Portable Handheld Laser Small Area Supplemental Coatings Removal System

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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. The results from this testing will provide stakeholders with information that will assist in the implementation of laser paint stripping operations at their facilities.

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TABLE OF CONTENTS

Page

ACRONYMS I

1.0 INTRODUCTION 1

1.1 BACKGROUND 1
1.2 OBJECTIVES OF THE DEMONSTRATION 1
1.3 REGULATORY DRIVERS 1
1.4 STAKEHOLDER/END-USER ISSUES 2

2.0 TECHNOLOGY DESCRIPTION 3

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION 3
2.2 PREVIOUS TESTING OF THE TECHNOLOGY 5
2.2.1 Dwell Time of Laser Energy and Thermal Conductivity 5
2.2.2 Pulse Duration Effects on Coating Removal Methods 6
2.2.3 Coating Characteristics and Removal Efficiency 6
2.2.4 Laser Characteristics and Removal Efficiency 7
2.2.5 Penn State Comparisons 7
2.3 FACTORS AFFECTING COST AND PERFORMANCE 7
2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY 8

3.0 DEMONSTRATION DESIGN 9

3.1 PERFORMANCE OBJECTIVES 9
3.2 SELECTING TEST PLATFORMS/FACILITIES 9
3.3 TEST PLATFORM/FACILITY HISTORY/CHARACTERISTICS 10
3.4 PRESENT OPERATIONS 12
3.5 PRE-DEMONSTRATION TESTING AND ANALYSIS 13
3.6 TESTING AND EVALUATION PLAN 13
3.6.1 Demonstration Set-Up and Start-Up 13
3.6.2 Period of Operation 15
3.6.3 Amount/Treatment Rate of Material To Be Treated 15
3.6.4 Operating Parameters for the Technology 15
3.6.5 Experimental Design 17
3.6.6 Product Testing 19
3.6.7 Ergonomics Assessment 22
3.6.8 Demobilization 22
3.7 SELECTION OF ANALYTICAL/TESTING METHODS 23
3.8 SELECTION OF ANALYTICAL/TESTING LABORATORY 25

4.0 PERFORMANCE ASSESSMENT 26

4.1 PERFORMANCE CRITERIA 26
4.2 PERFORMANCE CONFIRMATION METHODS 26

4.3 DATA ANALYSIS, INTERPRETATION AND EVALUATION 29
4.3.1 Technology Comparison 29

5.0 COST ASSESSMENT 33

5.1 COST REPORTING 33
5.2 COST ANALYSIS 33
5.2.1 Cost Drivers 33
5.2.2 Cost Basis 33
5.2.3 Cost Comparison 35
5.2.4 Life Cycle Cost Analysis 37

6.0 IMPLEMENTATION ISSUES 39

6.1 ENVIRONMENTAL PERMITS 39
6.2 OTHER REGULATORY ISSUES 39
6.3 END-USER / OEM ISSUES 40

7.0 REFERENCES 41

8.0 POINTS OF CONTACT 43

LIST OF TABLES

Page
Table 3-1: Performance Objectives 9
Table 3-2: Optimized CO_2 Laser Settings 16
Table 3-3: Optimized 40 watt Nd:YAG Laser Settings.....16
Table 3-4: Optimized 120 watt Nd:YAG Laser Settings.....17
Table 3-5: Test Panel Substrates.....18
Table 3-6: Coating Systems 19
Table 3-7: Chemicals Evaluated for Flammability Testing.....21
Table 3-8. Common and Extended Engineering and Test Requirements.....24
Table 4-1: Performance Criteria 26
Table 4-2: Expected Performance and Performance Confirmation Methods.....27
Table 4-3: Metallic Matrix for Paint Removal Methods 32
Table 4-4:. Matrix for Composite Flexural Data 31
Table 5-1: Annual Usage for the Baseline Chemical Depainting Operation.....34
Table 5-2: Comparison of Process Costs 36
Table 5-3: Life Cycle Cost Analysis.....37
Table 5-4: ECAM Economic Analysis Results 38
Table 5-5: Summary of Investment Criteria 38
Table 6-1: Agency and Laser Safety Standard 39

LIST OF FIGURES

Page
Figure 2-1: Light Amplification by Stimulated Emission of Radiation (LASER) 3
Figure 2-2: Laser Ablation Mechanism 4
Figure 2-3: Laser Thermal Decomposition Mechanism 5
Figure 3-1: 250W Portable CO2 Laser System 10
Figure 3-2: 40W Portable Nd:YAG System with End Effector 11
Figure 3-3: 120W Portable Nd:YAG System with End Effector 12
Figure 3-4: 250W Diode Laser System 12
Figure 3-5: Representative Chemical Depainting Process for Aircraft Parts 13
Figure 3-6: Dedicated Test Area.....14
Figure 5-1: Representative Chemical Depainting Process for Aircraft Parts 34

ACRONYMS

AFRL	Air Force Research Laboratory
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
CAA	Clean Air Act
CBA	Cost Benefit Analysis
CCAD	Corpus Christi Army Depot
CFR	Code of Federal Regulations
CTC	Concurrent Technologies Corporation
CTIO	Coatings Technology Integration Office
CWA	Clean Water Act
DERA	Defense Evaluation and Research Agency
DoD	Department Of Defense
ECAM	Environmental Cost Analysis Methodology
EPA	Environmental Protection Agency
HAP	Hazardous Air Pollutants
IRR	Internal Rate Of Return
JTP	Joint Test Protocol
LASER	Light Amplification By Stimulated Emission of Radiation
LHMEL	Laser Hardened Materials Evaluation Laboratory
MCLB Barstow	Barstow Marine Corp Logistics Base
NAS-JAX	Jacksonville Naval Aviation Depot
Nd:YAG	Yttrium Aluminum Garnet Crystals Doped with Neodymium Ions
NDCEE	National Defense Center For Environmental Excellence
NPV	Net Present Value
OSHA	Occupational Safety & Health Administration
PMB	Plastic Media Blasting
RCRA	Resource Conservation and Recovery Act
SAIC	Science Applications International Corporation
TEA	Transversely Excited At Atmospheric Pressure
TRI	Toxics Release Inventory
UDRI	University Of Dayton Research Institute
USC	University of Southern California
VOC	Volatile Organic Compounds
WPAFB	Wright Patterson Air Force Base
WR-ALC	Warner Robins Air Logistics Center

ABSTRACT

The traditional coating removal methods that are employed throughout the Department of Defense (DoD) involve the use of hazardous chemical or abrasive blast media. These conventional methods result in major waste streams consisting of toxic chemicals and spent blast materials. The chemicals that are 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 that is subject to high disposal costs and scrutiny under environmental regulations.

Coatings removal activities are impacted by a number of regulations including portions of the Clean Water Act (CWA), Clean Air Act (CAA), 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. The 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 Act (OSHA).

Because of these environmental concerns, all branches of the DoD that are currently involved in coatings removal operations are concerned with the identification of 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.

If proven viable, laser coating removal systems could provide DoD depots and field units 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. The results from this testing will provide stakeholders with information that will assist in the implementation of laser paint stripping operations at their facilities.

The testing conducted included evaluation of the effects of the laser on the material properties of aerospace substrates as well as evaluations of the environmental safety and occupational health aspects of the systems themselves. These test results show that the portable handheld neodymium:yttrium-aluminum-garnet (Nd:YAG) laser systems that were 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. During this economic analysis the process that was specifically targeted for implementation of the handheld laser systems 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 waste disposal cost savings of approximately $10,660 and an annual cost avoidance of approximately $81,520 since the depot will not have to purchase or use a percentage of the chemicals, personal protective equipment (PPE), and water that is presently used during the chemical depainting process. Additionally, the cost benefit analysis showed an adjusted environmental compliance cost avoidance of $6,958 per year associated with the elimination of the chemical nitpicking step. These cost savings translate into a payback period for the implementation of either of the portable Nd:YAG laser systems of under three 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 of the 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.

1.0 INTRODUCTION

1.1 Background

Conventional coatings removal methods that are employed throughout the Department of Defense (DoD) result in a major waste stream consisting of toxic chemicals and media blast materials. The chemicals that are typically used in this process are also 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 hazardous waste. This waste is subject to high disposal costs and scrutiny under environmental regulations.

Portable hand held laser systems have been identified as a potential technology to supplement the existing depainting processes. A laser is a device that generates monochromatic, coherent light that can be focused and concentrated into a narrow, intense beam of energy. Lasers are currently used in multiple manufacturing operations, including welding, cutting, drilling, and surface treatment. The use of laser energy to strip coatings is a relatively new technology developed primarily for the aerospace industry.

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. The high level absorption of energy at the surface of a coating material results 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.

1.2 Objectives of the Demonstration

The objective of this demonstration was to verify the ability of portable hand held laser coating removal systems to effectively remove coatings that are commonly used throughout the Department of Defense without causing physical damage to the substrate. The results from this testing will provide stakeholders with information that will assist in the implementation of laser paint stripping operations at their facilities.

This demonstration was performed at the Laser Hardened Materials Evaluation Laboratory (LHMEL) at Wright Patterson Air Force Base (WPAFB) in Dayton, Ohio. This facility is managed by the Air Force Research Laboratory, Hardened Materials Branch (AFRL/MLPJ) and is operated by Anteon Corporation. This demonstration was conducted using test panels constructed of aluminum, steel, and graphite epoxy.

1.3 Regulatory Drivers

Large quantities of hazardous waste are commonly generated by DoD depot-related activities. The wastes that are associated with coatings removal include the disposal of methylene chloride from chemical stripping operations and media waste from a variety of blasting processes. Waste

disposal quantities such as these are commonly found on the Environmental Protection Agency's (EPA) Toxics Release Inventory (TRI) Report. Approximately 20% of the 1994 TRI figures came from coatings removal activities.

Coatings removal activities are impacted by a number of regulations including portions of the Clean Water Act (CWA), Clean Air Act (CAA), and Resource Conservation and Recovery Act (RCRA). 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. The RCRA regulates 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 Act (OSHA).

1.4 Stakeholder/End-User Issues

All branches of the DoD are currently involved in coatings removal operations and are concerned with the identification of alternative methodologies. Specifically, the elimination or reduction of the chemical paint strippers methylene chloride and methyl ethyl ketone, dry media blasting using either plastic media or wheat starch, and hand sanding is of primary interest. If proven viable, laser coatings removal systems could provide depots with an environmentally friendly alternative to all of these operations. The use of laser paint stripping systems would be applicable to depainting activities on aircraft components, aviation support equipment, ground fighting support equipment, and weapons systems for the Air Force, Army, Navy, Marine Corps, and NASA.

2.0 TECHNOLOGY DESCRIPTION

2.1 Technology Development and Application

LASER, which is an acronym, stands for Light Amplification by Stimulated Emission of Radiation. A 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 2-1).

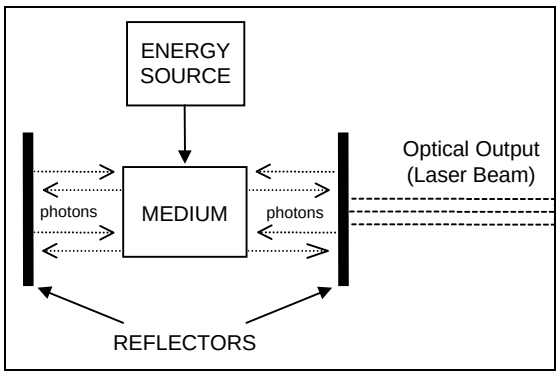

Figure 2-1: Light Amplification by Stimulated Emission of Radiation (LASER)

The energy source is typically an electrical discharge, flashlamp, or diode laser. The wavelength of the light emitted is determined by the type of medium used to generate the beam. The lasing medium 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 lasing material that is distributed in a solid matrix such as ruby or Nd:YAG lasers. The Nd:YAG laser emits infrared light at 1,064 nanometers (nm) and can be delivered via fiber optical cable.
- **Gas** lasers commonly use helium, helium-neon, Argon, and CO_2 as the lasing medium and have an output of visible red light. CO_2 lasers emit energy in the far-infrared spectrum (10,600 nm), and have been used frequently in the metal fabrication industry for cutting hard materials. CO_2 laser 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.

Optical output from a laser may be a continuous wave or pulsed beam, depending on how the reflectors are controlled. Continuous wave lasers reflect photons so that the number of

stimulated emissions equals the number of photons in the optical output. These lasers are efficient in converting electrical energy to coherent radiation and, thus, have widespread industrial use.

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 2-2 is a graphical representation of this mechanism.

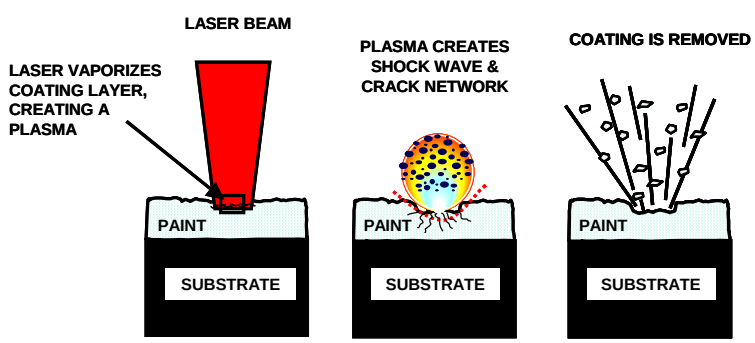

Figure 2-2: Laser Ablation Mechanism

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 2-3.

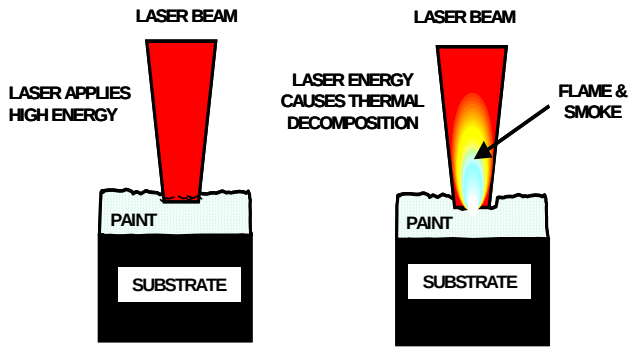

Figure 2-3: Laser Thermal Decomposition Mechanism

For coatings removal systems a laser beam delivery system is used to transfer the laser output to the work surface. Beam delivery optics homogenize the laser to give a uniform footprint by dividing the beam into many segments and then recombining them to smooth out hot spots and produce a uniform wavefront. The beam is directed to the target with the appropriate spot size and shape for delivering the energy density required for efficient coating removal. The beam delivery system must be designed with sufficient depth of focus to accommodate surface contours.

2.2 Previous Testing of the Technology

2.2.1 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. 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 8 nanoseconds (ns).

2.2.2 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, for 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.

2.2.3 Coating Characteristics and Removal Efficiency

One property of the coating system that was thought to effect the ability of the laser technology to remove it was the age of the coating system. 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 effect 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). They 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, than 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, that being threshold intensity, 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. Also reported in the USC 1995 report was 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.

2.2.4 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. From Penn State, they have 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 decision of whether the efficiency of removal and integrity of the substrate or overall cleaning rate is more important (PS 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.

2.2.5 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 3kW. 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 3kW laser was unsuited for handheld applications. Next, the researchers evaluated a 10W 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 10W laser was not suited for fiber optic delivery. The last laser that was evaluated was a 400W 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 capable of maintaining a high peak power that generated less soot and smoke. Researchers recommended the 400W laser for both fiber optic delivery and use in a handheld application (Note: This 400W turnkey laser system was manufactured by US Laser Corp.).

2.3 Factors Affecting Cost and Performance

An Initial Cost Benefit Analysis (CBA) was performed to evaluate the cost factors associated with the use of a portable hand held laser coatings removal system. This study established that the financial viability of these systems depended on three factors. The first key is to ensure a

low acquisition cost for the laser system. Next it must be established that the laser system strip rates are faster than the coating removal rate of the process that is being replaced. Finally it is important to ensure that the laser system is utilized close to 100 percent of its available time, this will allow for expedient recovery of the systems initial cost. When these three factors are met the laser systems are financially viable as an alternative coatings removal technology. The handheld lasers are a supplemental technology that is designed for coatings removal of small areas and hard to reach crevices and corners.

2.4 Advantages and Limitations of the Technology

In the past decade, laser systems have generated significant interest as a cleaning and paint removal tool. The advantages of using lasers for paint removal are that it requires little sample preparation, is non-contact, 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 over heat 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 are preferred over sharp angles for speed of manipulation.
- Organic coating system to be partially or completely removed – selective coating removal is an option.
- Relatively continuous process throughput – a laser system performs better if used regularly, rather than intermittently.

3.0 DEMONSTRATION DESIGN

3.1 Performance Objectives

The main performance objective of this demonstration is to remove coatings from test panels using the portable hand held laser paint stripping systems without causing damage to the substrate materials. The performance objectives for this demonstration are detailed in Table 3-1.

Table 3-1: Performance Objectives

Type of Performance Objective	Primary Performance Criteria	Expected Performance Metric	Actual Performance Objective Met? (120 W Nd:YAG)	Actual Performance Objective Met? (40 W Nd:YAG)	Actual Performance Objective Met? (250 W CO_2)
Quantitative	Maintain specifications for affected parts/substrates	Pass individual product tests described in the JTP	Majority of Performance Criteria met, failures to meet some criteria require further evaluation	Majority of Performance Criteria met, failures to meet some criteria require further evaluation	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 – Not Tested
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 are required to determine the significance.

3.2 Selecting Test Platforms/Facilities

The LHMEL facility at WPAFB was selected as the location for this demonstration due to their extensive experience with lasers. LHMEL has over 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 & 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 Platform/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 hand held laser coatings removal systems were placed at this facility: one CO_2, two Nd:YAG and one diode laser systems. These systems were selected based on their performance during screening testing that was performed 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 hollow 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 3-1, 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 Watts (W) with a maximum energy of 6.5 Joules (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.

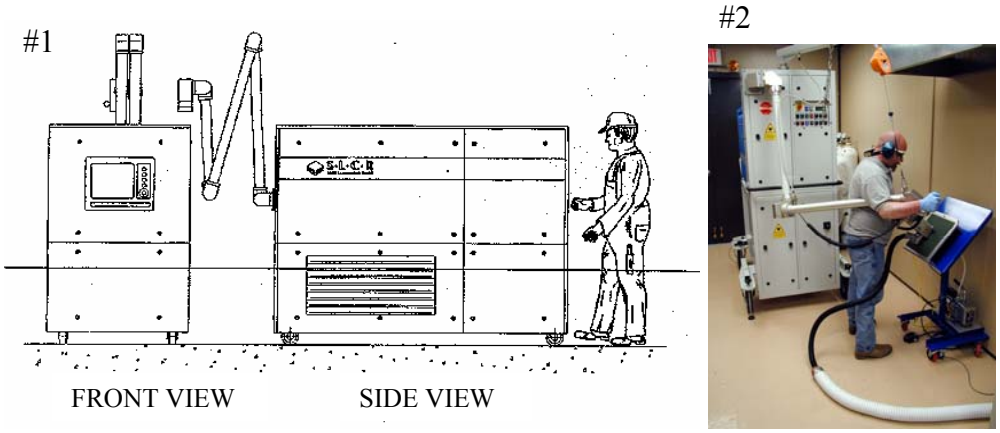

Figure 3-1: 250W Portable CO2 Laser System

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 only used through two of the four planned test cycles and was returned to the manufacturer.

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 3-2, 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 3-2, 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 ns.

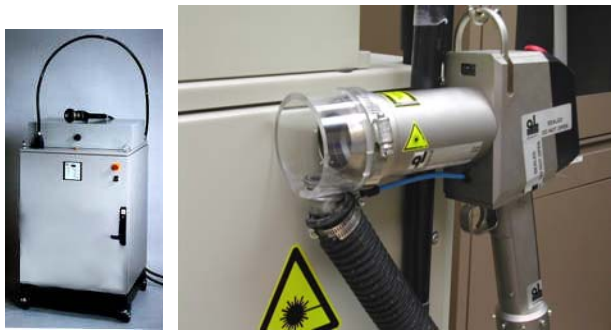

Figure 3-2: 40W Portable Nd:YAG System with End Effector

The 120 W Nd:YAG system, shown in Figure 3-3, 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. Thus far, the system has proven to be quite versatile and practically maintenance free.

Figure 3-3: 120W Portable Nd:YAG System with End Effector

Diode Laser System. The diode laser system, shown in Figure 3-4, 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. 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, a 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.

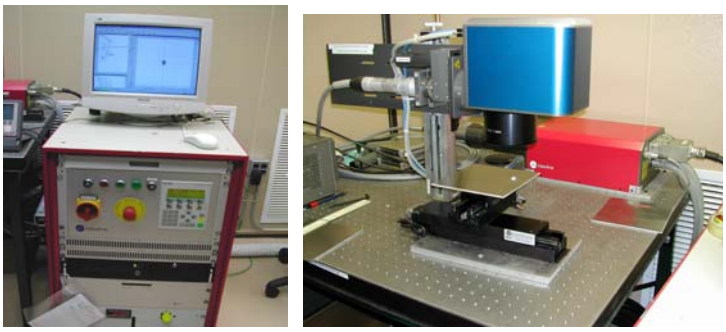

Figure 3-4: 250W Diode Laser System

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.

3.4 Present 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 Corp 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*, dated May 2001.

Figure 3-5 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 3-2 is the chemical depainting step that was identified as the first candidate process for replacement by portable handheld lasers.

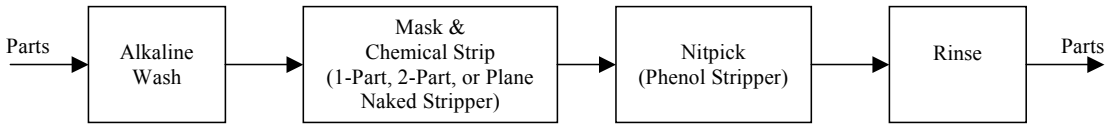

Figure 3-5: Representative Chemical Depainting Process for Aircraft Parts

The nitpicking step of the chemical stripping process is only the first of many application at the depot facilities for which the candidate laser systems may be utilized. This nitpicking process is has been targeted as the initial process for implementation of 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 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 have begun use of these portable laser systems for the nitpicking process and developed a level of comfort with their operation.

3.5 Pre-Demonstration Testing and Analysis

Practice test panels were stripped for each coating/substrate combination that was evaluated during this demonstration. The processing of these practice panels allowed the laser operator to become familiar with the interaction of the laser stripping equipment with the particular coating system prior to processing the actual test panels that used for testing.

3.6 Testing and Evaluation Plan

3.6.1 Demonstration Set-Up and Start-Up

The demonstration was conducted at the LHMEL facility at WPAFB in Dayton, OH. 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 in which to conduct the coating removal testing. A layout of this area is shown

in Figure 3-6. 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 operator(s) to monitor visitors entering the area.

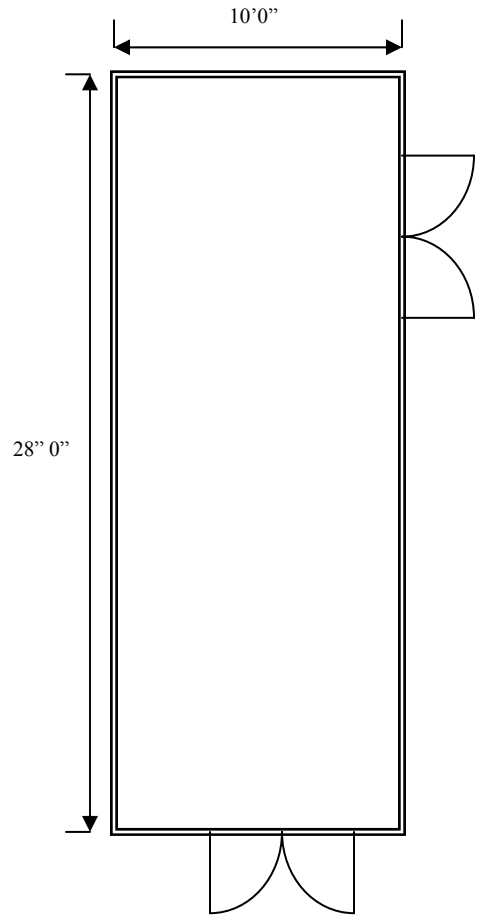

Figure 3-6: Dedicated Test Area

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.

3.6.2 Period of Operation

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.

3.6.3 Amount/Treatment Rate of Material To Be Treated

A total of 466 ft^2 (466, 12" x 12" test panels) of surface area was processed during this demonstration. 334 ft^2 of this surface area was on metallic substrates while the remaining 132 ft^2 of surface area was performed on composites.

3.6.4 Operating Parameters for the Technology

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

The adjustable parameters for the CO_2 laser system included electrical power input (P_i), pulse repetition frequency (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 3-2.

The 40 watt Nd:YAG laser had adjustable settings of output power (P_o), PRF, and spot size (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 3-3.

Table 3-2: 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 = 33kV, PRF = 50 Hz, SW = 50mm, Offset = 1.5mm	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					

Table 3-3: Optimized 40 watt 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 watt Nd:YAG laser had adjustable settings that included pulse repetition frequency (PRF), scan speed (SP), and scan width (SW). The optimized settings that were established when using this system are presented in Table 3-4.

Table 3-4: Optimized 120 watt 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
MIL-PRF-23377G / APC	X						PRF = 26.5 kHz, SP = 80 Hz, SW = 50 mm	116.2	0.020	3.48

3.6.5 Experimental Design

Testing during this demonstration was conducted on 12” x 12” test panels. The test results from laser stripping of these test panels was compared to standard test results that have been previously published for conventional depainting processes. The substrates that these test panels were constructed from are listed in Table 3-5.

Table 3-5: Test Panel Substrates

Substrate	Thickness	Pretreatment	Code
2024-T3 Aluminum (Alclad)	0.025”	Chromate conversion coated, MIL-C-5541E, Class 1A.	Al-1a
2024-T3 Aluminum (bare)	0.025”	Chromate conversion coated, MIL-C-5541E, Class 1A.	Al-1b
7075-T6 Aluminum (Alclad)	0.025”	Chromate conversion coated, MIL-C-5541E, Class 1A.	Al-2a
7075-T6 Aluminum (bare)	0.025”	Chromate conversion coated, MIL-C-5541E, Class 1A.	Al-2b
2024-T3 Aluminum (bare)	0.025”	Chromic Acid Anodized per MIL-A-8625, Type IB.	Al-3b
7075-T6 Aluminum (bare)	0.016”	Chromate conversion coated, MIL-C-5541E, Class 1A.	Al-5a
2024-T3 Aluminum (Alclad)	0.032”	Chromate conversion coated, MIL-C-5541E, Class 1A.	Al-6a
7075-T6 Aluminum (Alclad)	0.032”	Chromate conversion coated, MIL-C-5541E, Class 1A.	Al-7a
7075-T6 Aluminum (bare)	0.032”	Chromate conversion coated, MIL-C-5541E, Class 1A	Al-7b
4130 Steel	0.025”	None	ST
Fiberglass/Epoxy (GM3006)	Woven 4-ply (0/45)S	None	FE
Graphite/Epoxy (IM7/977-3)	14-ply (0/0/+45/-45/0/+45/-45)S.	None	GE-4
Kevlar (AMS 3902 and MIL-R-9300)		None	K
Metallic Honeycomb Core	face 2024-T3 0.020 inch; core 5056-H39 A1, 3/16 inch cell, 0.002 inch foil, 0.625 inch thick	None	MH

All test specimens were painted or coated within 24 hours of the application of the pre-treatment (e.g., conversion coating or anodize seal). Each test was performed on identical test specimens prepared with the DoD, NASA, and Aerospace Industry standard coating systems. The various combinations of primer and topcoat that were used during this evaluation are listed in Table 3-6.

Each liquid coating system was prepared and applied in accordance with the appropriate specifications. Application was conducted at a minimum temperature of 70 Degrees F and 50% +/- 10% relative humidity (RH). To ensure uniform coating thickness, coating applications were conducted per ASTM D823, Standard Practices for Producing Films of Uniform Thickness of Paint, Varnish, and Related Products on Test Panels.

During each recoating cycle all topcoats were applied over the primer within the manufacturer's recommended time. Additionally, in order to simulate the removal of coatings from aged aircraft, all coatings were artificially aged for 7 days at room temperature followed by 7 days at 150º F (+/- 5º). This aging regimen is standard practice for producing coatings representative of those found on the aged parts that are subjected to coating removal operations at depots.

Table 3-6: Coating Systems

Coating System Number	Primer	Topcoat	Topcoat Color FED-STD-595
1	MIL-PRF-23377G	MIL-C-46168, Type IV	383 Green
2	MIL-P-53030	CARC MIL-DTL-64159, Type II	383 Green
3	10PW 22-2	MIL-PRF-85285, Type I	17925 Gloss White
4	Super Koropon 515-K01A	MIL-PRF-85285, Type	17925 Gloss White
5	MIL-PRF-23377G	MIL-PRF-85285 Type I	36251 flat med gray
6	PR1432GP	MIL-PRF-85285 Type I	36495 flat med gray

All test panels processed during this demonstration were stripped using a consistent set of parameters for each laser system used. 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 can be run on any one specimen was determined by the destructiveness of the test.

3.6.6 Product Testing

3.6.6.1 Joint Test Protocol Testing

All product testing was performed in accordance with the Joint Test Protocol, and reported in the Joint Test Report (Appendix A). This Test Report details the tests that were performed, the frequency of these tests, and the results of the testing.

3.6.6.2 Worker Exposure Evaluation

A worker exposure evaluation was performed to determine the amount and species of effluent being given off while de-painting each of the various coatings and how much, if any, was escaping from the air filtration system connected to each laser. Additionally, this evaluation included determinations of noise and IR exposure. MACTEC Engineering & Consulting, based in Herndon, VA, was contracted to conduct these tests based on their previous experience in conducting similar tests on behalf of the Air Force.

Numerous samples were collected including both personal and area air samples for acid gas, hydrogen cyanide, metals, hexavalent chromium, and chromates, 15-minute air samples for acid gases, cyanides and diisocyanates, and direct reading detector tube sampling to screen for the presence of nitric oxide, nitrogen dioxide, carbon monoxide, carbon dioxide, sulfur dioxide and ozone. Additionally, "in-line" fugitive emission testing in the air filter duct system were conducted to determine the presence of metals, chromium, acid gases, cyanides, dusts and or volatile organic compounds (VOCs) commonly used in paints. This sampling strategy was designed to provide a feasible comprehensive evaluation of operator and observer exposures. Noise measurements were also conducted during these air sampling activities as was a review of the ergonomic and thermal stress levels associated with the coating removal activities. All these measurements were aimed at determining the proper personal protection equipment (PPE) needed by both operators and observers to safely conduct laser coating removal operations.

Air sampling was conducted using each of the four laser systems against the six primary coating types to be investigated. Sampling occurred in April 2002 using the 250 watt CO2 unit, in August 2002, October 2003, and September 2004 using the 40 and 120 watt Nd:YAG systems, in February 2003 using the diode laser system and finally in February 2005 using the 120 watt Nd:YAG system. Additionally, during the September 2004 evaluation, noise measurements were taken using the AF Occupational Safety and Health Standards (AFOSH) rather than the Occupational Safety and Health Administration (OSHA) standards. During this round, ultraviolet/infrared (UV/IR) emissions from the testing were also measured to determine any safety hazards from these sources to both operator and observers.

An additional evaluation was conducted in March 2005 by the Industrial Hygiene Branch of the Air Force Institute for Operational Health (AFIOH/RSHI). This testing served as an exposure assessment of the 120 watt Nd:YAG laser.

Findings from these air samplings indicated that operator and observer exposure to hazardous by-products during coating removal was below the established safety limits. Findings also showed that the air filtration unit (i.e., a Fumex FA2HD system) was very effective at removing particulate from the sample surface. These findings allowed the PPE to be reduced from the original disposable nitrile gloves, disposable coveralls, a hooded powered air purifying respirator, laser safety goggles and both ear plugs and muffs to only latex gloves, laser safety goggles and ear plugs. A half-face respirator was added to this equipment list, however, when replacing the Fumex filter bags, due to the potential exposure to metal/dust contaminants trapped within those filters. UV/IR experiments determined that operator exposure to these sources may exceed recommended levels depending on type of laser, end effector type, and operator position, size and posture. It is recommended that operators wear gloves during testing and that their laser safety eyewear include protection against the wavelength that the laser is operating at.

The various reports detailing the procedures and results of these worker exposure tests is included as Appendix C to this report.

3.6.6.3 Flammability Testing

Testing was conducted to provide data for determining whether handheld lasers, used for supplemental de-painting, pose an explosion risk and/or a safety risk. This testing addressed the potential safety risk of a highly intense laser energy beam being applied to a work surface and possibly igniting common aircraft maintenance fluids or vapors. It should be noted that the testing did not address the potential explosion risk posed by (electrical) laser components and/or ancillary equipment used in conjunction with the laser system. A 40W pulsed Nd:YAG laser and a 120W pulsed Nd:YAG laser were evaluated in this test sequence.

The objective of this testing was to conduct testing and to document possible explosive or flammability hazards associated with the portable handheld laser de-painting process. The first test scenario was designed to address potential hazards of laser de-painting a surface exhibiting accumulations of commonly used aircraft chemicals (surface contamination testing). The second test scenario addressed the explosion and flammability hazards associated with entrapped fluids and vapors (cavity testing). Additional testing was conducted to assess the compatibility of lasers de-painting with solvent-based chemical strippers (additional testing).

These following nine (9) chemicals were used to determine laser ignition /flammability issues. These chemicals are frequently found on aircraft and/or found in aircraft de-painting operations. Note, however, that the chemical strippers (7, 8, 9) are not subject to Pass/Fail criteria and were only intended for the additional tests.

Table 3-7: Chemicals Evaluated for Flammability Testing

	Flashpoint	**MSDS Fire Hazard Rating**
1) Engine Lubricating Oil MIL-L-23699	>475˚F	1
2) Engine Lubricating Oil MIL-PRF-7808	440˚F	1
3) Hydraulic Fluid MIL-PRF-83282	388˚F (est.)	1
4) Hydraulic fluid MIL-H-5606-	225˚F	1
5) Skydrol LD-4 (fire resistant hydraulic fluid)	320˚F	1
6) JP-8 Turbine Fuel	100˚F	2
Plus Turbine Fuel Additive +100	165˚F	2
7) Turco EA Stripper 6930	> 212˚F	Not listed
8) Eldorado Non-chlorinated Paint Stripper PR-3131	> 200˚F	> 200˚F
9) CEE-BEE R MeCl 256 Paint Stripper	None Listed	1

For the surface contamination testing the lasers did not ignite the standing liquid on the surface of the test panel nor did the lasers ignite the vapor, liquid in the cavity, or standing liquid on the surface of the test panel during cavity testing for any of the chemicals evaluated.

Additional testing that was performed using chemical strippers produced mixed results. The 120W Nd:YAG laser did not produce any flames or explosion in the artifical cavity tests; however, it did produce a flame in one surface contamination trial (Turco EA Stripper 6930). The 40 W Nd:YAG laser did not produce a flame or explosion in the surface contamination tests; however, artificial cavity testing could not be accomplished with the 40 W Nd:YAG system because chemical stripper splattered on the laser lens and end piece during the first such test. To avoid further damage to the equipment, testing was halted. This "splattering" may be attributable to the emulsion-like nature of the solvent in the cavity and the mechanical shock effect of the laser pulse. No flame or explosion was observed. It should be noted that the appropriate standoff distance for coating ablation was used for this test. Altering the standoff distance to avoid this "splattering" was not practical because larger standoff distances reduce the ability of the laser to properly ablate the coating.

The complete report detailing the procedures and results of these flammability tests is included as Appendix D to this report.

3.6.7 Ergonomics Assessment

The Air Force Institute for Operational Health (AFIOH/RSH) conducted an assessment of the ergonomic properties of the various handheld laser systems. This study identified possible ergonomic hazards and potential ergonomic improvements that could be made to the 120 watt and 40 watt Nd:YAG systems.

This study found that there were no ergonomic issues that should prevent the fielding of this equipment, however it did result in recommendations for improvement in several areas that manufacturers should consider in future designs. The findings of this evaluation suggest that the pistol shape of the end effector of both pieces of equipment is not the most desirable configuration from an ergonomic standpoint. The recommendations of AFIOH/RSH regarding these end effectors has been provided to each of the laser manufacturers for their consideration in future designs. Additionally, AFIOH/RSH stressed the need for proper training on body mechanics to reduce the ergonomic impacts associated with this equipment.

The report that AFIOH/RSH prepared detailing this evaluation is included as Appendix E to this report.

3.6.8 Demobilization

The equipment used during this demonstration will be transitioned to the Air Force depots or the Technical Training Center at the completion of all testing programs. All test panels will be disposed of as scrap at the completion of the demonstration in accordance with Air Force instructions.

3.7 Selection of Analytical/Testing Methods

Table 3-8 lists the test requirements that were identified for validating alternatives to traditional coating removal methods. These procedures and plans may be found in the Joint Test Protocol for Validation of a Portable Laser System for Coatings Removal (J-00-CR-017). These testing procedures correspond with the Common and Extended Tests that were established in this JTP.

Several tests that were originally called out in the JTP were eliminated or modified during laboratory testing. These tests included the Hardness, Tensile Strength, Determination of Cladding Loss, and Surface Profile.

The Hardness test, JTP Section 3.2.2c, was to be performed on 2024-T3 and 7075-T3 bare aluminum substrates. This test was actually performed on the 2024-T3 bare and 7075-T6 clad substrates.

The Tensile Strength testing was to be performed on 0.025 inch thick 2024-T3 and 7075-T6 bare aluminum substrates according to JTP Section 3.2.2d. During the course of testing, though, it was determined that additional tensile testing would be conducted. In addition to the testing on the required substrates, testing was performed on 0.025 inch thick 2024-T3 and 7075-T6 Alclad substrates and on 0.016 inch thick 7075-T6 bare aluminum.

Based upon positive results that were obtained during the Confirmation of Cladding Penetration Test (JTP Section 3.1.3a(1)) the Determination of Cladding Loss Test (JTP Section 3.1.3a(2)) was eliminated from the test matrix.

According to the requirements established in JTP Section 3.2.4b, Surface Profile testing was to be performed on test specimens after the first and fourth coating removal cycles. The CO_2 laser was returned to the manufacturer after two strip cycles, limiting the profile testing for this laser to the information collected during the two strip cycles. Profilometer testing was suspended for the 120 watt Nd:YAG laser after the third strip cycle. This was because results from the first three cycles indicated that the surface roughness was not significantly changed between the stripping cycles.

Table 3-8. Common and Extended Engineering and Test Requirements

Test Name	Acceptance Criteria	Reference(s)
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
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 E18
Tensile Testing	Compare Tensile Strength of samples values obtained with control samples of base materials (non-stripped and non-coated 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 shall be documented for review and determination of pass/fail values	ASTM D790, ASTM D638, ASTM D695, ASTM E647

3.8 Selection of Analytical/Testing Laboratory

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 due to the laboratories well-established record of material testing. Another factor in this decision was the location, due to the fact that this laboratory is also located on sight at WPAFB.

4.0 PERFORMANCE ASSESSMENT

4.1 Performance Criteria

The general performance criteria used to evaluate the portable laser coating removal systems are summarized in Table 4-1. These performance criteria have been categorized as either primary or secondary criteria.

Table 4-1: 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

4.2 Performance Confirmation Methods

An overview of the results of the testing that was conducted is presented in Table 4-2. 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 red. Any value that is reported that shows a statically significant difference from the value obtained on the unprocessed baseline material is presented in bold text.

Table 4-2: Expected Performance and Performance Confirmation Methods

Performance Criteria	120 watt Nd:YAG	250 watt CO_2	40 watt Nd:YAG	Expected Performance
4.1 Coating Strip Rate (ft^2/min)	6 Mils			
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				
4.2 Warping/Denting	None	None	None	
4.3.1 Metal Erosion	None	None	None	Visual Examination
4.3.2 Composite Erosion	Loose fibers	N/A	Loose fibers	No resin erosion/damage
4.4 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**	
4.5 Tensile Testing (ASTM E8)				No significant change at 90% confidence (Debit)
Yield Strength (ksi) ***Baseline = 47.8***	48.0	**46.8**	47.4	
Ultimate Tensile Strength (ksi) ***Baseline = 63.3***	**66.7**	**62.0**	**65.8**	
Elongation (%) ***Baseline = 16.6%***	**18.1**	**17.8**	**18.2**	
4.6 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	
4.7 Clad Penetration (SAE MA4872)	None	None	None	Determine Clad Penetration
4.8 Surface Profile / Roughness (µin) (SAE MA4872)	37 – 65	10 – 18	13 – 29	Not to exceed 125 µin
4.9 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 4-2: Expected Performance and Performance Confirmation Methods (cont.)

Performance Criteria	120 watt Nd:YAG	250 watt CO_2	40 watt Nd:YAG	Expected Performance
4.10 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	
4.11 Rotary Wing Metallic Substrate Assessment				
4.11.1 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	
4.11.2 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**	
4.11.3 Fatigue Crack Growth Rate (ASTM E647)				
2024 T3 Clad ΔK 6	FCGR Debit	No Change	No Change	No Significant change at 90% confidence (Debit)
2024 T3 Clad ΔK 14	FCGR Debit	FCGR Debit	FCGR Debit	
7075 T6 Clad ΔK 6	No Change	No Change	No Change	
7075 T6 Clad ΔK 14	No Change	No Change	No Change	
7075 T6 Thin ΔK 6	No Change	No Change	No Change	
7075 T6 Thin ΔK 14	No Change	No Change	No Change	
4.12 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	

4.3 Data Analysis, Interpretation and Evaluation

The results for the coating strip rate testing did not meet the JTP acceptance criteria. 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, though. This acceptance criterion does not account for the time savings that would be achieved in set-up and preparation time that is required prior to the existing chemical stripping operations. The use of these handheld laser systems requires virtually no set-up 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 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 the following section of this report.

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 only used through two of the four planned test cycles and was returned to the manufacturer.

4.3.1 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 non-metallic 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 Reference Section 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 the Statistical Analysis Software® (SAS) software package. This software 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 4-3 summarizes the composite flexural strength results while Table 4-4 summarizes the effects of the paint removal methods on the mechanical properties of the metallic substrates and the reference data. It should be noted, that although there may be a statistically significant difference at the 90% confidence level for these 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.

Table 4-3:. Matrix for Composite Flexural Data

Paint Removal Method	Graphite/Epoxy	Fiber Glass/Epoxy	Kevlar/Epoxy
Reference	Flexural Strength	Flexural Strength	Flexural Strength
(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			

A complete report on this comparative analysis is provided in Appendix G. This report details the analysis methods and reference materials that were used.

Table 4-4: Metallic Matrix for Paint Removal Methods

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	
	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

5.0 COST ASSESSMENT

5.1 Cost Reporting

The primary objective of the cost assessment is to determine whether hand held laser systems can be implemented with an acceptable payback period. In order to calculate this an economic analysis was conducted using the Environmental Cost Analysis Methodology (ECAM^{SM}) cost estimating tool, comparing the current chemical depainting process of aircraft parts that is performed at an Air Force Depot (Baseline Scenario) to the purchase and installation of a 120 watt Nd:YAG laser system (Alternative Scenario 1) and a 40 watt 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 EPA's 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 several cost drivers were used. These costs 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 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 have begun use of these portable laser systems for the nitpicking process and developed 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 3.4 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 5-1. The nitpicking step in the chemical depainting process is the candidate step for replacement by portable handheld lasers.

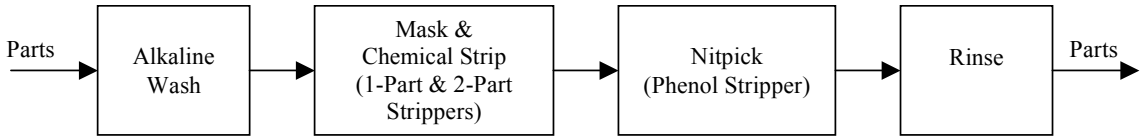

Figure 5-1: Representative Chemical Depainting Process for Aircraft Parts

Based on the 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 5-1.

Table 5-1: Annual Usage for the Baseline Chemical Depainting Operation

Annual Number of Parts Depainted	5,040 parts/yr
Annual Material Usage	
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
Annual Utility Usage	
Rinse Water	287,400 gal/yr
Annual Waste Management	
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 is 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 that are associated with the baseline chemical depainting process

The following data and assumptions were used in evaluating the alternative depainting process that would use 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 bi-annual 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 5-2.

Table 5-2: 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 then there would be an associated capital equipment cost.

Table 5-2 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 there will be a labor savings that 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 that were achieved on flat panels during testing difficult. 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. For this cost assessment specifically, 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 5-2 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), and
- Compares these measures with acceptance criteria.

This evaluation was begun by calculating the life cycle cost associated with 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 that are associated with the handheld laser systems is provided in Table 5-3.

Table 5-3: 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 of 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 5-4 shows the calculated 15 year net present value, internal rate of return, and discounted payback period for the two different handheld laser systems.

Table 5-4: 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 5-5 summarizes the investment criteria that were used to compare the capital costs of the proposed portable Nd:YAG laser technology to the estimate discounted future savings resulting from its replacement of existing coating removal processes.

Table 5-5: 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 upon the investment criteria that was presented in Table 5-5, 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 watt laser system.

The IRR for both of these systems is higher than the 3.5% discount rate that was used for the financial evaluation. Based upon the investment criteria for IRR presented in Table 5-5 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 Environmental Permits

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

6.2 Other Regulatory Issues

The current federal regulation governing the safe use of lasers is U.S. Code of Federal Regulations (CFR), Title 21, Part 1040.10. Due to the limited quantity of hazardous waste generated during the use of lasers in coating removal applications, current environmental regulations are not relevant. There are, however, standards for the safe use of lasers with general text to cover all applications. The American National Standards Institute (ANSI) document 136.1-1993 is the guidance document for the Military Services and NASA laser safety standards. ANSI 136.1-1993 contains detailed information on the classification of lasers as well as safe handling procedures and health effects from exposure.

A Laser Safety Plan was developed as part of this project. The purpose of this safety plan is to provide guidance for safely operating portable handheld lasers, used for the purpose of coating removal on aircraft and/or aircraft components. The manual is designed to achieve a safe environment for users, visitors, and workers in potentially hazardous areas. This is a general series document, intended for use with maintenance/repair/overhaul manuals or engineering documents, laser technical manuals, the Air Force Occupational Safety and Health (AFOSH) Standard 48-139 *Laser Radiation Protection Program*, and Technical Order (T.O.) 1-1-8 *Application and Removal of Organic Coatings.* Additionally, a T.O. supplement that specifically addresses laser coatings removal is currently under development.

The primary objectives of the Laser Safety Plan are to provide guidance to the laser safety approval authorities and to enable safe laser coating removal operations. The establishment of standard safety procedures will ensure that no laser radiation in excess of the maximum permissible exposure (MPE) reaches the human eye or skin as a result of the operation of portable handheld laser systems. In particular, this safety plan is designed to address and manage against the risk of laser injury, electrical shock, fire, and exposure to hazardous chemicals, which may be present during coating removal operations. This Laser Safety Plan is provided in Appendix F.

The Air Force, Navy, and NASA have their own standards as illustrated in Table 6-1.

