnostic information that can be used to determine the engineering design for a laser removal application. Penn State, reported that Q-switched lasers do not have the pulse rate or high average power that pulse lasers do to achieve comparable cleaning rates. However, the Q-switched laser does have an order of magnitude higher removal efficiency than pulsed lasers. This leads to the question of which is more important, the efficiency of removal and integrity of the substrate or the overall cleaning rate (Penn Sate, 1998). USC researched the effects of beam size and pulse width on coating removal rates. They reported that across laser types, the rate of removal increases as beam size or pulse width decrease. This observation indicates that as the laser energy is focused, the ability of that energy to remove a coating system increases; however, as reported earlier, the efficiency of removal decreases.

2.3.5 Penn State Comparisons

In an experiment with actual laser units, Penn State compared three Nd:YAG lasers of various powers in the areas of ability to remove coatings, type of effluent released, and ease of use with fiber optics and a handheld headpiece. The first laser had an average power of 3 kW. It was determined that at this power the laser unevenly removed the coating and insufficiently broke down the paint. In addition, the appropriate raster and linear motion was difficult to integrate into handheld unit and the high average power would require water cooled mirrors, thus increasing the weight of the handheld unit. The researchers concluded that the 3 kW laser was unsuited for handheld applications. Next, the researchers evaluated a 10 W laser. This laser had a high ablation to burning ratio and removed the coating more efficiently than high power lasers. However, the rate of removal was very slow and the beam was not easily delivered through fiber optics. The researchers concluded that the 10 W laser was not suited for fiber optic delivery. The last laser that was evaluated was a 400 W laser. This laser was capable of removing the coating in a wide swath, had a simple optical configuration leading to ease of fiber-optic use, and was capable of maintaining a high peak power that generated less soot and smoke. Researchers recommended the 400 W laser for both fiber-optic delivery and for use in a handheld application. (Note: This 400 W turnkey laser system was manufactured by U.S. Laser Corporation)

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

In the past decade, laser systems have generated significant interest as cleaning and paint removal tools. The advantages of using lasers for paint removal are that it requires no sample preparation, is noncontact, and uses no secondary medium that increases the amount of material to dispose.

A potential limitation to the technology is the potential for the energy beam to overheat the substrate while performing stripping operations. The controllable nature of the energy beam that is used in the systems being evaluated in this task addresses this issue. With the proper parameters, coatings can be selectively removed with minimal influence to the underlying substrate.

In general, these systems are most suited for use on parts that have the following characteristics:

- Metallic, composite, or fiberglass substrate—preferably (but not necessarily) of a different color than the coating to be removed to facilitate feedback control

- Simple to moderately complex part geometry—gradual contours preferred over sharp angles for speed of manipulation

- Organic coating system to be partially or completely removed—selective coating removal an option

- Relatively continuous process throughput—a laser system performs better if used regularly, rather than intermittently.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The main performance objective of this demonstration was to remove coatings from test panels using the candidate portable handheld laser coating removal systems without causing damage to the substrate materials. The performance objectives for this demonstration are detailed in Table 1.

Table 1. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance Metric	Actual Performance (120 W Nd:YAG) Objective Met?	Actual Performance (40 W Nd:YAG) Objective Met?	Actual Performance (250 W CO_2) Objective Met?
Quantitative	Maintain specifications for affected parts/substrates	Pass individual product tests described in the JTP	Majority of Performance Criteria met; failure to meet some criteria requires further evaluation	Majority of Performance Criteria met; failure to meet some criteria requires further evaluation	System returned prior to completion of JTP testing
Qualitative	Coating removal without substrate damage	No visual damage	Metallic substrates—YES Composite substrates—NO*	Metallic substrates—YES Composite substrates—NO*	Metallic substrates—YES Composite substrates—NO*
Qualitative	Ease of handling, ease of use, reliability	System can remove coatings with manning of two. System can be moved and manipulated around equipment by two persons. Portable laser gun head weighs less than 5 pounds.	YES	YES	NO Poor ergonomic design

* Under magnification, some fiber damage was seen, and an engineering analysis of these results is required to determine the significance.

3.2 SELECTING TEST PLATFORM/FACILITY

The Laser Hardened Materials Evaluation Laboratory (LHMEL) facility at Wright Patterson Air Force Base (WPAFB) was selected as the location for this demonstration due to their extensive experience with lasers. LHMEL has more than 25 years of experience in conducting laser materials interaction testing. The LHMEL facility has a certified laser safety officer on site to assist in laser licensing and installation and has the necessary safeguards in place for the operation of Class 4 lasers. Another factor that contributed to the decision was the close proximity of LHMEL to the facilities that would be performing the panel coating and quantitative testing of the processed test panels.

3.3 TEST PLATFORMS/FACILITY HISTORY/CHARACTERISTICS

The LHMEL was established to evaluate laser and materials interactions and laser effects on current and emerging materials for future aerospace applications. This organization is equipped to provide a cost-effective, well-characterized, reliable test facility for materials response phenomenology, thermal modeling validation, and laser effects testing to support basic research through mid-scale demonstrations.

Four portable handheld laser coating removal systems were placed at this facility. An overview of the capabilities of each of these systems is detailed in Table 2.

Table 2. Portable Handheld Laser Coating Removal Systems.

	TEA CO_2	Nd:YAG	Nd:YAG (Q-Switched)	Diode
Power	250 W	40 W	120 W	250 W
Beam Delivery	Umbilical Arm	Fiber Optical Cable	Fiber Optical Cable	Fiber Optical Cable
Wavelength	10,600 nm	1,064 nm	1,064 nm	808 & 940 nm
Pulse Duration	1,000 ns	10 – 12 ns	200 ns	N/A
Pulse Frequency	0 – 50 Hz	1, 2, 6, 30, 60, or 120 Hz	8,000 – 35,000 Hz	Continuous Wave
Max. Pulse Energy	6.5 J	333 mJ	5 mJ	N/A
Fluence Range	4.3 – 27.1 J/cm^2	1.3 – 3.7 J/cm^2	2.8 – 10.0 J/cm^2	N/A
Scan Width	0 – 50 mm	N/A	10 – 50 mm	40 mm x 40 mm

N/A = not applicable

3.4 PHYSICAL SETUP

The LHMEL facility is an active test facility with a steady stream of external users. As a result, provisions were made to allow for the coating removal tests to be conducted on a non-interference basis. A modular enclosure was constructed within LHMEL to house the candidate laser systems and conduct the coating removal testing. A layout of this area is shown in Figure 8. The area was equipped with heat, lighting, and electrical service to support the candidate laser systems and their associated support equipment.

Because the candidate lasers were all of European origin, some power conversions (i.e., transformers) were required to provide the proper electrical connections.

Exhaust was another area of concern. The test area itself was rather small and the candidate laser systems exhausted a large quantity of excess heat in the process of their operation. All equipment that could be located remotely from the systems was moved outside the test area to reduce the heat load. Air conditioning was considered for the area but the British Thermal Units (BTU) load and the air exchanges required made such an option impractical. Instead, a number of high volume fans were installed in the modular walls with a roof-mounted exhaust fan added to provide a continuous flow of air through the area. This solution was helpful but frequent breaks were still required by the operators, particularly during the summer months.

Once the test area was constructed and wired, the laser safety precautions were designed and installed. All safeguards that were installed were in accordance with Air Force standard laser safety requirements (AFOSH 48-10 Laser Radiation Protection Program). Each door to the test area was interlocked with each of the candidate laser systems so that the lasers would be deactivated should a door be opened unexpectedly. Each door was also equipped with the necessary laser safety warning lights, and warning signs were clearly posted. Each laser system also had to be permitted by the Base Laser and Ground Safety Offices. This permitting required the preparation of a Standard Operating Procedure for each of the lasers.

A video camera system was also installed in this test area to record the results of the experiments. Cameras recorded the surface response as well as a wide-angle view encompassing the operator and the test article. Cameras were also installed to allow visitors to watch laboratory activities without needing to be present in the test area with potentially hazardous materials and for the operators to monitor visitors entering the area.

Finally, protection equipment was also procured to provide a safe working environment for the operators. Protective suits and breathing apparatus were originally procured to protect the operator from the potentially hazardous by-products (i.e., the removed coatings). Subsequent air sampling studies showed that this level of protection was not required. Half-face respirators were later used for removal of the vacuum system filters. Protective gloves were used to guard against ultraviolet/infrared exposure along with laser safety goggles, appropriate for each candidate laser, and disposable ear protection when required.

This demonstration took 20 months to complete all four paint stripping cycles and the associated mechanical testing of the processed panels. The demonstration began in October 2002 and ran until May 2004.

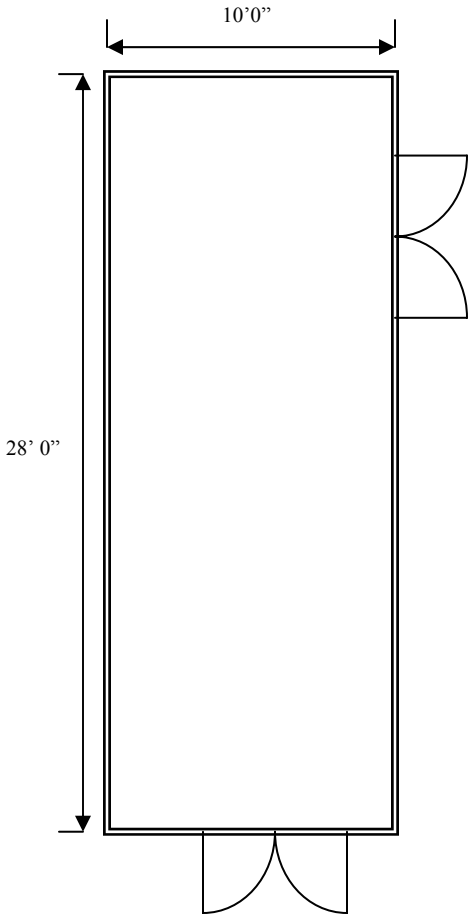

Figure 8. Dedicated Test Area.

3.5 CURRENT OPERATIONS

Current paint removal operations were surveyed at one Air Force Depot as part of the cost benefit analysis (CBA) that was performed for this project and is the focus of this ESTCP Cost Report. An Initial CBA was also performed for the PLCRS project at four facilities: Jacksonville Naval Aviation Depot, Barstow Marine Corps Logistics Base, Corpus Christi Army Depot, and Warner Robins Air Logistics Center. For additional information on the Initial CBA, refer to the Science Applications International Corporation (SAIC) report, *Initial/Early Cost Benefit Analysis for the Portable Handheld Laser Small Area Coating Removal System* (SAIC, 2001b).

Figure 9 shows the chemical depainting process of aircraft parts (i.e., nose domes, cowlings, spoilers, etc.) that was evaluated for this ESTCP Cost Report. The nitpicking step in Figure 9 is the chemical depainting step that was identified as the first candidate process for replacement by portable handheld lasers.

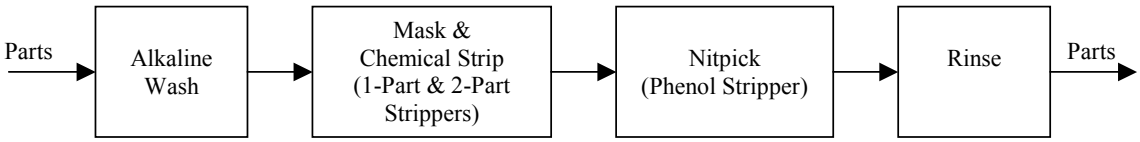

Figure 9. Representative Chemical Depainting Process for Aircraft Parts.

The nitpicking step of the chemical stripping process is only the first of many applications at the depot facilities for which the candidate laser systems may be utilized. This nitpicking process has been targeted as the initial process for implementing the laser system, but the candidate portable laser systems may be utilized on many more applications throughout the depots. For example, the portable laser systems may supplement or replace media blasting and hand sanding applications. There are also other nonaircraft related applications for which the portable laser system may be utilized. It is expected that the laser systems will be utilized for these applications after depots have begun use of these portable laser systems for the nitpicking process and developed a level of comfort with their operation.

3.6 SAMPLING/MONITORING PROCEDURES

A total of 466 test panels (12 inches x 12 inches) were processed during this demonstration. Of that total, 334 panels were metallic substrates and 132 panels were composite substrates. The substrates of these test panels included aluminum (2024-T3 and 7075-T6, alclad and bare), steel (4130), aluminum honeycomb, fiberglass/epoxy, graphite/epoxy, Kevlar, and metallic honeycomb. Each panel was coated with approved Department of Defense (DoD) and industry standard coating systems, which included MIL-PRF-23377, MIL-P-53030, MIL-C-46168, MIL-C-64159, MIL-PRF-85285, 10PW 22-2, Super Koropon 515-K01A, and PR1432GP.

All test panels that were processed during this demonstration were stripped using a consistent set of parameters for each laser system. All testing was performed in a manner that optimized the use of each test piece and/or panel. Where possible, more than one test was performed on each specimen. The number and type of tests that were run on any one specimen was determined by the destructiveness of the test. All testing was performed in accordance with the approved JTP and ESTCP Demonstration Plan.

3.7 ANALYTICAL PROCEDURES

Analytical testing procedures were used for the evaluation of the panels stripped during this demonstration. The various standards that were followed during these tests are provided in Table 3.