Table 6-1: Agency and Laser Safety Standard

Agency	Standard
Air Force	Air Force Occupational Safety and Health (AFOSH) Standard 48-139
NASA	NASA Guidelines for Laser Safety (Chapter 8)
Navy	SPAWAR Instructions 5100.12B

Additionally, the OSHA promulgated an instruction standard, PUB8-1.7, as a guideline for laser safety and hazard assessment. Some states and local governments have passed legislation concerning the use and safety of lasers. Ten states have passed comprehensive laser regulations. These states are Alaska, Arizona, Arkansas, Florida, Georgia, Illinois, Massachusetts, New York, Texas, and Washington. An outline of the features of each states' legislation is addressed in an article by R.J. Rockwell and J. Parkinson in the Journal of Laser Applications dated October 1999 (Volume 11. Number 5). This article focuses on laser pointers, but offers some insight into the attention states have and might be planning to put on this technology.

Environmental concerns associated with the use of lasers in this application are due to the by-products and emissions generated when coatings are removed. Each type of coating has the potential to produce different types of waste emissions. Until the components of the emissions are identified, they should be characterized as hazardous. Any particulate waste generated should also be characterized as hazardous until properly identified as non-hazardous. Laser operators should be properly fitted with personal protective equipment in accordance with OSHA 29 CFR 1910.134 - *Personal Protective Equipment-Respiratory Protection* and OSHA 29 CFR 1910.132 – *Personal Protective Equipment – General Requirements* to protect them from breathing airborne particles and emissions from the ablated paint that is not captured in the vacuum system.

6.3 End-User / OEM Issues

In fiscal year 2005, two Nd:YAG laser units were purchased and planned for installation in 2005 at Ogden Air Logistics Center and Oklahoma City Air Logistics Center. 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.

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Appendix A
Joint Test Report

The following is the Joint Test Report that was developed for this project.

Environmental Security Technology Certification Program

Joint Test Report

for

Validation of Portable Laser Coating Removal Systems

May 25, 2005

Distribution Statement "A" applies.
Approved for public release; distribution is unlimited.

PREFACE

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TABLE OF CONTENTS

PAGE

EXECUTIVE SUMMARY 1
1. INTRODUCTION 2
2. ENGINEERING AND TESTING REQUIREMENTS 3
    2.1 Engineering and Test Requirements 3
3. ALTERNATIVES TESTED 6
4. TEST RESULTS 8
    4.1 Coating Strip Rate 10
    4.2 Warping/Denting 10
    4.3 Metal/Composite Erosion 10
        4.3.1 Metal Erosion 10
        4.3.2 Composite Erosion 11
    4.4 Hardness 13
    4.5 Tensile Testing 13
    4.6 Paint Adhesion Testing Following De-painting and Reapplying Coatings 14
    4.7 Clad Penetration Tests 14
    4.8 Surface Profile/Roughness 15
    4.9 Substrate Temperatures during Coating Removal Process 16
    4.10 Four Point Flexure 20
    4.11 Rotary Wing Metallic Substrate Assessment 21
        4.11.1 Fatigue Life – Smooth Test Method 21
        4.11.2 Fatigue Life – Open Hole Test Method 22
        4.11.3 Fatigue Crack Growth Rate 22
        4.12 Damage Assessment to Honeycomb Structural Materials 27
5.0 ANALYSIS OF TEST RESULTS 30
    5.1 Tensile Results 30
        5.1.1 Aluminum 2024-T3 Bare 31
        5.1.2 Aluminum 2024-T3 Clad 31
        5.1.3 Aluminum 7075-T6 Bare 34
        5.1.4 Aluminum 7075-T6 Clad 34
        5.1.5 Summary Of Tensile Results Analysis 37
    5.2 Fatigue Results 37
        5.2.1 Aluminum 2024-T3 Clad Smooth Fatigue 38
        5.2.2 Aluminum 2024-T3 Clad Notch Fatigue 38
        5.2.3 Aluminum 7075-T6 Bare Smooth Fatigue 39
        5.2.4 Aluminum 7075-T6 Bare Notch Fatigue 40
        5.2.5 Aluminum 7075-T6 Clad Smooth Fatigue 40
        5.2.6 Aluminum 7075-T6 Clad Notch Fatigue 41
        5.2.7 Summary of Fatigue Results Analysis 42
    5.3 Four-Point Flexural Testing 42
    5.4 Summary of Literature Comparison Study 45
6. SUMMARY AND RECOMMENDATIONS 48
7. REFERNCES 49

Table of Tables

PAGE

Table 1. Portable Laser Coating Removal System Target HazMat Summary 3
Table 2. Common and Extended Engineering and Test Requirements 5
Table 3. Portable Hand Held Laser Paint Stripping Systems 6
Table 4. Test Panel Specimens 6
Table 5. Control Coating Systems 7
Table 6. Data Summary 8
Table 7. Coating Strip Rate Summary 10
Table 8. Hardness 13
Table 9. Average Tensile Property Information 13
Table 10.Adhesion Ratings – Modified X. 14
Table 11.Surface Profile Measurements 15
Table 12.Graphite Epoxy Temperature Readings.....16
Table 13. Four Point Flexure Results 21
Table 14. Average Fatigue Lives (Smooth Test Method) 22
Table 15. Average Fatigue Lives (Open Hole Test Method) 22
Table 16. Statistical Analysis of Fatigue Crack Growth Rate Results 25
Table 17. Core Shear Data Summary – Honeycomb 28
Table 18. Tensile Properties for Various Paint Stripping Methods.....37
Table 19. Fatigue Properties 42
Table 20. Metallic Matrix for Paint Removal Methods.....46
Table 21. Matrix for Composite Flexural Data.....47

Table of Figures

PAGE

Figure 1. 2024 T3 Clad Erosion Examination 11
Figure 2. 7075 T6 Bare Erosion Examination 11
Figure 3. Graphite Epoxy Panel – 120 watt Nd:YAG Stripped....12
Figure 4. Graphite Epoxy Panels – 40 watt Nd:YAG Stripped 12
Figure 5. Graphite Epoxy Temperature Determination (120 watt Nd:YAG)....17
Figure 6. Graphite Epoxy Temperature Determination (40 watt Nd:YAG)....18
Figure 7. Aluminum Substrate Temperature Determination (120 watt Nd:YAG) 19
Figure 8. Aluminum Substrate Temperature Determination (40 watt Nd:YAG) 20
Figure 9. FCGR Results for 2024-T3 Clad Aluminum (a)raw data (b) power-law fits 23
Figure 10. FCGR Results for 7075-T6 Bare Aluminum (a)raw data (b)power-law fits 23
Figure 11. FCGR Results for 7075-T6 Clad Aluminum (a)Raw data (b)power-law fits 24
Figure 12. Statistical Representation of FCGR data for 7075-T6 Clad....26
Figure 13. Ultrasonic Testing of Honeycomb Panels – Check for Dis-bonds....27
Figure 14: Bar Graphs – Mechanical Properties of Honeycomb Substrate....29
Figure 15. Tensile Strength Results for 2024-T3 Bare Substrate 32
Figure 16. Tensile Strength Results for 2024-T3 Clad Substrate 33
Figure 17. Tensile Strength Results for 7075-T6 Bare Substrate 35
Figure 18. Tensile Strength Results for 7075-T6 Clad Substrate 36
Figure 19. 2024-T3 Clad S-N Smooth Fatigue Results 38
Figure 20. 2024-T3 Clad S-N Notch Fatigue Results....39
Figure 21. 7075-T6 Bare Smooth Fatigue Results 39
Figure 22. 7075-T6 Bare S-N Notch Fatigue Results....40
Figure 23. 7075-T6 Clad Smooth Fatigue Results 41
Figure 24. 7075-T6 Clad S-N Notch Fatigue Results....41
Figure 25. Graphite/Epoxy Flexural Strength Results....43
Figure 26. Graphite, Fiberglass, and Kevlar /Epoxy Flexural Strength Results....44
Figure 27. Graphite/Epoxy Flexural Strength Results for Project Data and PMB 45

EXECUTIVE SUMMARY

The processes that are currently used throughout the Department of Defense (DoD) to remove coatings from parts result in a major waste stream consisting of toxic chemicals, spent media blast materials, and waste water. The chemicals that are typically used in this process are high in volatile organic compounds (VOC) and hazardous air pollutants (HAP). When coatings removal operations that use abrasive blast media are used instead of chemical methods a large quantity of hazardous waste, which is subject to high disposal costs and scrutiny under environmental regulations, is produced.

The use of laser energy for coating removal is a new technology that is environmentally acceptable and less labor intensive than current removal methods. 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. The high level absorption of energy at the surface of a coating material results in the decomposition and removal of the coating. The energy that is applied by the laser 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.

This demonstration was performed in order to verify the ability of portable hand held laser coating removal systems to effectively remove common DoD coating systems without causing substrate damage. The results from this testing will provide stakeholders with information that will assist in the implementation of laser paint stripping operations at their facilities.

The approved Joint Test Protocol (JTP) was followed throughout this demonstration. The JTP contained the critical requirements and tests necessary to qualify the portable hand-held laser coating removal systems for use on metallic and non-metallic substrates. Three hand held laser systems were tested against this JTP: a 120 watt yttrium aluminum garnet crystal doped with neodymium ions (Nd:YAG) laser, a 40 watt Nd:YAG laser, and a 250 watt Carbon Dioxide (CO_2) laser.

The test results that were achieved during this demonstration indicate that, the 120 watt and 40 watt Nd:YAG lasers may be used for small coating removal applications on metallic substrates. Several of the tests produced results that were below the JTP acceptance criteria, but upon a closer review of the test results it was revealed that their performance was comparable to other approved and currently used coating removal techniques.

Test results for the testing that was performed on composite substrates indicate that further refinement of the technology will be required prior to use on composite materials. Due to the high degree of resin erosion and composite surface damage further testing should be performed to optimize these lasers for use to remove coatings down to a composite surface.

Full test results are not available for the CO2 laser. Due to the poor ergonomic design of this laser it was returned to the manufacturer prior to completion of all JTP testing. The preliminary results that were obtained indicate that CO2 lasers have potential for use in applications that would not require a handheld design.

1. INTRODUCTION

Conventional coatings removal methods that are employed throughout the Department of Defense (DoD) result in a major waste stream consisting of toxic chemicals, spent media blast materials, and waste water. The chemicals that are 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 hazardous waste that is subject to high disposal costs and scrutiny under environmental regulations.

Portable hand held laser systems have been identified as a potential technology to supplement the existing depainting processes. A laser is a device that generates monochromatic, coherent light that can be focused and concentrated into a narrow, intense beam of energy. Lasers are already in use by the DoD for multiple manufacturing operations, including welding, cutting, drilling, and surface treatment. The use of laser energy to strip coatings is a relatively new application of this technology that was developed primarily for the aerospace industry.

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. The high level absorption of energy at the surface of a coating material results in the decomposition and removal of the coating. Because the applied energy is mostly absorbed and utilized in coating decomposition (i.e., instant evaporation, which carries away most of the radiation energy) the substrate experiences only a minimal increase in temperature.

The objective of this demonstration was to verify the ability of portable hand held laser coating removal systems to effectively remove common DoD coating systems without causing physical damage to the substrate. The results from this testing will provide stakeholders with information that will assist in the implementation of laser paint stripping operations at their facilities.

A Joint Test Protocol (JTP) was developed and followed throughout this demonstration. The JTP contained the critical requirements and tests necessary to qualify portable hand-held laser coating removal systems for use on metallic and non-metallic substrates. All tests were derived from engineering, performance, and operational impact (supportability) requirements defined by a consensus of government and industry participants.

This Joint Test Report (JTR) documents the results of the testing as well as any testing modifications that were made during the execution of testing. The JTR is available as a reference for future pollution prevention endeavors by other Department of Defense (DoD) and commercial users to minimize duplication of effort.

The Environmental Security Technology Certification Program (ESTCP) sponsored funding for the demonstration/validation of this technology, as well as the creation of the JTP and JTR.

2. ENGINEERING AND TESTING REQUIREMENTS

A joint group led by Headquarters Air Force Materiel Command (HQ AFMC), the ESTCP Project Lead, and consisting of technical representatives from Air Force Research Laboratory (AFRL), Ogden Air Logistics Center (OO-ALC), Warner Robins Air Logistics Center (WR-ALC), Oklahoma City Air Logistics Center (OC-ALC), Corpus Christi Army Depot (CCAD), National Aeronautics and Space Agency (NASA), the affected Department of Defense (DoD) Program Managers, representatives of the Sustainment Community, and other government technical representatives identified application, performance, supportability, and operational impact requirements. The group then reached consensus on the test procedures, methodologies, and acceptance criteria for each test.

Tests were conducted in a manner that eliminated duplication and maximized use of each test coupon. For example, where possible, more than one test was performed on each panel. The amount and type of tests that were run on any one panel were determined by the destructiveness of the test.

2.1 Engineering and Test Requirements

Testing is required for all of the affected services that are listed in **Table 1**.

Table 1. Portable Laser Coating Removal System Target HazMat Summary

Target HazMat or Hazardous Waste	Current Process	Applications	Affected Services	Candidate Substrates
Methylene Chloride Methyl Ethyl Ketone	Chemical stripping. Spray & dip application.	Aircraft components Aviation equipment Ground/Fighting equipment Weapon systems	Air Force Army Navy USMC NASA	Aluminum Steel
Plastic Media and Coatings residue	Dry media Pressure blasting	Aircraft components Aviation equipment Ground/Fighting equipment Weapon systems	Air Force Army Navy USMC NASA	Fiberglass Epoxy (F/E) Graphite Epoxy (G/E) Aluminum Steel
Wheat Starch and Coatings Residue	Dry media Pressure blasting	Aircraft components Aviation equipment Ground/Fighting equipment Weapon systems	Air Force Army Navy USMC NASA	Fiberglass Epoxy (F/E) Graphite Epoxy (G/E) Aluminum Steel
Coatings Residue	Hand Sanding	Aircraft components Aviation equipment Ground/Fighting equipment Weapon systems	Air Force Army Navy USMC NASA	Fiberglass Epoxy (F/E) Graphite Epoxy (G/E) Aluminum Steel

Table 2 lists the test requirements that were identified for validating alternatives to traditional coating removal methods. These procedures and plans may be found in the Joint Test Protocol for Validation of a Portable Laser System for Coatings Removal (J-00-CR-017). These testing procedures correspond with the Common and Extended Tests that were established in this JTP.

Several tests that were originally called out in the JTP were eliminated or modified during laboratory testing. These tests included the Hardness, Tensile Strength, Determination of Cladding Loss, Surface Profile, and Four Point Flexure.

The Hardness test, JTP Section 3.2.2c, was to be performed on 2024-T3 and 7075-T3 bare aluminum substrates. This test was actually performed on the 2024-T3 bare and 7075-T6 clad substrates.

The Tensile Strength testing was to be performed on 0.025 inch thick 2024-T3 and 7075-T6 bare aluminum substrates according to JTP Section 3.2.2d. During the course of testing, though, it was determined that additional tensile testing would be conducted. In addition to the testing on the required substrates, testing was performed on 0.025 inch thick 2024-T3 and 7075-T6 Alclad substrates and on 0.016 inch thick 7075-T6 bare aluminum.

Based upon positive results that were obtained during the Confirmation of Cladding Penetration Test (JTP Section 3.1.3a(1)) the Determination of Cladding Loss Test (JTP Section 3.1.3a(2)) was eliminated from the test matrix.

According to the requirements established in JTP Section 3.2.4b, Surface Profile testing was to be performed on test specimens after the first and fourth coating removal cycles. The CO_2 laser was returned to the manufacturer after two strip cycles, limiting the profile testing for this laser to the information collected during the two strip cycles. Profilometer testing was suspended for the 120 watt Nd:YAG laser after the third strip cycle. This was because results from the first three cycles indicated that the surface roughness was not significantly changed between the stripping cycles.

Four Point Flexure testing was to be performed on the Graphite Epoxy substrate test specimens (JTP Section 3.2.5b(1)). During execution of this test plan additional Four Point Flexure testing was conducted on Fiberglass Epoxy and Kevlar panels.

Table 2. Common and Extended Engineering and Test Requirements

Test Name	JTR Section	Acceptance Criteria	Testing Facility
Coating Strip Rate	4.1	Acceptance criteria based on requirements analysis or survey results and/or 0.06 ft^2 per minute at 6 mils, nominal thickness	LHMEL
Warping/Denting	4.2	No warping/denting as observed.	Anteon
Metal/Composite Erosion	4.3	No metal/composite erosion observable at 10X magnification.	UDRI AFRL/MLS
Hardness	4.4	No significant change in hardness.	AFRL/MLS
Tensile Testing	4.5	Compare Tensile Strength of samples values obtained with control samples of base materials (non-stripped and non-coated samples).	AFRL/MLS
Paint Adhesion	4.6	Wet Tape Adhesion performance greater than or equal to 4a as specified in ASTM D3359	AFRL/MLS
Confirmation of Cladding Penetration	4.7	No black indication	AFRL/MLS
Surface Profile/Roughness	4.8	2024-T3 Alclad: Not to exceed 125 micro inches. 2024-T3 Bare: Not to exceed 125 micro inches	AFRL/MLS
Substrate Temperature During Coating Removal Process	4.9	7075-T6 Aluminum: 300°F maximum spike condition. Carbon Epoxy Laminate: 200°F maximum spike condition	Anteon
Four Point Flexure	4.10	No significant change at 90% confidence	UDRI
Rotary Wing Metallic Substrate Assessment	4.11	No significant change at 90% confidence	AFRL/MLS
Damage Assessment to Honeycomb Structural Materials	4.12	Testing detail and results shall be documented for review and determination of pass/fail values	UDRI

3. ALTERNATIVES TESTED

Three portable hand held laser coatings removal systems were evaluated during this testing. An overview of the capabilities of each of these systems is detailed in **Table 3**.

Table 3. Portable Hand Held Laser Paint Stripping Systems

	TEA CO_2	Nd:YAG	Nd:YAG (Q-Switched)
Power	250 W	40 W	120 W
Beam Delivery	Umbilical Arm	Fiber Optical Cable	Fiber Optical Cable
Wavelength	10,600 nm	1,064 nm	1,064 nm
Pulse Duration	1000 ns	10 – 12 ns	200 ns
Pulse Frequency	0- 50 Hz	1, 2, 6, 30, 60, or 120 Hz	8000 – 35,000 Hz
Max. Pulse Energy	6.5 J	333 mJ	5 mJ
Fluence Range	4.3 – 27.1 J/cm^2	1.3 – 3.7 J/cm^2	2.8 – 10.0 J/cm^2
Scan Width	0- 50 mm	N/A	10 – 50 mm

N/A = not applicable

Test specimens of various substrates were used during this evaluation to determine the effects that use of the laser systems would have on the base material. The test specimes that were used were twelve (12) inches wide by twelve (12) inches long and various thicknesses. A full description of the various test specimens is provided in **Table 4**.

Table 4. Test Panel Specimens

Substrate	Thickness	Pretreatment
2024-T3 Aluminum (Alclad)	0.025”	Chromate conversion coated, MIL-C-5541E, Class 1A.
2024-T3 Aluminum (bare)	0.025”	Chromate conversion coated, MIL-C-5541E, Class 1A.
7075-T6 Aluminum (Alclad)	0.025”	Chromate conversion coated, MIL-C-5541E, Class 1A.
7075-T6 Aluminum (bare)	0.025”	Chromate conversion coated, MIL-C-5541E, Class 1A.
2024-T3 Aluminum (bare)	0.025”	Chromic Acid Anodized per MIL-A-8625, Type IB.
7075-T6 Aluminum (bare)	0.016”	Chromate conversion coated, MIL-C-5541E, Class 1A.
2024-T3 Aluminum (Alclad)	0.032”	Chromate conversion coated, MIL-C-5541E, Class 1A.
7075-T6 Aluminum (Alclad)	0.032”	Chromate conversion coated, MIL-C-5541E, Class 1A.

Table 4. Test Panel Specimens (cont.)

Substrate	Thickness	Pretreatment
7075-T6 Aluminum (bare)	0.032”	Chromate conversion coated, MIL-C-5541E, Class 1A
4130 Steel	0.025”	None
Fiberglass/Epoxy (GM3006)	0.124” 4-ply (0/90)	None
Graphite/Epoxy (IM7/977-3)	0.0734” 14-ply (0/0/45/135/45/135)	None
Kevlar (AMS 3902 and MIL-R-9300)	0.133” [0/90]	None
Metallic Honeycomb Core	face 2024-T3 0.020 inch; core 5056-H39 A1, 3/16 inch cell, 0.002 inch foil, 0.625 inch thick	None

All test specimens were painted or coated within 24 hours of the application of the pre-treatment. Each test was performed on identical test specimens that were coated with DoD, NASA, and Aerospace Industry standard coating systems. The various combinations of primer and topcoat that were used during this evaluation are listed in **Table 5**.

Table 5. Control Coating Systems

Coating System	Primer	Topcoat	Topcoat Color FED-STD-595
1	MIL-PRF-23377G	MIL-C-46168, Type IV	383 Green
2	MIL-P-53030	CARC MIL-DTL-64159, Type II	383 Green
3	10PW 22-2	MIL-PRF-85285, Type I	17925 Gloss White
4	Super Koropon 515-K01A	MIL-PRF-85285, Type	17925 Gloss White
5	MIL-PRF-23377G	MIL-PRF-85285 Type I	36251 flat med gray
6	PR1432GP	MIL-PRF-85285 Type I	36495 flat med gray

Each liquid coating system was prepared and applied in accordance with the appropriate specifications. Application was conducted at a minimum temperature of 70 Degrees F and 50% +/- 10% relative humidity (RH). To ensure uniform coating thickness, coating applications were conducted per ASTM D823, Standard Practices for Producing Films of Uniform Thickness of Paint, Varnish, and Related Products on Test Panels.

During each recoating cycle all topcoats were applied over the primer within the manufacturer’s recommended time and artificially aged for 7 days at room temperature followed by 7 days at 150º F (+/- 5º).

4. TEST RESULTS

An overview of the results of the testing that was conducted is presented in **Table 6**. 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 red. A description of each of the test procedures that were followed, the testing methodologies, and a discussion of the results of each test are provided in the following sections.

Table 6. Data Summary

Performance Criteria	120 watt Nd:YAG	250 watt CO_2	40 watt Nd:YAG	Expected Performance
4.1 Coating Strip Rate (ft^2/min)	6 Mils			
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				
4.2 Warping/Denting	None	None	None	
4.3.1 Metal Erosion	None	None	None	Visual Examination
4.3.2 Composite Erosion	Loose fibers	N/A	Loose fibers	No resin erosion/damage
4.4 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**	
4.5 Tensile Testing (ASTM E8)				No significant change at 90% confidence (Debit)
Yield Strength (ksi) ***Baseline = 47.8***	48.0	**46.8**	47.4	
Ultimate Tensile Strength (ksi) ***Baseline = 63.3***	**66.7**	**62.0**	**65.8**	
Elongation (%) ***Baseline = 16.6%***	**18.1**	**17.8**	**18.2**	
4.6 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	
4.7 Clad Penetration (SAE MA4872)	None	None	None	Determine Clad Penetration
4.8 Surface Profile / Roughness (µin) (SAE MA4872)	37 – 65	10 – 18	13 – 29	Not to exceed 125 µin
4.9 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 6. Data Summary (continued)

Performance Criteria	120 watt Nd:YAG	250 watt CO_2	40 watt Nd:YAG	Expected Performance
4.10 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	
4.11 Rotary Wing Metallic Substrate Assessment				
4.11.1 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	
4.11.2 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**	
4.11.3 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				
4.12 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	

4.1 Coating Strip Rate

Trials were conducted for each of the laser systems to determine the rate at which each of the coating systems could be removed. The coating strip rate test data that was compiled is based on removal of coatings from a test area equal to 1 ft^2.

The JTP acceptance criteria for this test is 0.06 ft^2/minute at 6 mils nominal thickness. During the course of this strip rate testing the coatings were completely stripped on the metallic substrates and were stripped to approximately 50% substrate exposure for composites. The results of this testing are summarized in **Table 7**.

Table 7. Coating Strip Rate Summary

Coating System	Substrates	120 watt Nd:YAG		250 watt CO2		40 watt Nd:YAG	
		3 Mil	6 Mil	3 Mil	6 Mil	3 Mil	6 Mil
MIL-P-23377G MIL-PRF-85285	Aluminum 2024 T-3 Al-Clad	0.064 ft^2/min	0.064 ft^2/min	0.046 ft^2/min	0.025 ft^2/min	0.0278 ft^2/min	Not Tested
MIL-P-23377G MIL-PRF-85285	Graphite Epoxy or Fiberglass Epoxy	0.15 ft^2/min	0.095 ft^2/min	0.068 ft^2/min	0.036 ft^2/min	0.0114 ft^2/min	0.0057 ft^2/min
MIL-P-53030 MIL-C-46168	1010 Steel	Not Tested	0.046 ft^2/min	0.023 ft^2/min	0.014 ft^2/min	0.0137 ft^2/min	0.0072 ft^2/min
MIL-P-23377G MIL-C-46168	Aluminum 2024 Clad	0.063 ft^2/min	0.039 ft^2/min	0.028 ft^2/min	0.014 ft^2/min	0.0152 ft^2/min	0.0065 ft^2/min
MIL-P-23377G APC Topcoat	Aluminum 2024 T-3 Al-Clad	0.078 ft^2/min	0.057 ft^2/min	0.047 ft^2/min	0.025 ft^2/min	Not Tested	Not Tested

4.2 Warping/Denting

All metallic substrate materials were inspected after application of the laser de-paint process for any indications of warping and/or denting. This evaluation was conducted after each of four removal cycles. Very minor warping was observed after the lasers system parameters had been optimized for the coating removal process.

4.3 Metal/Composite Erosion

Any tendency for the de-paint process to remove or erode either a metallic surface or the surface matrix layer of a composite lay-up was observed under 10x and 60x magnification and documented. Any pitting or apparent abrasion of either surface type was considered to be potential substrate erosion. The results of these evaluations are presented in sections 4.3.1 and 4.3.2.

4.3.1 Metal Erosion

Examples of metallic substrates after four strip cycles are shown in **Figures 1** and **2**. The photos indicate that the substrates, under 60x magnifications, do not show any abnormalities such as pitting, abrasions, cracking, or roughening. The color differences are a result of the coating systems and the type of lighting used when the magnification photographs were taken. There is no evidence of metal erosion after the strip cycles.

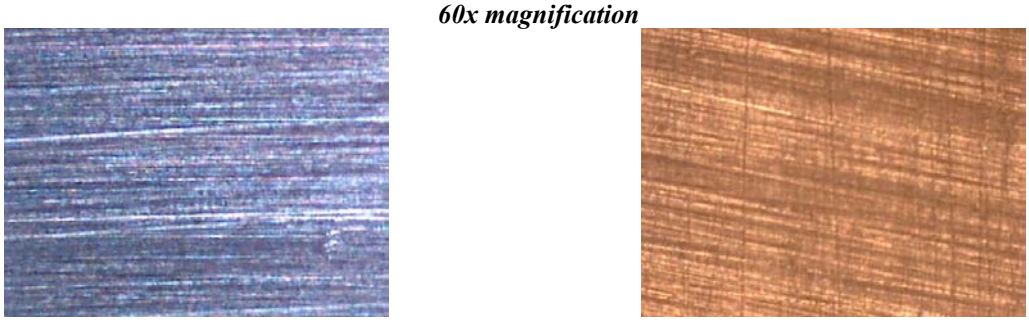


Figure 1. 2024 T3 Clad Erosion Examination

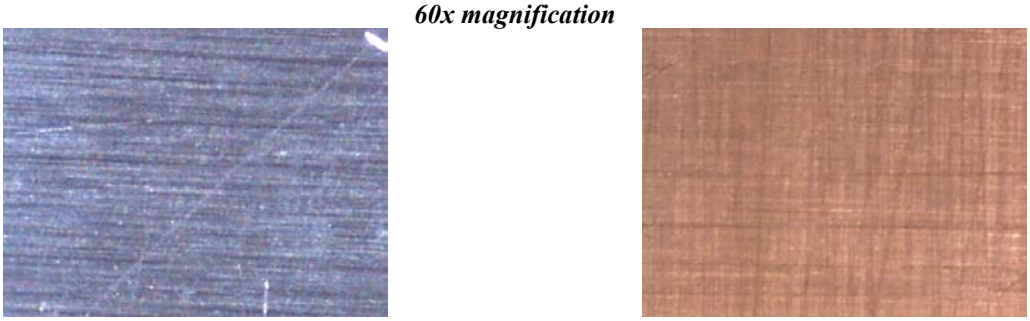


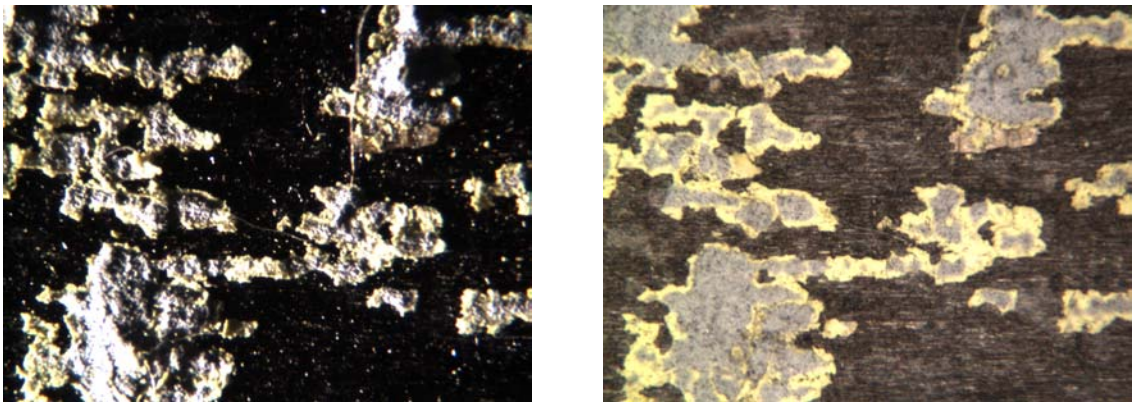
Figure 2. 7075 T6 Bare Erosion Examination

4.3.2 Composite Erosion

The top layers of the graphite epoxy (G/E) test panels showed signs of surface erosion. Photographs of G/E panels stripped three times by the 120 watt Nd:YAG laser and the 40 watt Nd:YAG laser are shown in **Figures 3** and **4** respectively. The 250 watt CO_2 laser was returned to its manufacturer prior to processing of any composite test panels.

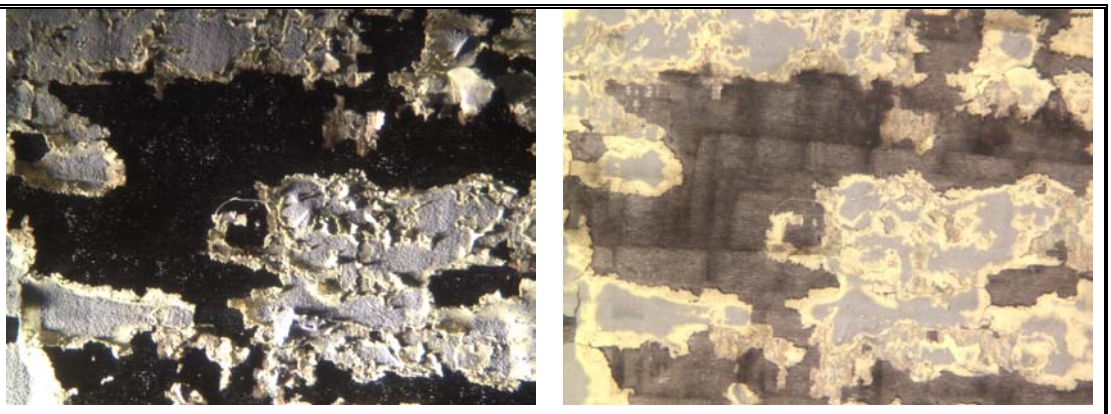
The two magnified photographs in **Figure 3** (approximately 10x magnification) are the same area on the panel with different lighting applied. The lighting method from the side shows contours and some fibers. The overhead light shows the different components of the layering system remaining on the panel. The dark area is the graphite, the light green periphery is the primer, and the gray area is the topcoat.

The magnified photographs in **Figure 4** (approximately 10x magnification) are taken from panels stripped three times with the 40 watt Nd:YAG laser. The 40 watt Nd:YAG laser appears to do less damage to the substrate than the 120 watt Nd:YAG because fewer fibers are present. There are two views, a side light view to show contour and an overhead light view to show the paint layers.



Side light view *Overhead light view*

Figure 3. Graphite Epoxy Panel – 120 watt Nd:YAG Stripped



Side light view *Overhead light view*

Figure 4. Graphite Epoxy Panels – 40 watt Nd:YAG Stripped

What the photographs do not show, but can be seen through the microscope, are the loose fibers on the surface of the stripped panels. This could indicate that the top layer of the G/E panels is experiencing some type of erosion and its properties could be altered.

The G/E panels painted after the third strip cycle show that the 120 watt Nd:YAG stripped panels have more evidence of fibers while the 40 watt Nd:YAG stripped panels show fewer fibers but also appear to have an adhesion problem with paint flakes on the surface.

The G/E panels stripped by the 120 watt laser have other characteristics besides the loose fibers and poor appearance. The dark spots on the painted panels indicate that the topcoat is being absorbed by the substrate. This is indicative of the top layer of the substrate becoming compromised and the coating penetrating into the intermediate layers of the G/E composite panels.

4.4 Hardness

Superficial Hardness testing was conducted on aluminum substrates following application of the de-painting process. The hardness values were examined to determine any change in the temper of the alloy. Testing was conducted per ASTM E18, Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials on 2024 T3 Bare and 7075 T6 Clad substrates. The results are found in **Table 8**.

Statistical analysis was performed to determine the significance of the hardness values. Although the means from the statistical analysis of the hardness data are very close in value, the data also indicate statistical significance with each of the lasers used on the 2024 T3 Bare substrate and with the 120 watt Nd:YAG when used over the 7075 T6 Clad substrate. The results that showed statistical significance from the baseline measurements are indicated as bold text and highlighted in blue in the table.

Table 8. Hardness

	Baseline	**40 watt Nd:YAG**	**120 watt Nd:YAG**	**250 watt CO2**
2024 T3 Bare	82.6	**81.6**	**80.8**	**82.1**
7075 T6 Clad	89.2	89.6	**88.4**	89.5

4.5 Tensile Testing

Tensile strength testing was performed per ASTM E8, Standard Test Methods for Tension Testing of Metallic Materials. This test was performed on test specimens that had been coated with the MIL-PRF-23377 primer and MIL-PRF-85285 topcoat and subjected to four (4) coatings removal cycles. Average tensile test results for the alloys and sheet thicknesses are presented **Table 9**. Also presented are those average values for laser-stripped materials where a statistically significant difference from the baseline occurs at a 90% confidence level, indicated as bold text and highlighted in blue in the table.

Table 9. Average Tensile Property Information

Alloy/Sheet Description	**Sheet Thick (in)**	**De-Coating Method**	**YS (ksi)**	**UTS (ksi)**	**Elongation (%)**
2024-T3 clad	0.025	Baseline	47.8	63.3	16.6
		250 watt CO_2	***46.8***	***62.0***	***17.8***
		40 watt Nd:YAG	47.4	***65.8***	***18.2***
		120 watt Nd:YAG	48.0	***66.7***	***18.1***
2024-T3 bare	0.025	Baseline	51.6	70.0	17.5
		250 watt CO_2	52.9	***71.9***	16.9
		40 watt Nd:YAG	52.2	***71.6***	17.4
		120 watt Nd:YAG	52.4	***71.2***	***16.6***
7075-T6 clad	0.025	Baseline	66.7	75.7	13.8
		250 watt CO_2	69.4	***78.8***	13.7
		40 watt Nd:YAG	68.3	***77.9***	13.8
		120 watt Nd:YAG	68.5	***76.9***	***12.8***

Table 9. Average Tensile Property Information (cont.)

Alloy/Sheet Description	Sheet Thick (in)	De-Coating Method	YS (ksi)	UTS (ksi)	Elongation (%)
7075-T6 bare	0.025	Baseline	75.3	82.9	11.9
		250 watt CO_2	***76.2***	***85.4***	12.7
		40 watt Nd:YAG	75.1	***84.1***	12.4
		120 watt Nd:YAG	75.1	83.9	12.2
7075-T6 bare	0.016	Baseline	73.5	81.8	11.8
		250 watt CO_2	75.2	***84.2***	12.4
		40 watt Nd:YAG	75.0	***82.7***	12.6
		120 watt Nd:YAG	75.4	82.1	12.3

4.6 Paint Adhesion Testing Following De-painting and Reapplying Coatings

Adhesion testing was conducted to determine the potential for adhesion problems to the substrate surface after the de-painting process with the portable laser coating removal system. The wet tape adhesion test was performed in accordance with ASTM D 3359 Standard Test Methods for Measuring Adhesion By Tape Test.

The results from this testing are listed in **Table 10**. The last panel in this table (average rating of 3.4 with individual readings of 3, 3, 3, 4, 4) did not pass the JTP acceptance criteria of an adhesion rating of 4 or better.

Table 10. Adhesion Ratings – Modified X.

Substrate	Coating System	Rating (Avg. of 5 Panels)	Laser Used
2024 T3 Clad	MIL-PRF-23377 + MIL-PRF-85285	4.0	40 watt Nd:YAG
		4.2	120 watt Nd:YAG
		4.8	250 watt CO_2
2024 T3 Bare	MIL-PRF-23377 + MIL-PRF-85285	4.8	250 watt CO_2
		4.4	40 watt Nd:YAG
		4.6	120 watt Nd:YAG
2024 T3 Bare Chromic Acid Anodized	MIL-PRF-23377 + MIL-PRF-85285	5.0	40 watt Nd:YAG
		5.0	250 watt CO_2
		5.0	120 watt Nd:YAG
4130 Steel	MIL-PRF-23377 + MIL-C-46168 CARC)	4.4	120 watt Nd:YAG
		5.0	250 watt CO_2
		3.4	40 watt Nd:YAG

4.7 Clad Penetration Tests

Cladding erosion evaluation was conducted to confirm that the coating removal process does not remove any significant portions of cladding. Drops of a solution that was prepared in accordance

with the guidelines established in the JTP were "pressed" on the substrate with the sharp point of a toothpick at the deepest point of damage. For the specimens that were tested the deepest point of damage could not be determined because the appearance of the panels was uniform and did not indicate any areas that were damaged. The drop(s) were observed for three minutes to see if they would change to a black color; black color indicates a reaction with the copper and would be reported as "fail."

No clad panels from any of the three laser systems tested showed any indication of clad penetration. The solution was also dropped on a 2024 T3 bare substrate to verify if the solution would react as needed if contact with copper was made; the solution did turn black over the 2024 T3 bare substrate.

4.8 Surface Profile/Roughness

Analysis of the substrate surface using a profilometer was performed to determine if the paint stripping process changes the roughness of the surface. Profilometry measurements were taken on 2024 T3 clad and 2024 T3 bare substrates. The JTP acceptance criteria for surface roughness was for the surface roughness to not exceed 125 micro-inches. The surface roughness was tested with a Pocket Surf profilometer using a standard probe with a long stroke cycle.

The surface roughness was checked on the test specimens after each of the coating and laser stripping cycles. Five readings were taken on each of the substrates and the readings were taken in different directions.

The CO_2 laser was returned to the manufacturer after two strip cycles, limiting the profile testing for this laser to the information collected to the two cycles. Profilometer testing was suspended for the 120 watt Nd:YAG laser after the third strip cycle. This was because results from the first three cycles indicated that the surface roughness was not significantly changed between the stripping cycles.

After checking all substrates from all lasers there was no evidence of excessive surface roughness; **Table 11** summarizes the data.

Table 11. Surface Profile Measurements

		2024 T3 Clad (µin)	2024 T3 Bare (µin)
Baseline		21.1	18.7
250 watt CO_2	Cycle 1	15.9	13.2
	Cycle 2	17.8	10.4
120 watt Nd:YAG	Cycle 1	41.1	57.5
	Cycle 2	45.9	58.9
	Cycle 3	46.8	53.3
40 watt Nd:YAG	Cycle 1	15.0	15.8
	Cycle 2	15.5	15.1
	Cycle 3	16.9	No Test
	Cycle 4	25.4	17.7

4.9 Substrate Temperatures during Coating Removal Process

This test was conducted in order to determine if peak temperatures that are high enough to change mechanical properties or damage the base substrates occur during coating removal operations. The maximum allowable temperature spike was 300°F for the aluminum panels and 200°F for the graphite epoxy panels.

The graphs in **Figures 5, 6, 7**, and **8**, are readings from graphite epoxy and aluminum panels that were tested for maximum temperature reached during the laser strip process. The four graphite epoxy panels were manufactured with embedded thermocouples inserted below the top ply layer of the composite panel. The aluminum panels had a thermocouple placed within 0.01" of the surface of the panel by drilling a "hole" in the back of the panel. The panels were then stripped and the temperatures were read every 0.2 seconds until the panel was stripped. The maximum temperatures reached for each of the graphite epoxy panels are found in **Table 12**.

Table 12. Graphite Epoxy Temperature Readings

Trial	1	2	3	4
Max Temperature Reached	138.1°F	132.8°F	113.7°F	123.3°F

The temperature spikes are very short and are in relation to when the laser passes over the thermocouple. The cure temperature of the graphite epoxy panels is 250°F; therefore, the maximum temperature reached, 138.1°F, is not high enough to cause damage to the graphite epoxy panels.

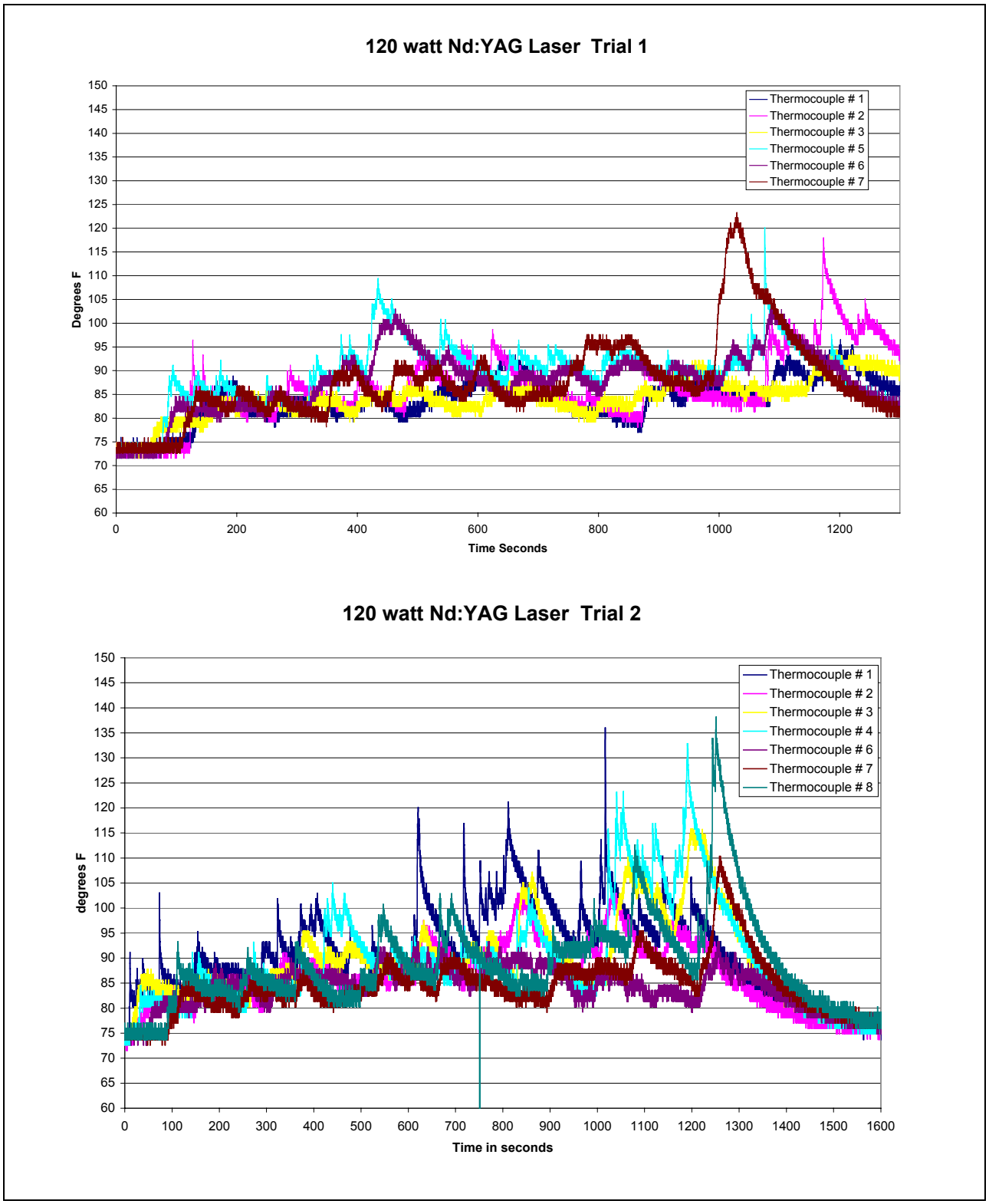
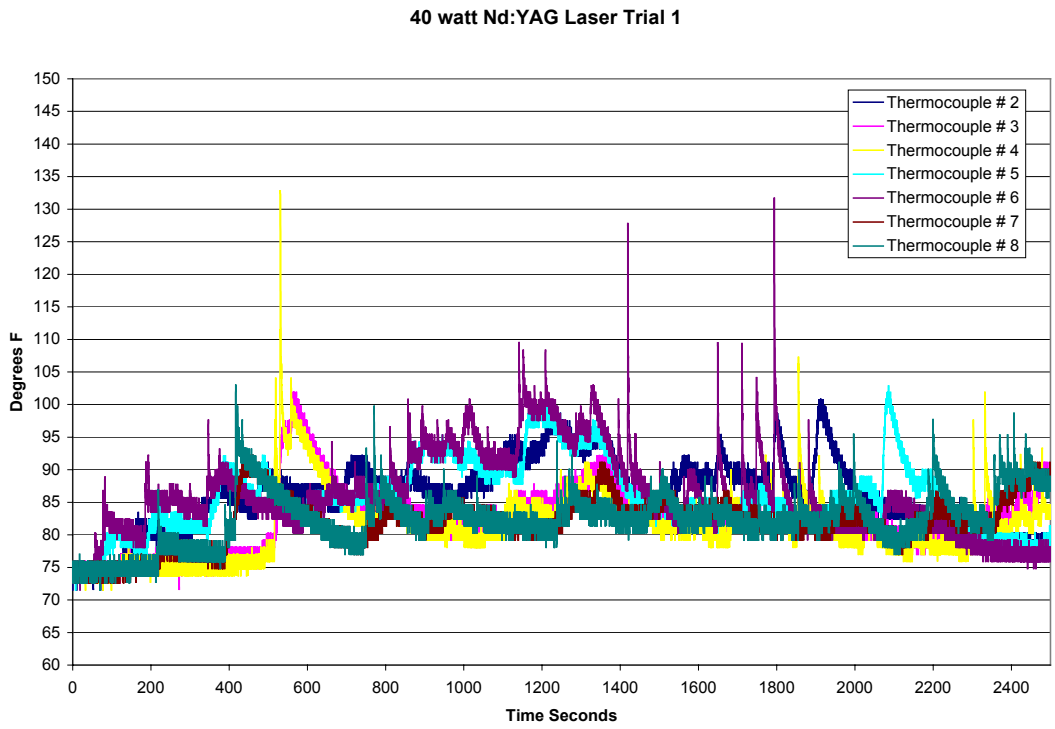


Figure 5. Graphite Epoxy Temperature Determination (120 watt Nd:YAG)



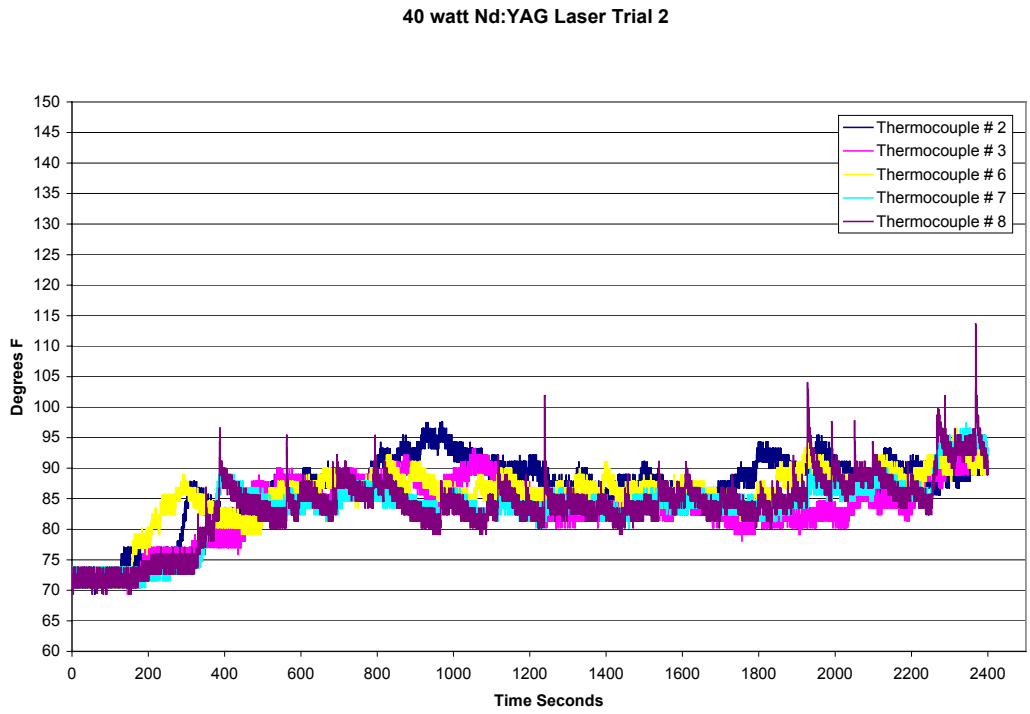


Figure 6. Graphite Epoxy Temperature Determination (40 watt Nd:YAG)

The maximum temperature reached with the 120 watt Nd:YAG laser is approximately 212°F (**Figure 7**). The large spikes above and below the actual temperature readings from thermocouple #8 are not true readings. The thermocouple was giving false readings between -34°C and 622°C. The maximum temperature from the 120 watt Nd:YAG does not reach 250°F, and therefore is not high enough to affect the properties of the aluminum substrate.