Two laboratories were utilized in completing the required testing. The Air Force Coatings Technology Integration Office (CTIO) applied the coatings to each of the test panels and performed the profilometer measurements. This laboratory was chosen because of its unique capabilities in the coating of test coupons in a controlled atmosphere. This facility is located on site at WPAFB.

AFRL/MLSC and their support contractor, the University of Dayton Research Institute (UDRI), performed all other testing that was required under the JTP. This facility was chosen because of the laboratory's well-established record of material testing. Another factor in this decision was the location—this laboratory is located on site at WPAFB.

Table 3. Common and Extended Engineering and Test Requirements.

Test Name	Acceptance Criteria	References
Coating Strip Rate	Acceptance criteria based on requirements analysis or survey results and/or 0.06 ft^2 per minute at 6 mils, nominal thickness	AF EQP[1]
Warping/Denting	No warping/denting as observed	AF EQP
Metal/Composite Erosion	No metal/composite erosion observable at 10X magnification	AF EQP
Hardness	No significant change in hardness	ASTM[2] E18
Tensile Testing	Compare tensile strength of sample values obtained with control samples of base materials (nonstripped and noncoated samples)	ASTM E8
Paint Adhesion	Wet tape adhesion performance greater than or equal to 4a as specified in ASTM D3359	ASTM D3359
Confirmation of Cladding Penetration	No black indication	SAE MA4872
Surface Profile/Roughness	2024-T3 Alclad: not to exceed 125 micro inches; 2024-T3 Bare: not to exceed 125 micro inches	SAE MA4872
Substrate Temperature During Coating Removal Process	7075-T6 aluminum: 300°F maximum spike condition; Carbon epoxy laminate: 200°F maximum spike condition	SAE MA4872
Four Point Flexure	No significant change at 90% confidence	ASTM D790
Rotary Wing Metallic Substrate Assessment	No significant change at 90% confidence	AF EQP, ASTM E647
Damage Assessment to Honeycomb Structural Materials	Testing detail and results to be documented for review and determination of pass/fail values	ASTM D790, ASTM D638, ASTM D695, ASTM E647

[1]Air Force equipment
[2]American Society for Testing and Materials

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4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

Three portable laser systems—CO_2, 40 W Nd:YAG, and 120 W Nd:YAG—were demonstrated at the LHMEL test site and evaluated based on the performance criteria that are detailed in Table 7 and Table 8.

Each of these laser systems has various adjustable parameters associated with their use. Prior to processing the test panels, optimization trials were conducted to determine the parameters that provide the most efficient coating removal based on the coatings and the substrates that were being processed.

The adjustable parameters for the CO_2 laser system included electrical power input (Pi), PRF, scan width (SW), and pulse offset. A 1.5 mm pulse offset translated into a 50% overlap between pulses. The optimized settings for each of these parameters are presented in Table 4.

Table 4. Optimized CO_2 Laser Settings.

Primer/Topcoat	Aluminum	Steel	Laser Settings	Avg. Power (W)	Peak Power (MW)	Fluence (J/cm^2)
MIL-PRF-23377G / MIL-C-46168D, Type IV	X	X	P_i = 33 kV, PRF = 50 Hz, SW = 50 mm, Offset = 1.5 mm	250	2.5	12.1
MIL-P-53030 / MIL-DTL-64159 Type II	X	X				
MIL-PRF-23377G / MIL-PRF-85285 Type I	X					
PR1432GP / MIL-PRF-85285 Type I	X					
MIL-PRF-23377G / APC	X					

The 40 W Nd:YAG laser had adjustable settings of power output (P_o), PRF, and spot size diameter (D) presented in terms of dial setting (i.e. dial setting 10 = 3.5 x 3.5 mm, 15 = 4 x 4 mm, and 20 = 4.5 x 4.5 mm). The optimized settings that were established when using this system are presented in Table 5.

Table 5. Optimized 40 W Nd:YAG Laser Settings.

Primer/Topcoat	Aluminum	Steel	Graphite Epoxy	Fiberglass Epoxy	Kevlar	Metallic Honeycomb	Laser Settings	Avg. Power (W)	Peak Power (MW)	Fluence (J/cm^2)
MIL-PRF-23377G / MIL-C-46168D, Type IV	X	X					P_o = 40 W, PRF = 120 Hz, D = 4.5 x 4.5 mm	40	37.0	1.65
MIL-P-53030 / MIL-DTL-64159, Type II	X	X					P_o = 40 W, PRF = 120 Hz, D = 4.5 x 4.5 mm	40	37.0	1.65
MIL-P-53030 / MIL-DTL-64159, Type II					X		P_o = 35 W, PRF = 120 Hz, D = 4 x 4 mm	35	32.4	1.82
MIL-PRF-23377G / MIL-PRF-85285, Type I	X		X	X			P_o = 30 W, PRF = 120 Hz, D = 4 x 4 mm	30	27.8	1.56
MIL-PRF-23377G / MIL-PRF-85285, Type I						X	P_o = 40 W, PRF = 120 Hz, D = 4 x 4 mm	40	37.0	1.65
PR1432GP / MIL-PRF-85285, Type I	X						P_o = 40 W, PRF = 120 Hz, D = 4.5 x 4.5 mm	40	37.0	1.65
MIL-PRF-23377G / APC	X						P_o = 30 W, PRF = 120 Hz, D = 4 x 4 mm	30	27.8	1.56

The 120 W Nd:YAG laser had adjustable settings that included PRF, scan speed (SP), and SW. The optimized settings that were established when using this system are presented in Table 6.

Table 6. Optimized 120 W Nd:YAG Laser Settings.

Primer/Topcoat	Aluminum	Steel	Graphite Epoxy	Fiberglass Epoxy	Kevlar	Metallic Honeycomb	Laser Settings	Avg. Power (W)	Peak Power (MW)	Fluence (J/cm^2)
MIL-PRF-23377G / MIL-C-46168D, Type IV	X	X					PRF = 18 kHz, SP = 80 Hz, SW = 50 mm	110.4	0.037	4.87
MIL-P-53030 / MIL-DTL-64159, Type II	X	X					PRF = 18 kHz, SP = 80 Hz, SW = 50 mm	110.4	0.037	4.87
MIL-P-53030 / MIL-DTL-64159, Type II					X		PRF = 17.5 kHz, SP = 80 Hz, SW = 50 mm	110.0	0.038	4.99
MIL-PRF-23377G / MIL-PRF-85285, Type I	X		X	X			PRF = 24.5 kHz, SP = 80 Hz, SW = 50 mm	114.7	0.023	3.72
MIL-PRF-23377G / MIL-PRF-85285, Type I	X					X	PRF = 26.5 kHz, SP = 80 Hz, SW = 50 mm	116.2	0.020	3.48
PR1432GP / MIL-PRF-85285, Type I	X						PRF = 26.5 kHz, SP = 80 Hz, SW = 50 mm	116.2	0.020	3.48

Both the 40 W and the 120 W Nd:YAG laser systems were successfully demonstrated and passed the majority of performance criteria listed in Table 3. Test results that did not meet the JTP acceptance criteria occurred in areas where engineering determinations will be required, not statistical analysis. The CO_2 laser system, due to the cumbersome nature of both the system and its end effector, was used only through two of the four test cycles of the demonstration before being returned to the manufacturer. The results of the testing performed are detailed in Table 7. The interpretation of these test results is further discussed in Sections 4.3 and 4.4.