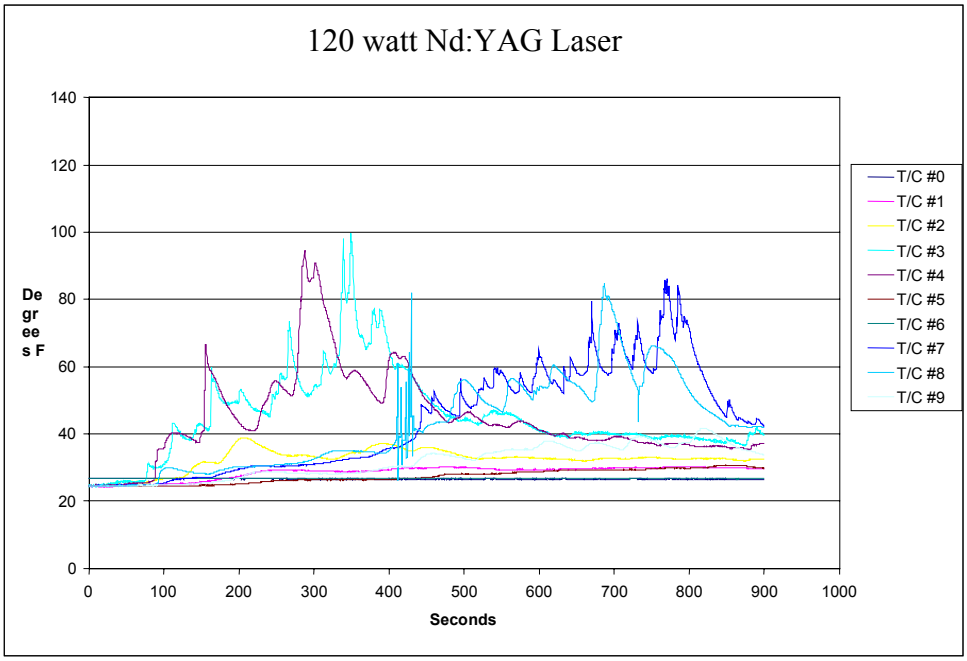


Figure 7. Aluminum Substrate Temperature Determination (120 watt Nd:YAG)

The maximum temperature reached with the 40 watt Nd:YAG laser is approximately 156°F (**Figure 8**). This temperature is not high enough to alter the properties of the aluminum substrate.

The 250 watt CO_2 laser was shipped back before temperature readings could be performed on either the composite or aluminum substrates.

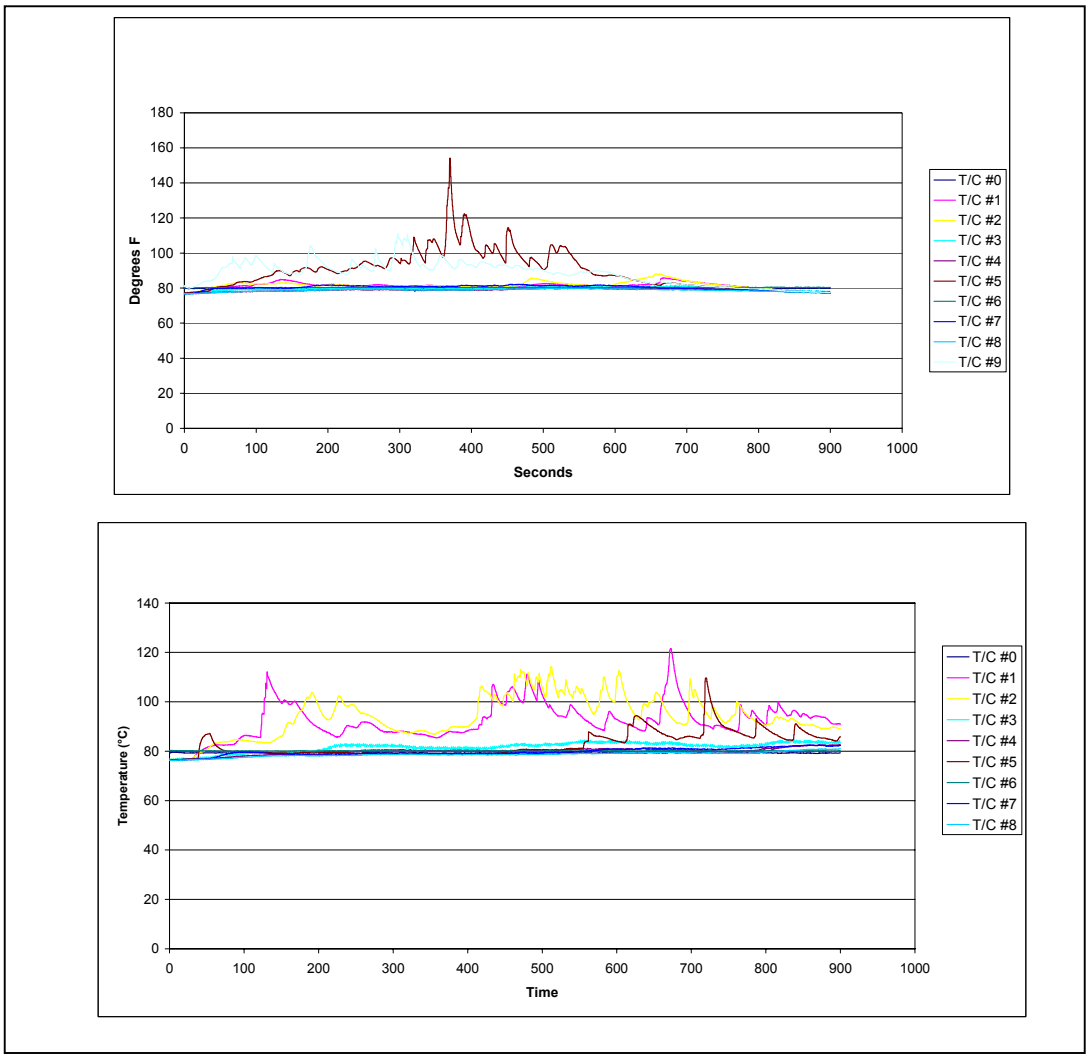


Figure 8. Aluminum Substrate Temperature Determination (40 watt Nd:YAG)

4.10 Four Point Flexure

The Four Point Flexure test was conducted on the composite materials to determine if any damage to the composite substrate occurred during the course of laser stripping activities.

Composite coupons underwent ultrasonic nondestructive inspection to verify the structural integrity of the material prior to de-painting. Laminate materials found to be free from defects were de-painted, reinspected and subjected to Four-point flexure testing per ASTM D790, Test Method I, Procedure A.

The results of the Four Point Flexure testing for panels stripped by the 40 and 120 watt Nd:YAG lasers may be found in **Table 13**. No testing was conducted on composite panels stripped using the 250 watt CO_2 laser because this laser was returned to its manufacturer prior to processing of composite panels. Statistical analysis was performed on the data using a "t-test: two sample assuming unequal variances" that is part of the Microsoft Excel data analysis package. Values

that were found to be of statistical significance appear as bold text and are highlighted in blue in the table.

Table 13. Four Point Flexure Results

	Graphite Epoxy		Fiberglass Epoxy		Kevlar	
	Flex Strength (ksi)	**Flex Modulus (Msi)**	**Flex Strength (ksi)**	**Flex Modulus (Msi)**	**Flex Strength (ksi)**	**Flex Modulus (Msi)**
Baseline	192	21.3	98	4.6	58	4.9
120 watt Nd:YAG	**168**	22.2	**88**	**3.5**	58	**3.9**
40 watt Nd:YAG	184	**20.0**	**86**	**3.5**	60	**4.0**
Percentage Difference From Baseline						
120 watt Nd:YAG	**-12.5%**	4.2%	**-10.2%**	**-23.9%**	0.0%	**-20.4%**
40 watt Nd:YAG	-4.2%	**-6.1%**	**-12.2%**	**-23.9%**	3.4%	**-18.4%**
*Positive value indicates increase						

Graphite epoxy coupons displayed statistically significant debit for the flexural strength when processed by the 120 watt Nd:YAG Laser and statistically significant debit for the flexural modulus for test specimens treated using the 40 watt Nd:YAG laser. Graphite epoxy coupons do not show statistical significance for the flexural strength for the 40 watt Nd:YAG and for the flexural modulus for the 120 watt Nd:YAG.

Fiberglass epoxy coupons displayed statistically significant debit for both flexural strength and flexural modulus for both laser systems.

Kevlar panels do not show statistical significance for flexural strength but do show statistically significant debit for flexural modulus for both laser systems.

4.11 Rotary Wing Metallic Substrate Assessment

Rotary Wing Metallic Substrates were tested for Fatigue Life on Smooth and Open Hole Specimens and Fatigue Crack Growth on Center Crack Specimens. This testing was conducted in accordance with ASTM E466 Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Test of Metallic Materials and ASTM E647 Standard Test Method for Measurement of Fatigue Crack Growth Rates. The rotary wing metallic substrate testing parameters are outlined in the table below:

4.11.1 Fatigue Life – Smooth Test Method

The average fatigue life for samples tested by the Smooth test methods are presented in **Table 14**. This table also presents the results that represent statistically significant differences at a 90% confidence from the baseline sample group as bold text and are highlighted in blue. The samples stripped by the 40 watt Nd:YAG laser displayed the largest debit in average fatigue life for two of the three alloys tested.

Table 14. Average Fatigue Lives (Smooth Test Method)

Alloy/Sheet Description	Sheet Thick. (in)	De-Coating Method	Max Fatigue Stress (ksi)	Avg. Cyclic Life (Cycles)	Difference From Baseline
2024-T3 clad	0.025	Baseline	40.5	112,246	
		250 watt CO_2	"	116,299	
		40 watt Nd:YAG	"	**89,844**	**-20%**
		120 watt Nd:YAG	"	101,182	
7075-T6 clad	0.025	Baseline	39.0	85,416	
		250 watt CO_2	"	77,803	
		40 watt Nd:YAG	"	79,597	
		120 watt Nd:YAG	"	79,369	
7075-T6 bare	0.016	Baseline	46.0	144,267	
		250 watt CO_2	"	351,987	
		40 watt Nd:YAG	"	**42,717**	**-70%**
		120 watt Nd:YAG	"	**54,606**	**-60%**

4.11.2 Fatigue Life – Open Hole Test Method

Results for the open hole fatigue sample groups are presented in **Table 15,** with results that are statistically significant differences from the baseline presented in bold text and highlighted in blue. These results indicated that for all three sheet materials tested, significant debits were observed for the two Nd:YAG lasers as compared to the uncoated open hole baseline results.

Table 15. Average Fatigue Lives (Open Hole Test Method)

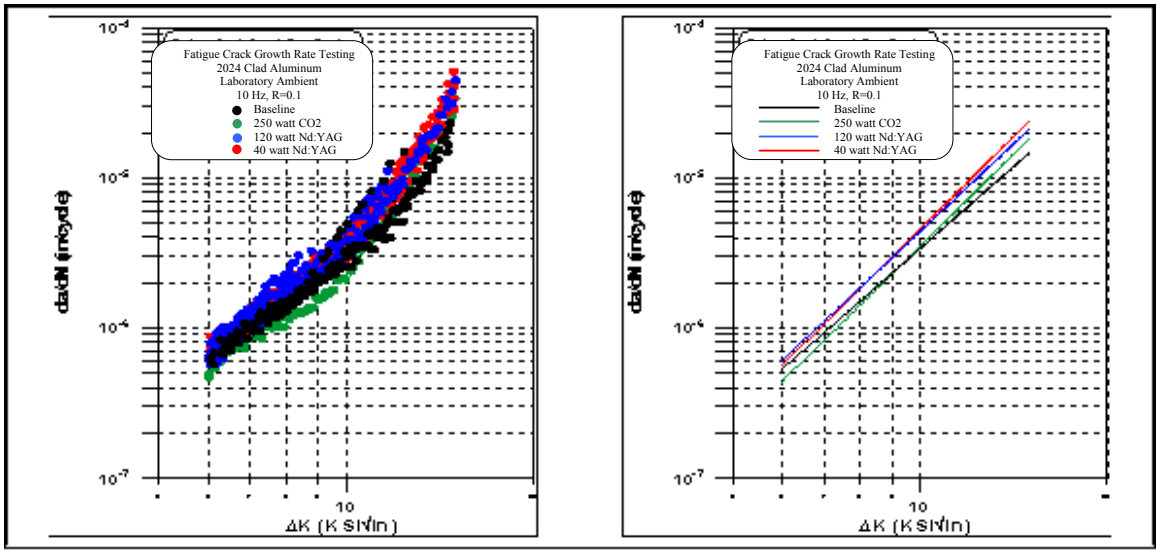
Alloy/Sheet Description	Sheet Thick. (in)	De-Coating Method	Max Fatigue Stress (ksi)	Avg. Cyclic Life (Cycles)	Difference From Baseline
2024-T3 clad	0.025	Baseline	25.0	91,230	
		250 watt CO_2	"	84,621	
		40 watt Nd:YAG	"	**70,003**	**-23%**
		120 watt Nd:YAG	"	**72,240**	**-21%**
7075-T6 clad	0.025	Baseline	23.0	65,074	
		250 watt CO_2	"	59,792	
		40 watt Nd:YAG	"	**45,975**	**-29%**
		120 watt Nd:YAG	"	**42,192**	**-35%**
7075-T6 bare	0.016	Baseline	31.0	43,386	
		250 watt CO_2 [a]	"	**29,524**	**-32%**
		40 watt Nd:YAG	"	**21,420**	**-51%**
		120 watt Nd:YAG	"	**20,080**	**-54%**

a - different coating system

4.11.3 Fatigue Crack Growth Rate

The results of the Fatigue Crack Growth Rate (FCGR) testing are shown in the following series of **Figures 9 - 11**. The figures are exhibited in such a way that the individual FCGR data for each sample (a) and power law fit model (i.e., $da/dN=C\Delta K^n$) corresponding to the raw data (b) are shown side-by-side. For each figure, only the data in the ΔK range of 6-15 ksi$\sqrt{in}$ are presented, as was defined in the JTP.

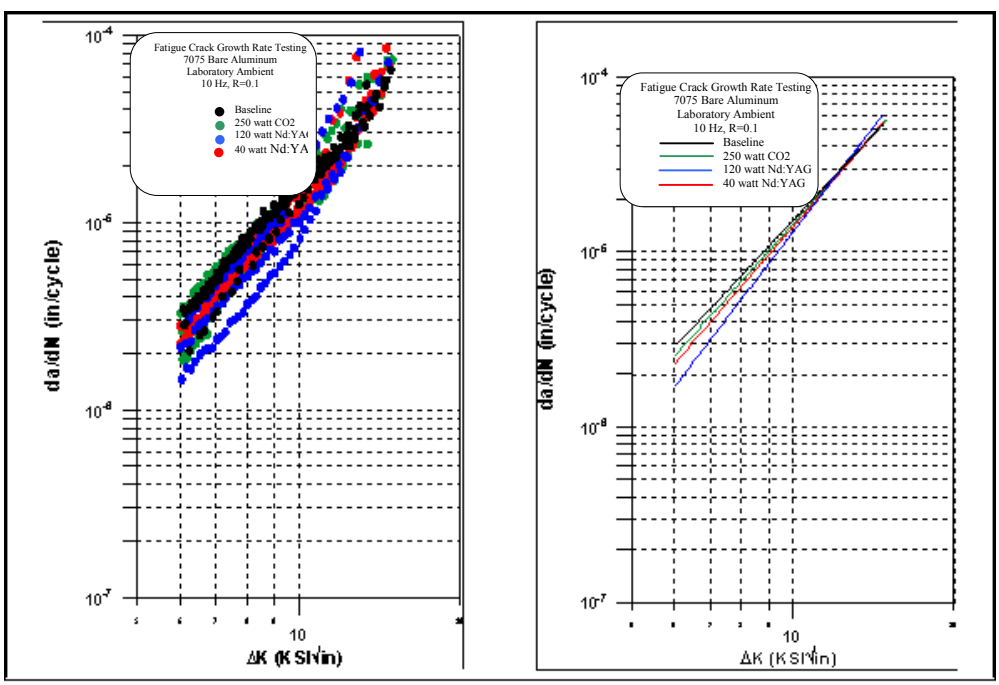
In **Figure 9**, the results from testing of 2024 clad aluminum are shown.



(a) (b)

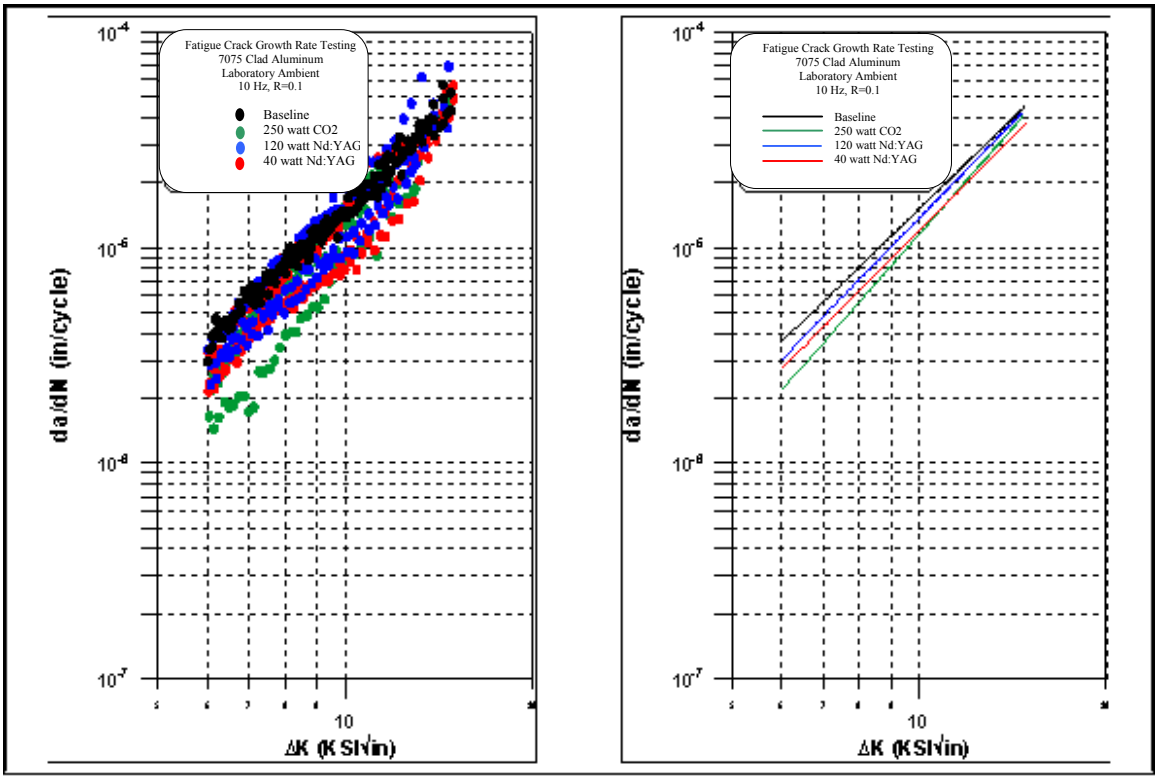
Figure 9. FCGR Results for 2024-T3 Clad Aluminum (a)raw data (b) power-law fits

Results for testing on 7075-T6 bare and clad aluminum are shown in **Figures 10 and 11**, respectively. For both cases, the laser stripped samples produced growth rates equal to or slightly below the baseline material throughout the range of stress intensities examined. Scatter in the data also appears greater for the laser stripped samples than that for the baseline.



(a) (b)

Figure 10. FCGR Results for 7075-T6 Bare Aluminum (a)raw data (b)power-law fits



(a) (b)

Figure 11. FCGR Results for 7075-T6 Clad Aluminum (a)Raw data (b)power-law fits

Statistical analysis was performed on the predicted crack growth rate values obtained from the growth rate models by first modeling the Paris region for each removal technique and substrate and examining the statistical variation in growth rates at a 90% confidence level at two distinct ΔK values: 6 and 14 ksi√in. **Table 16** shows the results of this statistical analysis for all of the FCGR tests with statistically significant results presented in bold text. The results of this analysis are further depicted graphically in **Figure 12**, where the Paris model is shown along with the ± 90% confidence levels. When the confidence levels of a particular data set fall below the baseline curve, a statistically significant decrease in growth rate is noted, beneficially from a life standpoint. Further more, when the confidence intervals are above the baseline, there is a statistical increase in growth rates, which corresponds to a decrease in fatigue crack growth life. When the confidence intervals of two data sets overlap, no statistical differences are noted. For the 7075-T6 clad data represented in **Figure 12**, all the paint strip data at 6 ksi√in fall below the baseline, indicating lower growth rates. At 14 ksi√in, no statistical differences are noted between the stripped data and the baseline with the exception of the results for the 40 watt Nd:YAG laser which are statistically lower than baseline.

Table 16. Statistical Analysis of Fatigue Crack Growth Rate Results

Material	Paint Removal Method	ΔK ksi-(in)$^{0.5}$	Predicted Value From Model	Lower 90% Confidence Interval	Upper 90% Confidence Interval	Predicted Value – Baseline Predicted Value
2024-T3 Clad	Baseline	6	-6.163	-6.184	-6.141	
		14	-4.879	-4.906	-4.852	
	40 watt Nd:YAG	6	-6.137	-6.146	-6.129	0.0254
		14	**-4.664**	**-4.676**	**-4.652**	**0.215**
	120 watt Nd:YAG	**6**	**-6.126**	**-6.137**	**-6.114**	**0.0370**
		14	**-4.689**	**-4.708**	**-4.670**	**0.190**
	CO_2	**6**	**-6.256**	**-6.277**	**-6.235**	**-0.0930**
		14	**-4.783**	**-4.813**	**-4.754**	**0.0961**
7075-T6 Clad	Baseline	6	-5.366	-5.377	-5.354	
		14	-4.339	-4.354	-4.324	
	40 watt Nd:YAG	**6**	**-5.484**	**-5.508**	**-5.460**	**-0.118**
		14	**-4.435**	**-4.469**	**-4.402**	**-0.0964**
	120 watt Nd:YAG	**6**	**-5.447**	**-5.473**	**-5.422**	**-0.0818**
		14	-4.347	-4.385	-4.309	-0.00786
	CO2	**6**	**-5.584**	**-5.615**	**-5.553**	**-0.218**
		14	-4.361	-4.411	-4.311	-0.0220
7075-T6 Bare	Baseline	6	-5.456	-5.474	-5.439	
		14	-4.259	-4.283	-4.236	
	40 watt Nd:YAG	**6**	**-5.552**	**-5.571**	**-5.533**	**-0.0955**
		14	-4.250	-4.279	-4.222	0.00892
	120 watt Nd:YAG	**6**	**-5.671**	**-5.707**	**-5.634**	**-0.214**
		14	-4.202	-4.255	-4.148	0.0574
	CO2	**6**	**-5.516**	**-5.539**	**-5.492**	**-0.0591**
		14	-4.244	-4.284	-4.204	0.0153

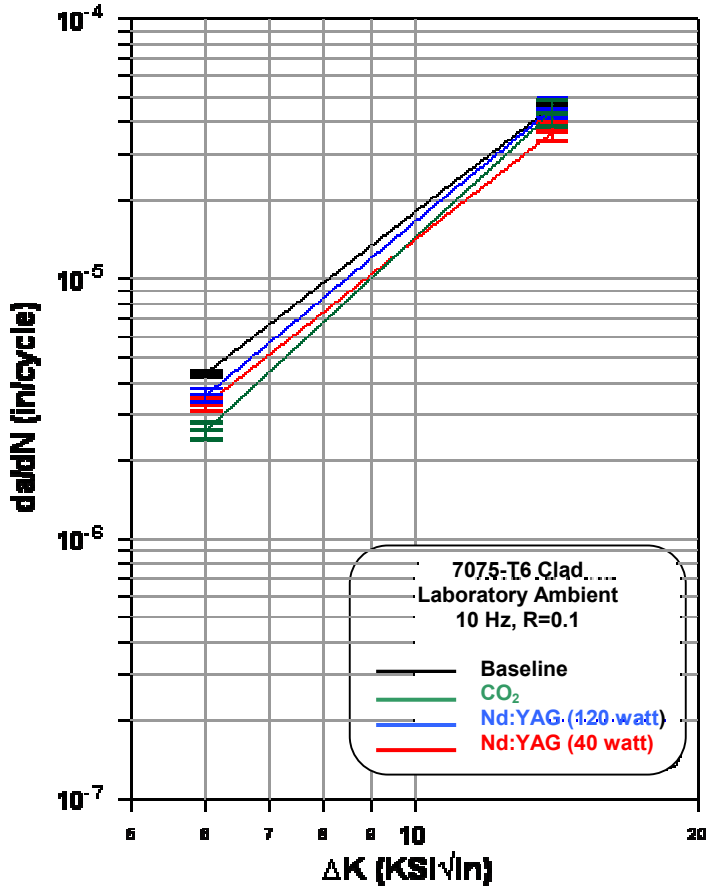


Figure 12. Statistical Representation of FCGR data for 7075-T6 Clad.

Reviewing the data shown in **Table 16** indicates that from a statistical standpoint, only the 2024-T3 clad data showed a decrease in growth rate resistance (i.e., higher growth rates) over baseline material. The significance of this difference (and all differences) noted in Table 3 from an engineering standpoint is discussed in the following section.

It is not unusual for FCGR data to show a large amount of specimen- to-specimen variability. ASTM E 647-00, *Standard Test Method for Measurement of Fatigue Crack Growth Rates*[1], in Section 8.1 states that:

> At crack growth rates greater than 10^{-8} m/cycle, the within-lot variability (neighboring specimens) of d*a*/d*N* at a given ΔK typically can cover about a factor of two. At rates below 10^{-8} m/cycle, the variability in d*a*/d*N* may increase to about a factor of five or more due to increased sensitivity of d*a*/d*N* to small variations in ΔK. This scatter may be increased further by variables such a micro structural difference, residual stresses, changes in crack tip geometry (crack branching) or near tip stress . . .

Furthermore, the standard states:

> … the reproducibility in *da/dN* within a laboratory to average ±27% and range from ±13 to ±50%, depending on laboratory…

[1] Section 3, Metals Test Methods and Analytical Procedures, ASTM International, West Conshohocken, PA.

Thus the statistical differences shown in Table 16 should thus be viewed with this in mind. The data comparisons are made at the discrete ΔK levels of 6 and 14 ksi√in. The corresponding levels of d*a*/d*N* are in the range of $1x10^{-4}$ to $1x10^{-6}$ in/cyc. Per the ASTM E647 standard, differences within a factor of two to five between data sets can be expected due to specimen-to-specimen variability. Therefore, since the data in Table 16 (shown as log da/dN) does not vary by more than a factor of two, differences from the baseline should be considered expected variability. As none of the data meet this criterion, there does not appear to be significant differences from an engineering standpoint between the baseline and FCGR data for any of the three examined substrates.

4.12 Damage Assessment to Honeycomb Structural Materials

A damage assessment was performed to determine the type and the extent of damage that could occur with honeycomb materials/structures as a result of the laser de-paint procedures. Three tests were part of this assessment: first a Non Destructive Inspection (NDI) was performed using acoustic testing; next the peel resistance of the adhesive bond between the face sheet and the honeycomb core was tested in accordance with ASTM D 1781 Standard Test Method For Climbing Drum Peel For Adhesives; finally, the flexural properties of the material were tested in accordance with ASTM C393 Standard Test Method For Flexural Properties of Sandwich Constructions.

The acoustic testing was performed on the honeycomb panels using both high frequency (10MHz) and low frequency (3MHz) testing. The testing performed on the samples searched for any dis-bonds due to laser depainting. The images received from testing are consistent across the panel, which indicates that the adhesive bond between the honeycomb material and the sandwich plates was not affected by the laser strip process. Representative photographs of the acoustic testing are shown in **Figure 13**.

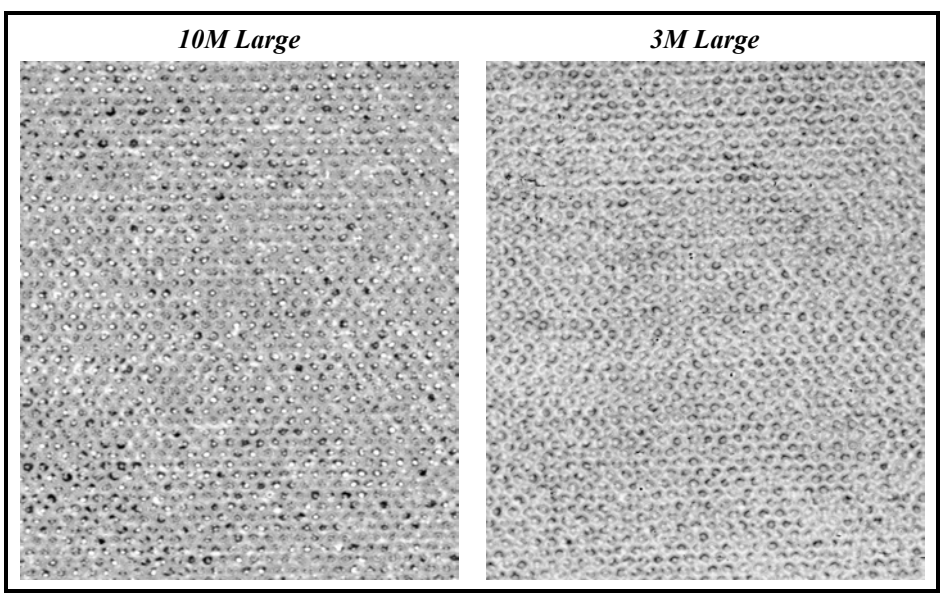


Figure 13. Ultrasonic Testing of Honeycomb Panels – Check for Dis-bonds.

The mechanical testing was then performed to verify the results from the acoustic testing. The results of the peel resistance tests are found in **Table 17**. This summary data indicates that all parameters have a value equal to or better than the baseline with the exception of one: the core shear modulus for the 40 watt Nd:YAG laser is approximately 10% lower than the baseline and the 120 watt Nd:YAG results. The bar graph data in **Figure 14** makes it easier to compare the differences in the performance of the baseline honeycomb substrate versus the 40 and 120 watt Nd:YAG laser stripped substrates.

Table 17. Core Shear Data Summary – Honeycomb

	Core Shear Strength (psi)		**Core Shear Modulus (ksi)**		**Flexural Stiffness (lb-in^2)**		**Facing Stress (ksi)**	
	Avg.	**Std. Dev.**	**Avg.**	**Std. Dev.**	**Avg.**	**Std. Dev.**	**Avg.**	**Std. Dev.**
Baseline	560.4	32.4	96	11.4	48761	1215	42	2.4
120 watt Nd:YAG	558.9	6.3	95.3	12.4	48763	1770	41.9	0.5
40 watt Nd:YAG	567	5	85.7	11	50135	986	42.5	0.4

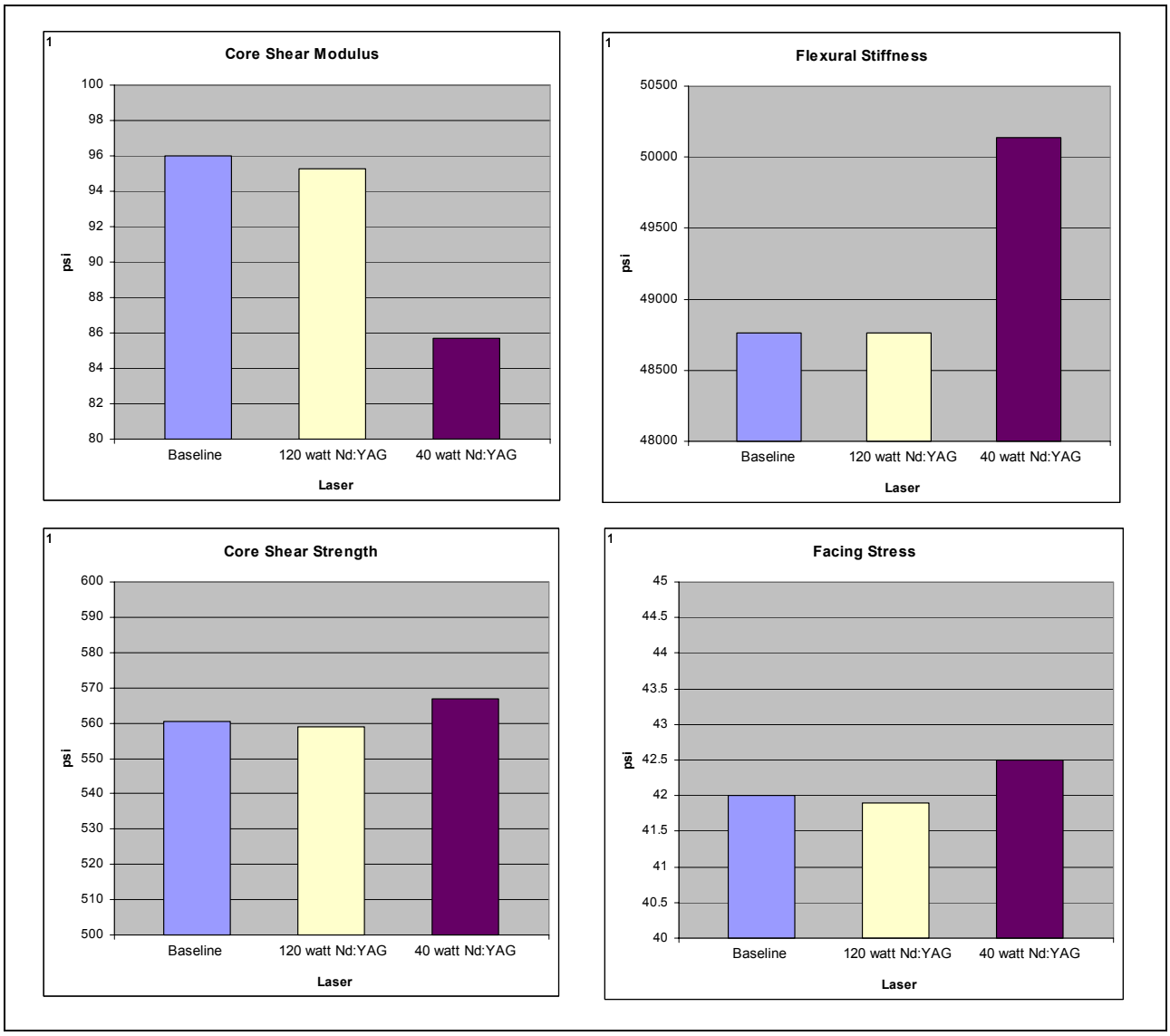


Figure 14: Bar Graphs – Mechanical Properties of Honeycomb Substrate.

5.0 ANALYSIS OF TEST RESULTS

In order to assist with engineering interpretations of the test results a literature search of 74 published references for test results was conducted on methods that are commonly used to remove paint from metallic and non-metallic 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.

Metallic substrate mechanical properties that were retrieved from the references were tensile strength, fatigue, and hardness. 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 that were examined included flash lamp, plastic media blasting (PMB), dry media blasting (DMB), chemical, and lasers.

Statistical analysis was performed on the selected project 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 the Statistical Analysis Software (SAS) software package. This software 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.

Statistical analysis was also performed on the literature search data using the same statistical analysis approach whenever possible. 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. The references that were subjected to this statistical analysis are references 1-9 in the Reference Section of this report.

5.1 Tensile Results

The test data and reference data tensile results are displayed in **Figures 15, 16, 17, and 18**. Each baseline and paint removal method were evaluated using at least ten replicates. The average tensile ultimate strength, tensile yield strength, and elongation for each of the aluminum substrates are represented in the graphs. The baseline data for the test data and the reference data are the first bar, plotted in black, in each data set. The bars right of the baseline are the results after coatings removal. Each bar is labeled with the removal method used and the reference from which the data was collected is displayed over the plot. A statistically significant difference between the baseline and after paint removal is indicated by a '√' mark. A data set without a '√ 'mark indicates no statistical significance between the baseline and after the paint removal.

The Metallic Materials Properties Development and Standardization (MMPDS) Handbook, formerly MIL-HDBK-5, 'A' allowable level is also indicated on the charts, where applicable. Although, one cannot directly compare an A design allowable that is statistically derived from 300 test results from 10 different lots to the mean of a handful of tests, the A allowable for the material form used is plotted in the graphs to give an indication of the relative strength level of the stripped panels.

For these graphs the paint removal method used in reference (2) was a dry media blast (DMB) while references (1) and (3) use different lasers for removing paint from the substrate.

5.1.1 Aluminum 2024-T3 Bare

The project test data for tensile properties for Al 2024-T3 bare shows a statistically significant increase in ultimate strength compared to the baseline (**Figure 15**). The same trend cannot be found in the reference data. The reference data either depicts a statistically significant decrease, as in reference (3), or no difference as in reference (1) and (2). Reference (2) had a statistical decrease in yield strength.

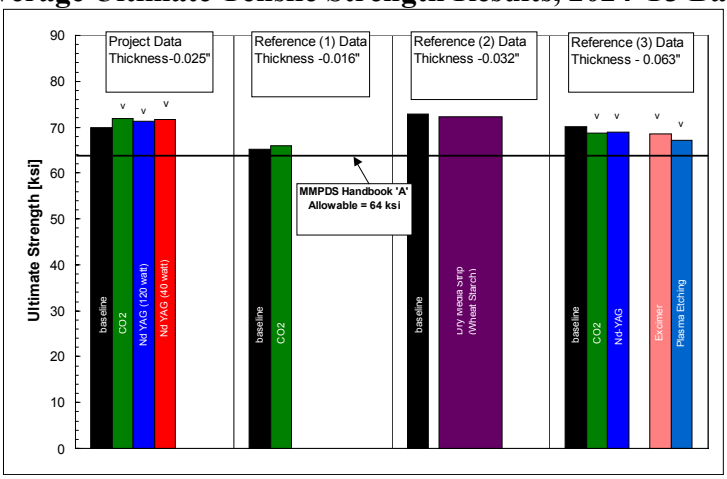
The percentage of elongation data from the test data and reference (3) displays a statistically significant decrease when compared to the baselines used in their respective testing. There was no statistically significant difference for the elongation in the reference (1) results. Reference (2) shows a statistical increase in elongation.

5.1.2 Aluminum 2024-T3 Clad

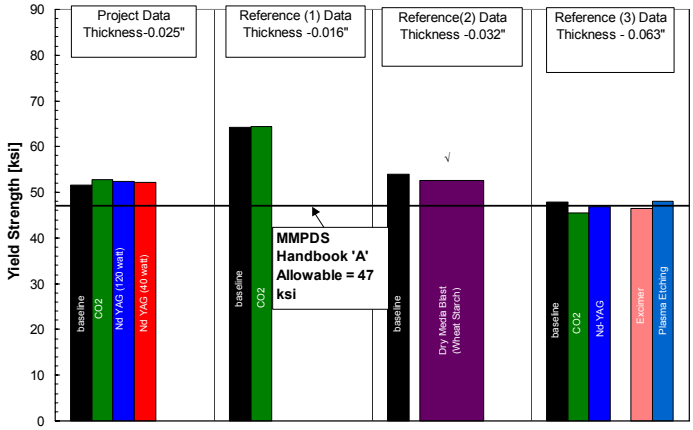
The Al 2024-T3 clad tests results (**Figure 16**) display a statistically significant increase in Ultimate Tensile Strength for both of the Nd:YAG lasers test results; however, there is a statistically significant decrease in strength for the CO_2 laser results. A statistically significant decrease in Tensile Yield Strength was seen in the test data for the CO_2 laser and DMB (2) paint removal methods. The yield strength variation for the other paint removal methods was not statistically significant.

The elongation for the CO_2 and 40 watt Nd:YAG lasers and DMB method show statistical difference compared to the baseline data. The test data for the 120 watt Nd:YAG elongation is statistically significant lower than the baseline data.

Average Ultimate Tensile Strength Results, 2024-T3 Bare



Average Yield Tensile Strength Results, 2024-T3 Bare



Average Percentage of Elongation Results, 2024-T3 Bare

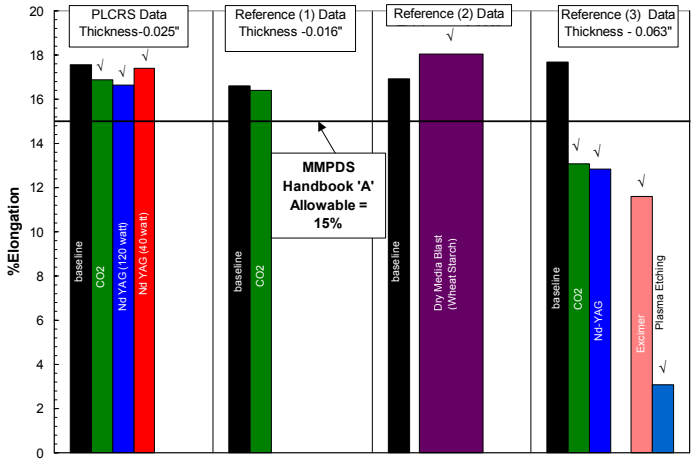


Figure 15. Tensile Strength Results for 2024-T3 Bare Substrate

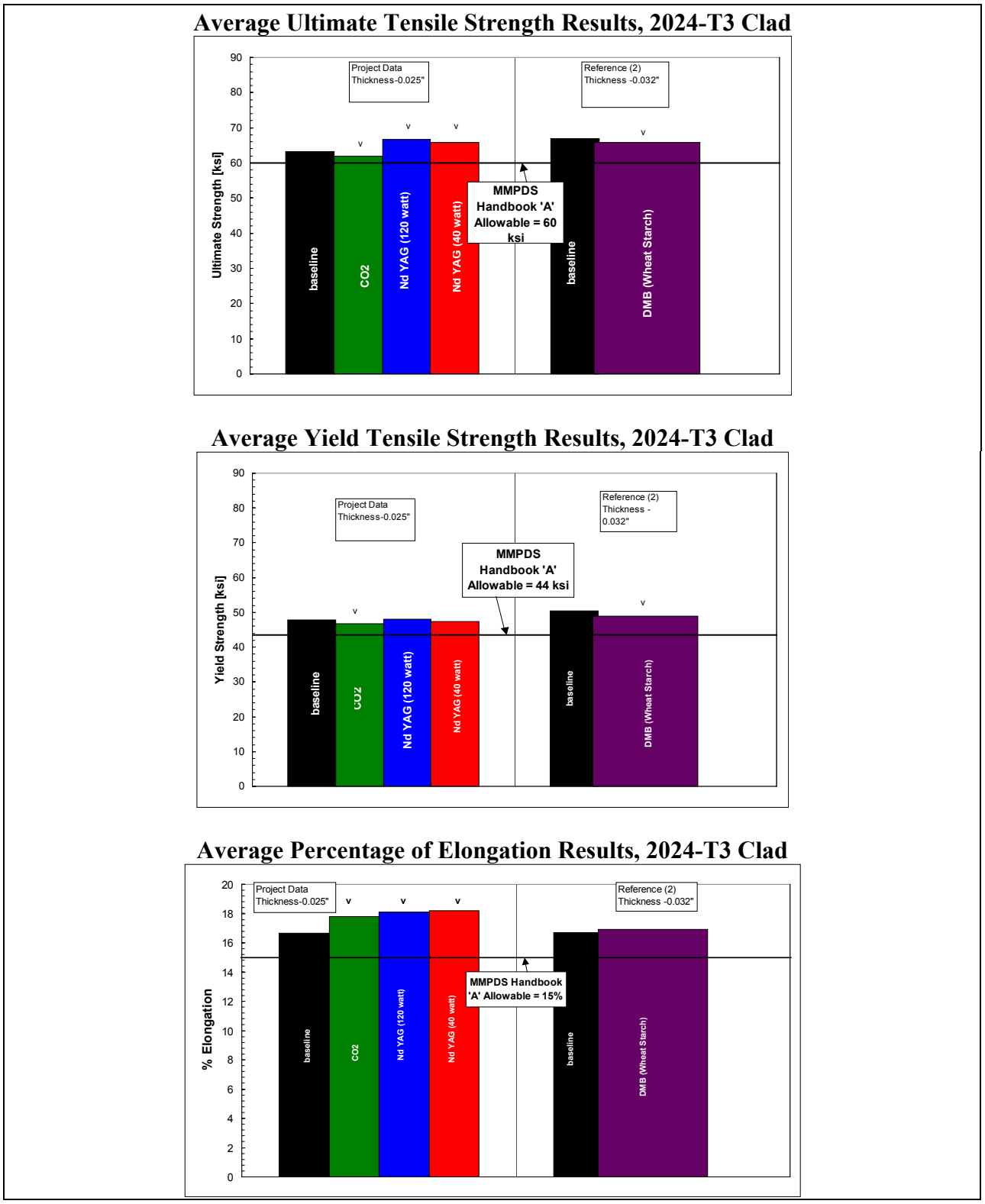


Figure 16. Tensile Strength Results for 2024-T3 Clad Substrate

5.1.3 Aluminum 7075-T6 Bare

The Al 7075-T6 bare tests results (**Figure 17**) show a statistically significant increase in Ultimate Tensile Strength for the test data for the CO_2 and 40 watt Nd:YAG laser paint removal methods and a decrease in Ultimate Tensile Strength for the DMB data in reference (2). No difference in Ultimate Tensile Strength using the 120 watt Nd:YAG strength results was observed. The Tensile Yield Strength test results show no statistical difference. The DMB (2) yield strength results show a statistical decrease compared to baseline data.