Table 7. Performance Test Results.

Performance Criteria	Baseline (unprocessed panel)	120 W Nd:YAG	250 W CO_2	40 W Nd:YAG
Coating Strip Rate (ft^2/min) (6 mils coating thickness)				
2024 T3 Clad	N/A	0.06	0.03	0.03[1]
Graphite epoxy	N/A	0.1	0.04	0.006
1010 Steel	N/A	0.05	0.01	0.007
2024 T3 Clad	N/A	0.04	0.01	0.007
2024 T3 Clad	N/A	0.06	0.03	N/A
[1]Strip rate determined on 3 mil coating thickness				
Warping/Denting	N/A	None	None	None
Metal Erosion	N/A	None	None	None

Table 7. Performance Test Results (continued)**.**

Performance Criteria	Baseline (unprocessed panel)	120 W Nd:YAG	250 W CO_2	40 W Nd:YAG
Composite Erosion	N/A	Loose fibers	N/A	Loose fibers
Hardness (ASTM E18)				
2024 T3 Bare	82.6	80.9	82.1	81.5
2024 T3 Clad	89.2	88.7	89.5	88.1
Tensile Testing (ASTM E8)				
Yield Strength (ksi)	47.8	48.0	46.8	47.4
Ultimate Tensile Strength (ksi)	63.3	66.7	62.0	65.8
Elongation (%)	16.6	18.1	17.8	18.2
Wet Tape Adhesion (ASTM D3359)				
2024 T3 Clad	N/A	4.2	4.8	4.0
2024 T3 Bare	N/A	4.6	4.9	4.4
2024 T3 Bare Chromic Acid Anodized	N/A	5.0	5.0	5.0
4130 Steel	N/A	4.4	5.0	3.4
Clad Penetration (SAE MA4872)	None	None	None	None
Surface Profile / Roughness (µin) (SAE MA4872)	N/A	37 – 65	10 – 18	13 – 29
Maximum Substrate Temperatures (°F)				
2024 T3 Bare	N/A	212°F	N/A	154°F
Graphite Epoxy		138°F		132°F
Composite - Four Point Flexure (ASTM D6273)				
Graphite Epoxy - Flex Strength (ksi)	192.3	168.0	N/A	184.3
Graphite Epoxy - Flex Modulus (Msi)	21.26	22.20		19.99
Fiberglass Epoxy - Flex Strength (ksi)	98.1	88.1	N/A	86.2
Fiberglass Epoxy - Flex Modulus (Msi)	4.59	3.52		3.51
Kevlar - Flex Strength (ksi)	58.4	57.8		60.3
Kevlar - Flex Modulus (Msi)	4.95	3.95		4.09
Rotary Wing Metallic Substrate Assessment				
Fatigue – Smooth (ASTM E466) (Average Cyclic Life [cycles])				
2024 T3 Clad	112,246	101,182	116,299	89,844
7075 T6 Clad	85,416	79,369	77,803	79,597
7075 T6 Bare	144,267	54,606	351,987	42,717
Fatigue – Notched (ASTM E466) (Average Cyclic Life [cycles])				
2024 T3 Clad	91,230	72,240	84,621	70,003
7075 T6 Clad	65,074	42,192	59,792	45,975
7075 T6 Bare	43,386	20,080	29,524	21,420
Damage Assessment to Honeycomb (ASTM D1781, ASTM C393, AF EQP)				
Core Shear Strength (psi)	560.4	558.9	N/A	567.0
Core Shear Modulus (ksi)	96.0	95.3		85.7
Flex Stiffness (lb-in^2)	48,761	48,763		50,135
Facing Stress (ksi)	42.0	41.9		42.5
Ease of Handling	N/A	Pass	Fail	Pass
Reliability	N/A	Pass	Pass	Pass
Ease of Operation	N/A	Pass	Fail	Pass

4.2 PERFORMANCE CRITERIA

The general performance criteria used to evaluate the portable laser coating removal systems are summarized in Table 8. These performance criteria have been categorized as either primary or secondary criteria.

Table 8. Performance Criteria.

Performance Criteria	Description	Primary or Secondary
Product Testing	Must pass individual product tests, which included the following: 1. Coating Strip Rate 2. Warping/Denting 3. Metal/Composite Erosion 4. Hardness 5. Tensile Testing 6. Wet Tape Adhesion 7. Cladding Loss 8. Surface Profile/Roughness 9. Substrate Temperature During Coating Removal 10. Four Point Flexure 11. Rotary Wing Metallic Substrate Testing (Fatigue) 12. Damage Assessment to Honeycomb Materials	Primary
Ease of Handling	System can remove coatings with manning of two. System can be moved and manipulated around equipment by two persons. Portable laser gun head weighs less than 5 pounds.	Secondary
Reliability	No maintenance increase	Secondary
Ease of Operation	Good ergonomic design; flexible design allowing for operation on multiple part geometries	Secondary

4.3 DATA EVALUATION

An overview of the results of the testing conducted is presented in Table 9. The test results that met the JTP established acceptance criteria are highlighted in green, while test results that are outside of the acceptance criteria are highlighted in pink. Any value reported that shows a statistically significant difference from the value obtained on the unprocessed baseline material is presented in bold text.

The results for the coating strip rate testing did not meet the JTP acceptance criteria, but failure of these lasers to meet the 0.06 ft^2/min criteria should not be seen as a failure of the systems to remove coatings in a timely manner. This acceptance criterion does not account for the time savings that would be achieved in setup and preparation time that is required prior to the existing chemical stripping operations. The use of these handheld laser systems requires virtually no setup or preparation time prior to depainting operations on a part.

For the composite erosion test (i.e., surface examination), the expected performance was that no resin erosion/damage would occur. For the actual surface examinations (under magnification) of the laser stripped panels, loose fibers and surface erosion was observed. The engineering

Table 9. Expected Performance and Performance Confirmation Methods.