No statistically significant difference was noted for Percentage of Elongation tests.

5.1.4 Aluminum 7075-T6 Clad

The Al 7075-T6 clad test results (**Figure 18**) display an increase in the Ultimate Tensile Strength for the test data and a statistical decrease for the DMB (2) paint removal method. The Tensile Yield Strength, using lasers, did not change, but the DMB paint removal method produced a decrease.

The elongation results displayed no difference for the CO_2 and 40 watt Nd:YAG laser and DMB (2) paint removal methods. The 120 watt Nd:YAG laser paint removal method produced a decrease in elongation.

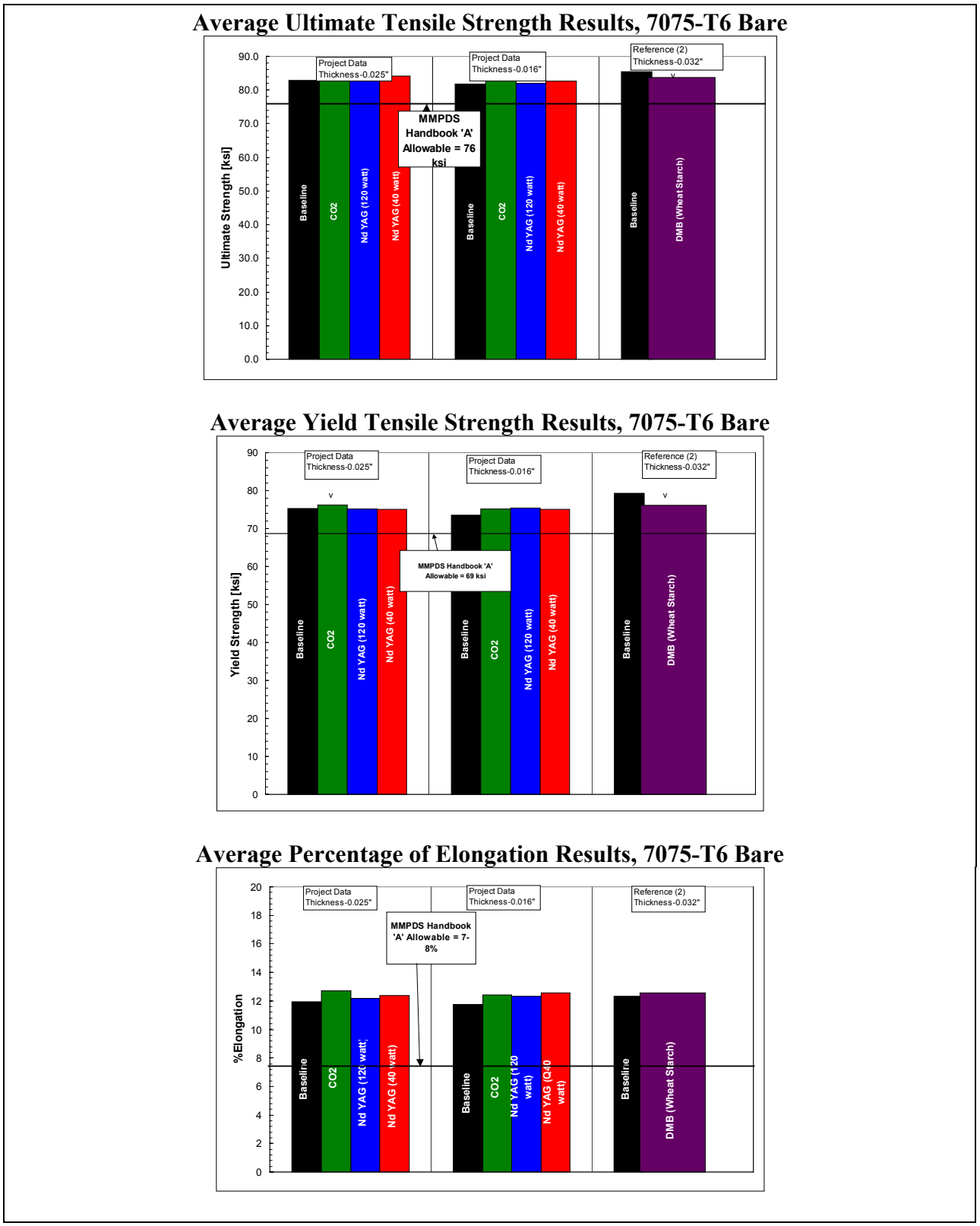
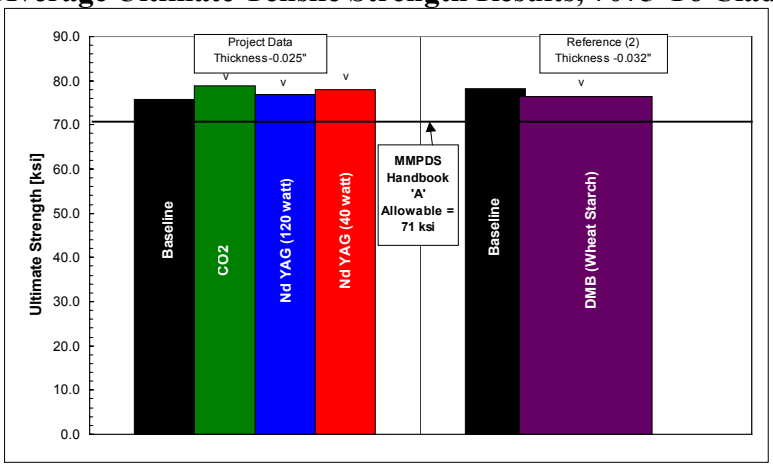
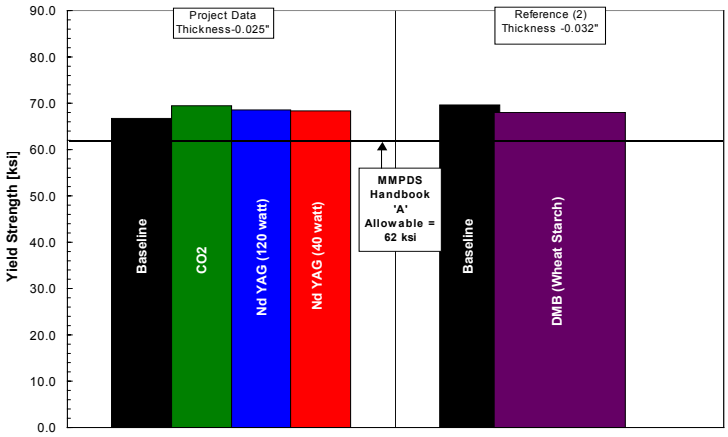


Figure 17. Tensile Strength Results for 7075-T6 Bare Substrate

Average Ultimate Tensile Strength Results, 7075-T6 Clad



Average Yield Tensile Strength Results, 7075-T6 Clad



Average Percentage of Elongation Results, 7075-T6 Clad

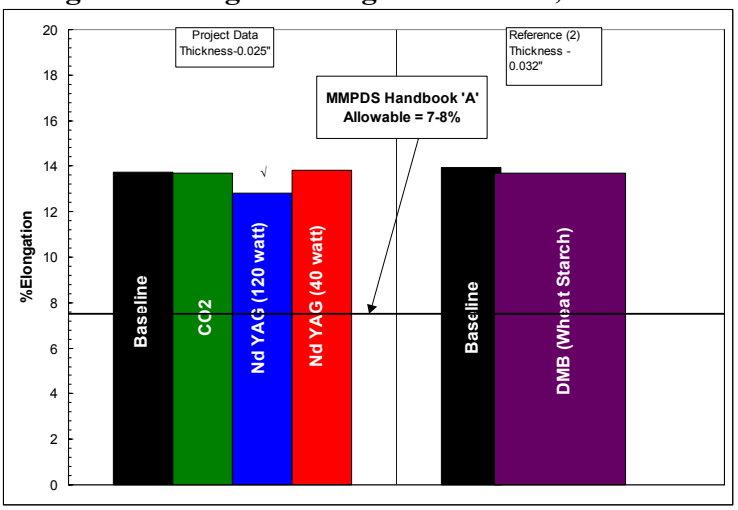


Figure 18. Tensile Strength Results for 7075-T6 Clad Substrate

5.1.5 Summary Of Tensile Results Analysis

A summary of the tensile results and the reference data is shown in **Table 18**. The space marked "+" indicates a statistically significant increase in the property, while "-" indicates a decrease. It should be noted, that although there may be a statistically significant difference at the 90% confidence level, there may not be a significant engineering difference. The differences observed are 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. It should also be noted that the Laser Stripping Methods showed a lesser, if any, reduction of tensile properties.

Table 18. Tensile Properties for Various Paint Stripping Methods

Paint Removal Methods	Al 2024-T3 bare			Al 2024-T3 clad			Al 7075-T6 bare			Al 7075-T6 clad		
	Tension			Tension			Tension			Tension		
Reference	UTS	YTS	%E	UTS	YTS	%E	UTS	YTS	%E	UTS	YTS	%E
(2), DMB (wheat starch)	-	-	NS	-	-	NS	-	-	NS	-	-	NS
(3), Plasma Etching	-	NS	-									
(3), Excimer	-	NS	-									
(1), (3), CO2 Laser	+	NS	+									
(3), Nd YAG	-	NS	-									
Test Data												
CO2	+	NS	NS	-	-	NS	+	NS	NS	+	NS	NS
Nd:YAG (40 watt)	+	NS	NS	+	NS	NS	+	NS	NS	+	NS	NS
Nd:YAG (120 watt)	+	NS	-	+	NS	-	NS	NS	NS	+	NS	-
NS – No Statistically Significant Difference												
- - Statistically Significant Decrease												
+ - Statistically Significant Increase												
- No tabulated reference data found												

5.2 Fatigue Results

The test data and the reference fatigue data are displayed as bar charts in the following sections. The average cycles-to-failure of at least five replicates for each baseline and paint removal method are presented in the graphs. The brackets on each bar represent the observed cycles-to-failure range of the replicates tested at the given stress level. The baseline data from testing and the reference data is the black bar that appears to the left in each plot. The bars next to the baseline information are the paint removal test results labeled by the removal method. The report reference number is displayed over the bar. A statistically significant difference is indicated by a '√' mark. A data set without a '√'mark indicates no statistical difference from the baseline results at a 90% confidence level.

5.2.1 Aluminum 2024-T3 Clad Smooth Fatigue

Al 2024-T3 clad smooth fatigue results (**Figure 19**) from the test program showed no statistically significant difference in fatigue life for the CO_2 and 120 watt Nd:YAG laser paint removal methods. The 40 watt Nd:YAG laser, Chemical (reference (4)), and PMB NSOD (reference (5)) removal methods showed a statistically significant decrease in fatigue life. Data from reference (2) (DMB) and (5) (PMB) paint removal method displayed no statistically significant difference in fatigue life.

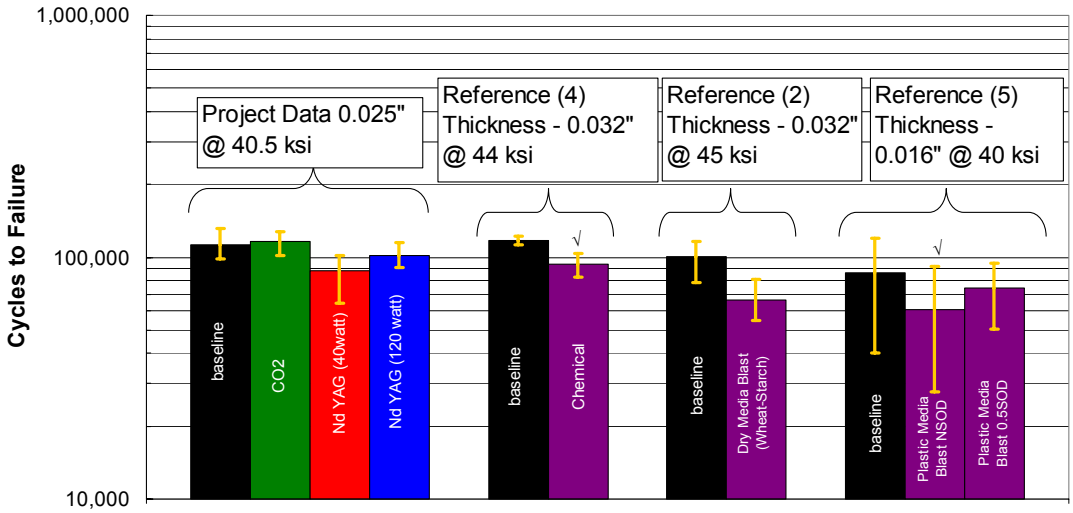


Figure 19. 2024-T3 Clad S-N Smooth Fatigue Results

5.2.2 Aluminum 2024-T3 Clad Notch Fatigue

The notch fatigue results for Al 2024-T3 clad (**Figure 20**) from both of the Nd:YAG paint removal methods showed a statistically significant reduction in fatigue life. The CO_2 and flash lamp paint removal methods (reference (6)) showed no statistically significant difference in fatigue life.

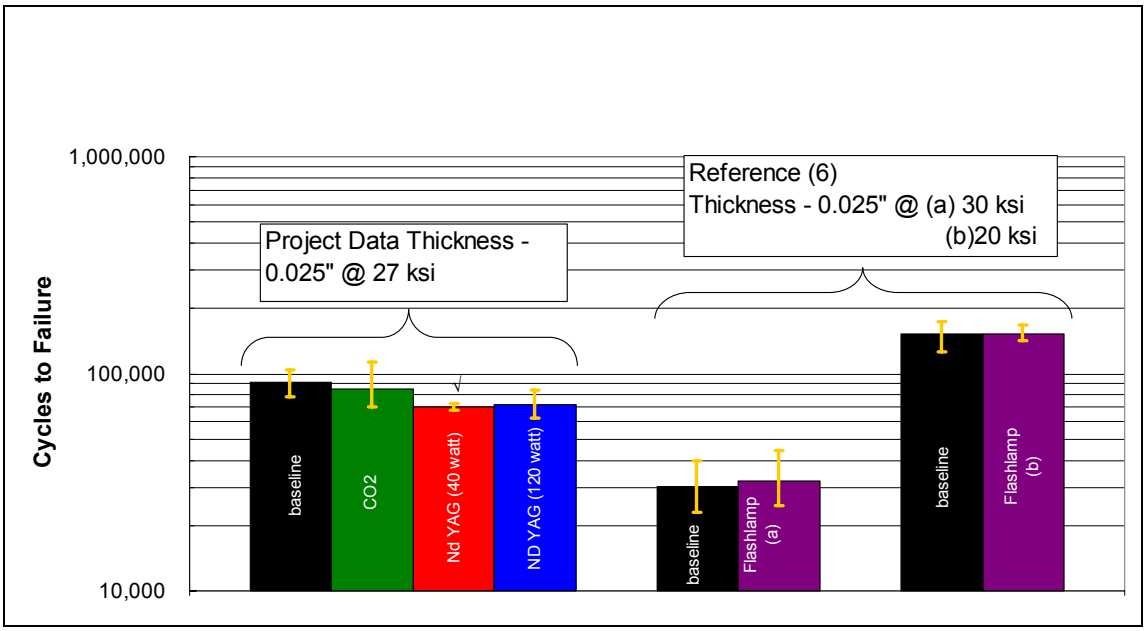


Figure 20. 2024-T3 Clad S-N Notch Fatigue Results

5.2.3 Aluminum 7075-T6 Bare Smooth Fatigue

The Al 7075-T6 bare smooth fatigue results for the CO_2 laser and DMB paint removal methods showed no statistically significant change in fatigue life (**Figure 21**). Both of the Nd:YAG laser paint removal methods and the chemical paint removal method resulted in shorter fatigue life.

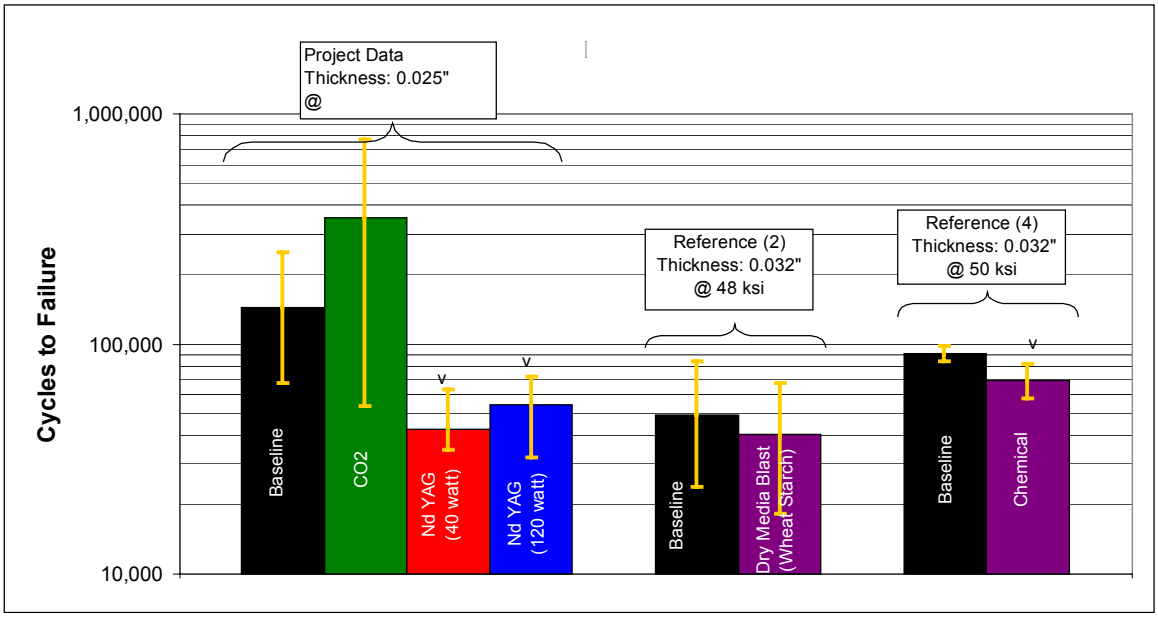


Figure 21. 7075-T6 Bare Smooth Fatigue Results

5.2.4 Aluminum 7075-T6 Bare Notch Fatigue

Al 7075-T6 bare notch fatigue results (**Figure 22**) show a statistically significant decrease in fatigue life for the CO_2 and Nd:YAG laser paint removal methods. No tabulated data was found for 7075-T6 bare notch fatigue in the reference data reports.

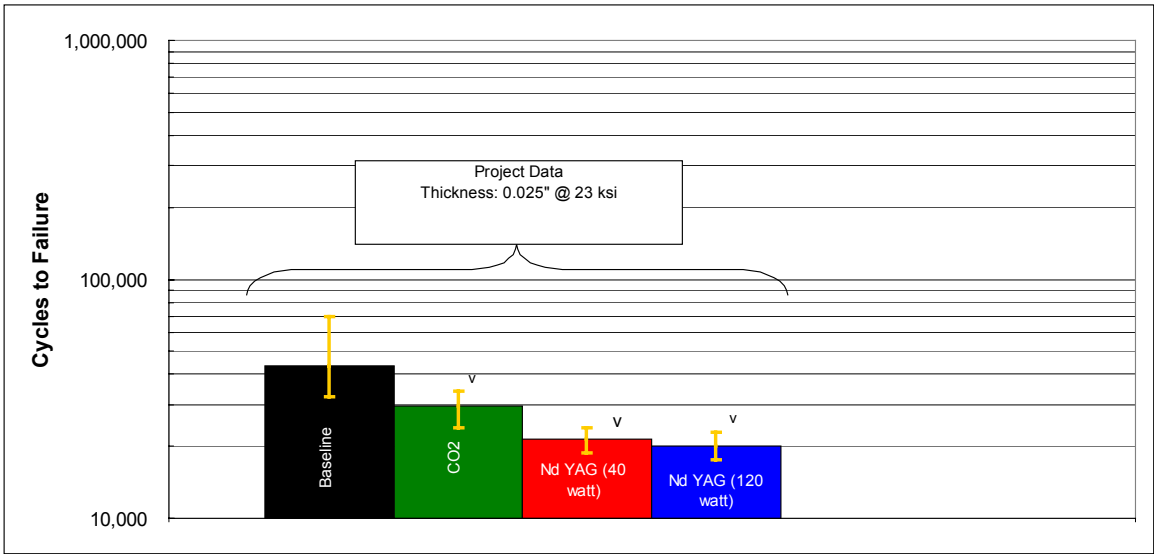


Figure 22. 7075-T6 Bare S-N Notch Fatigue Results

5.2.5 Aluminum 7075-T6 Clad Smooth Fatigue

The Al 7075-T6 clad smooth fatigue results (**Figure 23**) showed no statistically significant change in fatigue life for the lasers coating removal methods and PMB. Chemical strip and DMB showed a statistically significant decrease in fatigue life.

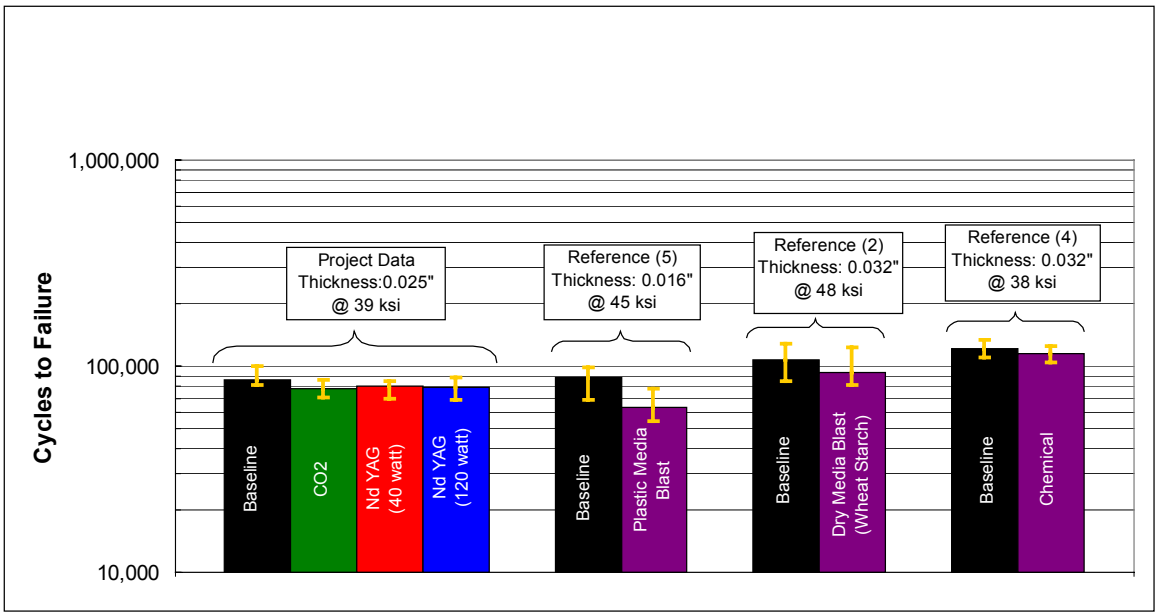


Figure 23. 7075-T6 Clad Smooth Fatigue Results

5.2.6 Aluminum 7075-T6 Clad Notch Fatigue

The notch fatigue results for Al 7075-T6 clad (**Figure 24**) for both of the Nd:YAG laser paint removal methods showed a statistically significant reduction in fatigue life. The CO_2 and flash lamp paint removal method (reference (6)) showed no statistically significant difference in fatigue life.

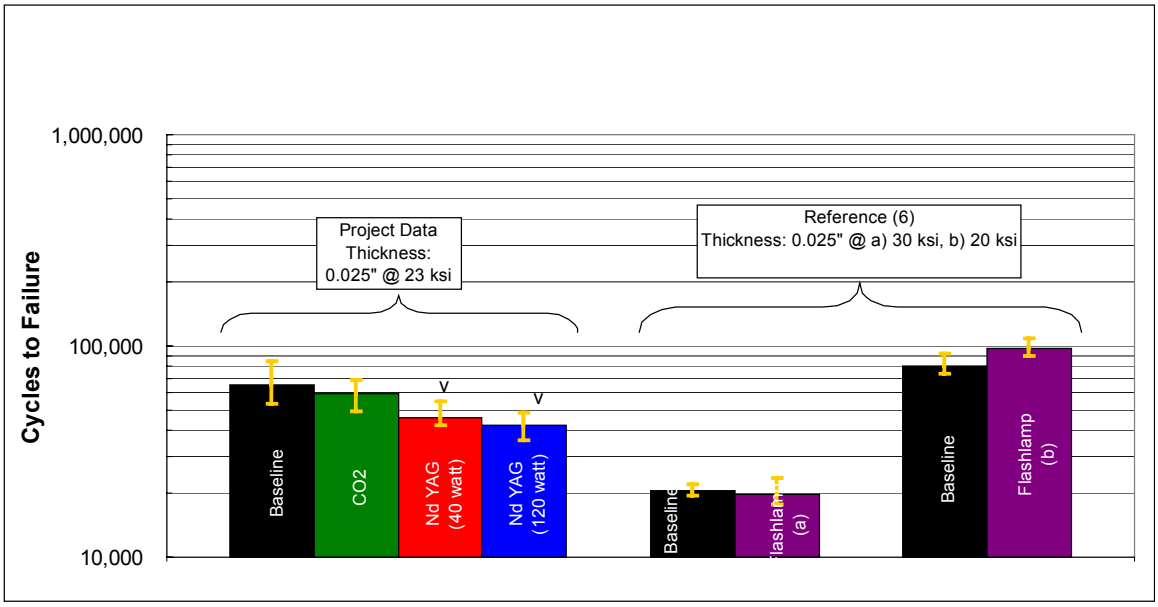


Figure 24. 7075-T6 Clad S-N Notch Fatigue Results

5.2.7 Summary of Fatigue Results Analysis

A qualitative summary of the fatigue test results and the reference data is listed in **Table 19**. The space marked "+" indicates a statistically significant increase, while "-" indicates a statistically significant decrease. Note that all differences fall well within the normal scatter in fatigue life, approximately one decade. Therefore, the differences are not significant from an engineering standpoint.

Table 19. Fatigue Properties

Paint Removal Methods	2024-T3 Clad		7075-T6 Bare		7075-T6 Clad	
Reference	Smooth	Notch	Smooth	Notch	Smooth	Notch
(4), Chemical	-		-		-	
(2),DMB (Wheat Starch)	-				-	
(5), PMB (Plastic)	-				NS	
(6), Flash lamp		NS		+		+
PLCRS						
CO_2	NS	NS	+	-	NS	NS
Nd YAG (Q)	-	-	-	-	NS	-
Nd YAG (C)	NS	-	-	-	NS	-
NS – No Statistically Significant Difference						
- Statistically Significant Decrease						
+ Statistically Significant Increase						
- No tabulated reference data found						

5.3 Four-Point Flexural Testing

The testing and the reference data results for Four Point Flexural Testing are displayed in **Figures 25, 26, and 27**. Each baseline and paint removal method had at least five replicates with the average flexural strength represented in the graphs. The baseline data for the project test data and the reference data are represented by the black bar that appears on the left in each data set. The bars next to the baseline information are the paint removal test results labeled by the removal method. The reference number is displayed over the data from which it was extracted and corresponds to the summary chart in Appendix A. A statistically significant difference in the data between the baseline and the paint removal method at a 90% simultaneous confidence interval is indicated by a '√' mark. A data set without a '√ 'mark indicates no statistical difference.

Figure 25 shows the results of the project testing of graphite/epoxy flexural test and the reference data found for that material. The 120 watt Nd:YAG laser results show a decrease in flexural strength in comparison to the baseline data. The reference data shows no statistical change in flexural properties except for the wet abrasive method, which showed an increase.

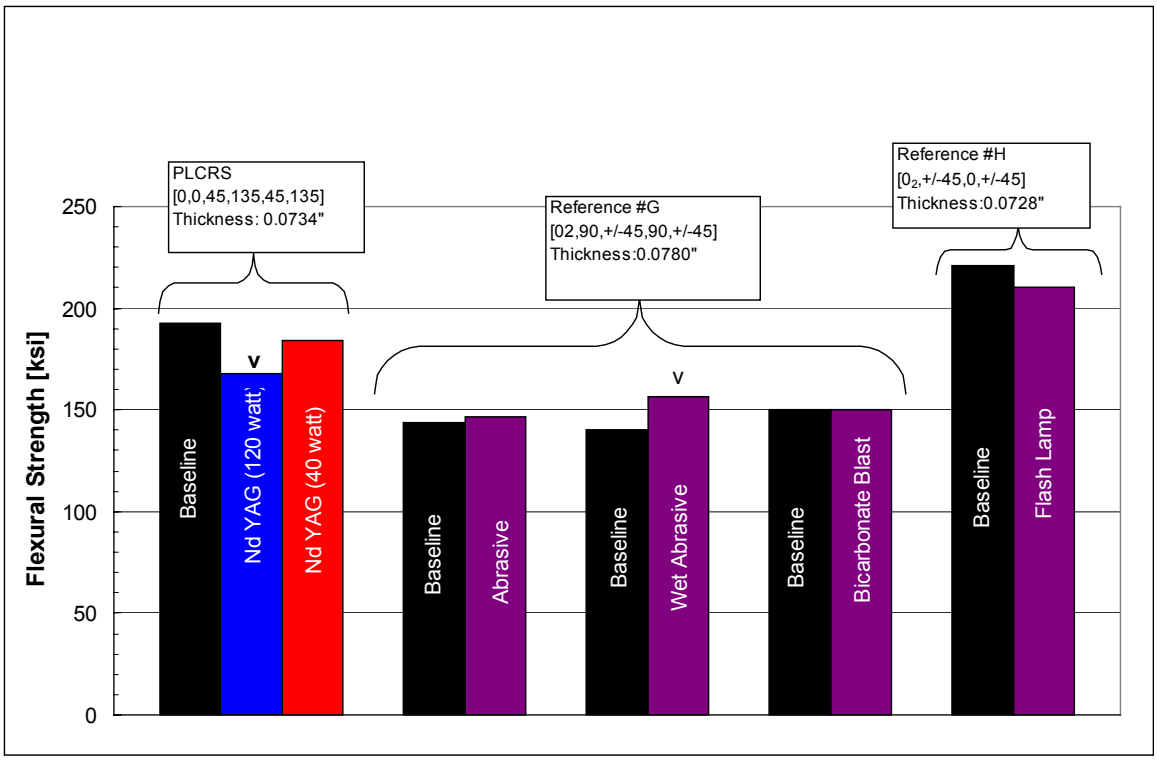


Figure 25. Graphite/Epoxy Flexural Strength Results

Figure 26 displays the project test results for flexural strength for the graphite, fiberglass and Kevlar epoxy laminate tests. The fiberglass results show a decrease in flexural strength for both of the Nd:YAG lasers compared to the baseline. The Kevlar results showed no difference between the Nd:YAG lasers.

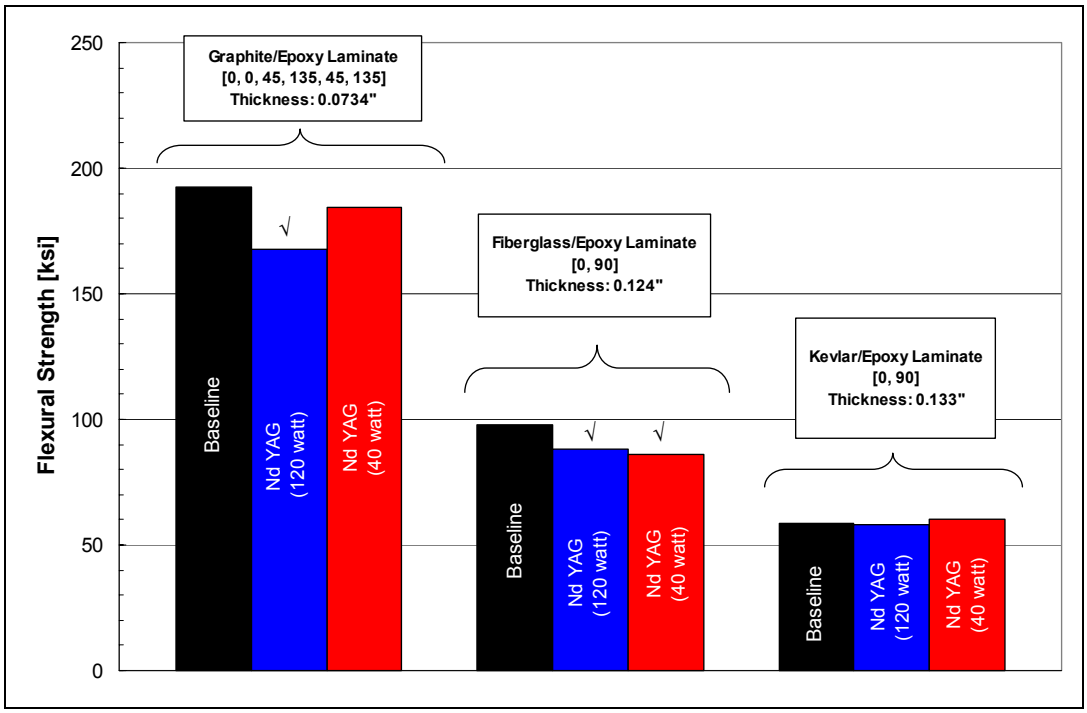


Figure 26. Graphite, Fiberglass, and Kevlar /Epoxy Flexural Strength Results

Figure 27 displays the project test data and a PMB reference data for graphite/epoxy laminate flexural strength results. Only the four cycle PMB at 38 and 60 psi showed a decrease in strength.

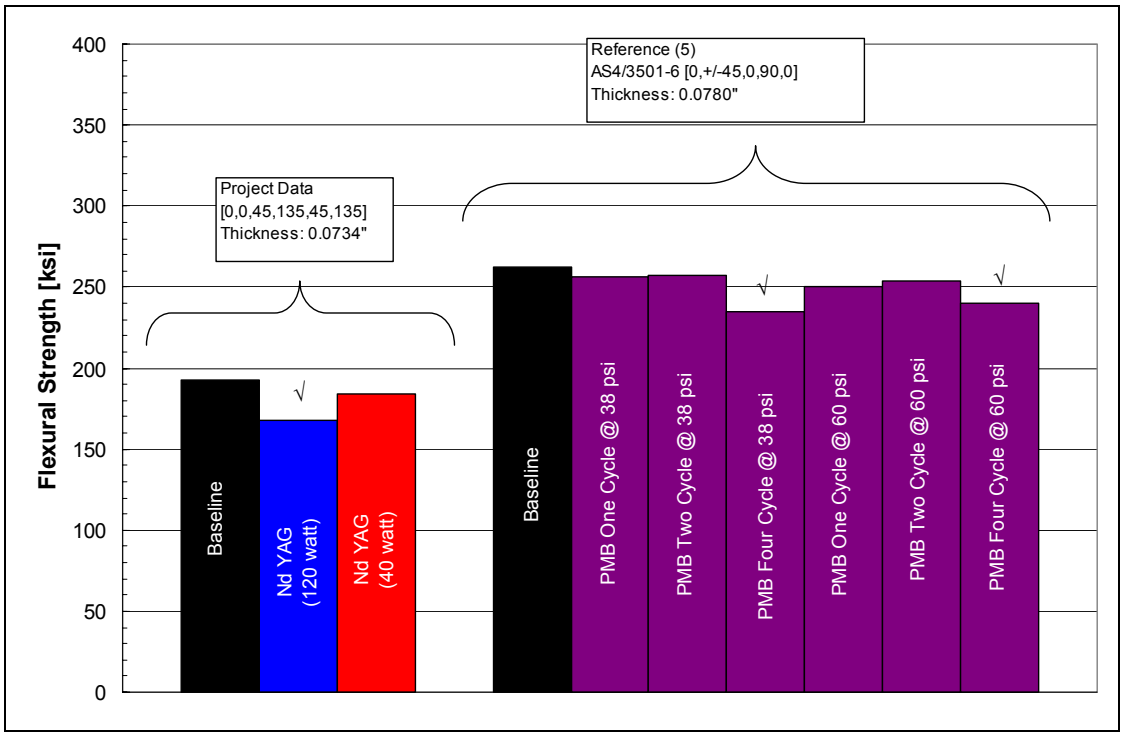


Figure 27. Graphite/Epoxy Flexural Strength Results for Project Data and PMB

5.4 Summary of Literature Comparison Study

Table 20 summarizes the effects of the paint removal methods on the mechanical properties of the metallic substrates. No conclusive data depict one paint removal method to be better or worse than the others. The statistical significance presented may not represent an engineering significance. Most of the metallic tension mean levels (TUS, TYS, percentage of elongation) are above the 'A' Allowable given in the MMPDS Handbook. The most notable view from this study was how little mechanical property test data has been published on the past paint removal methods.

Table 20. Metallic Matrix for Paint Removal Methods

	Material - 2024-T3 Ba															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

A matrix of the composite flexural strength results and the reference data is presented in **Table 21**. The space marked "+" indicates an increase (at a 90% confidence interval) in the flexural strength, while "-" indicates a decrease.

Table 21. Matrix for Composite Flexural Data

Paint Removal Method	Graphite/Epoxy	Fiber Glass/Epoxy	Kevlar/Epoxy
Reference	Flexural Strength	Flexural Strength	Flexural Strength
(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		

6. SUMMARY AND RECOMMENDATIONS

This testing was conducted in order to validate the use of handheld lasers for use in coatings removal operations. Use of this technology would reduce or eliminate DoD dependence on the hazardous chemicals and processes that are currently used to remove coatings from parts during depot maintenance. The chemicals that are typically used in this process are high in volatile VOCs and HAPs, which are targeted for reduction/elimination by environmental regulations.

The objective of this demonstration was to verify the ability of portable hand held laser coating removal systems to effectively remove common DoD coating systems without causing physical damage to the substrate. The results from this testing provide the DoD with information that can be used to assist in the implementation of laser paint stripping operations at their facilities.

Test results that were achieved during this demonstration indicate that, in general, the 120 watt and 40 watt Nd:YAG lasers may be used for small coating removal applications on metallic substrates. Some test results for these lasers are below the acceptance criteria that were outlined in the JTP, but upon a closer review of the test results it was revealed that their performance was comparable to other approved and currently used coating removal techniques.

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

7. REFERENCES

(1) "Laser Paint Stripping," Head, J.D., J. Peter Niedzielski, et al., Air Force Systems Command, June 1991.

(2) "Evaluation of Envirostrip for De-painting Thin-Skinned Aluminum Alloys," Spigel, Barry S., Janet Buchingham, and Craig McClung, Air Force Material Command, October 2000.

(3) "Mechanical Behavior of Al 2024 Alloy Specimen Subjected to Paint Stripping by Laser Radiation and Plasma Etching", Sp. G. Pantelakis, Elsevier Science, 1996.

(4) "Evaluation of the Effects of Chemical and Plastic Media Blasting Paint Removal", Alford, C., Decker, R.C., et al., Air Force Materiel Command, April 1994.

(5) "evaluation of the Effects of a Plastic Bead Paint Removal Process on Properties of Aircraft Structural Materials," Childs, Sidney, Air Force Systems Command, December 1985.

(6) "Flashjet Qualification Testing for Lifecycle De-Painting of Rotary Wing Fuselage Skins," Kozol, Joseph, Hartle, Steven, Raley, Paul, and Berkel, Thomas, Naval Air Warfare Center, April 2001.

(7) "Paint Removal From Composites and Protective Coating Development," Kopf, Peter W., Air Force Systems Command, January 1991.

(8) "Acoustic Fatigue Testing of the Flashjet Process," Berkel, Thomas, August 1999.

(9) "Xenon Flashlamp and Carbon Dioxide Advanced Coatings Removal Development and Evaluation Program," Breihan, David W., Reilly, James, McDonnell Douglas Corporation, Report #MDC 93B0341, July 1993.

(10) "Joint Test Protocol (J-00-CR-017) for Validation of Portable LASER System for Coating Removal." Science Applications International Corporation (SAIC), Contract No. F33615-95-D-5615-0068, February 2001 (revised March 12, 2002).

(11) "Final Report, Portable Handheld Laser Small Area Supplemental Coating Removal (PLCRS), Screening/Common Testing and Demonstration/Validation," Anteon Corporation, Contractor Report, Contract No. GS07T00BGD0029, Task No. 5TS5701D218 and 5TS5702D370, October 2003.

(12) "Portable Laser Coating Removal Process (PLCRS) Final Report," Joseph, C. University of Dayton Research Institute (UDRI), Contractor Report, Contract No. F42620-00-D0039-0001, UDRI Report No. UDR-TR-2004-00173, CTIO Tracking No. UDRI-2187-T1-03, December 2004.

(13) "Effects on Mechanical Properties From Laser Paint Stripping," Coleman, J. and Sjöblom, P, University of Dayton Research Institute (UDRI), Contractor Report, Contract No. F42620-00-D0039-0001, RZ16, March 2005.

Appendix B
Analytical Methods Supporting the Experimental Design

The Analytical methods' supporting the testing that was performed during this demonstration is listed below. Each of these standards is available from their issuing organization.

STANDARD NUMBER	STANDARD TITLE
ASTM C393	Standard Test Method for Flexural Properties of Sandwich Constructions
ASTM D 1781	Standard Test Method for Climbing Drum Peel for Adhesives
ASTM D 3359	Standard Test Method for Measuring Adhesion by Tape Test
ASTM D638	Standard Test Method for Tensile Properties of Plastics
ASTM D695	Standard Test Method for Compressive Properties of Rigid Plastics
ASTM D790	Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials
ASTM E1004	Standard Practice for Determining Electrical Conductivity Using the Electromagnetic (Eddy-Current) Method
ASTM E114	Standard Practice for Ultrasonic Pulse-Echo Straight-Beam Examination by the Contact Method
ASTM E18	Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials
ASTM E647	Standard Test Method for Measurement of Fatigue Crack Growth Rates
ASTM E8	Standard Test Methods for Tension Testing of Metallic Materials
MIL-A-8625	Anodic Coatings for Aluminum and Aluminum Alloys
MIL-C-46168	Coating, Aliphatic Polyurethane, Chemical Agent Resistant
MIL-C-5541E	Chemical Conversion Coatings on Aluminum and Aluminum Alloys
MIL-PRF-23377	Primer Coatings: Epoxy, High-Solids
MIL-P-53030	Primer Coating, Epoxy, Water Reducible, Lead and Chromate Free
MIL-PRF-85285	Coating: Polyurethane, Aircraft and Support Equipment
MIL-R-9300	Resin, Epoxy, Low-Pressure Laminating
MIL-STD-401	Sandwich Constructions and Core Materials, General Test Methods
SAE MA4872	Paint Stripping of Commercial Aircraft – Evaluation of Materials and Process

Appendix C
Air Sampling Reports

DEPARTMENT OF THE AIR FORCE
AIR FORCE INSTITUTE FOR OPERATIONAL HEALTH (AFMC)
BROOKS CITY-BASE TEXAS

29 Apr 05

MEMORANDUM FOR AFRL/MLSC

FROM: AFIOH/RSHI
2513 Kennedy Circle
Brooks City-Base, TX 78235-5116

SUBJECT: Consultative Letter, IOH-RS-BR-CL-2005-0044, Evaluation of Laser De-Painting System

1. INTRODUCTION

a. *Purpose:* On 1-2 March 05, the Industrial Hygiene Branch of the Air Force Institute for Operational Health (AFIOH/RSHI), per the request of HQ AFMC Bioenvironmental Engineering (HQ AFMC/SGPB), performed an exposure assessment of the Cleanlaser depainting system. This survey was performed as a pre-field use evaluation of this system. This letter provides the results of our evaluation.

b. *Survey Personnel:*

Capt David DeCamp, AFIOH/RSHI, Industrial Hygiene Consultant
Capt Ian Rybczynski, AFIOH/RSHI, Industrial Hygiene Consultant
TSgt Henry DeBose, AFIOH/RSHI, Industrial Hygiene Technician
SSgt Gabriel Almario, AFIOH/RSHI, Industrial Hygiene Technician
SSgt Justin Murphy, AFIOH/RSHI, Industrial Hygiene Technician

c. *Personnel Contacted:*

Lt Col Michael Elliot, HQ AFMC/SGPB
Tim Sumpter, AFRL/MLSC
Harold Hall, AFRL/MLSC
Derek Upchurch, AFRL/MLSC

d. Equipment Used:

SKC Air Check Sampler (Model 224PCXR8)
BIOS DryCal DC-Lite Primary Flow Meter
Metrosonics AQ-5000 Indoor Air Quality Meter
Quest Technologies SoundPro DLX-2-1/1 Sound Level Meter
Quest Model QC-10 Acoustic Calibrator

Distribution: Approved for public release; distribution unlimited.

Solar Light PMA2141 Class II Pyranometer
Solar Light PMA2100 Photometer

2. BACKGROUND:

a. *De-Painting.* De-painting aircraft is a standard step in the corrosion control processes found on nearly every AF installation. Depot-level de-painting processes can use chemicals such as methelyne chloride or similar chemical strippers to remove coatings from aircraft and support equipment. However, these chemical strippers typically have serious health and environmental concerns associated with their use as well. These concerns have led to research in alternative de-painting methods. Currently, laser de-painting is being investigated as an alternative and/or supplemental de-painting method at the depot and field levels.

b. *Laboratory Study:* For this assessment, AFIOH was asked to look at a laser de-painting system that is being considered for field use. This assessment took place in a laboratory setting; however, all removed coatings were standard aircraft primers and paints from the AF supply system. The coatings were applied to two-foot square aluminum or composite test panels and these panels were painted under the same technical requirements established for aircraft painting.

c. *Cleanlaser.* The Cleanlaser optical machining system was developed for use in industrial cleaning processes. The Cleanlaser 120 Q is an ANSI Class IV laser operating at 120 W average power at a nominal wavelength of 1,064 nm. The laser and laser system chiller are mounted on a cart for mobile operation (Figure 1). The laser beam is delivered via fiber optical cables and a manually operated laser head. The laser system was used with a Fumex FA2 HEPA filtration unit, which removes de-painting products at the laser head. Paint is removed from the substrate via laser ablation.