Performance Criteria	Actual Performance			Expected Performance
	120 W Nd:YAG	250 W CO_2	40 W Nd:YAG	
Coating Strip Rate (ft^2/min) (6 mils coating thickness)				
2024 T3 Clad	0.06	0.03	0.03[a]	0.06 ft^2/minute at 6 mils nominal thickness
Graphite Epoxy	0.1	0.04	0.006	
1010 Steel	0.05	0.01	0.007	
2024 T3 Clad	0.04	0.01	0.007	
2024 T3 Clad	0.06	0.03	N/A	
[a] Strip rate determined on 3 mil coating thickness				
Warping/Denting	None	None	None	
Metal Erosion	None	None	None	Visual Examination
Composite Erosion	Loose fibers	N/A	Loose fibers	No resin erosion/damage
Hardness (ASTM E18)				
2024 T3 Bare ***Baseline = 82.6***	**80.9**	82.1	**81.5**	No significant change at 90% confidence
2024 T3 Clad ***Baseline = 89.2***	**88.7**	89.5	**88.1**	
Tensile Testing (ASTM E8)				
Yield Strength (ksi) ***Baseline = 47.8***	48.0	**46.8**	47.4	No significant change at 90% confidence (Debit)
Ultimate Tensile Strength (ksi) ***Baseline = 63.3***	**66.7**	**62.0**	**65.8**	
Elongation (%) ***Baseline = 16.6%***	**18.1**	**17.8**	**18.2**	
Wet Tape Adhesion (ASTM D3359)				
2024 T3 Clad	4.2	4.8	4.0	Minimum of 4A
2024 T3 Bare	4.6	4.9	4.4	
2024 T3 Bare Chromic Acid Anodized	5.0	5.0	5.0	
4130 Steel	4.4	5.0	3.4	
Clad Penetration (SAE MA4872)	None	None	None	Determine Clad Penetration
Surface Profile / Roughness (µin) (SAE MA4872)	37 – 65	10 – 18	13 – 29	Not to exceed 125 µin
Maximum Substrate Temperatures (°F)				
2024 T3 Bare	212°F	N/A	154°F	Maximum spike: 7075: 300º F G/E: 200º F
Graphite Epoxy	138°F		132°F	

Table 9. Expected Performance and Performance Confirmation Methods (continued).

Performance Criteria	Actual Performance			Expected Performance
	120 W Nd:YAG	250 W CO_2	40 W Nd:YAG	
Composite - Four Point Flexure (ASTM D6273)				
Graphite Epoxy - Flex Strength (ksi) ***Baseline = 192.3 ksi***	**168.0**	N/A	184.3	No significant change at 90% confidence (Debit)
Graphite Epoxy - Flex Modulus (Msi) ***Baseline = 21.26 Msi***	22.20		**19.99**	
Fiberglass Epoxy - Flex Strength (ksi) ***Baseline = 98.1 ksi***	88.1	N/A	86.2	Testing not required in JTP
Fiberglass Epoxy - Flex Modulus (Msi) ***Baseline = 4.59 Msi***	3.52		3.51	
Kevlar - Flex Strength (ksi) ***Baseline = 58.4 ksi***	57.8		60.3	
Kevlar - Flex Modulus (Msi) ***Baseline= 4.95 Msi***	3.95		4.09	
Rotary Wing Metallic Substrate Assessment				
Fatigue – Smooth (ASTM E466) (Average Cyclic Life [cycles])				
2024 T3 Clad ***Baseline = 112,246***	101,182	116,299	**89,844**	No significant change at 90% confidence (Debit)
7075 T6 Clad ***Baseline = 85,416***	79,369	77,803	79,597	
7075 T6 Bare ***Baseline = 144,267***	**54,606**	351,987	42,717	
Fatigue – Notched (ASTM E466) (Average Cyclic Life [cycles])				
2024 T3 Clad ***Baseline = 91,230***	**72,240**	84,621	**70,003**	No significant change at 90% confidence (Debit)
7075 T6 Clad ***Baseline = 65,074***	**42,192**	59,792	**45,975**	
7075 T6 Bare ***Baseline = 43,386***	**20,080**	**29,524**	**21,420**	
Fatigue Crack Growth Rate (ASTM E647)				
2024 T3 Clad ΔK 6				No Significant change at 90% confidence (Debit)
2024 T3 Clad ΔK 14				
7075 T6 Clad ΔK 6				
7075 T6 Clad ΔK 14				
7075 T6 Thin ΔK 6				
7075 T6 Thin ΔK 14				
Damage Assessment to Honeycomb (ASTM D1781, ASTM C393, AF EQP)				
Core Shear Strength (psi) ***Baseline = 560.4***	558.9	N/A	567.0	Test Results Reported
Core Shear Modulus (ksi) ***Baseline = 96.0***	95.3		85.7	
Flex Stiffness (lb-in^2) ***Baseline 48,761***	48,763		50,135	
Facing Stress (ksi) ***Baseline = 42.0***	41.9		42.5	

N/A = Not Applicable
ASTM = American Standard for Testing and Materials standards
SAE = Society of Automotive Engineers standards
mil = millionths of an inch

significance of these observations will need to be assessed by the individual weapons systems engineers prior to use on composite surfaces.

Finally, the results for the hardness, tensile, fatigue, and four-point flexure tests were reported as failures due to the JTP acceptance criteria of "no statistically significant change" from the results that were achieved on an unprocessed baseline material. Even though these results were reported as failures in terms of the JTP acceptance criteria because they showed statistical significance, the results may not be of engineering significance. This is explored further in Section 4.4.

An evaluation of the secondary performance criteria including Ease of Handling, Reliability, and Ease of Use were also performed for each of the laser systems. The two Nd:YAG laser systems were proven to be quite versatile and practically maintenance-free. The 40 W Nd:YAG system was very easy to use but was found to be slightly tedious to use when stripping larger surface areas. This was due to the end effector design that produces a small, unrastered beam diameter on the part substrate. Likewise, the 120 W Nd:YAG system was also very easy to use, but its end effector is designed to perform stripping on larger flat surfaces. Stripping of these flat or slightly controured surfaces was performed very efficiently using this system, but the end effector design was found to be slightly cumbersome when stripping components with complicated geometries.

While the CO_2 system proved to be very efficient at removing the various coatings on the metal substrates, the articulating arm design caused a high level of user fatigue and presented access limitations for an actual field application. The CO_2 end effector has an efficient particle removal (suction) system but restricts the operator's view of the surface being cleaned. Due to the cumbersome nature of both the system and the end effector, the unit was used through only two of the four planned test cycles and was returned to the manufacturer.

4.4 TECHNOLOGY COMPARISON

The interpretation of the data was to be performed on a pass/fail basis, but upon further investigation, the JTP testing that had acceptance criteria that required no statistically significant change to occur from baseline results was considered to be an unrealistically high standard. In order to frame the results that were achieved during this testing in context with other approved coating removal methods and to assist with engineering interpretations of the test results, an intensive literature search for published testing data was conducted. The literature search of 74 published references for test results was conducted on methods that are commonly used to remove paint from metallic and nonmetallic substrates. This reference data allows for engineers to compare the results that were obtained during this project testing on the laser systems with the mechanical test results that have previously been reported for other approved coating removal methods.