Figure 1. Cleanlaser 120 Q System

d. *Laser Ablation:* Laser ablation (Figure 2) is achieved by using pulsed lasers that create bursts of high intensity energy. Although it may seem otherwise, laser ablation is a mechanical process. A shock wave is created by vaporizing a thin layer of coating into plasma. The 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. These characteristics include power, wavelength, pulse width, pulse frequency, beam profile, and operating parameters.

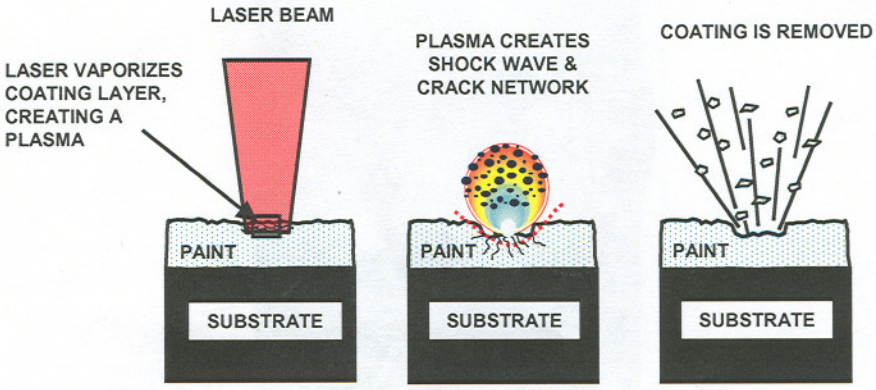


Figure 2. Illustration of Laser Ablation Mechanism

e. *Removal Process.* During de-painting tasks, the operator is required to place the laser head above the substrate surface and move the head over all areas where paint removal is required (Figure 3). Additional pictures of the process are shown in attachment 1. Repeated passes might be necessary to ensure complete coating removal. The laser head had rollers on it that allowed the operator to easily maneuver the laser head around the square test panels. The laser was turned on and off with a simple trigger system and the laboratory was equipped with interlocks on both entry doors.

Figure 3. De-painting a test plate

f. *Ventilation System.* A Fumex F-2 portable ventilation system was incorporated into the laser head. The Fumex system connects directly to the laser head and has a HEPA collection bag. After particles are removed within the collection bag, the exhaust air is sent to the building's industrial ventilation system, which eventually sends the air to a stack. The capture port was located directly behind the laser and the system was designed to capture the removed coating particles. Figures 4 and 5, below, depict how the ventilation system is incorporated into the laser head.

Figure 4. Laser head with operational nozzle

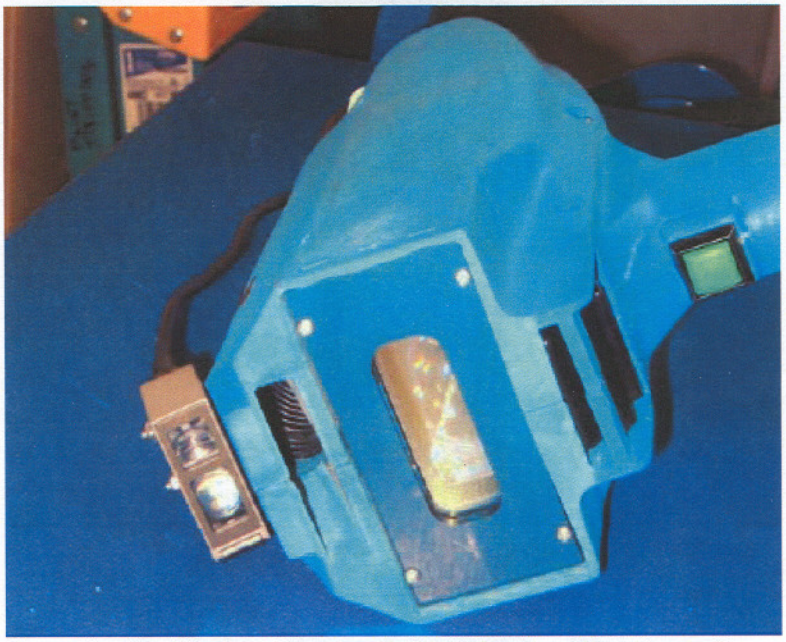


Figure 5. Laser head with nozzle removed. (Not operational configuration)

3. PROCEDURES

a. *Assessment Strategy:* Although laser ablation has been used for years, health hazards associated with this type of paint removal process are not well evaluated. Thus, AFIOH performed a complete assessment of the key hazards: laser radiation, airborne, and noise exposures. Ergonomic hazards also exist; however, AFIOH has already addressed the ergonomic issues associated with this Cleanlaser system in IOH-RS-BR-CL-2004-0030. Prior to our assessment, available literature on laser ablation were reviewed to limit our air sampling to the most likely contaminants. After reviewing the data, we decided to sample for metals, hydrogen cyanide, nitrogen oxide, nitrogen dioxide, carbon dioxide, carbon monoxide, and formaldehyde.

Although isocyanate-based paints are used, it is expected that these paint components have already reacted during the polymerization process. Although 'complete' reaction is always debatable, our research indicated measurable levels of isocyanates were highly unlikely during the ablation process.

b. *Substrate Differences:* The testing facility had two substrates available for us to assess: aluminum and composite. Although paint removal was performed on both substrates during a single day, we separated our assessments by substrate. We did this because we were interested in determining if substrate had an effect on exposure levels.

c. *Media and Collection Methods:*

(1) Metals: NIOSH Method 7300, *Elements by Inductively Coupled Plasma Spectroscopy (ICP)*, which employs a 37-mm closed face cassette containing a 0.8-μm mixed cellulose ester (MCE) filter, was used to sample airborne aluminum, barium, cadmium, chromium, copper, iron, lead, nickel, strontium, titanium and zinc.

(2) Hexavalent Chrome: NIOSH Method 7605, *Cr(VI) by Ion Chromatography*, which employs a 37-mm closed face cassette containing 5.0-μm polyvinyl chloride (PVC) filter, was used.

(3) Hydrogen Cyanide: NIOSH Method 6010, *HCN by Visible Absorption Spectrophotometry (VAS)*, which employs a 600/200 mg soda lime sorbent tube was used.

(4) Nitrogen Oxide/Dioxide: NIOSH Method 6014, *Nitric Oxides by VAS*, which employs a 400/200 mg triethanolamine treated molecular sieve sorbent tube, was used. A Metrosonics aq-5000 Indoor Air Quality (IAQ) meter was also used to monitor nitrogen dioxide (NO_2). The resolution for the NO_2 sensor was 0.1 ppm.

(5) Carbon Monoxide/Dioxide: A Metrosonics aq-5000 Indoor Air Quality (IAQ) meter was used to monitor carbon monoxide(CO)/dioxide(CO_2). The resolution for both the CO and CO_2 sensor was 1 ppm. Measurements were taken and logged once a second for the duration of the de-painting processes.

(6) Noise: A Quest Technologies SoundPro DLX-2-1/1 was used to measure the sound pressure level. The calibration was checked with a Quest Model QC-10 acoustic calibrator before and after sampling and found to be within ± 0.3 dB.

(7) Laser Radiation: A Solar Light PMA2141 class II pyranometer connected to a Solar Light PMA2100 photometer was used to measure the reflected scattered irradiance from the handheld laser during use.

(8) Ventilation: A TSI VelociCalc Plus ventilation meter was used to measure capture velocity. Measurements were taken at the center of the nozzle's capture port.

4. RESULTS

a. *Airborne Exposure Limits:* AFOSH Standard 48-8, *Controlling Exposures to Hazardous Materials*, adopts the most stringent Occupational Exposure Limits (OEL) of either the Permissible Exposure Limits (PELs) set by the Occupational Safety and Health Administration (OSHA), or Threshold Limit Values (TLVs) adopted by the American Conference of Governmental Industrial Hygienists (ACGIH).

(1) Aluminum Substrate De-Painting Process:

Table 1. Laser Ablation on Aluminum Plate Day 1

Analyte	Sample Time (min)	Sample Results (mg/m^3)	8-Hour TWA	8-Hour TWA-OEL Standard (mg/m^3)
Aluminum	120	<0.00298	<0.000745	10
Barium	120	<0.000595	<0.000149	0.5
Cadmium	120	<0.000298	<0.0000745	0.005
Chromium	120	0.000595*	0.000149*	0.5
Chrome (VI)	124	0.0000590*	0.0000152*	0.01
Copper	120	<0.00298	<0.000745	1
Iron	120	<0.00595	<0.00149	5
Lead	120	<0.00149	<0.000373	0.05
Nickel	120	<0.00149	<0.000373	1
Strontium	120	<0.000298	0.000149*#	0.0005#
Titanium	120	<0.000298	<0.0000745	n/a
Zinc	120	<0.00298	<0.000745	n/a
Formaldehyde	117	<0.00547	<0.00133	2.46
Nitric Oxide	119	<0.168	<0.0417	30
Nitrogen Dioxide	119	<0.168	<0.0417	5.6
Hydrogen Cyanide	130	<0.0769	<0.0208	11

Notes: < indicates a non-detect sample and is followed by maximum possible concentration.
* indicates blank corrected value
\# Strontium Chromate

Table 2. Laser Ablation on Aluminum Plate Day 2

Analyte	Sample Time (min)	Sample Results (mg/m^3)	8-Hour TWA	8-Hour TWA-OEL Standard (mg/m^3)
Aluminum	132	<0.00236	<0.000649	10
Barium	132	<0.000473	<0.000130	0.5
Cadmium	132	<0.000236	<0.0000649	0.005
Chromium	132	0.00236*	0.000649*	0.5
Chrome (VI)	132	0.0000553*	0.0000152*	0.01
Copper	132	<0.00236	<0.000649	1
Iron	132	<0.00473	<0.00130	5
Lead	132	<0.00118	<0.000325	0.05
Nickel	132	<0.00118	<0.000325	1
Strontium	132	<0.000236	0.0000152*#	0.0005#
Titanium	132	<0.000236	<0.0000649	n/a
Zinc	132	<0.00236	<0.000649	n/a
Formaldehyde	127	<0.00504	<0.00133	2.46
Nitric Oxide	137	<0.145	<0.0414	30
Nitrogen Dioxide	137	<0.145	<0.0414	5.6
Hydrogen Cyanide	136	<0.0735	<0.0208	11

Notes: < indicates a non-detect sample and is followed by maximum possible concentration.
* indicates blank corrected value
# Strontium Chromate

Table 3. STEL Sampling

Analyte	Sample Time (min)	Sample Results (mg/m^3)	STEL Standard (mg/m^3)
Formaldehyde	15	<0.0107	0.37
Nitrogen Dioxide	17	<0.159	9
Hydrogen Cyanide	15	<0.667	5

(2) Composite Substrate De-Painting Process:

Table 4. Laser Ablation on Composite Plate

Analyte	Sample Time (min)	Sample Results (mg/m^3)	8-Hour TWA	8-Hour TWA-OEL Standard (mg/m^3)
Aluminum	90	<0.00397	<0.000744	10
Barium	90	<0.000794	<0.000149	0.5
Cadmium	90	<0.000397	<0.0000744	0.005
Chromium	90	<0.000794	<0.000149	0.5
Chrome (VI)	91	0.0000804*	0.0000152*	0.01
Copper	90	<0.00397	<0.000744	1
Iron	90	<0.00794	<0.000149	5
Lead	90	<0.00198	<0.000371	0.05
Nickel	90	<0.00198	<0.000371	1
Strontium	90	<0.000397	0.0000152*#	0.0005#
Titanium	90	<0.000397	<0.0000744	n/a
Zinc	90	<0.00397	<0.000744	n/a
Formaldehyde	83	<0.00578	<0.0010	2.46
Nitric Oxide	90	<0.222	<0.0416	30
Nitrogen Dioxide	90	<0.222	<0.0416	5.6
Hydrogen Cyanide	90	<0.111	<0.0208	11

Notes: < indicates a non-detect sample and is followed by maximum possible concentration.
* indicates blank corrected value
\# Strontium Chromate

b. *Indoor Air Monitoring:* In order to measure CO and CO_2, a direct reading monitor was used. The results of these measurements are presented in Table 5, below.

(1) Aluminum Substrate De-Painting Process:

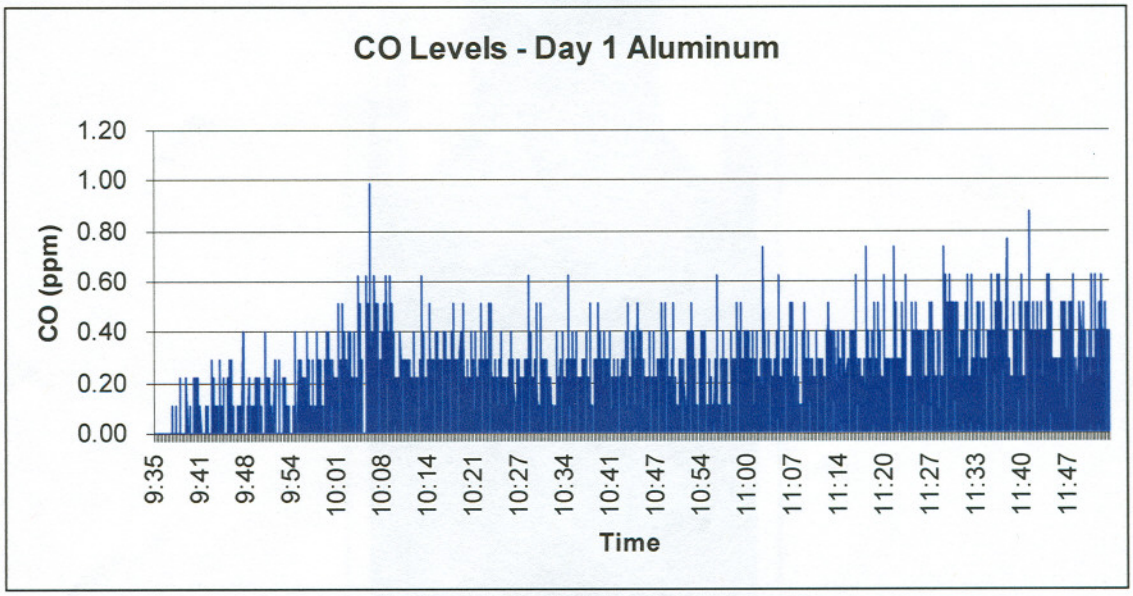


Figure 6. CO levels during first day of aluminum plate de-painting.

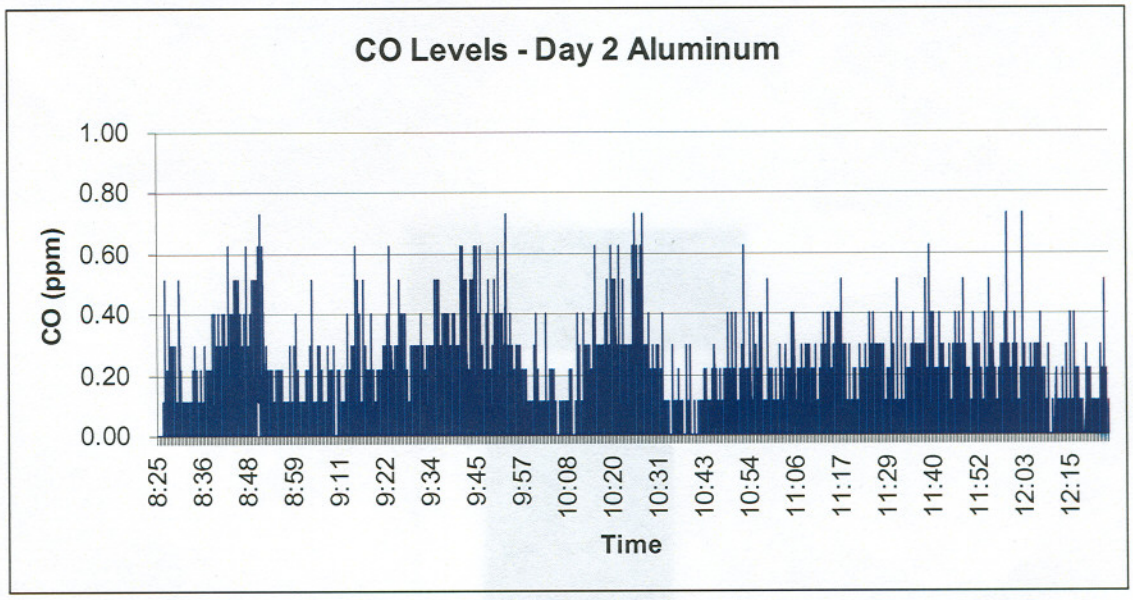


Figure 7. CO levels during second day of aluminum plate de-painting.

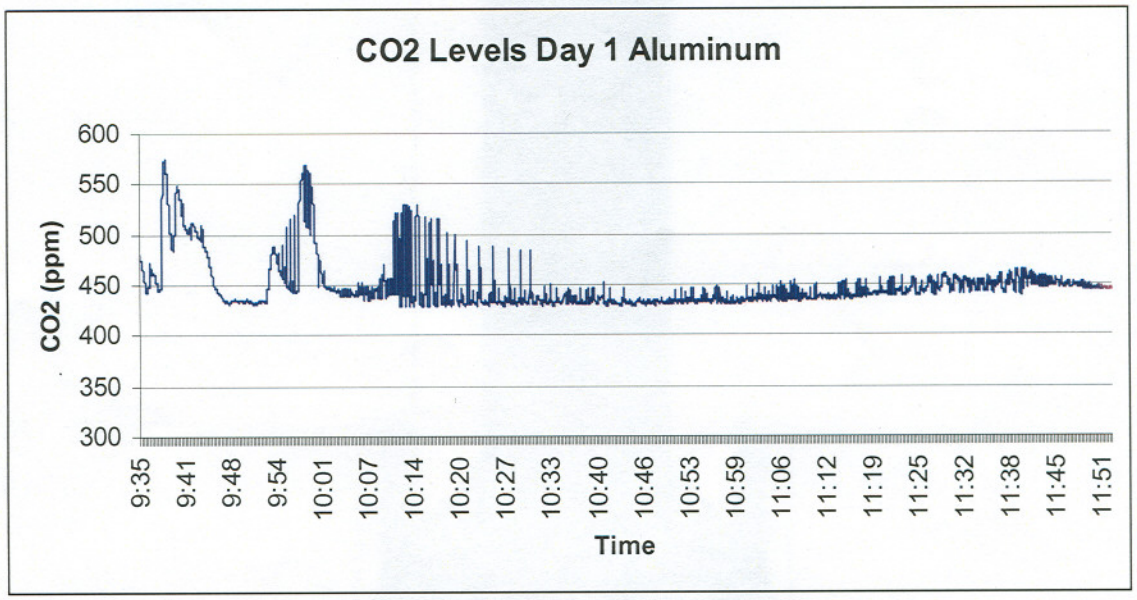


Figure 8. CO_2 levels during first day of aluminum plate de-painting.

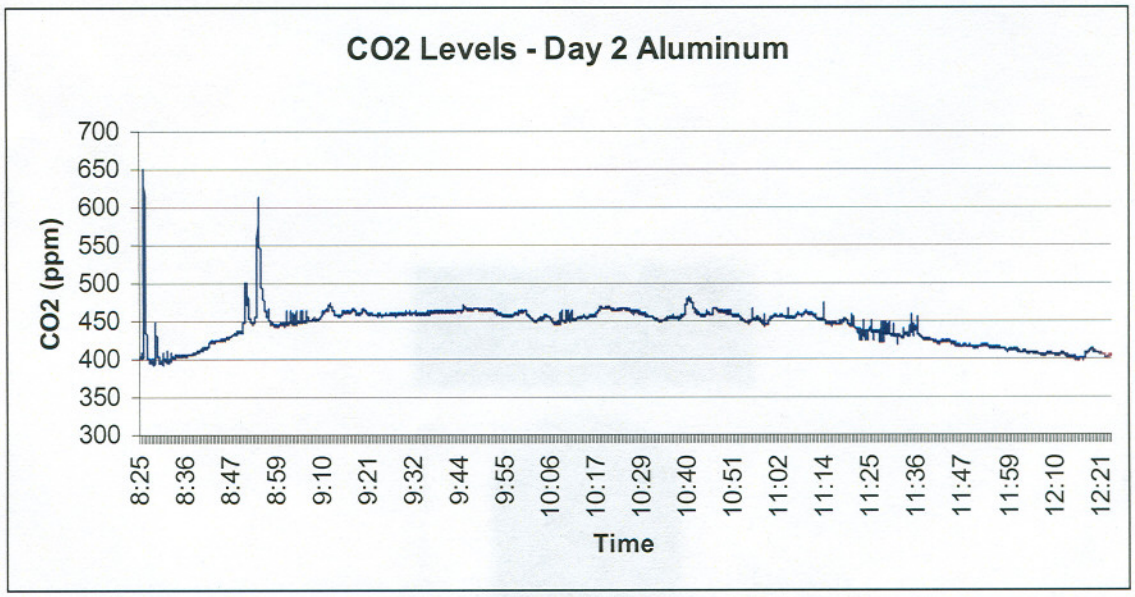


Figure 9. CO_2 levels during first day of aluminum plate de-painting.

(2) Composite Substrate De-Painting Process:

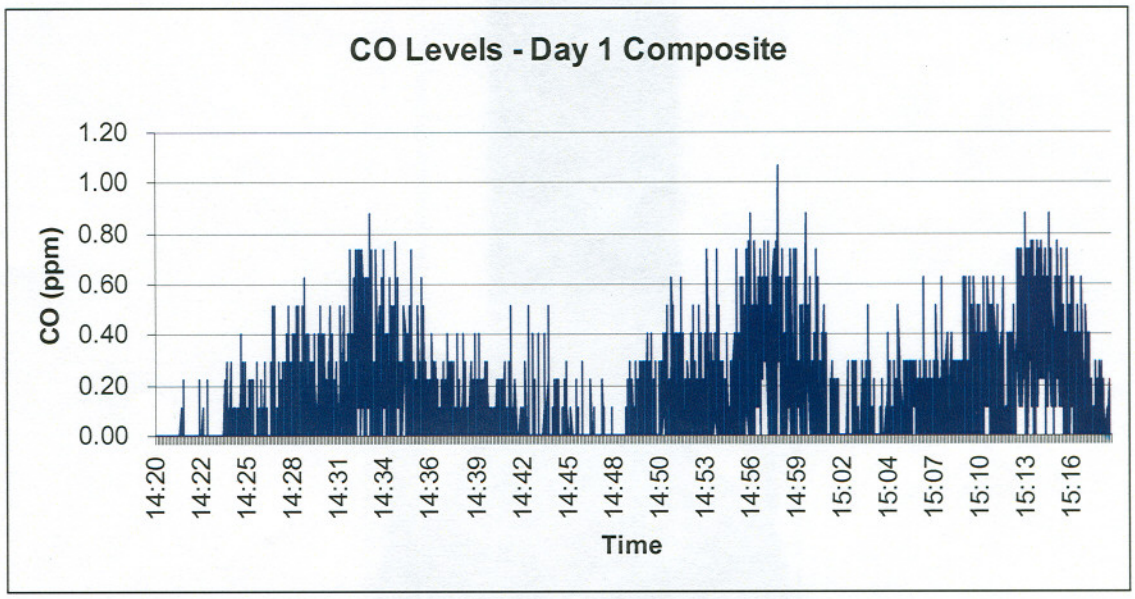


Figure 10. CO levels during composite plate de-painting.

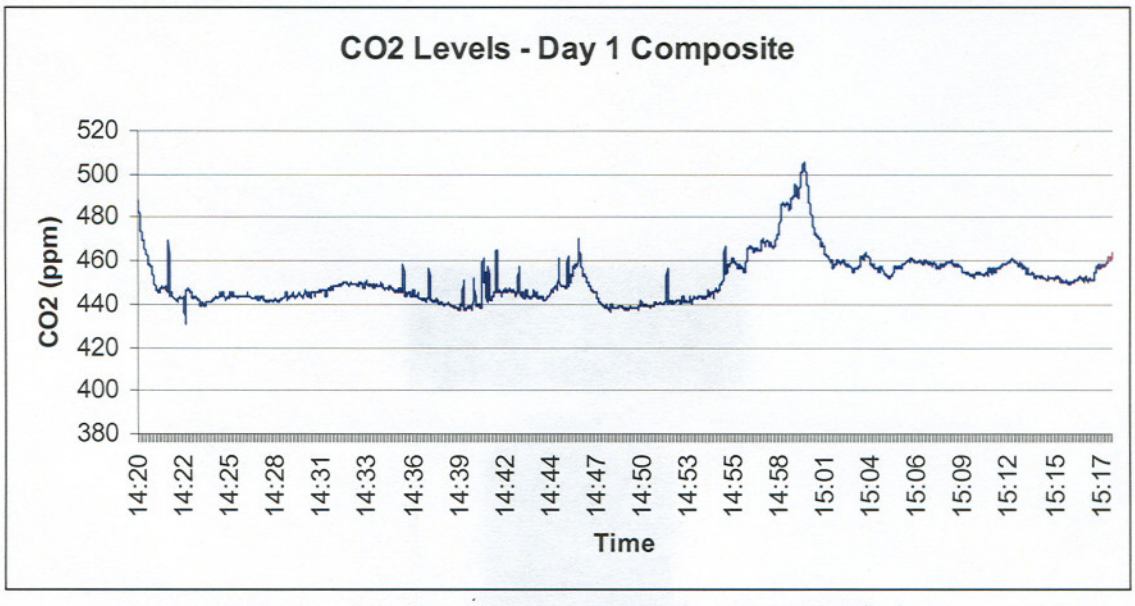


Figure 11. CO_2 levels during composite plate de-painting.

c. *Noise Levels:* The table below contains sound pressure levels measured during paint removal operations. Six sound level measurements were taken near the worker's ear. Measurements were taken for two different operators and for both substrates.

Table 5. Measured Octave Band Sound Pressure Levels (SPLs) Near the Worker's Ear

Octave Band Center Frequency, Hz	Measured Octave Band SPLs Near the Worker's Ear, dB						Geometric Mean SPL, dB
31.5	34.1	37.2	35.2	35.3	32.6	34.1	34.8
63	42.5	42.4	44.8	44	46.5	45.7	44.3
125	59.2	63.5	61.7	61.5	63	61.3	61.7
250	65.5	66.1	67	68.3	66.5	68.4	67.0
500	72.7	70.2	73.7	75.5	72.7	72.6	72.9
1000	73.5	73	74.9	76	73.8	73.7	74.2
2000	76.3	74.7	72.8	74.4	72.1	72.6	73.8
4000	73.9	72	73.1	71.1	71.3	69.6	71.8
8000	72.2	67.6	76.1	70.9	70.6	73.8	71.9
Calculated dB(A)	81.2	79.5	81.0	80.8	79.1	79.4	80.0

d. *Laser Radiation.*

(1) The Cleanlaser 120 Q is a Class 4 laser as defined in paragraph 3.3 of the American National Standards Institute (ANSI) Standard Z136.1-2000, *American National Standard for the Safe Use of Lasers*. A hazard analysis of the laser was preformed with the current USAF approved laser hazard analysis software (LHAZ), IAW paragraphs 3.2 and A3.2.6 of AFOSH Standard 48-139, *Laser Radiation Protection Program*. Based on data from Adapt Laser

Systems (service center in the U.S. for the Cleanlaser), the following parameters were entered into LHAZ version 4.4.26:

Parameters entered into LHAZ	
Wavelength:	1064 nm
Output Mode:	Multiple pulse
Average Power:	100 W
Energy Per Pulse:	12.5 mJ
Pulse Duration:	120 ns
PRF:	8 kHz
Beam Profile:	Circular
Beam Distribution:	Top hat
Beam Divergence:	75 mrad
Beam Waist Diameter:	0.4 mm
Beam Waist Range:	10 cm
Output Aperture Diamater:	1.5 cm
Source Size:	0 (conservative)

(2) Attachment 1 lists the variable parameters for the Cleanlaser system. The chosen values for LHAZ of the variable parameters were determined from the "worst-case" optical density calculation and do not represent the typical operational settings. The results from the calculations are shown in the following table. From discussion with the contractor testing the laser, the pulse repetition frequency (PRF) is set usually between 15 to 18 kHz. The thickness of the paint determines the appropriate PRF. The scan width is set usually to 50 mm and the scan speed is usually between 70 to 100 Hz.

MPE Computations:			
Exposure Duration:	10 seconds		
Exposure Range:	10 cm		
MPE (Eye):	2.97×10^{-7} J/cm^2		
MPE (Skin):	1.25×10^{-4} J/cm^2		
Hazard Distances and OD Requirements:		**Diffuse Reflection Hazard Analysis:**	
Ocular		**Ocular**	
Exposure Duration:	10 seconds	Exposure Duration:	600 seconds
NOHD:	30.9 cm	NHZ:	0 cm
At Viewing Distance:	10 cm	At Viewing Distance:	100 cm
Maximum OD:	5.04	OD Required:	0
Skin		**Skin**	
Exposure Duration:	600 seconds	Exposure Duration:	600 seconds
NOHD:	1.6 cm	NHZ (Skin):	0.00 cm
At Exposure Distance:	10 cm	At Exposure Distance:	100 cm
Maximum OD:	3.02	OD Required:	0

(3) The PMA2141 has a very flat response from 305 to 2800 nm (1604 nm for Cleanlaser) and has very little response outside of this region. The pyranometer read up to 0.3 mW/cm^2 within the room when the laser was not operating. The highest measurement recorded with the pyranometer during operation of the laser was 15.9 mW/cm^2, which was measured about six inches away from the laser to the right of the worker's position for about two seconds. Since the laser is constantly moving during operation, the integrated dose measured at any given point in space was relatively small.

e. *Ventilation Measurements.* Face velocity ventilation measurements were used to evaluate the performance of the system. Table 6, below, lists our measurements. Measurements were taken at startup and after every 30 minutes of de-painting tasks. A new HEPA filter bag was in place at the start of the operation and it was replaced between measurements 8 and 9.

Table 6. Face Velocity Ventilation Measurements

Mesurement Number	Face Velocity (f/min)
1	5640
2	5000
3	4810
4	5325
5	4760
6	4480
7	3800
8	3900
9	6300
10	5800
11	5400
12	6250

5. DISCUSSION

a. *Airborne Exposures:*

(1) Our air sampling results indicated that operator airborne exposures were very low. No calculated exposure levels were above an OEL or an action level. In fact, the only air sample results that came back with detectable levels were our samples for chromium. However, the chromium results are most likely caused by filter contamination, not actual airborne levels. (This is a known problem with SKC filters. Blanks have consistently had detectable levels for years). We sent in four MCE blanks for this effort and the lab reported 0.255, 0.261, 0.321, and 0.453 µg/sample. All of our 7300 air sampling results were below the high value in the range of our blanks and no other metals had detectable levels; thus, it is reasonable to assume all chromium results were from filter contamination. We had this same problem with our hexavalent chrome samples. We again had the lab analyze four PVC blanks and the lab reported none detected, 0.0300, 0.0540, 0.0620 µg/sample for these blanks. In the results section, we reported a blank corrected airborne exposure level; however, given the range of our blank results, it is once again

reasonable to conclude all hexavalent chrome results were caused by filter contamination. Regardless of where the chromium came from, all calculated exposure levels were below the AF OELs. No differences based on substrate were noted for airborne exposures.

(2) The indoor air quality meters allowed us to continuously monitor carbon monoxide and carbon dioxide levels within the work area. Significant increases in CO or CO_2 were not noted during our survey. We were most interested in seeing if there were any significant CO levels because this could indicate that some chemical reactions were occurring during the ablation process; however, our CO monitoring didn't indicate any significant CO production at any time during the day and half of de-painting operations. Although there has not been significant research on the breakdown of polyurethane paints during heating, research on polyurethane foams has indicated CO, NOX, and HCN production is most likely. Combustion processes typically yield smaller carbon molecules, so we also looked to see if there was any formaldehyde production; however, we did not find detectable levels of NO, NO_2, HCN, or formaldehyde. Again, no substrate-based differences were noted.

(3) CO_2 can also be produced during the combustion of polyurethanes, but the spikes we saw could have been produced from worker respiration as well. Given the lack of other gasses found, it seems reasonable that the latter explanation was the cause of our occasional CO_2 spikes. The CO_2 results were normal for any indoor workspace. Although we did not measure the workspace's ventilation, it seemed to be good. The lack of any significant CO_2 buildup throughout the workday is an indicator that the workspace itself had good dilution ventilation.

b. *Hazardous Noise:* The highest measured weighted sound pressure level near the ear was 82.5 dB(A) and 84.5 dB(C). Based on these results, workers who operate the Cleanlaser would not be exposed to hazardous noise levels. However, the laboratory environment where the measurements were conducted do not realistically account for other noise sources found in a typical corrosion control hangar. Also, in the laboratory setting, the operator was leaning over a table with the handheld laser. In the operational environment, the worker might be placing the handheld laser in many different positions relative to his body. Figure 12, below, shows that the sound pressure level will increase by about 10 dB if the worker positions the laser near his head (e.g., due to limited space). At this exposure level, depending on the exposure time, the worker could be exposed to hazardous noise levels IAW Table 2.2 of AFOSH Standard 48-19, *Hazardous Noise Program*. The large increase in noise might also be partially related to a body baffle effect, which occurs when a microphone is held too close to a body.

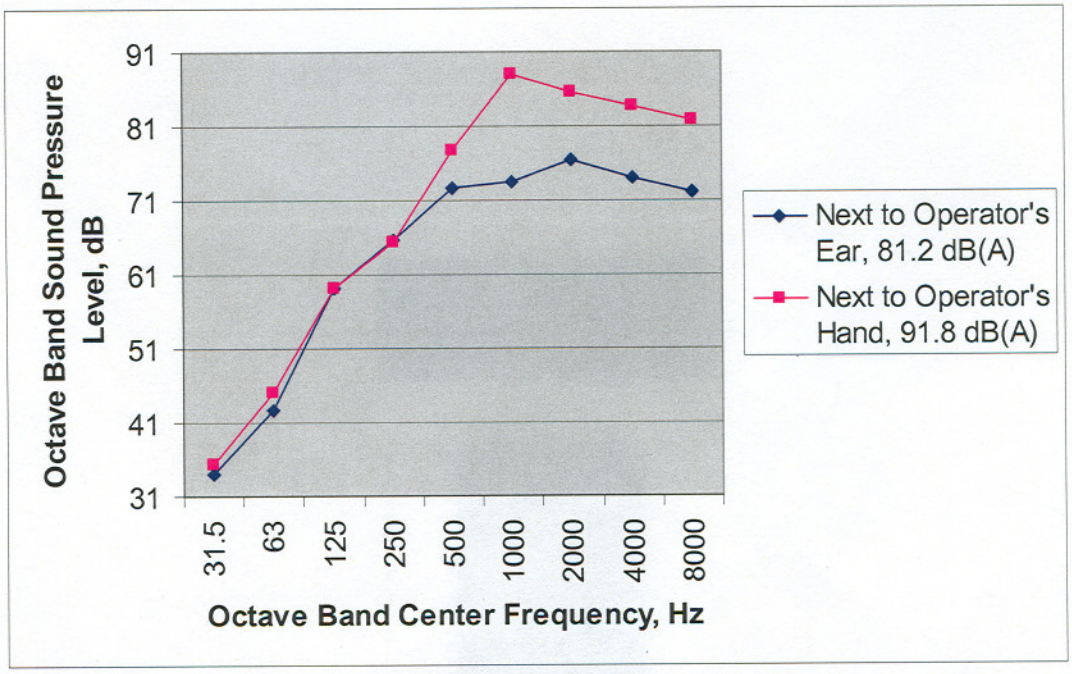


Figure 12. Comparison of the Octave Band Spectrum of the Cleanlaser near the ear and the hand.

c. *Laser Radiation*:

(1) Paragraph 9.1 of ANSI Standard Z136.1 states that measurements are necessary only if any the following criteria are true: (1) the laser has not been classified by the manufacturer, (2) alterations to the system may have changed its classification, or (3) when the borders of the nominal hazard zone (NHZ) cannot be determined from the analysis of the beam parameters. In this case, none of mentioned criteria were true. To measure the reflected laser light, the ideal detector would have a 7 mm acceptance aperture (to simulate a fully dilated pupil). Making a maximum permissible exposure (MPE) measurement over a larger aperture than 7 mm can introduce errors because any small, intense parts of a radiation pattern are averaged over a larger area. Since this pyranometer has an aperture greater than 7 mm and the response time was too slow, the results were not compared directly with the laser protection standards. AFOSH Standard 48-139, *Laser Radiation Protection Program*, states that it has adopted the current laser protection standards contained in the most recent version of ANSI Publication Z136.1 and the American Conference of Governmental Industrial Hygienists (ACGIH).

(2) The ACGIH threshold limit value (TLV) for the near infrared (IR-A) region protects against thermal injury to the cornea and lens (cataracts) by limiting exposure to 10 mW/cm^2 for durations of 1000 seconds or more. For shorter durations the TLV is time dependent (e.g., 1070 mW/cm^2 for a two second exposure at a wavelength of 1064 nm). The ACGIH TLV is not directly applicable in this case since the laser is not emitting broadband radiation.

(3) In the near infrared region, normal aversion responses to skin-heating usually minimize the potential for skin damage. Nevertheless, gloves and long sleeves shirts should be

worn during operation of the laser. All personnel in the room wore laser eye protection with an optical density of at least seven. Although the LHAZ calculation determined the ocular NOHD was 30.9 cm, we do not believe this is an accurate estimate. The modeling parameters LHAZ uses do not fit the Cleanlaser well. Some of the data describing the Cleanlaser needed to be estimated/converted into more standard laser parameters accepted by LHAZ. Although we tried to error on the conservative side, the actual ocular NOHD is unknown. A System Safety Engineering Analysis (SSAE) was published by HQ AFMC/SES on 24 Jun 04 and that reports a 17 m NOHD for this sysem. With regard to engineering controls, the laser contained interlocks to shut off the laser if the door to the room was opened. Whether this feature will be incorporated in the field is unclear; however, this control is most likely impractical for use in typical corrosion control facilities and flightlines.

d. *Ventilation*:

(1) The absence of any detectable metal exposures during our sampling indicated that ventilation system was very effective for this type of de-painting task. In typical de-painting operations, workers are not always able to de-paint surfaces that are well below their breathing zone, though. No debris or dust was noticed around the de-painted surface, but the adequacy of this ventilation system should be challenged further during operational use, especially when workers are required to de-paint areas above and closer to their breathing zone.

(2) As expected, the capture velocity of the ventilation system slowly decreased as the HEPA collection bag filled. The Fumex F-2 system uses an indicator light to tell users that the HEPA bag needs to be replaced. Based on these sampling results, it appears the indicator light activates before the capture velocity decreases below an effective level. Our air sampling results also indicated that HEPA bag change out was an insignificant exposure for workers.

6. CONCLUSIONS

a. In the laboratory setting, there were no significant exposures to metals, NO, NO_2, CO, CO_2, HCN, or formaldehyde.

b. We did not find any differences in worker exposure related to the substrate (aluminum vs. composite).

c. When workers are able to de-paint at arms-length away from the surface, at the ear exposures are not at hazardous levels. However, if workers in an operational setting are required to be closer to the surface, they might be exposed to hazardous noise.

d. Laser hazards in this facility were well controlled. Since the laboratory was small and had a door equipped with interlocks, it was fairly simply to ensure workers were protected from direct laser exposures. A laser warning light is also visible outside the laboratory doors when the laser is in use. Having systems like these that protect unaware workers might be difficult to incorporate into traditional de-painting facilities/flightlines.

e. We were unable to find any significant indirect laser exposures; however, the lab's required laser eye protection (minimum OD of 7) is sufficient to protect workers from both indirect and direct exposures.

f. Direct laser hazard exposure is the most serious health concern for this system. Appropriate engineering controls, administrative controls, and personal protective equipment should always be used around this system.

g. The ventilation system used with this laser is appropriate. The system seemed to allow adequate operation time before filter change out was required and automatically notifies operator when filter change out is needed.

7. RECOMMENDATIONS

a. Operational exposure assessment are still needed for this system. As noted throughout this evaluation, the highly controlled laboratory setting does not adequately represent operational exposures. Although sampling for HCN, NO, NO_2, and formaldehyde seems unnecessary in the field, it is recommended that metal sampling and CO monitoring remain part of the field assessments. AFIOH can assist with the operational assessments; continue to work through HQ AFMC/SGPB to obtain our assistance.

b. Although we did not identify any significant airborne exposures, there was a noticeable odor around the process, possibly ozone. The source of this odor should be identified and evaluated as appropriate.

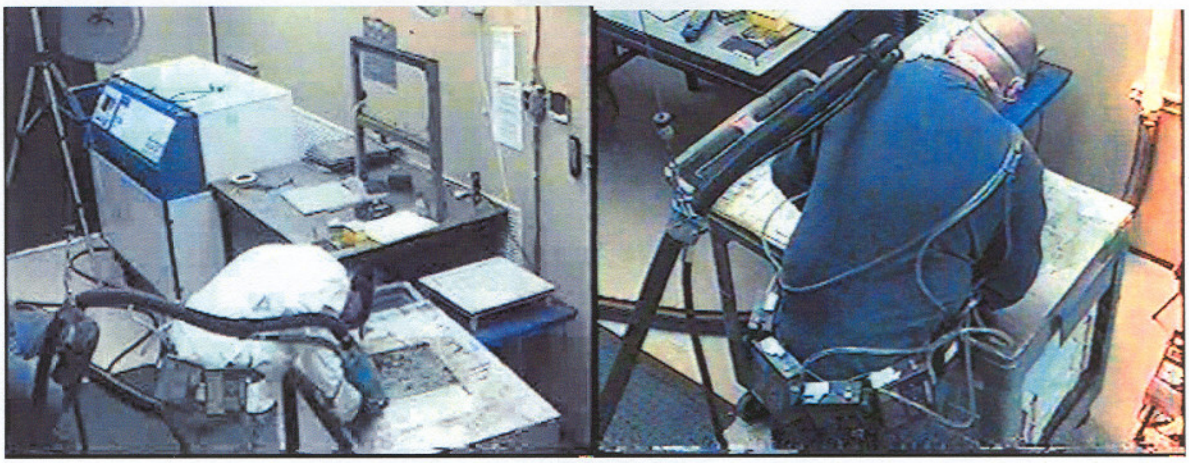
c. The most significant health hazard associated with this system is the possibility of direct laser radiation exposure. We recommend contacting AFRL/HEDO and working with them to obtain a measured NOHD. Controlling this hazard as much as possible with engineering controls for field use is highly recommended. If the NOHD is over a few feet, a system that automatically turns the laser off if a surface isn't within a few inches of the laser head could be added.

8. We appreciate the cooperation of AFRL/MLSC and Anteon personnel during this survey. If you have any questions concerning this report, please contact me at DSN 240-8441 or via email, ian.rybczynski@brooks.af.mil.

IAN C. RYBCZYNSKI, Capt, USAF, BSC
Senior Industrial Hygiene Consultant

Attachments:
1. Pictures of the Laser Stripping
2. Clean CL 120 Q Parameters

Pictures of the Laser Stripping



Clean CL 120 Q

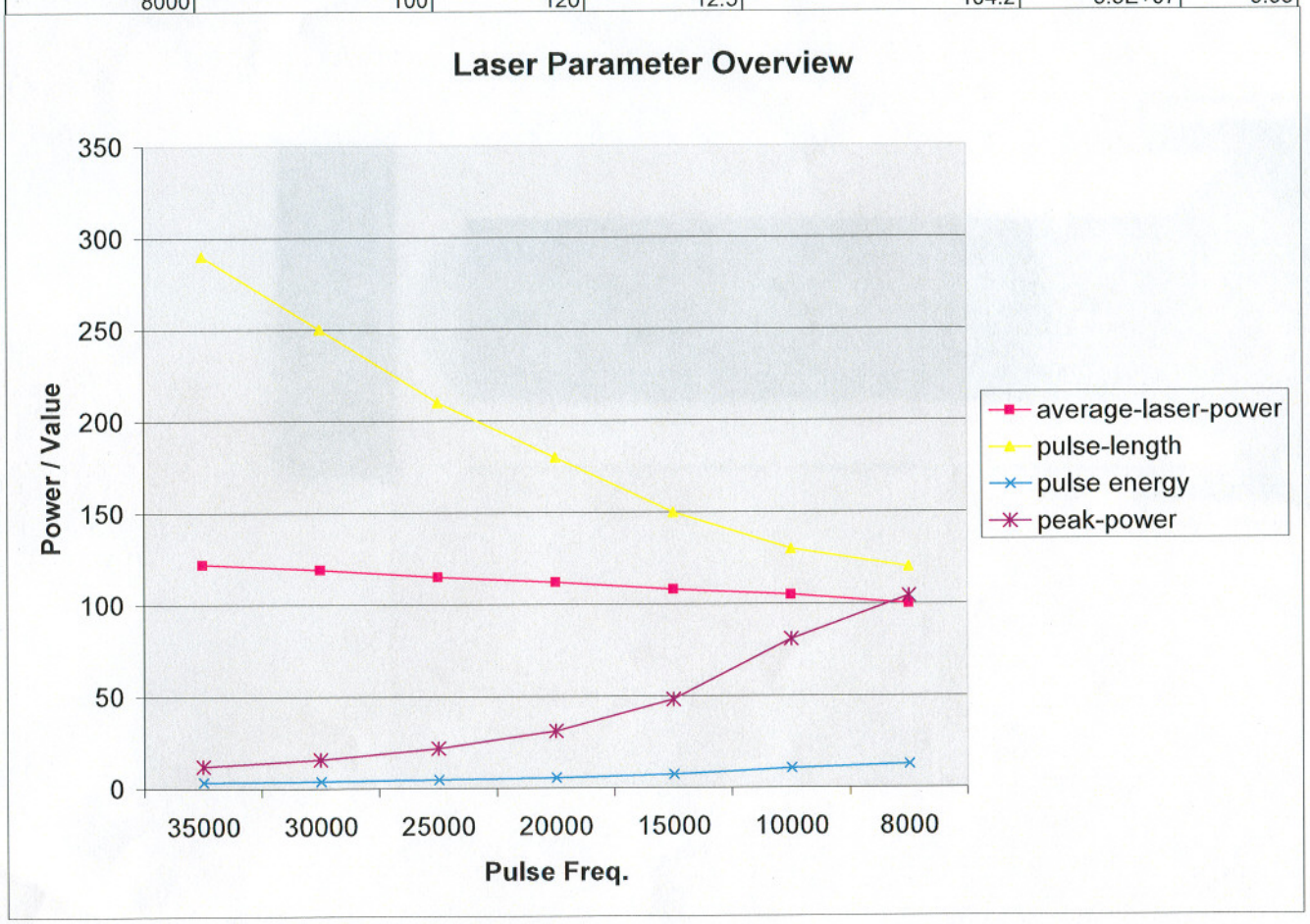
Parameter list — Focal-Diameter (Spot)[µm]: 400 (related to optical system)

resulting focal area [cm^2] 0.00126

(all parameters at max lamp current)

pulse-frequency	average-laser-power	pulse-length	pulse energy	peak-power	Puls-Intensity	Fluence
[Hz]	[W]	[ns]	[mJ]	[kW]	[W/cm^2]	[J/cm²]
35000	122	290	3.5	12.0	9.6E+06	2.77
30000	119	250	4.0	15.9	1.3E+07	3.16
25000	115	210	4.6	21.9	1.7E+07	3.66
20000	112	180	5.6	31.1	2.5E+07	4.46
15000	108	150	7.2	48.0	3.8E+07	5.73
10000	105	130	10.5	80.8	6.4E+07	8.36
8000	100	120	12.5	104.2	8.3E+07	9.95

Laser system variables
Pulse Frequency: 8-35KHz
Scan Width: 10-50mm
Scan Speed: 30-100Hz



AIR SAMPLING AND ANALYSIS

LASER PAINT STRIPPING PROJECT

IN SUPPORT OF THE

AIR FORCE RESEARCH LABORATORY
CORROSION TECHNOLOGY INTEGRATION OFFICE

Prepared By:

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1.0 INTRODUCTION

Anteon Corporation, using a subcontractor, MACTEC, is supporting a laser coatings removal operation as part of a demonstration and validation project supporting a Compliance Assurance and Pollution Prevention project for the Air Force Research Laboratory (AFRL) Corrosion Technology Integration Office (CTIO). As part of the project Anteon was tasked to perform an occupational health hazard assessment of the operation. A detailed discussion of the proposed industrial hygiene air sampling strategy and methodology will be discussed.

2.0 BACKGROUND

Between April 9-11, 2002 and August 20-23, 2002 MACTEC Federal Programs, Inc. (MACTEC), f/k/a/ Pacific Environmental Services, Inc., provided air sampling, noise monitoring and analysis for Anteon Corporation at Anteon's Wright Patterson Air Force Base laser test facility. MACTEC conducted this investigation under RFP 02-D-218, Delivery Order (DO) 5TS5701D218. MACTEC is supporting a demonstration and validation (Dem/Val) project using hand held lasers to strip paints and coatings from test panels for the Air Force Research Laboratory (AFRL) Corrosion Technology Integration Office (CTIO). The DO requires MACTEC to quantify laser operators' and observers' exposures to potential ablation byproducts generated during the Dem/Val process.

Three separate laser systems were tested to determine their effectiveness at removing different paints and coatings on test panels of various substrates. Testing for each laser system took approximately two to two and one half days to complete. The lasers tested included:

- Selective Laser Coating Removal (SLCR) CO_2 Laser, Class 4, Model ML 105E, tested April 9-11, 2002
- Clean Systems Cleanlaser, CL 120 Q, Neodymium: YAG (Nd:YAG) Laser tested, August 20-21, 2002
- Quantel Laserblast 1000, Q-Switched Nd:YAG Laser, tested August 22-23, 2002

MACTEC collected a total of 133 air samples for each laser tested. These samples included personal, area and direct reading samples. MACTEC's air sampling strategy is summarized in the table below.

Summary of Air Sampling Strategy April 9-11, 2002 and August 20-23, 2002 Sampling					
Ablation By-Products	Number of Samples/Laser			Sample Media	Analytical Method
	SLCR	Clean	Quantel		
Acid Gas	42	42	42	Silica Tube	Acid Gas Screen NIOSH 7903
Isocyanates	12	12	12	Treated GFF	OSHA 42
Hydrogen Cyanide	7	7	7	Soda Lime Tube	NIOSH 6010
Metals	30	30	30	MCEF Filter	Metals Screen NIOSH 7300
Hexavalent Chromium (water insoluble)	6	6	6	PVC Filter	NIOSH 7600
Nitric Oxide	3	3	3	Detector Tube	Colorimetric
Nitrogen Dioxide	3	3	3		
Carbon Monoxide	3	3	3		
Carbon Dioxide	3	3	3		
Ozone	3	3	3		
Sulfur Dioxide	3	3	3		
Lead Chromate	6	6	6	Stochiometric Calculations are Based on Results of Hexavalent Chromium and Attached Metals	
Strontium Chromate	6	6	6		
Zinc Chromate	6	6	6		
Total	133	133	133	Not Applicable	Not Applicable

Additionally, MACTEC conducted noise monitoring and evaluated area ventilation systems, potential non-ionizing radiation hazards, personal protective equipment (PPE), and task ergonomics/thermal stress.

3.0 FINDINGS

3.1 Air Sampling

Air sampling results are below the limit of laboratory detection with the exception of one sample, which was at the limit of laboratory detection. All results are well within established Occupational Exposure Limits (OELs). Summaries of air sampling results are found in the Appendix.

3.2 Noise

Noise monitoring performed during the Cleanlaser operation indicates an operator Time Weighted Average (TWA) of 61.9 dbA. This result is well below OSHA's noise exposure limit of TWA 90 dbA and OSHA's Action Level for noise of 85 dbA.

Noise monitoring performed during the Quantel Laserblast operation indicates an operator Time Weighted Average (TWA) of 85.3 dbA. This result is well below OSHA's noise exposure limit of TWA 90 dbA but exceeds OSHA's Action Level for noise of 85 dbA. The Quantel glove box was not used during laser paint stripping activities.

Noise monitoring performed during the SCLR operation indicates an operator Time Weighted Average (TWA) of 104.5 dbA. Monitoring results for area sampling indicate a TWA of 94.9 dbA. These results exceed OSHA's noise exposure limit of TWA 90 dbA and OSHA's Action Level for noise of 85 dbA.

The laser operator participates in Anteon's Hearing Conservation Program and has been fitted for custom personal hearing protection.

3.3 Ventilation

To simulate field conditions, the laser testing room overhead fume hood was not operational during MACTEC's April 9-11 sampling effort. The fume hood was removed prior to MACTEC's August 20-23 sampling effort. A Fumex FA 102 local ventilation system (Fumex) was operational during all laser-testing activities. This system included a 2.5 X 0.75 inch capture slot hood located at the laser/test panel interface, a portable floor fan unit with filtration and an exhaust duct.

MACTEC did not visually detect any particulates, smoke and/or other ablation by-product material during laser stripping activities. However, a slight odor similar to "welding fume" could be detected at and/or near the Fumex floor unit on two occasions during the April 2002 sampling effort and again during the August 2002 sampling effort. In all three cases, the main filter located inside the Fumex floor unit was overloaded with

captured ablation by-product material (particulates, solids, etc.). As a result, airflow through the filter became restricted and blocked. The Fumex filter change-out frequency was increased to approximately 1-1.5 filters per test panel. MACTEC will continue to assess filter efficiency during future site visits.

3.4 Non-Ionizing Radiation

Administrative and engineering controls are in place to reduce the potential exposure to non-ionizing radiation. The operator was wearing approved laser eye protection during all laser paint stripping activities.

3.5 Personal Protective Equipment (PPE)

The operator was adequately protected during all laser paint stripping activities.

SLCR laser system: The operator wore Derma-Lite disposable nitrile work gloves, SAS disposable coveralls, Powered Air Purifying Respirator (PAPR) with P100 filters/Hood, approved laser eye protection and hearing protection.

Clean and Quantel laser systems: The operator wore Derma-Lite disposable nitrile work gloves, a half face respirator with P100 filters and approved laser eye protection. Hearing protection was worn during the operation of the Quantel laser system (see Noise section).

3.6 Ergonomics and Thermal Stress

Awkward body, thumb and hand positions were required to effectively operate the SLCR laser. To reduce potential musculoskeletal disorder hazards, Anteon personnel performed configuration and control location field adjustments during the laser-testing period.

Ergonomics evaluations are on going. Recommendations and findings will be addressed in MACTEC's final report.

Thermal conditions during laser activities were warm, especially while wearing PPE. Natural and mechanical ventilation systems are turned off in the testing room to simulate natural conditions. The operator took appropriate rest breaks.

4.0 Appendix

Tables 1-3 on the following pages reflect a summary of the personal and area sample results.

Table 1
Personal and Area Sampling Results

SUMMARY TABLE - ALL LASERS

Sampling Performed April 9-11, August 20-23
< Indicates results are below laboratory limit of detection

Ablation By-Product	Laboratory Result Ranges	Time Weighted Average Ranges (TWA)	OSHA Permissible Exposure Limits (PELs)	ACGIH Threshold Limit Values (TLVs)
Cadmium	<0.0002 - <0.0006 mg/m^3	<0.0002 - <0.0006 mg/m^3	TWA: 0.005 mg/m^3	TWA: 0.01 mg/m^3
Chromium	<0.002 - <0.006 mg/m^3	<0.002 - <0.006 mg/m^3	NA	TWA: 0.5 mg/m^3
Inorganic Lead	<0.0008 - <0.001 mg/m^3	<0.001 - <0.0007 mg/m^3	TWA: 0.05 mg/m^3	TWA: 0.05 mg/m^3
Zinc	<0. 002 - <0.006 mg/m^3	<0. 002 - <0.006 mg/m^3	NA	NA
Strontium	<0.0004 - <0.004 mg/m^3	<0.0004 - <0.002 mg/m^3	NA	NA
Lead Chromate	NA	Not present (NP)	NA	TWA: 0.012 mg/m^3 as Cr
Strontium Chromate	NA	<0.00007 - <0.0004 mg/m^3	NA	TWA: 0.012 mg/m^3 as Cr
Zinc Chromate	NA	NP - <0.00018 - mg/m^3	NA	TWA: 0.012 mg/m^3 as Cr
Chromium (VI) as CrO3	<0.0002 - <0.0005 mg/m^3	<0.0002 - <0.0005 mg/m^3	NA	TWA: 0.01 mg/m^3

Table 1
Personal and Area Sampling Results

SUMMARY TABLE - ALL LASERS

Sampling Performed April 9-11, August 20-23
< Indicates results are below laboratory limit of detection

Ablation By-Product	Laboratory Result Ranges	Time Weighted Average Ranges (TWA)	OSHA Permissible Exposure Limits (PELs)	ACGIH Threshold Limit Values (TLVs)
Phosphoric Acid	<0.009 - <0.2 mg/m^3	<0.009 - <0.2 mg/m^3	TWA: 1.0 mg/m^3	TWA 1.0 mg/m^3
Hydrogen Bromide	<0.003 - <0.009 ppm	<0.003 - <0.009 ppm	TWA: 3.0 ppm	NA
Hydrochloric Acid	<0.04 - <0.1 ppm	<0.04 - <0.1 ppm	NA	NA
Hydrofluoric Acid	<0.01 - <0.04 ppm	<0.01 - <0.04 ppm	TWA: 3.0 ppm as F	NA
Nitric Acid	<0.02 - <0.06 ppm	<0.02 - <0.06 ppm	TWA: 2.0 ppm	TWA: 2.0 ppm
Sulfuric Acid	0.01 - <0.03 mg/m^3	0.01 - <0.03 mg/m^3	TWA: 1.0 mg/m^3	TWA: 1.0 mg/m^3
Hydrogen Cyanide	<0.02 - <0.07 ppm	<0.02 - <0.07 ppm	TWA: 10 ppm	NA

Table 1
Personal and Area Sampling Results

SUMMARY TABLE - ALL LASERS

Sampling Performed April 9-11, August 20-23
< Indicates results are below laboratory limit of detection

Ablation By-Product	Laboratory Result Ranges	Time Weighted Average Ranges (TWA)	OSHA Permissible Exposure Limits (PELs)	ACGIH Threshold Limit Values (TLVs)
2,6-Toluene Diisocyanate	<0.00003 - <0.00005 ppm	<0.00003 - <0.00005 ppm	NA	TWA: 0.005 ppm
Hexamethylene Diisocyanate	<0.00003 - <0.00005 ppm	<0.00003 - <0.00005 ppm	NA	TWA: 0.005 ppm
HMDI	<0.00004 - <0.00007 ppm	<0.00004 - <0.00007 ppm	NA	TWA: 0.005 ppm
Isophorone Diisocyanate	<0.0001 - <0.0002 ppm	<0.0001 - <0.0002 ppm	NA	TWA: 0.005 ppm
MDI	<0.00002 - <0.00004 ppm	<0.00002 - <0.00004 ppm	NA	TWA: 0.005 ppm
TDI	<0.00003 - <0.00005 ppm	<0.00003 - <0.00005 ppm	NA	TWA: 0.005 ppm

Table 2 Detector Tube Summary Table - All Lasers Sampling Performed April 9-11, August 20-23			
Ablation By-Product	**Result**	**OSHA Permissible Exposure Limits (PELs)**	**ACGIH Threshold Limit Values (TLVs)**
Nitric Oxide	0.0 ppm	TWA: 25 ppm	TWA: 25 ppm
Nitrogen Dioxide	0.0 ppm	Ceiling: 5.0 ppm	TWA: 3.0 ppm STEL: 5.0 ppm
Carbon Monoxide	0.0 ppm	TWA: 50 ppm	TWA 25 ppm
Carbon Dioxide	0.0 ppm	TWA: 5,000 ppm	TWA: 5,000 ppm STEL: 30,000 ppm
Sulfur Dioxide	0.0 ppm	TWA: 5.0 ppm	TWA: 2.0 ppm STEL: 5.0 ppm
Ozone	0.0 ppm	TWA: 0.1 ppm	TWA: 0.08 ppm (moderate work)

Table 3
Short Term Exposure Level (STEL) Results
SUMMARY TABLE - ALL LASERS

Sampling Performed April 9-11, August 20-23
< Indicates results are below laboratory limit of detection

Ablation By-Product	Laboratory Result	OSHA Permissible Exposure Limits (PELs)	ACGIH Threshold Limit Values (TLVs)
Phosphoric Acid	<0.8 mg/m^3	NA	STEL: 3.0 mg/m^3
Hydrogen Bromide	<0.05 ppm	NA	Ceiling: 3.0 ppm
Hydrochloric Acid	<0.5 ppm	Ceiling: 5.0 ppm	Ceiling: 5.0 ppm
Hydrofluoric Acid	<0.2 ppm	NA	Ceiling: 3.0 ppm as F
Nitric Acid	<0.3 ppm	NA	STEL: 4.0 ppm
Sulfuric Acid	<0.2 mg/m^3	NA	STEL: 3.0 mg/m^3
Hydrogen Cyanide	<0.3 - <0.4 ppm	NA	Ceiling: 4.7 ppm
2,6-Toluene Diisocyanate	<0.0007 - <0.0008 ppm	NA	STEL: 0.02 ppm
Hexamethylene Diisocyanate	<0.0007 - <0.0008 ppm	NA	NA
HMDI	<0.0009 - <0.001 ppm	NA	NA
Isophorone Diisocyanate	<0.003 ppm	NA	NA
MDI	<0.0005 - <0.0006 ppm	Ceiling: 0.02 ppm	NA
TDI	<0.0007 - <0.0008 ppm	Ceiling: 0.02 ppm	STEL: 0.02 ppm

FIELD WORK SUMMARY REPORT

AIR SAMPLING AND ANALYSIS
LASER PAINT STRIPPING PROJECT
IN SUPPORT OF THE
AIR FORCE RESEARCH LABORATORY
CORROSION TECHNOLOGY INTEGRATION OFFICE

Site Visits: October 2003, September 2004, February 2005

Order I.D. #5TS5703D434

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Report Table of Contents

Cleanlaser Executive Summary Table			i
Quantel Executive Summary Table			ii
1.0	Background		1
2.0	Clean Systems Cleanlaser - Summary of Findings		1
	2.1	Air Sampling	1
	2.2	Noise Monitoring	4
	2.3	Ventilation	5
	2.4	Ultraviolet/Infrared (UV/IR) Survey	5
	2.5	Ergonomics and Thermal Stressors	7
3.0	Quantel Laserblast - Summary of Findings		7
	3.1	Air Sampling	7
	3.2	Noise Monitoring	10
	3.3	Ventilation	10
	3.4	Ultraviolet/Infrared (UV/IR) Survey	11
	3.5	Ergonomics and Thermal Stressors	12
4.0	Conclusions		13

Appendix One	Cleanlaser Air Sampling Results Summary Tables, Panel Coating Tables, and Activity Logs
Appendix Two	Cleanlaser Laser Noise Summary Reports
Appendix Three	Cleanlaser UV/IR Summary Tables
Appendix Four	Quantel Air Sampling Results Summary Tables, Panel Coating Tables, and Activity Logs
Appendix Five	Quantel Laser Noise Summary Reports
Appendix Six	Quantel UV/IR Summary Tables
Appendix Seven	Laboratory Reports

Executive Summary Tables

MACTEC Field Work Summary Report
Cleanlaser Executive Summary Table
Site Visits: October 2003, September 2004, February 2005

Hazard	Sampling Method	Sample Results	Exposure Standard	PPE/Control Recommendations
Air	NIOSH 7300 NIOSH 7300 NIOSH 7300 NIOSH 0500 NIOSH 0500 NIOSH 0500 NIOSH 0500	Manganese: 0.0006 mg/m^3 Manganese: 0.0005 mg/m^3 Manganese: 0.0027 mg/m^3 PNOC: 0.37 mg/m^3 PNOC: 0.3 mg/m^3 PNOC: 0.3 mg/m^3 PNOC: 0.13 mg/m^3	ACGIH: 0.2 mg/m^3 ACGIH: 0.2 mg/m^3 ACGIH: 0.2 mg/m^3 OSHA: 15 mg/m^3 OSHA: 15 mg/m^3 OSHA: 15 mg/m^3 OSHA: 15 mg/m^3	Continue Fumex local exhaust ventilation
Noise	ACGIH/ AFOSH	TWA: 84.0 dbA TWA: 82.3 dbA TWA: 81.8 dbA	82 dbA AL, 85 dbA TWA 82 dbA AL, 85 dbA TWA 82 dbA AL, 85 dbA TWA	Continue to ensure all personnel are in the Anteon Hearing Conservation Program
Thermal Stress	General Industry	Room Temp: 85-90° F	General Industry	Continue employee rotation, routine breaks, and fluid replacement
Ergonomics	NIOSH/ AFOSH	Operator maintains an upward pressure to operate hand held laser System utilizes "trigger" controls Operator in standing position	Reduce potential musculoskeletal disorders by workstation evaluation re-engineering	Alternative control systems (e.g. foot controls, spring arms, etc) should be considered. Task chairs, sit/stand swivels should be considered.
Ultraviolet/ Infrared (UV/IR)	ACGIH	UV wrist: 0.31-493 uW/cm^2 UV eye: 0.4-2.3 uW/cm^2 UV chest: 0.4-1.6 uW/cm^2 IR eye: 10.5-316 mW/cm^2	<10 seconds - 3 hours <30 seconds - 2 hours <30 minutes - 2 hours 10 mW/cm^2	Verify laser glasses are suitable for UV/IR applications. Continue to wear gloves and long sleeve shirt during paint stripping activities

ACGIH: American Conference of Governmental Industrial Hygienists
AFOSH: Air Force Occupational Safety and Health
AL: Action Level
dbA: decibels A scale
NIOSH: National Institute of Occupational Safety and Health
mg/m^3: milligrams per cubic meter
mW/cm^2: milli-Watts per square centimeter
OSHA: Occupational Safety and Health Administration
PNOC: Particulates Not Otherwise Classified
TWA: Time Weighted Average
uW/cm^2: micro-Watts per square centimeter

MACTEC Field Work Summary Report
Quantel Laserbast Executive Summary Table
Site Visits: October 2003, September 2004, February 2005

Hazard	Sampling Method	Sample Results	Exposure Standard	PPE/Control Recommendations
Air	NIOSH 7300 OSHA 42 OSHA 42 OSHA 42	Manganese: 0.0004 mg/m^3 2,6-TDI: 0.00005 ppm 2,6-TDI: 0.00019 ppm 2,6-TDI(STEL): 0.0011 ppm	ACGIH: 0.2 mg/m^3 ACGIH: 0.005 ppm ACGIH: 0.005 ppm ACGIH: 0.02 ppm	Continue Fumex local exhaust ventilation
Noise	OSHA	TWA(80): 84.6 dbA	85 dbA AL, 90 dbA TWA	Continue to ensure all personnel are in the Anteon Hearing Conservation Program
Thermal Stress	General Industry	Room Temp: 85-90° F	General Industry	Continue employee rotation, routine breaks, and fluid replacement
Ergonomics	NIOSH/ AFOSH	Operator maintains an upward pressure to operate hand held laser System utilizes "trigger" controls Operator in standing position	Reduce potential musculoskeletal disorders by workstation evaluation re-engineering	Alternative control systems (e.g. foot controls, spring arms, etc) should be considered. Task chairs, sit/stand swivels should be considered.
Ultraviolet/ Infrared (UV/IR)	ACGIH	UV eye: 1.0 uW/cm^2 UV chest: 0.83 uW/cm^2 IR eye: 380 mW/cm^2	<1 hour 1 hour 10 mW/cm^2	Verify laser glasses are suitable for UV/IR applications. Continue to wear gloves and long sleeve shirt during paint stripping activities. Continue to use extension shield.

ACGIH: American Conference of Governmental Industrial Hygienists
AFOSH: Air Force Occupational Safety and Health
dbA: decibels A scale
NIOSH: National Institute of Occupational Safety and Health
mg/m^3: milligrams per cubic meter
mW/cm^2: milli-Watts per square centimeter
OSHA: Occupational Safety and Health Administration
PNOC: Particulates Not Otherwise Classified
TWA: Time Weighted Average
uW/cm^2: micro-Watts per square centimeter

Field Work Summary Report

Field Work Summary Report
Site Visits: October 2003, September 2004, February 2005

1.0 Background

On 7-9 October 2003, 15 September 2004, and 8-10 February 2005, MACTEC Federal Programs, Inc. (MACTEC) provided additional support for the Anteon Corporation at the Wright Patterson Air Force Base (WPAFB) Laser Hardened Materials Evaluation Laboratory (LHMEL). MACTEC conducted this support under Anteon contract 5TS5703D434. MACTEC continued to support a demonstration and validation (Dem/Val) project involving hand held lasers to strip paints and coatings from test panels for the Air Force Research Laboratory (AFRL) Corrosion Technology Integration Office (CTIO).

The effort required MACTEC to quantify laser operators' and observers' exposures to certain potential ablation by-products generated during the Dem/Val process. Specific ablation by-product constituents and components, primers, topcoats, and metals were unknown until MACTEC arrived on site. MACTEC's efforts were conducted and reported in accordance with the approved 22 March 2004 Technical and Cost Proposal, the 28 July 2004 Projected Work Plan, and on-site discussions with Anteon's Project Managers. Previously, MACTEC provided a similar effort in support of Anteon's Dem/Val project which MACTEC summarized in the 30 September 2004 Field Work Summary Report.

Two separate laser systems were tested to determine their effectiveness at removing different paints and coatings on test panels of various substrates. The lasers tested included:

- Clean Systems Cleanlaser, CL 120 Q, Neodymium: YAG (Nd:YAG) Laser, tested 7 & 8 October 2003; 15 September 2004 (morning), and 8-10 February 2005.
- Quantel Laserblast 1000, Q-Switched Nd:YAG Laser, tested 9 October 2003 and 15 September 2004 (afternoon).

2.0 Clean Systems Cleanlaser - Summary of Findings

2.1 Air Sampling

MACTEC performed air sampling to evaluate operator (personal) and observer (area) exposures to metals, hexavalent chromium, acid gases, hydrogen cyanide, isocyanates, particulates, silica, and chromates during paint stripping activities on the test panels. Short-Term Exposure Limit (STEL) samples were collected to evaluate the operator's potential exposure to acid gases, cyanides and diisocyanates.

MACTEC collected a total of 79 samples including 34 area samples (A), 35 personal samples (P), and 10 Short-Term Exposure Level (STEL) samples. These samples were analyzed for a total of 345 constituents.

Based on MACTEC's prior experience evaluating exposures during corrosion control activities and a review of the process' material safety data sheets (MSDS), the air sampling strategy and protocol was designed to provide a feasible comprehensive evaluation of both the operator's and observer(s) potential exposures. MACTEC's air sampling strategy is summarized in the following table. This table shows the ablation by-products that were sampled, the number of samples collected, sampling media and analytical methods.

Clean Systems Cleanlaser Air Sampling Summary					
Ablation By-Product	**October 2003 Quantity**	**September 2004 Quantity**	**February 2005 Quantity**	**Sampling Media**	**Method**
(Acid Gases) Phosphoric Acid Hydrogen Bromide Hydrochloric Acid Hydrofluoric Acid Nitric Acid Sulfuric Acid	2 A 2 P 1 STEL	1 A 1 P 1 STEL	3 A 3 P 1 STEL	Silica Tube	Acid Gas Screen NIOSH 7903
(Isocyanates) 2,6 Toluene Hexamethylene HMDI Isophorone MDI TDI	0 A 1 P 2 STEL	1 A 1 P 1 STEL	3 A 3 P 1 STEL	Treated GFF	OSHA 42
Hydrogen Cyanide	2 A 2 P 1 STEL	1 A 1 P 1 STEL	3 A 3 P 1 STEL	Soda Lime Tube	NIOSH 6010
(Metals) Cadmium Chromium Inorganic Lead Zinc Zinc Oxide (2/05) Strontium Barium Calcium Cobalt Magnesium Manganese	2 A 2 P	1 A 1 P	3 A 3 P	MCE Filter	Metals Screen NIOSH 7300
Hexavalent Chromium (water insoluble)	2 A 2 P	1 A 1 P	3 A 3 P	PVC Filter	NIOSH 7600
Total Dust Total Silica	2 A 2 P	1 A 1 P	3 A 3 P	PVC Filter	NIOSH 500
Total	**25**	**15**	**39**	-	-
A: area sample; P: personal sample; STEL: Short-Term Exposure Limit sample					

MACTEC followed standard sampling and analytical methods that were validated and approved by the National Institute for Occupational Safety and Health

(NIOSH) or the Occupational Safety and Health Administration (OSHA).

All air sampling was conducted with Mine Safety Appliances Company (MSA) ELF and/or SKC AirChek 52 air sampling pumps. Specific sampling pump serial numbers and flow rates are presented in the sampling worksheets found in Appendix One. All sampling pumps were calibrated with primary standard BIOS Dry-Cal Flow Calibrators with serial numbers: B1620/S1517 and B1619/S1516. MACTEC calibrated the air sampling pumps with the filter media in-line prior to and at the end of the sampling period. All air samples were analyzed by Galson Laboratories in Syracuse, New York. Galson Laboratories is accredited by the American Industrial Hygiene Association (AIHA) and participates in the NIOSH Proficiency Analytical Testing (PAT) program. All samples were collected and submitted in accordance with "chain of custody" procedures. MACTEC submitted field blanks to the laboratory for analysis IAW the NIOSH and/or OSHA analytical methods.

MACTEC turned on all sampling pumps within ten minutes of the start of the operator's workday. MACTEC placed all air sampling pumps on hold or "stand-by" during the operator's lunch break. MACTEC turned off all sampling pumps approximately ten minutes prior to the end of the operator's workday.

MACTEC determined 8-hour time-weighted average (TWA) concentrations by multiplying the total sampling time (T) by the laboratory concentration (C), and dividing by 480 minutes: (T)(C)/480. MACTEC assumed zero operator/area exposure during down times. MACTEC determined exposures to chromates by using stoichiometric calculations based on the sampling results for hexavalent chromium and the attached metals. Stoichiometric calculations utilize a partition method which assigns chromate to the metal with the most restrictive occupational exposure levels (OELs) first (i.e., strontium), followed by the metals with less restrictive OELs (i.e., calcium, zinc, and lead). Additionally, MACTEC tabulated the laboratory results for lead, zinc, calcium, and strontium, as assumed chromates.

Air Sampling Findings

Laboratory results from samples collected during panel S-20-1 and S-12-32 paint stripping activities found 0.0006 mg/m^3 of manganese on one area sample, 0.0005 mg/m^3 of manganese on one personal sample, 0.37 mg/m^3 of particulates not otherwise classified (PNOC) on one area sample and 0.3 mg/m^3 of PNOC on one personal sample. Panel S-12-32 had a thick coating of Epoxy powder which when ablated, may produce a trace amount of PNOC. Laboratory results from samples collected during panel S-2-36, S-14-31 and S-11-31 paint stripping activities found 0.13 mg/m^3 of PNOC on one personal sample. Laboratory results from samples collected during panel S-14-32 and S-11-31 paint stripping activities found 0.0027 mg/m^3 of manganese on one area sample, and 0.3 mg/m^3 PNOC on one personal sample. The 8-hour TWAs for all of these concentrations

were below the established manganese Occupational Exposure Level (OEL) of 0.2 mg/m^3 and/or the established PNOC Occupational Exposure Level (OEL) of 15 mg/m^3. The remaining sampling results were below the laboratory level of quantitation (LOQ). MACTEC performed stoichiometric calculations to obtain strontium chromate, calcium chromate, lead chromate and zinc chromate TWAs.

During panel S-20-1/S-12-32 and S-15-36 paint stripping activities the concentration of strontium chromate exceeded the OEL when the TWA was calculated based on the length of the laser stripping process. However, when the TWA was calculated as an 8-hour TWA (including downtime), the concentration of strontium chromate was below the established strontium chromate OEL of 0.0005 mg/m^3.

Air sampling results summary tables, sampling activity logs, and panel coating tables, are included in Appendix One. Laboratory reports are included in Appendix Seven

2.2 Noise Monitoring

Personal noise monitoring was conducted during paint stripping activities using a Quest Q-300 noise dosimeter. This dosimeter was calibrated prior to the sampling period and again at the end of the sampling period using a Quest QC-10 sound calibrator. The Q-300 dosimeter's applicable settings (e.g. response rate, filter exchange rate, cutoffs, ceiling, dose criterion level and dose criterion length) were set in accordance with the American Conference of Governmental Industrial Hygienists (ACGIH) and Air Force Occupational Safety and Health (AFOSH) Standard 48-19 specifications of 3 dbA exchange rate, 85 dbA Dose Criteria, and 80 dbA cut-off. MACTEC assumed zero operator/area exposure during down times.

Noise Monitoring Findings

Noise monitoring results collected during panel S-20-1, S-13-28, S-12-27, 432-D-05-06-118, S-10-35, S-8-30 and S-12-32 paint stripping activities, found a TWA of 84.0 dbA. Noise monitoring results collected during panel S-15-35 and S-2-36 paint stripping activities found a TWA of 82.3 dbA. These results exceed the ACGIH and AFOSH action level criteria of 82 dbA. Additionally, noise monitoring results collected during panel S-14-32 and S-11-31 paint stripping activities found a TWA of 81.8 dbA which is below ACGIH and AFOSH action level criteria.

MACTEC noted that the laser arm local exhaust ventilation system (Fumex) generated an additional 3.3-5.6 dbA in background noise while the system was operational. The laser operator wore Howard Leight NRR-33 ear plug hearing protection during all paint stripping activities. It is MACTEC' understanding that the laser operator is included in Anteon's Hearing Conservation Program.

Overall, these sampling results are consistent with previous MACTEC/Anteon noise monitoring performed during similar paint stripping activates at the same location as referenced in MACTEC's 30 September 2004, Field Work Summary Report. Quest noise summary reports are presented in Appendix Two.

2.3 Ventilation

The laser paint stripping room's general HVAC system was not used during paint stripping activities in order to simulate conditions expected in the field. However, a Fumex FA102 ventilation system including a floor air handling unit and flex duct was operational during all laser paint stripping activities This unit provided exhaust through a 2.5 x 0.75 inch (approximate) slot located at the end of the wheeled nozzle's and free hand nozzle's "nose piece". Ventilation capture point measurements ranged from 440 to 536 feet per minute (fpm) at the face of the slot.

Airborne particulates could be seen during panel S-11-31 paint stripping activities, however personal air monitoring performed by MACTEC found the PNOC concentration well below the OEL. A slight odor similar to "welding fume" could be detected at and/or near the Fumex area during panel S-2-36/S-14-31/S-11-31 paint stripping activities. The operator then replaced the Fumex filter. The Fumex filter change-out frequency averages one and one half "capture" bag filters per test panel. All Fumex filter change-out activities were performed in accordance with facility hazardous waste guidelines.

2.4 Ultraviolet/Infrared (UV/IR) Survey

MACTEC performed UV/IR monitoring with an International Light Model IL 1400A Radiometer. The monitor reads the average steady state light level over a period of 0.5 seconds, and then calculates a "rolling" average with the last two readings to remove unwanted energy noise. UV monitoring was performed using a SEL 240 UV probe (serial numbers 4444 & 4713). The probe utilizes a solar blind vacuum photodiode to provide accurate measurement in deep UV while excluding all visible and IR radiation from 190-320 nm. IR monitoring was performed using a SEL 623 IR probe (serial number 474). This probe utilizes a multifunction thermopile and a built in preamplifier to provide flat spectral responses over a range of 200-3000 nm.

Prior to all monitoring activities, MACTEC checked the zero of the instrument before taking measurements. The monitor and all applicable probes were within factory calibration requirements. Monitoring was performed in the laser room during laser stripping activities. Ultimately, UV/IR exposure results determine if certain tasks exceed the allowable duration of exposure recommend by ACGIH. These apply to radiation from arcs, gas, and vapor discharges, fluorescent and incandescent sources and solar radiation, and do not apply directly to lasers.

Initial UV/IR measurements were collected at the operator's wrist and eye locations, and from 5 feet in front of the spot locations. It was determined that the number of sampling point locations should be increased. Accordingly, monitoring points were increased to include the interface right and left between the spot and panel, 3, 6, and 9 feet from the interface rear, 1 and 2 feet from the interface front, the operator's wrist, arm, eye, chest, and belt locations, and at the observer's location.

Ultraviolet/Infrared (UV/IR) Survey Findings

According to the ACGIH, a person may be exposed to 5 uW/cm^2 of UV for 10 minutes which equals 5 uW/cm^2 x 10 minutes x 60 seconds or 3000 uW/cm^2 for 1 second. ACGIH emphasizes that the probability of developing health effects from ultraviolet (UV) exposure depends on a variety of factors such as skin pigmentation, a history of blistering sunburns, and the accumulated UV dose. Outdoor workers, for example in latitudes within 40 degrees of the equator can be exposed to levels above the TLVs in as little as 5 minutes. Hypersensitivity should be suspected if workers present skin reactions when exposed to sub-TWA doses or when exposed to levels that did not cause a noticeable skin erythema in the same individual in the past. Hypersensitivity to UV radiation can be caused by certain plants and chemicals such as some antibiotics (e.g., tetracycline and sulphathiazole), some antidepressants (e.g., imipramine and sinequan), diuretics, cosmetics, antipsychotic drugs, coal tar distillates, some dyes, and lime oil (ACGIH: 2004).

Operator UV wrist exposures during panel S-20-1, S-2-36, S-11-31, S-15-36,S-12-27, 432-D-05-06-118, S-15-35, S-2-36 and S-11-31 paint stripping activities, exceeded the ACGIH recommended exposure durations. These specific panel wrist measurements ranged from between 0.31 and 493 uW/cm^2, allowing from <10 seconds up to 3 hours of recommended exposure. UV eye exposures during panel S-20-1, S-12-32 S-2-36, 432-D-05-06-118, S-10-35, S-2-36, and S-11-31 paint stripping activities, exceeded the ACGIH recommended exposure durations. These specific panel eye measurements ranged from between 0.4 and 2.3 uW/cm^2, allowing from between <30 seconds up to 2 hours of recommended exposure. UV chest exposures during panel S-12-27, 432-D-05-06-118, S-10-35, S-11-31 paint stripping activities exceeded the ACGIH recommended exposure durations. These specific panel chest measurements ranged from between 0.4 and 1.6 uW/cm^2, allowing from <30 minutes up to 2 hours of recommended exposure. Predictably, UV measurements at locations within 2 feet to the right, left, front and rear of the interface ranged from between 0.63 and 107 uW/cm^2.

To avoid thermal injury of the cornea and delayed effects on the lens of the eye, the ACGIH recommends that infrared radiation exposure should be limited to 10 mW/cm^2 for periods greater than 1,000 seconds. IR eye exposures during panel

S-13-28, S-12-27, 432-D-05-06-118, S-10-35, S-8-30, S-15-35, S-2-36 paint stripping activities, operator exceeded the ACGIH recommended exposure durations. These specific panel eye measurements ranged from between 10.5 and 316 mW/cm^2, allowing from several seconds up to 16 minutes of recommended exposure. IR interface measurements collected on several panels exceeded the IR probe's collection range. Additionally, measurements taken at 45 and 60 degree angles from 1 and 2 feet in front of panel 432-D-05-06-118, S-10-35, and S-15-35 during paint stripping activities exceeded the IR probe collection range.

The operator was wearing approved laser safety glasses; however, it could not be verified if these glasses were rated for appropriate UV/ IR protection. Additionally, the operator was not wearing gloves or a long sleeved shirt at the time of this survey. As MACTEC understands, however, leather work gloves and long sleeve shirts are currently a PPE requirement. UV/IR sampling summary tables are included in Appendix Three

2.5 Ergonomics and Thermal Stressors

The operator was required to provide a constant upward pressure to operate the laser with the free hand nozzle. The design of the laser required the operator to maintain the weight of the laser hand unit. Additionally, the operator is standing while performing all paint stripping activities. The laser system utilized a "trigger" control requiring the operator to activate the laser with a finger trigger. Traditionally, "trigger" controls are designed for short-term activities (e.g., drilling, mixing, sanding, etc) and are not designed for long term production work loads. With "trigger" controls, operator wrist position, finger position and the constant repetitive motion may potentially contribute to future musculoskeletal injuries. As MACTEC understands, a formal ergonomics survey has been conducted during paint stripping activities; however, MACTEC did not have access to the report's findings.

To simulate worst case field conditions, natural and mechanical ventilation systems were turned off in the testing room and all room doors and ducts were closed during the laser paint stripping activities. During each sampling effort, the laser operator worked in very warm thermal conditions. However, the operator did take several appropriate rest breaks.

3.0 Quantel Laserblast - Summary of Findings

3.1 Air Sampling

MACTEC performed air sampling to evaluate operator (personal) and observer (area) exposures to metals, hexavalent chrome, acid gas, hydrogen cyanide, isocyanates, particulates, silica, and chromates during paint stripping activities on test panels. Short-Term Exposure Limit (STEL) samples were collected to

evaluate operator exposure to acid gases, cyanides and diisocyanates. MACTEC collected a total of 29 samples including 11 area samples (A), 12 personal samples (P) and 6 Short-Term Exposure Limit (STEL) samples. These samples were analyzed for a total of 124 constituents.

Based on MACTEC' prior experience evaluating exposures during corrosion control activities and a review of the process material safety data sheets (MSDS), the air sampling strategy and protocol was designed to provide a feasible comprehensive evaluation of both the operator's and observer(s) potential exposures. MACTEC' air sampling strategy is summarized in the following table. This table shows the ablation by-products that were sampled, the number of samples collected, sampling media and analytical methods.

Quantel Laserblast Air Sampling Summary				
Ablation By-Product	**October 2003 Quantity**	**September 2004 Quantity**	**Sampling Media**	**Method**
(Acid Gases) Phosphoric Acid Hydrogen Bromide Hydrochloric Acid Hydrofluoric Acid Nitric Acid Sulfuric Acid	1 A 1 P 1 STEL	1 A 1 P 1 STEL	Silica Tube	Acid Gas Screen NIOSH 7903
(Isocyanates) 2,6 Toluene Hexamethylene HMDI Isophorone MDI TDI	0 A 1 P 1 STEL	1 A 1 P 1 STEL	Treated GFF	OSHA 42
Hydrogen Cyanide	1 A 1 P 1 STEL	1 A 1 P 1 STEL	Soda Lime Tube	NIOSH 6010
(Metals) Cadmium Chromium Inorganic Lead Zinc Strontium Barium Calcium Cobalt Magnesium Manganese	1 A 1 P	1 A 1 P	MCE Filter	Metals Screen NIOSH 7300
Hexavalent Chromium (water insoluble)	1 A 1 P	1 A 1 P	PVC Filter	NIOSH 7600/7605
Total Dust Total Silica	1 A 1 P	1 A 1 P	PVC Filter	NIOSH 0500
Total	**14**	**15**	-	-
A: area sample; P: personal sample; STEL: Short-Term Exposure Limit sample				

MACTEC followed standard sampling and analytical methods that were validated and approved by the National Institute for Occupational Safety and Health (NIOSH) or the Occupational Safety and Health Administration (OSHA).

All air sampling was conducted using Mine Safety Appliances Company (MSA) ELF and/or SKC AirChek 52 air sampling pumps. Specific sampling pump serial numbers and flow rates are presented in the sampling worksheets found in the Appendix Four. All sampling pumps were calibrated with primary standard BIOS Dry-Cal Flow Calibrators with serial numbers: B1620/S1517 and B1619/S1516. MACTEC calibrated the air sampling pumps with the filter media in-line prior to and at the end of the sampling period. All air samples were analyzed by Galson Laboratories in Syracuse, New York. Galson Laboratories is accredited by the American Industrial Hygiene Association (AIHA) and participates in the NIOSH Proficiency Analytical Testing (PAT) program. All samples were collected and submitted in accordance with "chain of custody" procedures. MACTEC submitted field blanks to the laboratory for analysis IAW the NIOSH and/or OSHA analytical methods.

MACTEC turned on all sampling pumps within ten minutes of the start of the operator's workday. MACTEC placed all air sampling pumps on hold or "stand-by" during the operator's lunch break. MACTEC turned off all sampling pumps approximately ten minutes prior to the end of the operator's workday.

MACTEC determined 8-hour time-weighted average (TWA) concentrations by multiplying the total sampling time (T) by the laboratory concentration (C), and dividing by 480 minutes: (T)(C)/480. MACTEC assumed zero operator/area exposure during down times. MACTEC determined exposures to chromates by using stoichiometric calculations based on the sampling results for hexavalent chromium and the attached metals. Stoichiometric calculations utilize a partition method which assigns chromate to the metal with the most restrictive occupational exposure levels (OELs) first (i.e., strontium), followed by the metals with less restrictive OELs (i.e., calcium, zinc and lead). Additionally, MACTEC tabulated the laboratory results for lead, zinc, calcium, and strontium, as assumed chromates,

Air Sampling Findings

Laboratory results from samples collected during panel S-20-2, S-12-31, S-2-36, S-14-31 and S-11-31 paint stripping activities found 0.0004 mg/m^3 of manganese on one area sample and 0.00005 ppm of 2,6-toluene diisocyanate on one personal sample. The 8-hour TWA for the manganese concentration was below the established manganese OEL of 0.2 mg/m^3. The 8-hour TWA for the 2,6-toluene diisocyanate was below the established 2,6-toluene diisocyanate OEL of 0.005 ppm. Laboratory results from samples collected during panel S-15-36 paint stripping activities found 0.00019 ppm of 2,4-toluene diisocyanate (TDI) on one area sample and 0.0011 ppm of TDI on one STEL sample. The 8-hour TWA for the TDI concentration was below the established TDI OEL of 0.005 ppm. The TDI STEL concentration was below the established TDI STEL of 0.02 ppm. MACTEC performed stoichiometric calculations to obtain strontium chromate,

calcium chromate, lead chromate and zinc chromate TWAs. During panel S-15-36 paint stripping activities, the concentration of strontium chromate exceeded the OEL when the TWA was calculated based on the length of the laser stripping process. However, when the TWA was calculated as an 8-hour TWA (including downtime), the concentration of strontium chromate was below the established strontium chromate OEL of 0.0005 mg/m^3. The MSDS from the S-15-36 panel topcoat confirmed that isocyanates were present in the panel's coating.

Detailed air sampling results summary tables, sampling activity logs, and panel coating tables are included in Appendix Four. Laboratory reports are included in Appendix Seven.

3.2 Noise Monitoring

Personal noise monitoring was conducted during paint stripping activities using a Metrosonics db-3100 noise dosimeter. This dosimeter was calibrated prior to the sampling period and again at the end of the sampling period using a Metrosonics sound calibrator. At the time of this sampling, October 2003, the dosimeter's applicable settings (e.g. response rate, filter exchange rate, cutoffs, ceiling, dose criterion level and dose criterion length) were set in accordance with the Occupational Safety and Health Administration's (OSHA's) specifications of 5 dbA exchange rate and 90 dbA dose criterion. All future monitoring was conducted in accordance with AFOSH noise specifications of 3 dbA exchange rate and 90 dbA dose criterion. MACTEC assumed zero operator/area exposure during down times.

Noise Monitoring Findings

Noise monitoring results collected during panel S-20-2, S-12-31, S-2-36, S-14-31, and S-11-31 paint stripping activities, found a TWA (80) of 84.6 dbA. These results were below OSHA action level criteria of 85 dbA. The level average (LAVG), or actual dosimeter run time average, was 85.9 dbA

The laser operator wore Howard Leight NRR-33 ear plug hearing protection during all paint stripping activities. It is MACTEC' understanding that the operator is included in Anteon's Hearing Conservation Program.

Overall, these sampling results are consistent with previous MACTEC/Anteon noise monitoring performed during similar paint stripping activates at the same location as referenced in MACTEC's 30 September 2004, Field Work Summary Report. The dosimeter summary report is presented in Appendix Five.

3.3 Ventilation

The laser paint stripping room's general HVAC system was not in use; i.e., not running, during paint stripping activities in order to simulate conditions expected

in the field. However, a Fumex FA102 ventilation system including a floor air handling unit and flex duct was operational during all laser paint stripping activities. This unit provided exhaust through a 2.5 x 0.75 inch (approximately) slot located at the end of the wheeled nozzle's and free hand nozzle's "nose piece". The Fumex filter change-out frequency was increased from one filter per day to approximately one and one half "capture" bag filters per test panel. All Fumex filter change-out activities were performed in accordance with the facility's hazardous waste guidelines.

3.4 Ultraviolet/Infrared (UV/IR) Survey

MACTEC performed UV/IR monitoring with an International Light Model IL 1400A Radiometer. The monitor reads the average steady state light level over a period of 0.5 seconds, and then calculates a "rolling" average with the last two readings to remove unwanted energy noise. UV monitoring was performed using a SEL 240 UV probe (serial numbers 4444 & 4713). The probe utilizes a solar blind vacuum photodiode to provide accurate measurement in deep UV while excluding all visible and IR radiation from 190-320 nm.

IR monitoring was performed using a SEL 623 IR probe (serial number 474). This probe utilizes a multifunction thermopile and a built in preamplifier to provide flat spectral responses over a range of 200-3000 nm.

Prior to all monitoring activities, MACTEC checked the zero of the instrument before taking measurements. The monitor and all applicable probes were within factory calibration requirements. Monitoring was performed in the laser room during laser stripping activities. UV/IR exposure results determine if certain tasks exceed the allowable duration of exposure recommend by ACGIH. These apply to radiation from arcs, gas and vapor discharges, fluorescent and incandescent sources and solar radiation, and do not apply directly to the lasers.

Initial UV/IR measurements were collected at the operator's wrist, eye, and from 5-feet in front of the spot locations. After monitoring paint stripping activities on 3-panels, it was determined that the number of sampling point locations should be increased. Accordingly, monitoring points were increased to include the interface, 3, 6, and 9-feet from the interface rear, the operator's wrist, arm, eye, chest, and at the observer's location.

<u>Ultraviolet/Infrared (UV/IR) Survey Findings</u>

According to the ACGIH, a person may be exposed to 5 uW/cm^2 of UV radiation for 10 minutes which equals 5 uW/cm^2 x 10 minutes x 60 seconds or 3000 uW/cm^2 for 1 second. The ACGIH emphasizes that the probability of developing adverse health effects from ultraviolet (UV) radiation exposure depends on a variety of factors such as skin pigmentation, a history of blistering sunburns, and the accumulated UV dose. Outdoor workers, for example in latitudes within 40

degrees of the equator can be exposed to levels above the TLVs in as little as 5 minutes. Hypersensitivity should be suspected if workers present skin reactions when exposed to sub-TWA doses or when exposed to levels that did not cause a noticeable skin erythema in the same individual in the past. Hypersensitivity to UV radiation can be caused by certain plants and chemicals such as some antibiotics (e.g., tetracycline and sulphathiazole), some antidepressants (e.g., imipramine and sinequan), diuretics, cosmetics, antipsychotic drugs, coal tar distillates, some dyes, and lime oil (ACGIH: 2004).