The references were categorized by substrate and mechanical property data presented. Metallic substrate mechanical properties retrieved from the references were tensile and fatigue properties. No fatigue crack growth data was found in the literature survey. Therefore, no comparison to the test data generated in this program could be made. The nonmetallic substrate mechanical property commonly found in the literature was flexure strength. The paint removal methods

examined were flash lamp, plastic media blasting (PMB), dry media blasting (DMB), chemical, and lasers.

Statistical analysis was performed on the test results compared to the literature search data using the same statistical analysis approach whenever possible, and the coating-removed test results were compared to the baseline test results. The evaluation process consisted of a statistical analysis of the baseline test results compared to the paint-removed test results in each reference, where sufficiently detailed data were available, as well as from the project data. The reference materials that were used for the test results comparison are detailed as References 1–9 in the References section at the end of this report.

Statistical analysis was performed on the selected JTP test data. Confidence intervals were constructed at a 90% confidence level for the difference between baselines and de-paint treated specimens. The analyses produces an estimate of the difference between the baseline mean value and the de-paint method mean using calculated confidence intervals (CI) of 90%. A statistical significance is present if the 90% CI is completely positive or negative. A 90% CI straddled across zero represents no statistical significance.

The 90% CI calculations were completed using Statistical Analysis Software® (SAS), which is a widely accepted statistical software package used by statisticians. A reference to the exact methodology used can be found on page 941 of SAS/STAT Users Guide, Volume 2, GLM-VARCOMP, Version 6, Fourth Edition.

Table 10 summarizes the composite flexural strength results while Table 11 summarizes the effects of the paint removal methods on the mechanical properties of the metallic substrates and the reference data.

Table 10. Matrix for Composite Flexural Data.

Paint Removal Method	Flexural Strength		
	Graphite/Epoxy	Fiber Glass/Epoxy	Kevlar/Epoxy
Reference			
(8) Flash Lamp	NS		
(5) PMB (Plastic)	NS		
(7) Bicarbonate Blast	NS		
(7) Abrasive	NS		
(7) Wet Abrasive	+		
PLCRS			
40 watt Nd:YAG	NS	-	NS
120 watt Nd:YAG	-	-	NS

NS = No Statistical Significance
- Statistical decrease
+ Statistical increase
No tabulated reference data found

Table 11. Metallic Matrix for Paint Removal Methods.

	Material - 2024-T3 Bare					Material - 2024-T3 Clad					Material - 7075-T6 Clad					Material - 7075-T6 Bare 0.016"				
	Tensile			Fatigue		Tensile			Fatigue		Tensile			Fatigue		Tensile			Fatigue	
Paint Removal Methods	UTS	YTS	%Elong	Smooth	Notched	UTS	YTS	%Elong	Smooth	Notched	UTS	YTS	%Elong	Smooth	Notched	UTS	YTS	%Elong	Smooth	Notched
Chemical (Reference (4))									-					NS					-	
PMB (Reference (5))									-					NS						
DMB (Wheat-Starch) (Reference (2))	-	-	NS			-	-	NS	NS		-	-	NS	NS		-	-	NS	NS	
Flash Lamp (Reference (6)										NS					NS					
CO_2 Laser (Reference (1))	+	-	NS																	
Plasma Etching (Reference (3))																				
Excimer (Reference (3))																				
Nd:YAG Laser (Reference (3))																				
CO_2 Laser (AFRL Testing)	+	NS	NS			-	-	NS	NS	NS	+	NS	NS	NS	NS	+	NS	NS	NS	-
40 watt Nd:YAG Laser (AFRL Testing)	+	NS	NS			+	NS	NS	-	-	+	NS	NS	NS	-	+	NS	NS	-	-
120 watt Nd:YAG Laser (AFRL Testing)	+	NS	-			+	NS	-	NS	-	+	NS	-	NS	-	NS	NS	NS	-	-

+ - Positive Statistical Significance against the baseline material data
NS - No Statistical Significance against the baseline material data
- -Negative Statistical Significance against the baseline material data
- Historial data not found for Statistical Analysis
- No fatigue data generated

It should be noted that, although there may be a statistically significant difference at the 90% confidence level for the tests, there may not be a significant engineering difference. The 90% confidence level was selected as the performance criteria during the beginning stages of this program but, subsequently, it has been determined that an engineering review of expected material properties rather than the statistical analysis of test results would have been the most appropriate method for evaluation of these test results.

The differences observed for tensile strength, fatigue, and flexural properties were small and are well within the expected scatter in material properties. This scatter has been accounted for in the design of the aircraft and should not be cause for alarm.

In terms of the tensile properties, the laser stripping methods showed a lesser, if any, reduction of properties as compared to the published data from other coating removal means. In terms of fatigue life, all differences fall well within the normal scatter, approximately one decade; therefore, the differences are not significant from an engineering standpoint.

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5.0 COST ASSESSMENT

5.1 COST REPORTING

The primary objective of the cost assessment is to determine whether handheld laser systems can be implemented with an acceptable payback period. An economic analysis was conducted using the Environmental Cost Analysis Methodology (ECAM) cost estimating tool comparing the chemical depainting process of aircraft parts currently is performed at an Air Force depot (baseline scenario) to the purchase and installation of a 120 W Nd:YAG laser system (alternative scenario 1) and a 40 W Nd:YAG laser system (alternative scenario 2). Information was collected on the baseline scenario as well as the alternative scenarios and was entered into the Environmental Protection Agency's (EPA) pollution prevention cost accounting software, P2 Finance. This software performs the calculations for payback period, net present value (NPV), and internal rate of return (IRR).

5.2 COST ANALYSIS

5.2.1 Cost Drivers

For the analysis of this technology, the cost drivers included capital cost, annual equipment maintenance, material usage, utility costs, hazardous waste disposal, and any recurring environmental compliance costs.

5.2.2 Cost Basis

For this cost assessment, the candidate laser systems were assumed to eliminate the chemical nitpicking step that is part of the current stripping processes performed at the surveyed Air Force depot. The nitpicking process was targeted as the initial process for implementation of the laser system, but the candidate portable laser systems can potentially be utilized on many more applications throughout the depots. For example, the portable laser systems may supplement or replace media blasting and hand sanding applications. There are also other non-aircraft related applications for which the portable laser system may be utilized. It is expected that the laser systems will be utilized for these applications after depots start using these portable laser systems for the nitpicking process and ascertain a level of comfort with their operation.