UV eye and chest exposures during panel S-15-36 paint stripping activities exceeded the ACGIH recommended exposure durations. The UV eye exposure measurement was 1.0 uW/cm^2 allowing <1 hour of recommended exposure. The UV chest exposure was 0.83 uW/cm^2 allowing 1 hour of exposure. During laser stripping operations, the extension shield was on the "nose piece" reducing the interface gap between the spot and laser by at least 3-inches.

UV eye exposure during panel S-21-31 paint stripping activities exceeded the ACGIH recommended exposure durations. The UV eye measurement was 380 uW/cm^2 allowing <10 seconds of recommended exposure. The extension shield was on the "nose piece", however, most of the paint and primer had been removed from Panel S-12-31 at the time of UV sample collection. Consequently, this may have contributed to the high UV radiation findings.

To avoid thermal injury of the cornea and delayed effects on the lens of the eye, the ACGIH recommends that infrared radiation exposure should be limited to 10 mW/cm^2 for periods greater than 1,000 seconds. IR exposures during panel S-20-2 and S-14-31 paint stripping activities exceeded the ACGIH recommended exposure durations. IR chest location measurements were 5,150 and 59 mW/cm^2 respectively, allowing from several seconds up to several minutes of recommended IR exposure.

The operator was wearing approved laser safety glasses; however, it could not be verified if these glasses were rated for the appropriate UV and/or IR protection. Additionally, the operator was not wearing gloves or a long sleeved shirt at the time of this survey. As MACTEC understands, however, leather work gloves and long sleeve shirts are currently a PPE requirement. UV/IR sampling summary tables are presented in Appendix Six.

3.5 Ergonomics and Thermal Stressors

The operator was required to provide a constant upward pressure to operate the laser with the free hand nozzle. The design of the laser required the operator to maintain the weight of the laser hand unit. Additionally, the operator is standing while performing all paint stripping activities. The laser system utilized a "trigger" control requiring the operator to activate the laser with a finger trigger. Traditionally, "trigger" controls are designed for short-term activities (e.g., drilling,

mixing, sanding, etc) and are not designed for long term production work loads. With "trigger" controls, operator wrist position, finger position and the constant repetitive motion may potentially contribute to future musculoskeletal injuries. As MACTEC understands, a formal ergonomics survey has been conducted during paint stripping activities; however, MACTEC did not have access to the report's findings.

To simulate worst case field conditions, natural and mechanical ventilation systems were turned off in the testing room and all room doors and ducts were closed during the laser paint stripping activities. During each sampling effort, the laser operator worked in very warm thermal conditions. The operator did take several appropriate rest breaks.

4.0 Conclusions

The laser stripping evaluations were performed under highly controlled conditions (e.g., ventilation, temperature, stripping position, etc) and may not represent intended and/or actual field use conditions. MACTEC offers the following conclusions based on the laser stripping evaluations:

1. Based on quantitative sampling data, observations and evaluations, MACTEC believes that employee's exposures to ablation by-products appeared to be adequately controlled at the time of the sampling. Personal and area air sampling results obtained throughout this sampling effort were consistently below the established OELs and/or the laboratory's limit of quantitation (LOQ). However in several instances, the concentration of strontium chromate exceeded the OEL when the TWA was calculated based on the duration or length of the laser stripping process.

2. Previous MACTEC sampling results (February 2003) found significant levels of metal/dust contaminants. Therefore, the local exhaust system appears to be required to minimize exposures to the laser operator and observers. Consequently, operators can be exposed to these contaminants during filter change-out activities. As such, operators must wear appropriate PPE including but not limited to respirators. Used filter bags should be disposed of in accordance with the user's hazardous material disposal procedures.

3. Noise monitoring results found that background noise levels were high throughout the sampling efforts. Noise monitoring results found that the laser systems exceeded ACGIH/AFOSH's action level of 82 dbA. Accordingly, laser operators should therefore continue be incorporated into an appropriate hearing conservation program.

4. Operators may be exposed to concentrations of ultraviolet and infrared radiation greater than the ACGIH recommended levels. Operator concentrations are variable and influenced by the type of laser used, the laser's end effector and nozzle configuration, panel type, and operator's position, size, and posture. There are variable elements that contribute to an operator's UV/IR exposure concentration. Based on observations and verified by quantitative data, MACTEC noted several factors that may contribute to an operator's potential UV/IR exposure.

    - The operator's location and posture in relation to the spot on the panel is critical. Data has shown that UV/IR exposure can be cut in half by moving 12 inches away from the spot. Additionally, operating from behind the spot will decrease eye and wrist exposure since the laser's pistol-like end effector and nozzle protect the operator's eyes and wrist.

    - MACTEC's UV/IR measurements during this sampling effort and previous sampling efforts have illustrated that when the Quantel laser is operated with an Anteon designed and manufactured extension shield, UV/IR concentrations are reduced. This polyurethane shield fits on the exposed gap between the end of the laser arm and the panel. Consequently, additional UV/IR radiation is confined.

    - The diameter of the laser spot affects the amount of UV/IR radiation generated. The spot size is variable and solely dependant on the material being stripped especially the substrate. Certain substrates require larger spot diameters (e.g., Bondo vs. paint, etc.). Additionally, spot movement can influence UV/IR concentrations. During the stripping process the operator physically moves the spot from one location to another on the test panel. As such, the speed of movement, pace, amount of substrate remaining on the panel, and length of time spot is on the panel will affect the UV/IR concentration.

    - The configuration of the stripping area and the operator's physical size can influence UV/IR concentrations. A tall operator working at the top of a test panel will be exposed to higher concentrations of UV/IR than a smaller operator stripping the bottom of a panel. The angle of the laser's end effector and distance of the spot in relation to the operator can affect the concentration. A taller operator has the ability to look over the laser and directly at the spot, while a smaller operator has the end effector, nozzle/shield, etc to help obstruct exposure. It is apparent that while working on the top portion of a panel the operator's eyes are closer to the spot, assuming the panel table is in a semi-vertical position.

- The laser type and configuration influences UV/IR exposure concentrations. Utilizing the free hand nozzle vs. the wheeled nozzle can potentially increase a chance of UV/IR exposure concentration. The free hand nozzle has a larger gap between the pistol-like end effector and the panel. As such, less UV/IR radiation is able to be contained. The Cleanlaser wheeled nozzle, however protects the operator's body (e.g., eyes, wrist, etc) better than the free hand nozzle but emits high concentrations of UV/IR from the rear of the nozzle approximately 8-15 inches from the operator's belt area.

5. Operators were required to provide a constant upward pressure to operate the hand held laser. The systems utilized a "trigger" control requiring the operator to activate the laser with a finger trigger. However, the prolonged use of lasers with trigger controls may potentially contribute to future musculoskeletal injuries. Additionally, the operator was required to remain standing during all laser paint stripping activities. Alternative control systems (i.e., systems that do not require the active use of hands/fingers) including foot operated pedals during laboratory research and development may help reduce potential ergonomic related injuries. Continuous standing may contribute to potential musculoskeletal disorders and may affect circulation in the legs and/or lower torso. Operator lower back and legs stressors may be reduced with sit/stand swivels which will reduce the load that the legs support by reducing and distributing weight.

This report provides results of personal exposure levels under laboratory controlled test conditions. Based on the results of this report, there were several hazards associated with personal exposures to ablation byproducts, noise, UV/IR, and physical stressors, which were and can be controlled in both the laboratory and field environment. Even though many of these results could be used and applied to depot operational conditions, MACTEC recommends that these results only be used as initial conditions for further sampling and analysis to be conducted by highly experienced industrial hygienists as these lasers field deployed.

Appendix D
Flammability Testing Report

Contract Number: GS09K99BHD0010 (ANSWER)
Task Order Number: T0501BM1801
Task ID: 5TS5701D101M

Laser Explosion/Flammability Test Report

for the Portable Laser Coating Removal System (PLCRS) Program

April 22, 2004

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Table of Contents

EXECUTIVE SUMMARY 2
SCOPE & OBJECTIVES 3
METHODOLOGY 4
Background 4
Materials 4
Fluids / Contaminants 4
Panel Preparation 5
Surface Contamination Testing 5
Artificial Cavity Testing 5
Data Recording 8
Laser De-painting Operations 8
LASER SYSTEMS AND PARAMETER SETTINGS 10
TEST RESULTS 12
Artificial Cavity Testing 12
I. JP-8 Turbine Fuel +100 Additive 13
II. Hydraulic Fluid MIL-PRF-83282 16
III. Hydraulic fluid MIL-H-5606 18
IV. Royco Engine Lubricating Oil MIL-PRF-808 20
V. Mobile Jet Oil 254 22
VI. Skydrol LD-4 (fire resistant hydraulic fluid) 26
Surface Contamination Testing 29
I. JP-8 Turbine Fuel +100 Additive 30
II. Royco Engine Lubricating Oil MIL-PRF-808 31
III. Hydraulic Fluid MIL-PRF-83282 31
IV. Hydraulic Fluid MIL-H-5606 32
V. Mobile Engine Lubricating Oil MIL-PRF- 254 32
VI. Skydrol LD-4 (fire resistant hydraulic fluid) 33
ADDITIONAL TESTING 34
Artificial Cavity Testing 35
I. Eldorado Non-chlorinated Paint Stripper PR-3131 35
II. Turco EA Stripper 6930 36
III. CEE-BEE R MeCl 256 Paint Stripper 37
Surface Contamination 39
I. Turco EA Stripper 6930 39
II. Eldorado Non-chlorinated Paint Stripper PR-3131 40
III. CEE-BEE R MeCl 256 Paint Stripper 41
CONCLUSIONS 43

Executive Summary

The objective of this testing was to address the possibility of explosion and/or flammability hazards associated with the portable handheld laser de-painting process. This test protocol involved a 120W Nd:YAG and a 40W Nd:YAG handheld laser system. The following chemicals were evaluated.

Chemicals	Flashpoint
1) Engine Lubricating Oil MIL-L-23699	>475˚F
2) Engine Lubricating Oil MIL-PRF-7808	440˚F
3) Hydraulic Fluid MIL-PRF-83282	388˚F (est.)
4) Hydraulic fluid MIL-H-5606-	225˚F
5) Skydrol LD-4 (fire resistant hydraulic fluid)	320˚F
6) JP-8 Turbine Fuel plus Turbine Fuel Additive +100	100˚F

The lasers evaluated in this test series were not able to produce a flame or explosion in the artificial cavity or surface contamination - even at elevated temperatures.(up to 190ºF).

Testing also involved additional compatibility testing with the following chemical strippers: Turco EA Stripper 6930, Eldorado Non-chlorinated Paint Stripper PR-3131, and CEE-BEE R MeCl 256 Paint Stripper. A flame was observed in one such (additional) test. This testing re-confirmed that common laser safety procedures must be observed to operate the laser in potentially hazardous environments It is recommended (and already common practice) that chemical strippers or flammable fluid residues be rinsed and removed from the work surface and the immediate work area. To avoid the risk of fire, the laser should only be operated on surfaces that are clear of chemical strippers and/or flammable materials.

This report is intended to provide information to the safety approval authorities. This testing does not address all possible (field) scenarios. Additional testing may be required to fulfill specific requirements and/or unique applications.

Scope & Objectives

Testing was conducted to provide data for determining whether handheld lasers, used for supplemental de-painting, pose an explosion risk and/or a safety risk. This testing addressed the potential safety risk of a highly intense laser energy beam being applied to a work surface and possibly igniting common aircraft maintenance fluids or vapors. It should be noted that the testing did not address the potential explosion risk posed by (electrical) laser components and/or ancillary equipment used in conjunction with the laser system. A 40W pulsed Nd:YAG laser and a 120W pulsed Nd:YAG laser were evaluated in this test sequence.

The objective of this testing was to conduct testing and to document possible explosive or flammability hazards associated with the portable handheld laser de-painting process. The first test scenario was designed to address potential hazards of laser de-painting a surface exhibiting accumulations of commonly used aircraft chemicals (surface contamination testing). The second test scenario addressed the explosion and flammability hazards associated with entrapped fluids and vapors (cavity testing). Additional testing was conducted to assess the compatibility of lasers de-painting with solvent-based chemical strippers (additional testing).

Methodology

Background

The testing was modeled after the Flashtech Coportation's Flashjet® explosion testing, documented on VHS tape supplied by the Flashtech/Boeing Corporation and further described in the McDonnell Douglas Corporation report "Xenon Flashlamp and Carbon Dioxide Advanced Coatings Removal Development and Evaluation Program", U.S. Navy Add-on Program; Final Report, 1993. It is important to note that there are significant technical and operational differences between Flashjet and laser technology: In addition, handheld lasers do not contain/shroud the immediate work environment and do not employ CO_2 pellets to clean the surface, and do not operate in a relatively oxygen-starved, flame-reducing environment.

Materials

Substrate materials consisted of Aluminum and Steel test panels used during Portable Laser Coating Removal System (PLCRS) JTP testing. Panels previously partially stripped and rendered unusable for JTP testing were used for this testing. These panels were re-painted by the Coatings Technology Integration Office (CTIO). The testing reported in this document was conducted by SAIC and Anteon at the LHMEL facility at Wright Patterson AFB. Fire and safety clearances were obtained prior to conducting the tests.

Fluids / Contaminants

These following nine (9) chemicals were used to determine laser ignition /flammability issues. These chemicals are frequently found on aircraft and/or found in aircraft de-painting operations. Note, however, that the chemical strippers (7, 8, 9) are not subject to Pass/Fail criteria and were only intended for the additional tests.

Table 1: Chemicals (MSDS Source Information)

	Flashpoint	**MSDS Fire Hazard Rating**
1) Engine Lubricating Oil MIL-L-23699	>475˚F	1
2) Engine Lubricating Oil MIL-PRF-7808	440˚F	1
3) Hydraulic Fluid MIL-PRF-83282	388˚F (est.)	1
4) Hydraulic fluid MIL-H-5606-	225˚F	1
5) Skydrol LD-4 (fire resistant hydraulic fluid)	320˚F	1
6) JP-8 Turbine Fuel	100˚F	2
Plus Turbine Fuel Additive +100	165˚F	2
7) Turco EA Stripper 6930	> 212˚F	Not listed
8) Eldorado Non-chlorinated Paint Stripper PR-3131	> 200˚F	> 200˚F
9) CEE-BEE R MeCl 256 Paint Stripper	None Listed	1

Panel Preparation

Type I panels were designated to address the safety risk of accidentally igniting fluids on the surface of the panel (surface contamination testing). The dimensions of Type I panels varied in size to accommodate the laser parameters (scan width).

Type II panels simulated entrapped fluids and vapors. The test panels required for addressing safety risks from entrapped fluids and/or vapors exhibited a number of holes, consisting of various sizes and shapes. Type II panels were 12" by 12" in size.

Table 2: Substrates

Test	**Type**	**Substrate Material**	**Chemicals (see Table 2)**	**Panels per Laser**	**Lasers**	**Total**
Surface Contamination	Type I	Aluminum	9	1	2	18
Entrapped fluids/vapors	Type II	Aluminum	9	1	2	18

Surface Contamination Testing

Type I panels were pre pre-soaked in the chemical/fluid. For the first trial, the panels had a "wet" appearance immediately prior to testing. The second trial involved applying additional fluid immediately prior to testing (i.e. standing liquid). *Figure 1.* and *Figure 2.* illustrate sample test-set-ups.

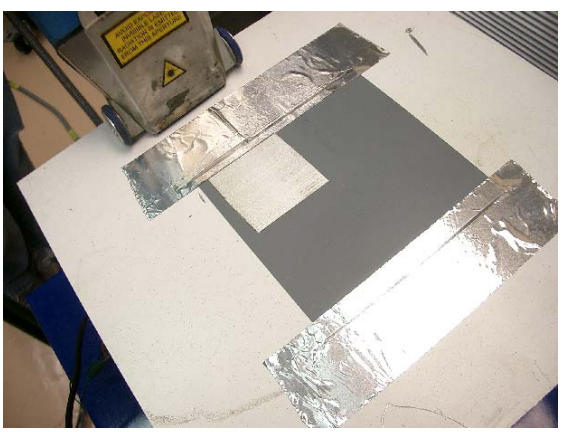

FIGURE 1. 120W LASER SURFACE TEST (JP-8)

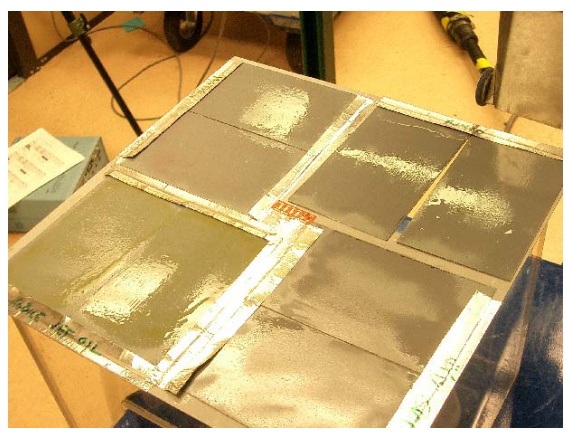

FIGURE 2 120W LASER SURFACE TEST (MISC. FLUIDS)

Artificial Cavity Testing

Openings were machined into Type II panels. The openings of Type II panels were positioned such that the laser could be easily manipulated over the openings during de-painting process. In particular, Type II panels exhibited the following openings:

TABLE 3. PANEL TYPE II OPENINGS

Description	Number per Panel	Dimensions
Small Hole	2	0.25” DIA
Large Hole	2	0.50” DIA
Small Crack (Horizontal)	2	0.125” x 2.0”
Large Crack (Horizontal)	2	0.250” x 2.0”
Small Crack (Vertical)	2	0.125” x 2.0”
Large Crack (Vertical)	2	0.250” x 2.0”

A small transparent container (4 oz. volume), filled with 1 or 2 ounces of fluid, was then attached under each hole of the prepared panels. The container was attached to the panel (with 2 component epoxy adhesive/sealant) such that the only opening was the hole through the test panel. The transparent containers (and openings) were positioned such that the camera is able to capture the testing. *Figure 3.* and *Figure 4*. show the test set-up.

FIGURE 3. 2 COMPONENT EPOXY

FIGURE 4. ARTIFICIAL CAVITY TEST SET-UP

The test panel (with a number of these simulated fluid/vapor traps) was then placed over a larger container to contain a fire/explosion, should it occur. See test schematic (*Figure 5 and 6*) for set-up.

FIGURE 5. ARTIFICIAL CAVITY SET-UP (1)

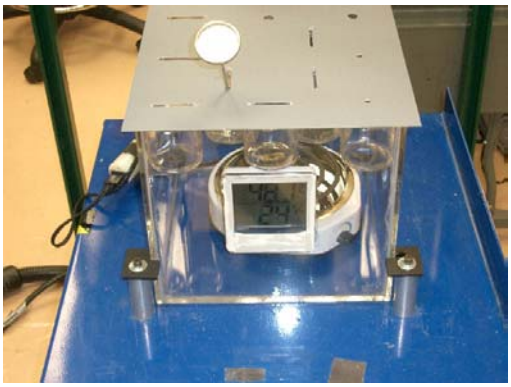

FIGURE 6. ARTIFICIAL CAVITY SET-UP (2)

Data Recording

Ambient temperature and humidity were recorded continuously, ensuring that ambient conditions are reflective of eventual (field) environment, preferable a" worst-case scenario" of 125˚F temperature, low humidity, and a hot/warm test panel. Every effort was made to simulate this "worse-case scenario", given the facility and equipment limitations. Observations before, during and after the tests were noted and documented using digital photos, digital movies, and a laboratory notebook. *Figure 7* and *Figure 8.* show the liquid temperature measurements.

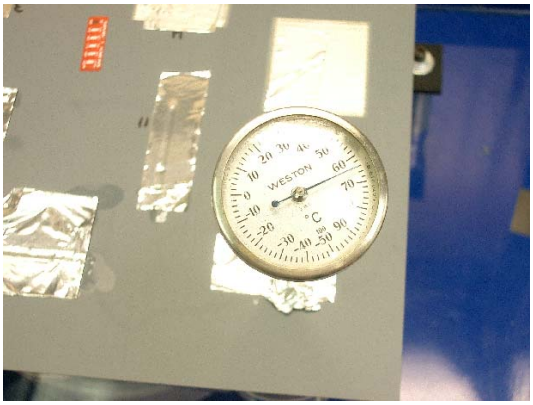

FIGURE 7. LIQUID TEMP. MEASUREMENTS (1)

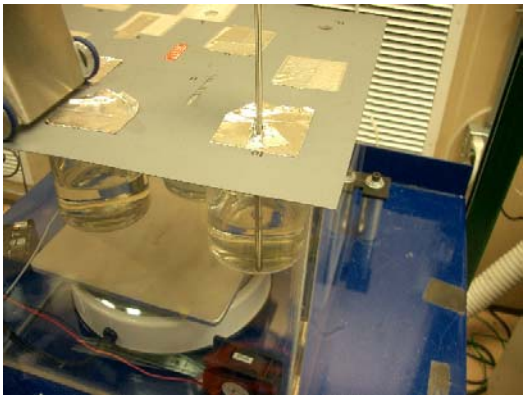

FIGURE 8. LIQUID TEMP. MEASUREMENTS (2)

Laser De-painting Operations

With additional fire extinguishers and proper fire protection procedures in place, the laser was operated, simulating a manual motion using a unidirectional traversing mechanism and a remote (piston) trigger mechanism. The testing was recorded using digital video and VHS recorders. The operator(s) were able to activate the laser from the outside of the room, using close-circuit television and/or camera to record and observe the tests. *Figure 9, Figure 10,* and *Figure 11,* illustrate the general test set-up and traversing/actuation mechanisms.

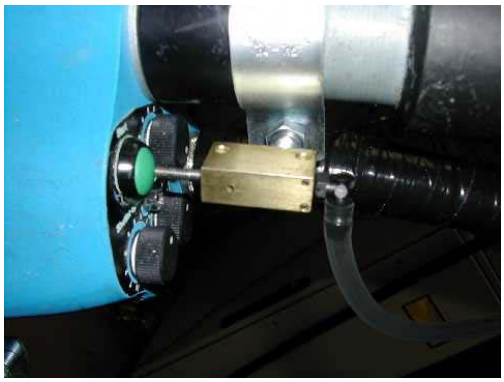

FIGURE 9. REMOTELY ACTIVATED PISTON TRIGGER MECHANISM

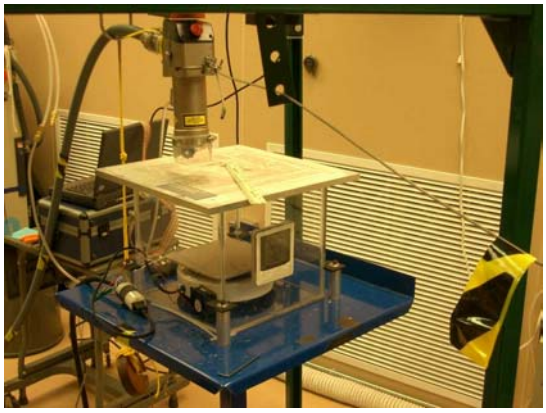

FIGURE 10. 40W ND:YAG LASER SET-UP

FIGURE 10. 120W ND:YAG LASER SET-UP

An electrical "kill switch" was installed on the FUMEX vacuum system. This switch could have been activated remotely in the event of an emergency (e.g. fire, malfunction, etc.).

FIGURE 11. FUMEX VACUUM SYSTEM

FIGURE 12. ELECTRICAL "KILL-SWITCH"

Laser Systems and Parameter Settings

A 120W Nd:YAG and a 40W Nd-YAG laser were used for this test. *Figure 13* shows the 120W system; *Figure 14* shows the 120W in manual operation. Note that due to safety concerns, explosion/flammability testing was not performed using manual/handheld operations.

FIGURE 13. 120W ND:YAG LASER SYSTEM

FIGURE 14. 120W ND:YAG LASER SYSTEM

(Manually operated)

Figure 15 shows the 40 W Nd:YAG system. *Figure 16* shows the chiller and *Figure 17* illustrates the hand-piece.

FIGURE 15. 40W ND:YAG SYSTEM

FIGURE 16. CHILLER FOR 40W ND:YAG SYSTEM

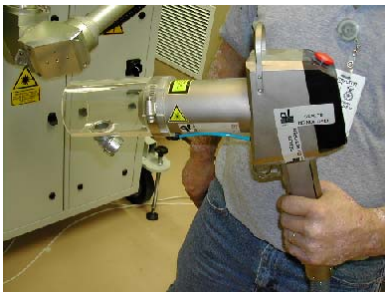

FIGURE 17. 40W ND:YAG SYSTEM HAND-PIECE

It's important to note that lasers were used robotically – i.e. with fixed stand-off distance. Using the robotic devices, the focal plans were fixed and relatively optimized. In actual handheld applications, the focal distance may vary, causing the laser to lose focus and intensity at the surface. Some parameters for each laser are adjustable. The laser parameters used for this testing represent a good snapshot of typical parameter settings used for laser de-painting.

Table 4. 120 W Nd:YAG Parameter Settings

120W Nd:YAG Laser Parameters	
Maximum Power Output	120 W
Laser Wavelength	1,064 nm
Pulse Frequency / Repetition Rate	~ 16.5 kHz
Pulse Length / Duration	~ 160 ns
Scan Head Frequency	80 Hz
Scan Width	50 mm
Spot Size	0.4 mm
Pulse Energy	~ 6.6 mJ

Table 5. 40 W Nd:YAG Parameter Settings

40W Nd:YAG Laser Parameters	
Maximum Power Output	40 W
Laser Wavelength	1,064 nm
Pulse Frequency Repetition Rate	120 Hz
Pulse Length / Duration	~ 9 ns
Slide Setting (stand-off)	15
Spot Size	~ 3 mm square
Pulse Energy	~ 333 mJ

Test Results

Artificial Cavity Testing

The charts on the following pages illustrate the results and observations of the artificial cavity testing. Note that this document has been modified with hyperlinks to movie and/or picture files. No flames or explosions were observed in these test trials. For example, *Figure 18* shows the test panel after conducting an artificial cavity test with JP-8+100 fluid (120W Nd:YAG laser). *Figure 19*. shows the same test with the 40W Nd:YAG system. Note that the lasers did not ignite the vapor, the liquid in the cavity (below), or the standing liquid on the surface of the test panel.

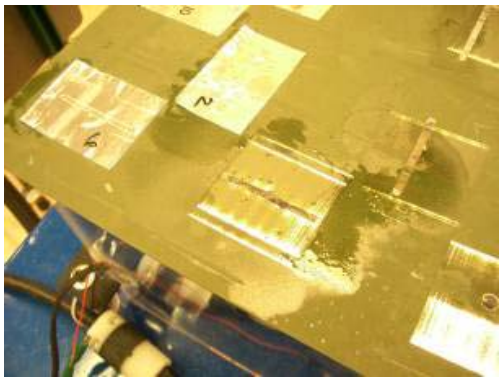

FIGURE 18. ARTIFICIAL CAVITY TEST (120W LASER)

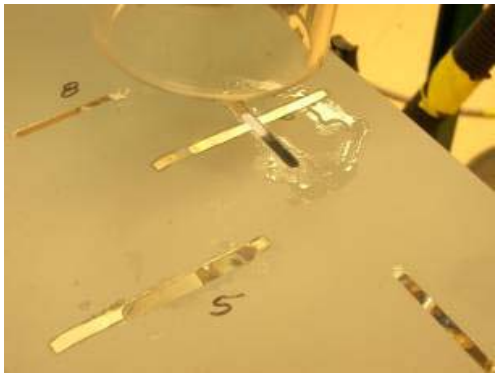

FIGURE 19. ARTIFICIAL CAVITY TEST (40W LASER)

Artificial Cavity Testing

I. JP-8 Turbine Fuel +100 Additive

Laser	Opening	Fluid Amt.	Surface	Fluid Temp.	Chamber		Comments	Vacuum	Observations	Video Links	Picture Links
					Temp.	Hum.					
Cleanlaser	Large Hole	2 oz.	Dry	111˚F	115˚F	12%	Hole open before and during testing	On	No flame / explosion, no smoke	1-1	
Cleanlaser	Large Horizontal Slot	2 oz.	Dry	109˚F	122˚F	10%	Slot open before and during testing	On	No flame / explosion, no fluid temperature rise	1-2	
Cleanlaser	Large Vertical Slot	2 oz.	Dry	122˚F	123˚F	10%	Slot open before and during testing	On	No flame / explosion, no smoke, no fluid temperature rise	1-3	
Cleanlaser	Small Vertical Slot	2 oz.	Dry	NM	123˚F	10%	Slot open before and during testing	On	No flame / explosion, no smoke	1-4	
Cleanlaser	Large Horizontal Slot	2 oz.	Dry	136˚F	135˚F	14%	Slot open before and during testing	On	No flame / explosion, no smoke	1-5	
Cleanlaser	Small Horizontal Slot	2 oz.	Dry	140˚F	135˚F	13%	Slot open before and during testing	On	No flame / explosion, no smoke	1-6	
Cleanlaser	Small Hole	2 oz.	Dry	122˚F	135˚F	13%	Hole open before and during testing	On	No flame / explosion, no smoke	1-7	
Cleanlaser	Large Horizontal Slot	2 oz.	Dry	147˚F	136˚F	10%	Hole taped and opened seconds before testing	On	No flame / explosion, no smoke	1-8	
Cleanlaser	Small Vertical Slot	2 oz.	Dry	NM	136˚F	10%	Hole taped and opened seconds before testing	On	No flame / explosion, no smoke	1-9	
Cleanlaser	Small Hole	2 oz.	Dry	151˚F	136˚F	10%	Hole taped and opened seconds before testing	On	No flame / explosion, no smoke	1-10	
Cleanlaser	Small Horizontal Slot	2 oz.	Wet Spots	NM	136˚F	10%	Hole taped and opened seconds before testing; surface temp (IR gun) 149˚F	Off	No flame / explosion, some smoke	1-11	After test
Cleanlaser	Large Hole	2 oz.	Wet Spots	147˚F	138˚F	9%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke	1-12	1) Test set-up 2) Liquid Temperature 3) Panel after all tests

Laser	Opening	Fluid Amt.	Surface	Fluid Temp.	Chamber		Comments	Vacuum	Observations	Video Links	Picture Links
					Temp.	Hum.					
Cleanlaser	Small Hole	1 oz.	Wet Spots	149˚F	141˚F	6%	Hole taped & opened seconds before testing; surface temp (IR gun) 100-125˚F	On	No flame / explosion, no smoke; fuel vapors seep around tape (Picture)	2-1	Panel before tests
Cleanlaser	Large Horizontal Slot	1 oz.	Wet Spots	140˚F	142˚F	6%	Hole taped and opened seconds before testing; surface temp (IR gun) 100-125˚F	On	No flame / explosion, no smoke	2-2	
Cleanlaser	Small Hole	1 oz.	Wet Spots	140˚F	141˚F	6%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke, some debris, odor	2-3	Panel after three tests
Cleanlaser	Large Horizontal Slot	1 oz.	Wet Spots	151˚F	141˚F	6%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke, some debris, odor	2-4	1) After test 2) Panel after four tests
Cleanlaser	Narrow Horizontal Slot	1 oz.	Very Wet (Standing Liquid)	147˚F	143˚F	6%	Hole taped and opened seconds before testing; link to Video of preparation	On	No flame / explosion, some smoke, fuel being sucked into system, deposits on lens	2-5	
Cleanlaser	Narrow Vertical Slot	1 oz.	Very Wet (Standing Liquid)	133˚F	142˚F	6%	Hole taped and opened seconds before testing	On	No flame / explosion, some smoke, fuel being sucked into system, deposits on lens	2-6	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Very Wet (Standing Liquid)	140˚F	143˚F	6%	Hole taped and opened seconds before testing; link to Video of preparation	Off	No flame / explosion, lots of smoke	2-7	
Cleanlaser	Narrow Vertical Slot	1 oz.	Very Wet (Standing Liquid)	158˚F	142˚F	6%	Hole taped and opened seconds before testing; link to Video of preparation	Off	No flame / explosion, lots of smoke, fumes	2-8	After test
Cleanlaser	Large Hole	1 oz.	Wet Spots	142˚F	141˚F	6%	Hole taped and opened seconds before testing; metal piece inserted into cavity (painted side pointed down)	Off	No flame / explosion, little smoke	2-9	Test set-up
Cleanlaser	Large Vertical Slot	1 oz.	Wet Spots	142˚F	142˚F	6%	Hole taped and opened seconds before testing; metal piece inserted into cavity (painted side pointed up)	Off	No flame / explosion, little smoke	2-10	
Cleanlaser	Large Hole	2 oz.	Wet Spots	127˚F	142˚F	6%	Hole taped and opened seconds before testing; metal piece inserted into cavity (painted side pointed up)	Off	No flame / explosion, no smoke	2-11	
Cleanlaser	Large Vertical Slot	2 oz.	Wet Spots	151˚F	141˚F	6%	Hole taped and opened seconds before testing; metal piece inserted into cavity (painted side pointed down); link to Video of preparation	Off	No flame / explosion, little smoke	2-12	Panel after tests

Laser	Opening	Fluid Amt.	Surface	Fluid Temp.	Chamber		Comments	Vacuum	Observations	Video Links	Picture Links
					Temp.	Hum.					
Quantel	Large Hole	2 oz.	Dry	153˚F	144˚F	9%	Hole taped and opened seconds before testing; links to Picture of set-up; link to Movie of set-up	On	No flame / explosion, no smoke	3-1	1) Panel before tests 2) After test
Quantel	Large Vertical Slot	2 oz.	Dry	140˚F	142˚F	8%	Hole taped & opened seconds before testing; surface temp (IR gun) 96-110˚F; link to Picture	Off	No flame / explosion, no smoke	3-2	
Quantel	Large Hole	1 oz.	Dry	136˚F	145˚F	7%	Hole taped and opened seconds before testing	Off	No flame / explosion, no smoke	3-3	
Quantel	Small Hole	1 oz.	Dry	136˚F	146˚F	7%	Hole taped and opened seconds before testing	On	No flame / explosion, no smoke	3-4	
Quantel	Large Vertical Slot	1 oz.	Dry	147˚F	146˚F	7%	Hole taped and opened seconds before testing	Off	No flame / explosion, no smoke	3-5	
Quantel	Narrow Horizontal Slot	1 oz.	Wet Spots	151˚F	146˚F	7%	Hole taped and opened seconds before testing	Off	No flame / explosion, little smoke	3-6	After test
Quantel	Narrow Horizontal Slot	1 oz.	Very Wet (Standing Liquid)	154˚F	140˚F	7%	Hole taped & opened seconds before testing; surface temp (IR gun) 110-125˚F; link to Movie of prep.	On	No flame / explosion, no smoke	3-7	1) Liquid temperature 2) After test
Quantel	Narrow Horizontal Slot	1 oz.	Very Wet (Standing Liquid)	165˚F	139˚F	6%	Hole taped and opened seconds before testing	On	No flame / explosion, no smoke	3-8	After test
Quantel	Narrow Vertical Slot	1 oz.	Very Wet (Standing Liquid)	180˚F	138˚F	6%	Hole taped and opened seconds before testing; metal piece inserted into cavity (painted side pointed down)	Off	No flame / explosion, light smoke; test repeated (laser partially missed opening)	3-9a 3-9b	1) Liquid temperature 2) After test
Quantel	Small Hole	1 oz.	Very Wet (Standing Liquid)	147˚F	141˚F	6%	Hole taped and opened seconds before testing; metal piece inserted into cavity (painted side pointed up)	Off	No flame / explosion, light smoke	3-10	
Quantel	Large Horizontal Slot	1 oz.	Very Wet (Standing Liquid)	169˚F	143˚F	6%	Hole taped and opened seconds before testing; metal piece inserted into cavity (painted side pointed up)	Off	No flame / explosion, no smoke; laser affects paint on metal piece (Picture)	3-11	1) Liquid temperature 2) After test 3) Metal piece after test
Quantel	Large Horizontal Slot	2 oz.	Very Wet (Standing Liquid)	154˚F	144˚F	6%	Hole taped and opened seconds before testing; metal piece inserted into cavity (painted side down)	Off	No flame / explosion, no smoke	3-12	1) Liquid temperature 2) Vapors under tape After test 3) Panel after tests

II. Hydraulic Fluid MIL-PRF-83282

Laser	Opening	Fluid Amt.	Surface	Fluid Temp.	Chamber		Comments	Vacuum	Observations	Video Links	Picture Links
					Temp.	Hum.					
Cleanlaser	Large Hole	2 oz.	Dry	165˚F	148˚F	5%	Hole taped and opened seconds before testing; link to Picture of set-up	On	No flame / explosion, no smoke	4-1	1) Panel before tests 2) Test set-up 3) After test
Cleanlaser	Large Vertical Slot	2 oz.	Dry	144˚F	151˚F	5%	Hole taped and opened seconds before testing; some adhesive deposits from tape	Off	No flame / explosion, some smoke	4-2	1) Set-up 2) During test
Cleanlaser	Large Hole	1 oz.	Dry	180˚F	153˚F	6%	Hole taped and opened seconds before testing; surface temp. (IR gun) 85-145˚F	Off	No flame / explosion, no smoke	4-3	After first three tests
Cleanlaser	Small Hole	1 oz.	Dry	172˚F	154˚F	6%	Hole taped and opened seconds before testing	On	No flame / explosion, no smoke	4-4	
Cleanlaser	Large Vertical Slot	1 oz.	Dry	153˚F	154˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke	4-5	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Dry	180˚F	154˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke and dust	4-6	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Dry	171˚F	152˚F	5%	Hole taped and opened seconds before testing, surface temp (IR gun) 85-128˚F	On	No flame / explosion, no smoke	4-7	After test
Cleanlaser	Narrow Horizontal Slot	1 oz.	Dry	147˚F	152˚F	5%	Hole taped and opened seconds before testing; surface temp (IR gun) 105-135˚F	On	No flame / explosion, no smoke	4-8	
Cleanlaser	Narrow Vertical Slot	1 oz.	Dry	165˚F	152˚F	5%	Hole taped and opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, light smoke/dust	4-9	
Cleanlaser	Small Hole	1 oz.	Dry	144˚F	152˚F	5%	Hole taped and opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, some smoke/dust	4-10	
Cleanlaser	Large Horizontal Slot	1 oz.	Dry	172˚F	146˚F	6%	Hole taped and opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, some smoke/dust	4-11	1) After test 2) Panel after test
Cleanlaser	Large Horizontal Slot	2 oz.	Dry	176˚F	145˚F	6%	Hole taped & opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, lots of smoke/dust	4-12	1) After test 2) Panel after tests

Laser	Opening	Fluid Amt.	Surface	Fluid Temp.	Chamber		Comments	Vacuum	Observations	Video Links	Picture Links
					Temp.	Hum.					
Quantel	Large Hole	2 oz.	Small wet spots around opening	169˚F	146˚F	5%	Hole taped & opened seconds before testing; surface temp. (IR gun) 98-146˚F	On	No flame / explosion, no smoke; tempi-label in center of panel indicates 150˚F	4-1	
Quantel	Large Vertical Slot	2 oz.	Small wet spots around opening	158˚F	146˚F	5%	Hole taped and opened seconds before testing; some adhesive deposits from tape	Off	No flame / explosion, some smoke	4-2	
Quantel	Large Hole	1 oz.	Small wet spots around opening	144˚F	146˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, no smoke	4-3	
Quantel	Small Hole	1 oz.	Dry	158˚F	147˚F	5%	Hole taped and opened seconds before testing	On	No flame / explosion, no smoke	4-4	
Quantel	Large Vertical Slot	1 oz.	Dry	176˚F	146˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, no smoke	4-5	
Quantel	Narrow Horizontal Slot	1 oz.	Small wet spots around opening	171˚F	145˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, no smoke	4-6	
Quantel	Narrow Horizontal Slot	1 oz.	Dry	183˚F	143˚F	5%	Hole taped and opened seconds before testing	On	No flame / explosion, no smoke	4-7	
Quantel	Narrow Horizontal Slot	1 oz.	Small wet spots around opening	165˚F	142˚F	5%	Hole taped and opened seconds before testing	On	No flame / explosion, no smoke	4-8	
Quantel	Narrow Vertical Slot	1 oz.	Dry	178˚F	138˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, no smoke	4-9	
Quantel	Small Hole	1 oz.	Dry	140˚F	141˚F	5%	Hole taped &opened seconds before testing; metal piece in cavity painted side up; surface temp 96-120˚F	Off	No flame / explosion, no smoke	4-10	
Quantel	Large Horizontal Slot	1 oz.	Dry	180˚F	142˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, no smoke	4-11	
Quantel	Large Horizontal Slot	2 oz.	Dry	176˚F	142˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, no smoke	4-12	Panel after tests

III. Hydraulic fluid MIL-H-5606

Laser	Opening	Fluid Amt.	Surface	Fluid Temp.	Chamber		Comments	Vacuum	Observations	Video Links	Picture Links
					Temp.	Hum.					
Cleanlaser	Large Hole	2 oz.	Wet around opening	165˚F	153˚F	5%	Hole taped and opened seconds before testing; link to Picture of test set-up	Off	No flame / explosion, some smoke and dust	5-1	Panel before tests
Cleanlaser	Large Vertical Slot	2 oz.	Wet around opening	140˚F	153˚F	5%	Hole taped & opened seconds before testing; surface temp. (IR gun) 88-135˚F	Off	No flame / explosion, some smoke and dust	5-2	
Cleanlaser	Large Hole	1 oz.	Wet around opening	169˚F	153˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, no smoke	5-3	After test
Cleanlaser	Small Hole	1 oz.	Wet around opening	176˚F	154˚F	5%	Hole taped and opened seconds before testing; visible fluid vapors	On	No flame / explosion, no smoke	5-4	
Cleanlaser	Large Vertical Slot	1 oz.	Standing liquid on front side	153˚F	154˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke and dust	5-5	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Wet around opening	190˚F	153˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke and dust	5-6	After test
Cleanlaser	Narrow Horizontal Slot	1 oz.	Very Wet (Standing Liquid)	163˚F	154˚F	5%	Hole taped and opened seconds before testing, surface temp (IR gun) 101-134˚F	On	No flame / explosion, no smoke	5-7	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Wet around opening	138˚F	152˚F	5%	Hole taped & opened seconds before testing; surface temp (IR gun) 105-135˚F	On	No flame / explosion, no smoke	5-8	
Cleanlaser	Narrow Vertical Slot	1 oz.	Very Wet (Standing Liquid)	163˚F	148˚F	5%	Hole taped and opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, lots of smoke/dust	5-9	After test
Cleanlaser	Small Hole	1 oz.	Dry	147˚F	142˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, little smoke/dust	5-10	
Cleanlaser	Large Horizontal Slot	1 oz.	Wet around opening	154˚F	139˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, some smoke/dust	5-11	
Cleanlaser	Large Horizontal Slot	2 oz.	Very Wet (Standing Liquid)	165˚F	139˚F	5%	Hole taped and opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, some smoke/dust	5-12	Panel after tests

Laser	Opening	Fluid Amt.	Surface	Fluid Temp.	Chamber		Comments	Vacuum	Observations	Video Links	Picture Links
					Temp.	Hum.					
Quantel	Large Hole	2 oz.	Wet spots around opening	156˚F	152˚F	5%	Hole taped & opened seconds before testing; surface temp (IR gun) 97-150˚F	Off	No flame / explosion, no smoke; tempi label in center of panel indicates 150˚F	5-1	
Quantel	Large Vertical Slot	2 oz.	Wet around opening	151˚F	150˚F	5%	Hole taped & opened seconds before testing	Off	No flame / explosion, no smoke	5-2	
Quantel	Large Hole	1 oz.	Dry	145˚F	146˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, no smoke	5-3	
Quantel	Small Hole	1 oz.	Dry	162˚F	139˚F	5%	Hole taped & opened seconds before testing; surface temp (IR gun) 93-138˚F	On	No flame / explosion, no smoke	5-4	
Quantel	Large Vertical Slot	1 oz.	Dry	178˚F	135˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, no smoke	5-5	
Quantel	Narrow Horizontal Slot	1 oz.	Wet around opening	165˚F	133˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, no smoke	5-6	
Quantel	Narrow Horizontal Slot	1 oz.	Wet around opening	180˚F	147˚F	5%	Hole taped and opened seconds before testing	On	No flame / explosion, no smoke	5-7	
Quantel	Narrow Horizontal Slot	1 oz.	Wet around opening	167˚F	146˚F	5%	Hole taped & opened seconds before testing	On	No flame / explosion, no smoke	5-8	
Quantel	Narrow Vertical Slot	1 oz.	Wet around opening	176˚F	141˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side down; surface temp (IR gun) 81-127˚F	Off	No flame / explosion, no smoke	5-9	
Quantel	Small Hole	1 oz.	Wet around opening	149˚F	135˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, no smoke	5-10	
Quantel	Large Horizontal Slot	1 oz.	Wet around opening	187˚F	132˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, no smoke	5-11	
Quantel	Large Horizontal Slot	2 oz.	Very wet around opening	172˚F	129˚F	5%	Hole taped and opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, no smoke	5-12	Panel after tests

IV. Royco Engine Lubricating Oil MIL-PRF-808

Laser	Opening	Fluid Amt.	Surface	Fluid Temp.	Chamber		Comments	Vacuum	Observations	Video Links	Picture Links
					Temp.	Hum.					
Cleanlaser	Large Hole	2 oz.	Dry	171˚F	144˚F	5%	Hole taped and opened seconds before testing	On	No flame / explosion, no smoke or dust	6-1	Panel before tests
Cleanlaser	Large Vertical Slot	2 oz.	Dry	140˚F	147˚F	5%	Hole taped & opened seconds before testing	Off	No flame / explosion, some smoke and dust	6-2	
Cleanlaser	Large Hole	1 oz.	Dry	194˚F	148˚F	5%	Hole taped and opened seconds before testing; surface temp. (IR gun) 85-128˚F	Off	No flame / explosion, some smoke and dust; fluid temperature dropped to 158˚F	6-3	
Cleanlaser	Small Hole	1 oz.	Dry	165˚F	148˚F	5%	Hole taped and opened seconds before testing; visible fluid vapors	On	No flame / explosion, no smoke	6-4	
Cleanlaser	Large Vertical Slot	1 oz.	Dry	162˚F	149˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke and dust	6-5	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Dry	169˚F	147˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke and dust	6-6	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Dry	160˚F	150˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke/dust	6-7	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Wet spots around opening	140˚F	150˚F	5%	Hole taped & opened seconds before testing	On	No flame / explosion, no smoke	6-8	
Cleanlaser	Narrow Vertical Slot	1 oz.	Dry	154˚F	151˚F	5%	Hole taped and opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, some smoke/dust	6-9	
Cleanlaser	Small Hole	1 oz.	Dry	144˚F	151˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up; surface temp (IR gun) 100-126˚F	Off	No flame / explosion, some smoke/dust	6-10	
Cleanlaser	Large Horizontal Slot	1 oz.	Dry	154˚F	151˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, some smoke/dust	6-11	
Cleanlaser	Large Horizontal Slot	2 oz.	Dry	158˚F	151˚F	5%	Hole taped and opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, lots of smoke/dust	6-12	Panel after tests