Cost data that was used for this economic analysis was accumulated throughout the demonstration of the portable handheld laser systems. Additionally, a detailed survey of the current depainting operations was performed at one Air Force depot. As discussed in Section 3.5 of this ESTCP report, the current chemical depainting process of aircraft parts that was evaluated for this report consists of four process steps, as shown in Figure 10. The nitpicking step in the chemical depainting process is the candidate step for replacement by portable handheld lasers.

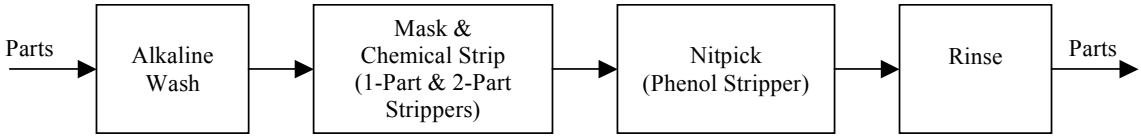

Figure 10. Representative Chemical Depainting Process for Aircraft Parts.

Based on feedback received from the surveyed Air Force depot facility, the approximate annual part throughput and approximate baseline annual operating usage quantities for this cost analysis are provided in Table 12.

Table 12. Annual Usage for the Baseline Chemical Depainting Operation.

Number of Parts Depainted Annually	5,040 parts/yr
Material Usage Annually	
2-Part Stripper	15,500 gal/yr
1-Part Stripper	4,300 gal/yr
Phenol (Methylene Chloride) Stripper	2,500 gal/yr
Safety Glasses	90 pairs/yr
Gloves	1,200 pairs/yr
Utility Usage Annually	
Rinse Water	287,400 gal/yr
Waste Management Annually	
Hazardous Waste Disposal	251,000 lbs/yr

The following data and assumptions were used in evaluating the baseline chemical depainting process:

- The surveyed Air Force depot processed an average of 60 planes annually, each plane having approximately 84 candidate parts
- Nitpicking step comprises approximately 13% of the total chemical depainting work
- A price of $14.55/gal was used for 2-Part stripper
- A price of $19.75/gal was used for 1-Part stripper
- A price of $7.07/gal was used for phenol stripper
- A unit cost of $3.00/pair was used for safety glasses
- A unit cost of $0.13/pair was used for gloves
- Waste management data and associated cost are based on actual numbers for the 2004 calendar year for disposal of rags, PPE, filters, paint chips, and paint sludge
- Chemical stripper usage data is based on actual numbers for the 2004 fiscal year
- Environmental compliance costs are based on compliance sites associated with the baseline chemical depainting process

The following data and assumptions were used in evaluating the alternative depainting process that would use a portable Nd:YAG laser system to replace the nitpicking depainting step:

- Annual usage of 1-Part and 2-Part chemical strippers would not change because only the nitpicking step would be replaced by the laser system. The other chemical depainting step would still be required.
- Assumed 100% reduction in phenol stripper, which is associated with the nitpicking step
- Assumed 13% reduction for annual usage of safety glasses and gloves
- Assumed 13% reduction for annual hazardous waste disposal amounts

- Environmental compliance cost reduction calculated is for the elimination of the chemical stripper used in the nitpicking step. No additional environmental compliance costs are associated with the implementation of the laser system.
- A one-time capital equipment cost for the purchase of a portable laser system, which included a laser unit, vacuum system, laser safety curtains, and three pairs of laser safety glasses.
- Annual maintenance costs for the lasers includes the replacement of vacuum filters twice a year, yearly replacement of the deionized water filters and flashlamps, and biannual replacement of the end effector protective window.

5.2.3 Cost Comparison

The cost basis information was utilized to determine actual process and cost data on the current depainting operations that are performed. A comparison of the baseline process to the alternative laser coating removal systems is provided in Table 13.

Table 13. Comparison of Process Costs.

	Baseline Scenario Chemical Stripping	Alternative Scenario 1 120 W Nd:YAG Laser	Alternative Scenario 2 40 W Nd:YAG Laser
Initial Investment Cost			
Capital equipment	$0*	$208,300	$216,600
Annual Operating Cost			
Direct Materials:			
2-Part Stripper	$225,361	$225,361	$225,361
1-Part Stripper	85,442	85,442	$ 85,442
Phenol Stripper (Nitpicking)	17,803	0	0
Safety Glasses	90	78	78
Gloves	156	136	136
Equipment Maintenance	200	2,036	2,036
Total	$329,052	$313,053	$313,053
Utilities:			
Water	$344,880	$279,360	$279,360
Waste Management:			
Hazardous Waste Disposal Costs	$82,011	$71,349	$71,349
Environmental Compliance Recurring Cost	$34,150	$27,192	$27,192

* It was assumed that the baseline process is already established and would not require an initial investment cost; however, if a DoD depot facility were to purchase equipment to install a new chemical depainting facility, there would be an associated capital equipment cost.

Table 13 shows that use of either of the laser systems would provide the facility with substantial savings in environmental costs. Yearly reductions in the use of rinse water would save approximately $65,520 annually. Additionally, the implementation of laser technology to perform nitpicking of the candidate parts would eliminate a substantial amount of hazardous waste, whose disposal currently costs $10,662 annually. Finally, minor savings of $6,985 in the yearly permitting fees associated with the current process would be realized. In total, these environmental savings would amount to $83,140 annual savings. When coupled with the

savings in annual direct materials, the total savings associated with these processes rises to approximately $99,140.

It is estimated that other Air Force depot facilities, as well as other DoD facilities, that perform chemical depainting of parts will also realize similar cost savings. For example, if similar cost savings were assumed at all three of the major Air Force depots that perform chemical depainting operations on aircraft parts, the combined cost estimates would provide the Air Force with an annual environmental savings of approximately $249,500 and a total annual savings of approximately $297,500.

It is also expected that, after the portable Nd:YAG laser systems are implemented into depot operations, labor cost will be less than those in the current chemical depainting process. This labor savings will result from the increased stripping rates over the chemical process as well as savings in preparation and cleanup time. These labor savings were not quantified during this program due to the large variance in geometries of the parts that are actually processed at DoD facilities. These varying geometries make it difficult to extrapolate the stripping rates that were achieved on flat panels during testing. Tracking of the actual labor savings will be performed during depot implementation of these systems.

In addition to cost savings, implementation of portable laser systems will also reduce worker exposure to hazardous chemicals and/or substances. With the replacement of the chemical nitpicking step with the laser system, the hazardous phenol stripper is eliminated, and, as a result, the worker's exposure to that hazardous chemical is eliminated.

5.2.4 Life-Cycle Cost Analysis

A life-cycle cost analysis was performed using the data from Table 13 to evaluate the decision of whether a portable Nd:YAG laser system is a viable alternative to currently used coating removal processes. Per ECAM guidance, this approach:

- Estimates the annual cash flows using the cost data described above
- Discounts future cash flows (per Office of Management and Budget Circular No. A-94: *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs,* rev. 1/2000) for the time value of money
- Calculates financial performance measures (NPV and IRR)
- Compares these measures with acceptance criteria.

This evaluation was based on the life-cycle cost associated with the implementation and use of either of the handheld laser systems. This was calculated by totaling the initial investment required as well as the operating, maintenance, and repair costs expected over the 15-year life of the equipment. A summary of the life-cycle cost and life-cycle cost savings associated with the handheld laser systems is provided in Table 14.

Table 14. Life-Cycle Cost Analysis.

Technology	Installation Cost	Annual Cost	Life-Cycle Cost	Life-Cycle Cost Savings
Chemical Stripping	$0	$790,093	$11,851,395	-
120 W Nd:YAG Laser	$208,300	$690,954	$10,572,610	$1,278,785
40 W Nd:YAG Laser	$216,600	$688,918	$10,580,910	$1,270,485

Three performance measures for investment opportunities were then considered in the ECAM evaluation: payback period, NPV, and IRR. The payback period is the time period required to recover all the capital investment with future cost avoidance. NPV takes this investment-return analysis one step further by calculating the difference between capital investments and the present value of future annual cost benefits associated with the alternatives. This value represents the life-cycle costs associated with each of the alternatives. The IRR is the discount rate at which NPV is equal to zero.

NPV and IRR account for the time value of money and discount the future capital investments or annual cost benefits to the current year. For NPV and IRR, a 3.5% discount rate and a 15-year life-cycle lifetime was used for this financial evaluation.

Table 15 shows the calculated 15 year net present value, internal rate of return, and discounted payback period for the two different handheld laser systems.

Table 15. ECAM Economic Analysis Results.

Technology	NPV at 15 Years	IRR at 15 Years	Discounted Payback Period
120 W Nd:YAG Laser	$933,514	47.5%	2.22 years
40 W Nd:YAG Laser	$925,214	45.6%	2.32 years

Table 16 summarizes the investment criteria that were used to compare the capital costs of the proposed portable Nd:YAG laser technology to the estimated discounted future savings resulting from its replacement of existing coating removal processes.

Table 16. Summary of Investment Criteria.

Criteria	Recommendations/Conclusions
NPV > 0	Investment return acceptable
NPV < 0	Investment return not acceptable
Highest NPV	Maximum value to the facility
IRR > discount rate	Project return acceptable
IRR < discount rate	Project return not acceptable
Shortest payback period	Fastest investment recovery and lowest risk

Adapted from *ECAM Handbook.*

The NPV for both the 40 W and 120 W Nd:YAG laser systems were both positive, which, based on the investment criteria presented in Table 16, means that procurement of either of the systems for nitpicking operations would provide an acceptable investment return. The 120 W system had the higher of the NPV values, meaning that this system would provide a higher value to the facility than the 40 W laser system.

The IRR for both these systems is higher than the 3.5% discount rate that was used for the financial evaluation. Based on the investment criteria for IRR presented in Table 16, the project return is acceptable.

Finally, with a discounted payback period of 2.18 years, the 120 W Nd:YAG laser would provide the maximum value and fastest investment recovery.

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

The cost of a 120 W Nd:YAG laser with end effector and vacuum system is approximately $195,300. This includes the installation and training on the unit. If a higher power laser system would be desired, the cost would increase. The only site preparations required are electrical power and approximately 20-ft^2 in floor space.

6.2 PERFORMANCE OBSERVATIONS

Testing confirmed the ability of the portable handheld Nd:YAG laser system to provide efficient, nonhazardous coating removal. The laser system provides a reliable, environmentally friendly alternative to the current chemical, blast media, and hand sanding coating removal methods. The use of these handheld laser systems requires virtually no setup or preparation time prior to depainting operations on a part.

The differences that were observed during panel testing for tensile strength, fatigue, and flexural properties were small and are well within the expected scatter in material properties. This scatter has been accounted for in the design of the aircraft and should not be cause for alarm. In terms of the tensile properties, the laser stripping methods showed a lesser, if any, reduction of properties as compared to the published data from other coating removal means. In terms of fatigue life, all differences fall well within the normal scatter, approximately one decade; therefore, the differences may not be significant from an engineering standpoint.

Four field demonstrations of handheld laser coating removal were conducted using a portable 120 W Nd:YAG laser with a handheld end effector and stylus. The laser demonstrations were conducted July-August 2004 at Ogden Air Logistic Center (OO-ALC), Oklahoma City Air Logistic Center (OC-ALC), Corpus Christi Army Depot (CCAD), and National Aeronautics and Space Administration (NASA) at WPAFB, to show the DoD the capabilities of handheld laser technology for coating removal applications. Some parts that were demonstrated included a hydraulic actuator housing, aircraft flight instrument housing, and A-10 wing leading edge section. The primary purpose of the field demonstrations was to introduce the technology to the depot-level systems engineers responsible for providing engineering authorization for coating removal processes and to the production-level personnel who will actually put the laser systems into use upon receipt of that authorization. A secondary benefit of the demonstrations was that they provided an opportunity to assess the transportability of the systems and to evaluate the overall suitability of the systems for use in a production environment. The overwhelming consensus from the participants was that the lasers have many potential applications throughout all DoD aircraft maintenance shops.

6.3 SCALE-UP

The demonstrations were conducted on full-scale laser systems; therefore, no scale-up, performance-related issues exist.

6.4 LESSONS LEARNED

Valuable information was noted during the demonstration of the laser systems. Lessons learned, which would help a facility with evaluation and implementation of portable handheld laser systems, are listed below:

- This program involved the Occupational Health and Safety Officers throughout the process of implementation and use of laser coatings removal equipment. The involvement of these individuals from the beginning of the program was highly beneficial and allowed for program buy-in from the Safety Office and a smooth implementation and start-up of the equipment. The involvement of these individuals is highly recommended for future demonstration and implementation of lasers.

- During execution of the JTP, it was realized that several of the acceptance criteria required that the laser systems be held to a higher standard than was achieved using the current coatings removal methods. Future JTPs should establish testing acceptance criteria that are rigorous but realistic. When compared to the currently used and approved coating removal systems, the laser systems affected substrates less.

6.5 END-USER/ORIGINAL EQUIPMENT MANUFACTURER (OEM) ISSUES

In fiscal year 2005, two Nd:YAG laser units were purchased and planned for installation in 2005 at OO-ALC and OC-ALC. These laser systems will be used for validation testing by each depot facility. While being used by the Air Logistic Centers, the portable laser systems will be tracked and data gathered to establish both labor and overall process time savings as well as the many benefits the laser system might have on the process parameters.

The Nd:YAG laser systems are COTS and may be purchased directly from the manufacturer.

6.6 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

No new or additional permits are required for the portable handheld laser systems.

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APPENDIX A

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