Laser	Opening	Fluid Amt.	Surface	Fluid Temp.	Chamber		Comments	Vacuum	Observations	Video Links	Picture Links
					Temp.	Hum.					
Quantel	Large Hole	2 oz.	Dry	149˚F	156˚F	8%	Hole taped and opened seconds before testing; surface temp. (IR gun) 84-127˚F	Off	No flame / explosion, no smoke or dust; tempi label in center of panel indicates 125˚F	6-1	
Quantel	Large Vertical Slot	2 oz.	Dry	147˚F	157˚F	5%	Hole taped & opened seconds before testing	On	No flame / explosion, some smoke and dust	6-2	
Quantel	Large Hole	1 oz.	Dry	140˚F	157˚F	8%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke and dust	6-3	
Quantel	Small Hole	1 oz.	Dry	145˚F	152˚F	5%	Hole taped and opened seconds before testing; visible fluid vapors	On	No flame / explosion, no smoke	6-4	
Quantel	Large Vertical Slot	1 oz.	Dry	151˚F	141˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke and dust	6-5	
Quantel	Narrow Horizontal Slot	1 oz.	Dry	136˚F	134˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke and dust	6-6	
Quantel	Narrow Horizontal Slot	1 oz.	Dry	136˚F	144˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke/dust	6-7	
Quantel	Narrow Horizontal Slot	1 oz.	Dry	144˚F	148˚F	5%	Hole taped & opened seconds before testing	On	No flame / explosion, no smoke	6-8	
Quantel	Narrow Vertical Slot	1 oz.	Dry	149˚F	150˚F	5%	Hole taped and opened seconds before testing; metal piece in cavity painted side down; surface temp. (IR gun) 79-117˚F	Off	No flame / explosion, some smoke/dust	6-9	
Quantel	Small Hole	1 oz.	Dry	145˚F	152˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, some smoke/dust	6-10	
Quantel	Large Horizontal Slot	1 oz.	Dry	151˚F	152˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, some smoke/dust	6-11	
Quantel	Large Horizontal Slot	2 oz.	Dry	154˚F	151˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, lots of smoke/dust	6-12	Panel after tests

V. Mobile Jet Oil 254

Laser	Opening	Fluid Amt.	Surface	Fluid Temp.	Chamber		Comments	Vacuum	Observations	Video Links	Picture Links
					Temp.	Hum.					
Cleanlaser	Large Hole	2 oz.	Small wet spots around opening	163˚F	151˚F	5%	Hole taped & opened seconds before testing; surface temp. (IR gun) 82-124˚F	On	No flame / explosion, no smoke or dust	7-1	Panel before tests
Cleanlaser	Large Vertical Slot	2 oz.	Dry	147˚F	150˚F	5%	Hole taped & opened seconds before testing	Off	No flame / explosion, some smoke and dust	7-2	
Cleanlaser	Large Hole	1 oz.	Dry	149˚F	150˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, little smoke and dust	7-3	
Cleanlaser	Small Hole	1 oz.	Dry	149˚F	147˚F	5%	Hole taped and opened seconds before testing; visible fluid vapors	On	No flame / explosion, no smoke	7-4	
Cleanlaser	Large Vertical Slot	1 oz.	Small wet spots around opening	131˚F	145˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke and dust	7-5	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Small wet spots around opening	147˚F	145˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke and dust	7-6	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Dry	147˚F	148˚F	5%	Hole taped & opened seconds before testing; surface temp (IR gun) 100-126˚F	On	No flame / explosion, no smoke/dust	7-7	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Wet spots around opening	129˚F	150˚F	5%	Hole taped & opened seconds before testing	On	No flame / explosion, no smoke/dust	7-8	
Cleanlaser	Narrow Vertical Slot	1 oz.	Dry	156˚F	150˚F	5%	Hole taped and opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, some smoke/dust	7-9	
Cleanlaser	Small Hole	1 oz.	Wet spots around opening	149˚F	150˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, some smoke/dust	7-10	
Cleanlaser	Large Horizontal Slot	1 oz.	Dry	151˚F	150˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, some smoke/dust	7-11	
Cleanlaser	Large Horizontal Slot	2 oz.	Wet spots around opening	151˚F	149˚F	5%	Hole taped and opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, some smoke/dust	7-12	Panel after tests

Laser	Opening	Fluid Amt.	Surface	Fluid Temp.	Chamber		Comments	Vacuum	Observations	Video Links	Picture Links
					Temp.	Hum.					
Quantel	Large Hole	2 oz.	Dry	165˚F	154˚F	5%	Hole taped & opened seconds before testing	On	No flame / explosion, no smoke or dust	7-1	
Quantel	Large Vertical Slot	2 oz.	Dry	151˚F	154˚F	NM	Hole taped & opened seconds before testing; surface temp. (IR gun) 89-134˚F	Off	No flame / explosion, no smoke or dust	7-2	
Quantel	Large Hole	1 oz.	Dry	140˚F	NM	NM	Hole taped and opened seconds before testing	Off	No flame / explosion, no smoke or dust	7-3	
Quantel	Small Hole	1 oz.	Dry	147˚F	NM	NM	Hole taped and opened seconds before testing; visible fluid vapors	On	No flame / explosion, no smoke or dust	7-4	
Quantel	Large Vertical Slot	1 oz.	Dry	176˚F	147˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, no smoke or dust	7-5	
Quantel	Narrow Horizontal Slot	1 oz.	Dry	176˚F	146˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, no smoke or dust	7-6	
Quantel	Narrow Horizontal Slot	1 oz.	Dry	180˚F	143˚F	5%	Hole taped & opened seconds before testing	On	No flame / explosion, no smoke or dust	7-7	
Quantel	Narrow Horizontal Slot	1 oz.	Dry	169˚F	140˚F	5%	Hole taped & opened seconds before testing	On	No flame / explosion, no smoke or dust	7-8	
Quantel	Narrow Vertical Slot	1 oz.	Dry	172˚F	138˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side down; surface temp 95-103˚F	Off	No flame / explosion, no smoke or dust	7-9	
Quantel	Small Hole	1 oz.	Dry	147˚F	135˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, no smoke or dust	7-10	
Quantel	Large Horizontal Slot	1 oz.	Dry	183˚F	134˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, no smoke or dust	7-11	
Quantel	Large Horizontal Slot	2 oz.	Dry	178˚F	132˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, no smoke or dust	7-12	Panel after tests

VI. Skydrol LD-4 (fire resistant hydraulic fluid)

Laser	Opening	Fluid Amt.	Surface	Fluid Temp.	Chamber		Comments	Vacuum	Observations	Video Links	Picture Links
					Temp.	Hum.					
Cleanlaser	Large Hole	2 oz.	Dry	167˚F	155˚F	6%	Hole taped and opened seconds before testing	On	No flame / explosion, no smoke or dust	10-1	
Cleanlaser	Large Vertical Slot	2 oz.	Wet spots around opening	149˚F	155˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, little smoke and dust	10-2	
Cleanlaser	Large Hole	1 oz.	Dry	147˚F	156˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, little smoke and dust	10-3	
Cleanlaser	Small Hole	1 oz.	Dry	154˚F	155˚F	5%	Hole taped and opened seconds before testing; visible fluid vapors	On	No flame / explosion, no smoke	10-4	
Cleanlaser	Large Vertical Slot	1 oz.	Wet spots around opening	154˚F	156˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke and dust	10-5	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Wet spots around opening	147˚F	156˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke and dust	10-6	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Wet spots around opening	144˚F	156˚F	5%	Hole taped and opened seconds before testing	On	No flame / explosion, no smoke/dust	10-7	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Wet spots around opening	144˚F	157˚F	5%	Hole taped & opened seconds before testing	On	No flame / explosion, no smoke	10-8	
Cleanlaser	Narrow Vertical Slot	1 oz.	Wet spots around opening	154˚F	157˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side down; surface temp (IR gun) 99-133˚F	Off	No flame / explosion, some smoke/dust	10-9	
Cleanlaser	Small Hole	1 oz.	Very wet around opening	158˚F	156˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, little smoke/dust	10-10	
Cleanlaser	Large Horizontal Slot	1 oz.	Small wet spots around opening	154˚F	155˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, some smoke/dust	10-11	
Cleanlaser	Large Horizontal Slot	2 oz.	Wet around opening	154˚F	155˚F	5%	Hole taped and opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, some smoke/dust	10-12	Panel after tests

Laser	Opening	Fluid Amt.	Surface	Fluid Temp.	Chamber		Comments	Vacuum	Observations	Video Links	Picture Links
					Temp.	Hum.					
Quantel	Large Hole	2 oz.	Dry	144˚F	162˚F	5%	Hole taped and opened seconds before testing; surface temp (IR gun) 85-118˚F	On	No flame / explosion, no smoke or dust; tempi label in center of panel indicates 125˚F	10-1	
Quantel	Large Vertical Slot	2 oz.	Dry	140˚F	164˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, no smoke or dust	10-2	
Quantel	Large Hole	1 oz.	Wet spots around opening	144˚F	163˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, no smoke or dust	10-3	
Quantel	Small Hole	1 oz.	Dry	160˚F	162˚F	5%	Hole taped and opened seconds before testing; visible fluid vapors	On	No flame / explosion, no smoke or dust	10-4	After test
Quantel	Large Vertical Slot	1 oz.	Dry	158˚F	156˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, no smoke or dust	10-5	
Quantel	Narrow Horizontal Slot	1 oz.	Dry	151˚F	150˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, no smoke or dust	10-6	
Quantel	Narrow Horizontal Slot	1 oz.	Dry	154˚F	142˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, no smoke or dust	10-7	
Quantel	Narrow Horizontal Slot	1 oz.	Dry	145˚F	136˚F	5%	Hole taped & opened seconds before testing	Off	No flame / explosion, no smoke or dust	10-8	
Quantel	Narrow Vertical Slot	1 oz.	Dry	133˚F	128˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side down; ; surface temp 79-90˚F	Off	No flame / explosion, no smoke or dust	10-9	
Quantel	Small Hole	1 oz.	Dry	144˚F	156˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, no smoke or dust	10-10	
Quantel	Large Horizontal Slot	1 oz.	Small wet spots around opening	154˚F	161˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, no smoke or dust	10-11	
Quantel	Large Horizontal Slot	2 oz.	Dry	154˚F	165˚F	6%	Hole taped & opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, no smoke or dust	10-12	Panel after tests

Surface Contamination Testing

The charts on the following pages illustrate the results and observations of the surface contamination testing. Note that this document has been modified with hyperlinks to movie and/or picture files. No flames or explosions were observed in these test trials. For example, *Figure 20* shows the test panel after conducting an artificial cavity test with JP-8+100 fluid (120W Nd:YAG laser). *Figure 21*. shows the same test with the 40W Nd:YAG system. Note that the lasers did not ignite the vapor or the standing liquid on the surface of the test panel.

FIGURE 20. SURFACE CONTAMINATION TEST (120W LASER)

FIGURE 21. SURFACE CONTAMINATION TEST (40W LASER)

Surface Contamination Testing

I. JP-8 Turbine Fuel +100 Additive

Laser System	Surface	Surface Temp. before Stripping	Surface Temp. after Stripping	Comments	Vacuum	Observations	Video Links	Picture Links
Cleanlaser	Wipe Dry	90-128˚F	No change	Roller Nozzle;	On	No flame, no explosion, no smoke	S1-1	After test
Cleanlaser	Very Wet (Standing Liquid)	100-135˚F	~101˚F	Roller Nozzle; Video of preparation	On	No flame, no explosion, no smoke	S1-2	After test
Cleanlaser	Wipe Dry	90-128˚F	~135˚F	Roller Nozzle; Video of preparation	Off	No flame, no explosion, lots of smoke	S1-3	After test
Cleanlaser	Very Wet (Standing Liquid)	100-130˚F	~140˚F	Roller Nozzle; Video of preparation	Off	No flame, no explosion, lots of smoke	S1-4	After tests (left)

Laser System	Surface	Surface Temp. before Stripping	Surface Temp. after Stripping	Comments	Vacuum	Observation	Video Links	Picture Links
Cleanlaser	Wipe Dry	102-128˚F	No change	Short Nozzle	Off	No flame, no explosion, no smoke	S2-1	After Test
Cleanlaser	Very Wet (Standing Liquid)	100-125˚F	~128˚F	Short Nozzle	Off	No flame, no explosion, no smoke	S2-2	After Test
Cleanlaser	Wipe Dry	102-128˚F	~138˚F	Short Nozzle	On	No flame, no explosion, lots of smoke	S2-3	
Cleanlaser	Very Wet (Standing Liquid)	115-129˚F	~124˚F	Short Nozzle	On	No flame, no explosion, lots of smoke	S2-4	After tests (right)

Laser System	Surface	Surface Temp. before Stripping	Surface Temp. after Stripping	Comments	Vacuum	Observation	Video Links	Picture Links
Quantel	Wipe Dry	95-115˚F	No change	Manual traverse	On	No flame, no explosion, no smoke	S3-1	Set-up
Quantel	Very Wet (Standing Liquid)	108-112˚F	No change	Manual traverse	Off	No flame, no explosion, little smoke	S3-2	After test
Quantel	Wipe Dry	111-115˚F	No change	Manual traverse	On	No flame, no explosion, no smoke	S3-3	After test
Quantel	Very Wet (Standing Liquid)	115-118˚F	No change	Manual traverse	Off	No flame, no explosion, little smoke	S3-4	After test

II. Royco Engine Lubricating Oil MIL-PRF-808

Laser System	Surface	Surface Temp. before Stripping	Surface Temp. after Stripping	Comments	Vacuum	Observation	Video Links	Picture Links
Cleanlaser	Wipe Dry	106-134˚F	104-166˚F	Short Nozzle;	Off	No flame, no explosion, lots of smoke	S4-1	(1) Panel before tests (2) Panel before tests
Cleanlaser	Very Wet (Standing Liquid)	125-140˚F	134-185˚F	Short Nozzle; Video of preparation	Off	No flame, no explosion, some smoke	S4-2	(1) After test (2) Panel after all test
Quantel	Wipe Dry	91-142˚F	104-126˚F		Off	No flame, no explosion, no smoke	S4-3	After test
Quantel	Very Wet (Standing Liquid)	89-106˚F	101-115˚F		Off	No flame, no explosion, little smoke	S4-4	

III. Hydraulic Fluid MIL-PRF-83282

Laser System	Surface	Surface Temp. before Stripping	Surface Temp. after Stripping	Comments	Vacuum	Observation	Video Links	Picture Links
Cleanlaser	Wipe Dry	129-146˚F	106-146˚F	Short Nozzle	Off	No flame, no explosion, lots of smoke & dust	S5-1	Before test
Cleanlaser	Very Wet (Standing Liquid)	119-136˚F	126-194˚F	Short Nozzle	Off	No flame, no explosion, lots of smoke & dust	S5-2	(1) After test (2) After test
Quantel	Wipe Dry	80-143˚F	No change		Off	No flame, no explosion, no smoke	S5-3	
Quantel	Very Wet (Standing Liquid)	83-135˚F	No change		Off	No flame, no explosion, little smoke	S5-4	(1) After test (2) Panel after tests (3) Panel after tests (4) Panel after tests

IV. Hydraulic Fluid MIL-H-5606

Laser System	Surface	Surface Temp. before Stripping	Surface Temp. after Stripping	Comments	Vacuum	Observation	Video Links	Picture Links
Cleanlaser	Wipe Dry	106-147˚F	94-164˚F	Short Nozzle	Off	No flame, no explosion, lots of smoke & dust	S6-1	Before test
Cleanlaser	Very Wet (Standing Liquid)	93-125˚F	104-164˚F	Short Nozzle	Off	No flame, no explosion, lots of smoke & dust	S6-2	(1) After test (2) Panel after all test
Quantel	Wipe Dry	99-110˚F	No change		Off	No flame, no explosion, no smoke	S6-3	
Quantel	Very Wet (Standing Liquid)	86-106˚F	No change		Off	No flame, no explosion, no smoke	S6-4	(1) Panel after tests (2) Panel after tests (3) Panel after tests

V. Mobile Engine Lubricating Oil MIL-PRF- 254

Laser System	Surface	Surface Temp. before Stripping	Surface Temp. after Stripping	Comments	Vacuum	Observation	Video Links	Picture Links
Cleanlaser	Wipe Dry	108-128˚F	115-150˚F	Short Nozzle	Off	No flame, no explosion, lots of smoke & dust	S7-1	Before test
Cleanlaser	Very Wet (Standing Liquid)	110-130˚F	149-198˚F	Short Nozzle	Off	No flame, no explosion, lots of smoke & dust	S7-2	(1) After test (2) Panel after all test
Quantel	Wipe Dry	88-103˚F	106-120˚F		Off	No flame, no explosion, no smoke	S7-3	
Quantel	Very Wet (Standing Liquid)	108-127˚F	90-129˚F		Off	No flame, no explosion, no smoke	S7-4	(1) Panel after tests (2) Panel after tests (3) Panel after tests

VI. Skydrol LD-4 (fire resistant hydraulic fluid)

Laser System	Surface	Surface Temp. before Stripping	Surface Temp. after Stripping	Comments	Vacuum	Observation	Video Links	Picture Links
Cleanlaser	Wipe Dry	107-130˚F	147-216˚F	Short Nozzle	Off	No flame, no explosion, lots of smoke & dust	S8-1	Before test
Cleanlaser	Very Wet (Standing Liquid)	133-148˚F	147-195˚F	Short Nozzle	Off	No flame, no explosion, lots of smoke & dust	S8-2	After tests (top left)
Quantel	Wipe Dry	86-106˚F	102-108˚F		Off	No flame, no explosion, no smoke	S8-3	
Quantel	Very Wet (Standing Liquid)	101-106˚F	110-123˚F		Off	No flame, no explosion, no smoke	S8-4	(1) Panel after tests (2) Panel after test (3) Panel after test (2) Panel after tests (3) Panel after tests

Additional Testing

Additional Test Data on chemical strippers to push operational capabilities and confirm standard laser safety practices. The charts on the following pages illustrate the results and observations of this additional testing. Note that this document has been modified with hyperlinks to movie and/or picture files. The 120W Nd:YAG laser did not produce any flames or explosion in the artifical cavity tests. However, it did produce a flame in one surface contamination trial (Turco EA Stripper 6930). *Figure 22* shows the panel after this test.
The 40 W Nd:YAG laser did not produce a flame or explosion in the surface contamination tests. *Figure 23* shows the panel after surface contamination test. However, artificial cavity testing could not be accomplished with the 40 W Nd:YAG system because chemical stripper splattered on the laser lens and end piece during the first such test. (see *Figure 24*) To avoid further damage to the equipment, testing was halted. This "splattering" may be attributable to the emulsion-like nature of the solvent in the cavity and the mechanical shock effect of the laser pulse. No flame ore explosion was observed.

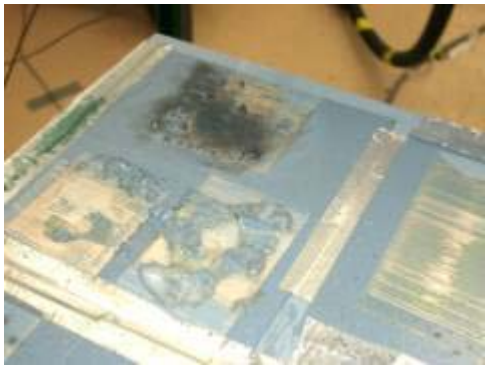

FIGURE 22. PANEL AFTER SURFACE CONTAMINATION TEST

(TURCO EA STRIPPER 6930; 120 W ND:YAG LASER)

FIGURE 23. PANEL AFTER SURFACE CONTAMINATION TEST

(MISC. FLUIDS, 40W ND:YAG LASER)

FIGURE 24. 40W ND:YAG LASER SYSTEM WITH CHEMICAL STRIPPER SPLATTER

Artificial Cavity Testing

I. Eldorado Non-chlorinated Paint Stripper PR-3131

Laser	Opening	Fluid Amt.	Surface	Fluid Temp.	Chamber		Comments	Vacuum	Observations	Video Links	Picture Links
					Temp.	Hum.					
Cleanlaser	Large Hole	2 oz.	Wet spots around opening	151˚F	160˚F	5%	Hole taped & opened seconds before testing; surface temp (IR gun) 84-124˚F	On	No flame / explosion, no smoke or dust	8-1	Panel before tests
Cleanlaser	Large Vertical Slot	2 oz.	Very Wet (standing liquid)	140˚F	157˚F	5%	Hole taped and opened seconds before testing; clear liquid (condensate)	Off	No flame / explosion, some smoke and dust; laser beam evident in cavity	8-2	
Cleanlaser	Large Hole	1 oz.	Wet spots around opening	144˚F	153˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke and dust	8-3	
Cleanlaser	Small Hole	1 oz.	Wet spots around opening	153˚F	157˚F	5%	Hole taped and opened seconds before testing; visible fluid vapors	On	No flame / explosion, no smoke	8-4	After test
Cleanlaser	Large Vertical Slot	1 oz.	Very Wet (standing liquid)	136˚F	158˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, little smoke and dust	8-5	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Wet spots around opening	144˚F	159˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, little smoke and dust	8-6	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Very Wet (standing liquid)	140˚F	155˚F	5%	Hole taped & opened seconds before testing; surface temp (IR gun) 96-111˚F	On	No flame / explosion, no smoke/dust	8-7	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Very Wet (standing liquid)	126˚F	154˚F	5%	Hole taped & opened seconds before testing	Off	No flame / explosion, some smoke/dust	8-8	
Cleanlaser	Narrow Vertical Slot	1 oz.	Very Wet (standing liquid)	136˚F	155˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, some smoke/dust	8-9	
Cleanlaser	Small Hole	1 oz.	Very Wet (standing liquid)	136˚F	156˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, some smoke/dust	8-10	
Cleanlaser	Large Horizontal Slot	1 oz.	Very Wet (standing liquid)	136˚F	156˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, some smoke/dust	8-11	
Cleanlaser	Large Horizontal Slot	2 oz.	Very Wet (standing liquid)	147˚F	155˚F	5%	Hole taped and opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, some smoke/dust	8-12	Panel after tests

II. Turco EA Stripper 6930

Laser	Opening	Fluid Amt.	Surface	Fluid Temp.	Chamber		Comments	Vacuum	Observations	Video Links	Picture Links
					Temp.	Hum.					
Cleanlaser	Large Hole	2 oz.	Wet spots around opening; some dissolved paint	154˚F	162˚F	5%	Hole taped & opened seconds before testing	On	No flame / explosion, no smoke or dust	9-1	Panel before tests
Cleanlaser	Large Vertical Slot	2 oz.	Dry	147˚F	163˚F	5%	Hole taped & opened seconds before testing; surface temp (IR gun) 80-132˚F	Off	No flame / explosion, little smoke and dust	9-2	
Cleanlaser	Large Hole	1 oz.	Dry	136˚F	163˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, little smoke and dust	9-3	
Cleanlaser	Small Hole	1 oz.	Dry	140˚F	163˚F	5%	Hole taped and opened seconds before testing; visible fluid vapors	On	No flame / explosion, no smoke	9-4	
Cleanlaser	Large Vertical Slot	1 oz.	Wet spots around opening	142˚F	164˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke and dust	9-5	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Dry	147˚F	164˚F	5%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke and dust	9-6	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Wet spots around opening	149˚F	164˚F	5%	Hole taped & opened seconds before testing; surface temp (IR gun) 84-121˚F	On	No flame / explosion, no smoke/dust	9-7	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Wet spots around opening	136˚F	164˚F	5%	Hole taped & opened seconds before testing	On	No flame / explosion, no smoke/dust	9-8	
Cleanlaser	Narrow Vertical Slot	1 oz.	Wet spots around opening	145˚F	164˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, some smoke/dust	9-9	
Cleanlaser	Small Hole	1 oz.	Very Wet (standing liquid)	144˚F	164˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, lots of smoke/dust	9-10	
Cleanlaser	Large Horizontal Slot	1 oz.	Very Wet (standing liquid)	144˚F	161˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, lots of smoke/dust	9-11	
Cleanlaser	Large Horizontal Slot	2 oz.	Very Wet (standing liquid)	154˚F	154˚F	5%	Hole taped & opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, lots of smoke/dust	9-12	Panel after tests

III. CEE-BEE R MeCl 256 Paint Stripper

Laser	Opening	Fluid Amt.	Surface	Fluid Temp.	Chamber		Comments	Vacuum	Observations	Video Links	Picture Links
					Temp.	Hum.					
Cleanlaser	Large Hole	2 oz.	Wet spots & dissolved paint around opening	127˚F	157˚F	6%	Hole taped & opened seconds before testing; liquid appears to be boiling (link to Movie); surface temp (IR gun) 78-120˚F	On	No flame / explosion, no smoke or dust	11-1	
Cleanlaser	Large Vertical Slot	2 oz.	Dry	117˚F	157˚F	6%	Hole taped & opened seconds before testing	Off	No flame / explosion, little smoke and dust	11-2	
Cleanlaser	Large Hole	1 oz.	Wet spots & dissolved paint around opening	126˚F	158˚F	6%	Hole taped and opened seconds before testing	Off	No flame / explosion, little smoke and dust	11-3	
Cleanlaser	Small Hole	1 oz.	Wet spots & dissolved paint around opening	136˚F	159˚F	6%	Hole taped and opened seconds before testing; visible fluid vapors	On	No flame / explosion, no smoke	11-4	
Cleanlaser	Large Vertical Slot	1 oz.	Wet spots & dissolved paint around opening	122˚F	159˚F	6%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke and dust	11-5	After test
Cleanlaser	Narrow Horizontal Slot	1 oz.	Dry	133˚F	161˚F	6%	Hole taped and opened seconds before testing	Off	No flame / explosion, some smoke and dust	11-6	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Wet spots & dissolved paint around opening	136˚F	161˚F	6%	Hole taped & opened seconds before testing; surface temp (IR gun) 84-121˚F	On	No flame / explosion, no smoke/dust	11-7	
Cleanlaser	Narrow Horizontal Slot	1 oz.	Dry	124˚F	159˚F	6%	Hole taped & opened seconds before testing	On	No flame / explosion, no smoke/dust	11-8	
Cleanlaser	Narrow Vertical Slot	1 oz.	Wet spots & dissolved paint around opening	133˚F	155˚F	6%	Hole taped & opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, some smoke/dust	11-9	
Cleanlaser	Small Hole	No data collected. Adhesive failed and glass jar dropped to the test chamber bottom									
Cleanlaser	Large Horizontal Slot	1 oz.	Wet spots & dissolved paint around opening	126˚F	150˚F	6%	Hole taped & opened seconds before testing; metal piece in cavity painted side up	Off	No flame / explosion, lots of smoke/dust	11-11	After test
Cleanlaser	Large Horizontal Slot	2 oz.	Wet spots & dissolved paint around opening	122˚F	143˚F	6%	Hole taped & opened seconds before testing; metal piece in cavity painted side down	Off	No flame / explosion, lots of smoke/dust; tempi-label = 125˚F	11-12	Panel after tests

Laser	Opening	Fluid Amt.	Surface	Fluid Temp.	Chamber		Comments	Vacuum	Observations	Video Links	Picture Links
					Temp.	**Hum.**					
Quantel	Large Hole	2 oz.	Dry	126˚F			Hole taped & opened seconds before testing; surface temp (IR gun) 101-127˚F	On	Liquid splatters on laser lens (links to Picture 1, Picture 2)– test aborted; tempi label in center of panel indicates 125˚F	11-1	1) After test 2) After test

Surface Contamination

I. Turco EA Stripper 6930

Laser System	Surface	Surface Temp. before Stripping	Surface Temp. after Stripping	Comments	Vacuum	Observation	Video Links	Picture Links
Cleanlaser	Apply fluid & wait 10 minutes	120-138˚F	Not measured	Short Nozzle	Off	**Flame**, no explosion, lots of smoke	S9-1-1 S9-1-2 S9-1-3	(1) Before test (2) After test
Cleanlaser	Apply fluid & wait 7 minutes	109-122˚F	132-160˚F	Short Nozzle; Movie of preparation	Off	No flame (close), no explosion, lots of smoke	S9-2	After test
Cleanlaser	Very Wet (Standing Liquid); Stripper not reacted	127-134˚F	125-143˚F	Short Nozzle	Off	No flame (close), no explosion, lots of smoke	S9-3	After test
Cleanlaser	After test S9-3, wait 4 minutes, and apply laser	121-135˚F	No change	Short Nozzle	Off	No flame (close), no explosion, lots of smoke	S9-4	After test
Cleanlaser	After test S9-4, wait 4 minutes, and apply laser	141-168˚F	No change	Short Nozzle	Off	No flame (close), no explosion, lots of smoke	S9-5	After test
Quantel	Wipe Dry	86-106˚F	102-108˚F		Off	No flame, no explosion, no smoke	S9-6	After test
Quantel	Very Wet (Standing Liquid)	101-106˚F	110-123˚F		Off	No flame, no explosion, no smoke	S9-7	After test

II. Eldorado Non-chlorinated Paint Stripper PR-3131

Laser System	Surface	Surface Temp. before Stripping	Surface Temp. after Stripping	Comments	Vacuum	Observation	Video Links	Picture Links
Cleanlaser	Apply fluid and wait 8 minutes	85-116˚F	90-123˚F	Short Nozzle	Off	No flame, no explosion, lots of smoke & dust	S10-1	(1) Before Test (2) After test
Cleanlaser	Very Wet (Standing Liquid); Stripper not reacted	113-122˚F	116-130˚F	Short Nozzle	Off	No flame, no explosion, lots of smoke & dust	No video	After tests
Quantel	Apply fluid and wait 10 minutes	99-110˚F	100-110˚F		Off	No flame, no explosion, no smoke	S10-3	
Quantel	Very Wet (Standing Liquid)	89-112˚F	91-105˚F		Off	No flame, no explosion, no smoke	S10-4	After test

III. CEE-BEE R MeCl 256 Paint Stripper

Laser System	Surface	Surface Temp. before Stripping	Surface Temp. after Stripping	Comments	Vacuum	Observation	Video Links	Picture Links
Cleanlaser	Apply fluid and wait 8 minutes	105-112˚F	101-140˚F	Short Nozzle; Picture of preparation	Off	No flame, no explosion, lots of smoke & dust	S11-1	After test
Cleanlaser	Very Wet (Standing Liquid); Stripper not reacted	110-120˚F	123-129˚F	Short Nozzle	Off	No flame, no explosion, lots of smoke & dust	S11-2	After test
Quantel	Apply fluid and wait 18 minutes	85-104˚F	100-111˚F		Off	No flame, no explosion, no smoke	S11-3	
Quantel	Very Wet (Standing Liquid)	88-107˚F	86-108˚F		Off	No flame, no explosion, no smoke	S11-4	(1) After test (2) After test (3) After test

Conclusions

(1) Given the environmental test conditions and list of tested maintenance fluids, this explosion/flammability testing showed that the lasers evaluated in this test series were not able to produce a flame or explosion in the artificial cavity or surface contamination.
(2) Laser de-painting operations will likely be conducted in hangars and/or work-cell environments. It is therefore unlikely that actual field conditions will exceed the test temperatures. However, additional testing may be required for very high temperatures environments and/or high sun intensity environments.
(3) The additional flammability testing using chemical strippers proved to be unrealistic of field conditions. It is unlikely that chemical stripper or solvent residues remain in large volume on the surface to be laser de-painted. Chemical stripper and solvent residues and dissolved paint are typically rinsed off with water prior to subsequent processing. Although a flame was only observed in one scenario, it is recommended that chemical strippers or flammable fluid residues be rinsed and removed from the work surface and the immediate work area. This testing re-confirmed that common laser safety procedures must be observed to operate the laser in potentially hazardous environments. To avoid the risk of fire or explosions, the laser shall only be operated on surfaces that are clear of chemical strippers or flammable materials. Lasers shall also not be fired into (flammable) liquids.
(4) This report is intended only to provide information to the safety approval authorities. This testing does not address all possible (field) scenarios. Additional testing may be required to fulfill specific requirements or unique applications.

Appendix E
Ergonomics Assessment

DEPARTMENT OF THE AIR FORCE
AIR FORCE INSTITUTE FOR OPERATIONAL HEALTH (AFMC)
BROOKS CITY-BASE TEXAS

11 March 2004

MEMORANDUM FOR HQ AFMC/SGBE
4225 Logistics Ave., N209
Wright Patterson AFB, OH 45433

FROM: AFIOH/RSH
2513 Kennedy Circle
Brooks City-Base, TX 78235-5116

SUBJECT: Consultative Letter IOH-RS-BR-CL-2004-0030,
Ergonomic Assessment of Handheld Laser Technology in De-painting Process

1. INTRODUCTION

a. *Purpose*:

(1) At the request of Maj Carolyn Macola of HQ AFMC/SGBE, the Health and Safety Division of the Air Force Institute for Operational Health (AFIOH/RSH) conducted a qualitative ergonomic survey to evaluate and describe the process used to remove paint from metal surfaces with a handheld, class IV, laser technology being assessed by the Air Force Research Laboratory at Wright Patterson AFB (WPAFB) for potential implementation at depots. This AFIOH ergonomic evaluation was requested as one aspect of an overall operational and environmental health assessment of handheld laser technology application in de-painting processes by AFRL; and is coordinated by personnel at Air Force Research Laboratory (AFRL), Gerard Mongelli and Stefan Susta.

(2) The purpose of this study was to identify possible ergonomic hazards and potential ergonomic improvements to the systems being researched by AFRL, and to collect background data to support the development of design and/or performance standards for potential future equipment purchases.

(3) Personnel from AFRL and AFIOH/RSH convened on 3 Feb 04 at AFRL, WPAFB Base to observe the current laboratory testing procedures on the handheld laser technology. Randy Straw reported that laser technology has been used in automated de-paint processes, and building exterior cleaning (removing soot) in Europe. The handheld laser tools they are assessing are manufactured in Europe. The direct health risks from the laser technology are to the eyes and the skin. Indirect health risks pertain to the interaction between the laser and the substances being cleaned that could result in an inhalation, absorption or ingestion hazard of particulates or fumes. Other hazards pertain to ergonomics, noise, electrical, compressed and

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toxic gases, radio frequencies, UV and visible radiation, ionizing radiation, and hazardous waste.

b. *AFIOH Personnel*:

Linda Schemm, Maj, USAF, BSC, Physical Therapist, MS-Occupational Ergonomics

c. *Personnel Contacted*:

Carolyn Macola, Maj, USAF, HQ AFMC
Stefan Susta, Contr, SAIC
Gerard Mongelli, Contr, HQ AFMC
Randy Straw, Contr, AFRL/MLSC
Pete Hall, AFRL, Technician/Operator

d. *Background*:

(1) This project was developed to migrate laser technology from AFRL research to demonstration and validation. Current depot de-painting process requires the use of chemicals such as methelyne chloride as normal maintenance practice to remove aircraft and support equipment coating systems. The focus of the AFRL project is to determine if a low powered hand-held laser system can be used to supplement automated de-painting of aircraft and components at the depot and field levels while eliminating chemical hazards associated with methelyne chloride use without creating other hazards.

(2) The proposed operating environments have not been fully defined. The portable laser may be used in an established depot and also in a deployed environment. Components requiring de-painting may be removed from the aircraft for cleaning; however, small areas on the aircraft may be de-painted directly. The portable laser may be used to supplement automated/robotic de-painting during an overhaul of an entire aircraft or during a repair to a portion of the aircraft. Randy Straw estimated that the handheld laser would be used no more than 2-4 hours a day, regardless of operating environment, but no data to this effect was available. AFRL personnel report that the operators of this device will be required to complete a specific training program and receive certification prior to using this technology.

Figure 1: Potential Use- directly on aircraft

Figure 2: Potential Use- directly on aircraft

(3) The laboratory operator conducts tests on steel panels coated with various substances that may be encountered in the field. The greatest concern expressed by AFRL regarding ergonomic hazards are related to the hand tool properties, the human-tool interface and the biomechanical process used to remove paint from metal surfaces with the handheld class IV laser. The system is being evaluated in the artificial environment of a laboratory in hopes of predicting and preventing concerns in the field. This was not an assessment of the laboratory work environment.

2. SURVEY PROCEDURES:

a. *Information Review*

(1) AFIOH investigator reviewed information from AFRL regarding the laser technology: 1) Standard Operating Procedure applied during trials at Hill AFB of the Class IV laser operating of Cleanlaser 120 wt handheld laser, 2) Operating Instructions- Laser Cleaning System CL80 Q/120 Q Basic System (Cleanlaser), 3) Operating Instructions- Manually Guidable Machining Optical Machining System OS H 50L with Exchangeable Nozzles (Cleanlaser), 4) Quantel's Laserblast 1000 Instruction Manual (40 wt), 5) Air and Noise Sampling Report by Pacific Environmental Services, 6) Safety Plan (Draft) – Portable Laser

Coating Removal by SAIC, 7) Laser Hazard Evaluation. Because this is a pre-deployment assessment, there are no injury/illness records pertaining to this process. The investigator interviewed the AFRL members involved in the project and the technician operating the devices. Personnel from AFRL and AFIOH/RSH convened on 3 Feb 04 at AFRL, WPAFB to observe the current laboratory testing procedures on the handheld laser technology.

(2) The operator reported that in the laboratory environment he uses the handheld lasers approximately 50% of his day (4 hours), with a work/rest cycle during the actual tool use of 30 minutes/10 minutes respectively. The operator is left hand dominant and reported no difficulty with using either tool in his left hand. He did note some discomfort in the left hand/forearm with the 40 watt laser. He reported some discomfort in his right hand, which he attributed to a recent increase in computer keyboarding. He had no other complaints of discomfort. The work surface he uses is at his waist level and angled at 45 degrees, and he stands on a cushioned rubber mat. He visually monitors the surface to assess quality of substance removal. He also noted that the 40 watt laser produces an audible sound, which he corresponds to visual confirmation of substance removal. The device needs to be held at a distance of 80-85 mm from surface. The 120 watt device has two hoses on the posterior side; the upper hose is for ventilation (cooling and capturing fumes and/or particles) and the lower hose is the fiber optic line (Figure 3). The 40 watt device has the fiber optic line entering the device at the bottom of the handle (Figure 10). The operator has added a ventilation hood to the firing end of the 40 watt device, with a ventilation hose attached to the bottom of it (Figure10).

b. *Workstation Configuration*:

(1) This evaluation is not specific to this workstation. The potential operating environments have not been fully defined. However, the work surface the laboratory operator uses is at his waist level and angled at 45 degrees, and he stands on a cushioned rubber mat. The pistol shape of each tool used at this workstation promotes awkward postures at the wrist (ulnar deviation) by tilting the front of the unit to meet the surface. It also creates awkward postures at the shoulder/neck and the trunk due to cradling lines and viewing the removal process at the laser-panel interface (Figure 4).

Figure 3: Laboratory use of 120watt hand held laser

c. *Specific Tool or System*.

(1) AFRL is conducting research on two particular systems, the Cleanlaser 120 watt system and the Quantel 40 watt system.

(2) General operation of either device reveals no significant vibration or reaction forces as reported by the operator and noted also by the evaluator during a trial use. The operation of either device also requires visual attention to substance removal, the 40 watt system more so than the 120 watt system. Both systems require appropriate vision protection (goggles/glasses). Both systems require the operator to protect the skin with clothing or sunscreen. The 40 watt system requires hearing protection.

(3) The 120 watt "Cleanlaser" handheld system is a pistol shaped unit equipped with a scanning laser that essentially fires multiple beams sequentially in a horizontal pattern. This allows for the laser to be moved in a vertical pattern manually, while cleaning an area approximately 2.5" in width. This width is adjustable through nozzle selection. This laser is equipped with interchangeable nozzles. A nozzle may have wheels attached to allow the operator to rest the wheels on the surface to be cleaned and move the handheld unit in a vertical direction (up/down) with a uniform distance of 80 mm between the laser and the surface. This allows for a uniform cleaning with less visual assessment required; however, the up/down motion is repetitive and may elevate the shoulder beyond 90 degrees of flexion. This handheld model also has a roller-free nozzle that allows for cleaning without contacting the surface directly. This may be useful when cleaning areas in a sharp angle such as seams, but would require greater skill and attention to maintain 80-85 mm distance. The handheld unit, with a nozzle and the ventilation hose and fiber optic line weighs 3 pounds, per the scale available at the laboratory. The handle length is 4" from the body of the unit. The diameter of the handle is 5 ½" (just under the activation button) and flares at the bottom.

(4) The 120 watt model is equipped with the fiber optic line and ventilation line on the posterior side of the handheld unit. It has a ventilation and particulate/fume capturing duct at the anterior of the unit. The unit feels balanced with the weight centered over the handle area, in line with the fist, when the lines are not attached. However, when the lines are attached, the weight shifts to the tail end. This requires the operator to manually tilt the unit in an anterior direction. This creates awkward postures at the shoulder, neck and trunk. In order to do this with the least hand effort, the operator balances the hose lines over his shoulder and employs the opposite hand to guide the tool. This requires the operator to keep his shoulder slightly elevated and abducted (similar to cradling a phone). This awkward posture can cause unnecessary stress at the shoulder (acromioclavicular joint and the glenohumeral joint) and may contribute to bursitis or tendonitis in that region.

(5) Starting the laser is a three-step process. First, the operator turns on the main body of the machine. Second, he/she makes any necessary adjustments based on criteria for the substance being cleaned. Third, the hand held unit becomes active when the operator depresses the one button trigger on the handheld unit while pressing the "start" (green) button with the opposite hand on the handheld unit. For a left hand user, this means reaching across the body and unit to press the green button. A right hand user would reach across the body, but would not have to reach over the unit. The trigger is easy to actuate, but it is so small that it would be easy to slide off it unintentionally. There is no "emergency stop" button on the handheld; however, when the trigger is released, the laser stops. The handheld unit does not require nitrogen, so the lens of the unit requires cleaning every 6 months. There is no holster or hanger on the main unit, for securing the handheld unit when not in use.

Figure 4: 120watt device- vertical movement
(up/down, forward/backward)

Figure 5: 120watt device- posterior side. Green button is pressed to initially start handheld unit. Top portal is for ventilation hose, bottom line is fiber-optic.

Figure 6: 120watt wheeled nozzle, unable to view small upper capture vent from this angle.

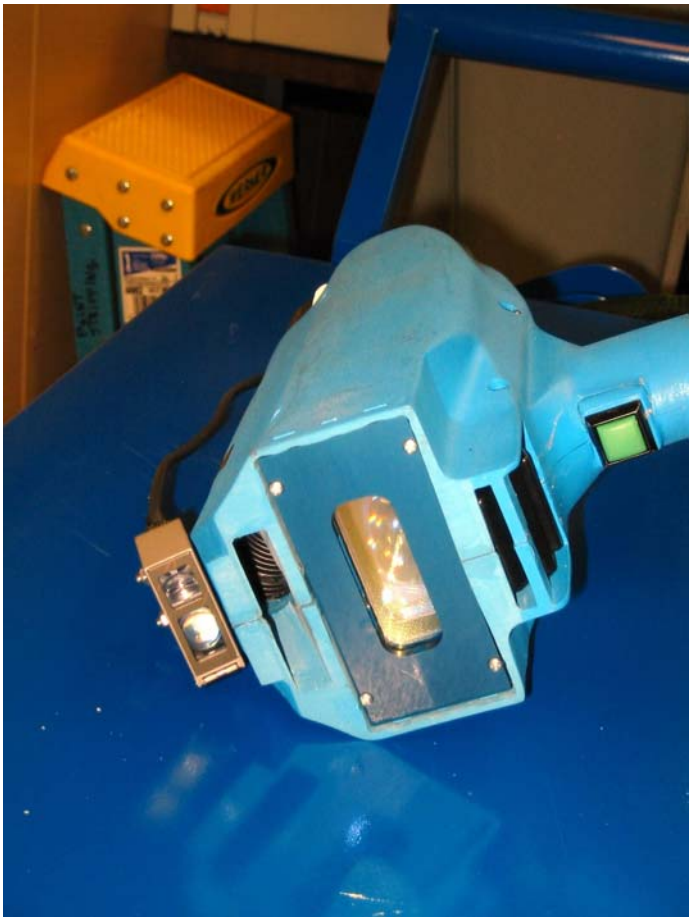

Figure 7: 120 watt- anterior end, without nozzle. Note upper capture vent.

Figure 8: 120 watt: note- no hanger or holster for handheld unit

(6) The Quantel 40 watt laser system is equipped with a focused single beam and requires compressed nitrogen gas, which keeps the lens clean. The operator must repetitively sweep the handheld unit laterally (side to side) in a 2-4" pattern, then move vertically and sweep laterally again, moving up the piece to be cleaned in small increments. This method requires the operator to be skilled at manipulating the unit to maintain a uniform distance of approximately 80 mm and to maintain a uniform cleaning depth. The operator reported that this model creates a high pitch sound that he correlates with visual assessments of cleaning at the appropriate depth. The operator wears hearing protection. This free-style method requires repetitive motions and a great deal of visual attention to the surface being cleaned. The 40 watt handheld unit is a pistol shape with a single digit trigger and a fixed nozzle. The nozzle seen in the photograph is a modification made by the operator as a capture vent for ventilation and a vacuum hose attaches to the bottom of the nozzle (Figure 9). The fiber optic line enters the handheld unit at the bottom of the handle. The handheld unit, with the capture vent and the ventilation hose and fiber optic line weighs 4.5 pounds, per the scale available at the laboratory.

(7) The handle is 1.5" in width, approximately 5" in diameter. The handle is a smooth aluminum, making it difficult to maintain a secure grip. There are also sharp edges against the palmar surface, combined with a large diameter handle and a single trigger, placing the hand at a biomechanical disadvantage to generate muscular force. The sweeping lateral motion necessary for the cleaning process can be achieved by repetitive wrist flexion and extension while exerting force to hold the unit upright. The grasping power of the hand is greatest when

the wrist is in neutral position or slightly extended (Vern Putz-Anderson). The unit does have a suspension ½ ring on top, so it could be used with a suspension device. The method employed by the AFRL operator is to hold the ventilation hose like a handle for two-hand operation, which then requires bilateral wrist flexion and extension and minimal trunk rotation and also places his hand close to the laser exit, which is a safety concern (Figure 10). Or the operator can hold the arms/hands steady and rotate the trunk to achieve the sweeping motion. These three methods are force and repetition hazards, either to the wrists or to the low back.

(8) The operator in the AFRL laboratory uses this tool against a surface that is approximately 45 degrees from horizontal or vertical. This means the operator has to tilt the hand tool anteriorly to address the work surface, which places him in an awkward posture. In this case, he is left hand dominant so the left arm is abducted in order to point the laser at the surface to be cleaned. This awkward posture can cause unnecessary stress at the shoulder (acromioclavicular joint and the glenohumeral joint) and may contribute to bursitis or tendonitis in that region.

(9) The single trigger activates the unit and must be depressed through out use, with the laser turning off when the trigger is released. The trigger is compressed at the distal end of the finger due to the large diameter of the handle. Actuation of the trigger is easy but requires static muscle contraction to maintain the activation while supporting the weight of the unit and lines. The muscles subjected to static work require more than 12 times longer than the original contraction-duration for complete recovery from fatigue (Vern-Putz Anderson). The operator reported some discomfort in the muscles of the forearm and in the index fingers. This type of motion, posture and force could contribute to musculoskeletal disorder such as tendonitis or tenosynovitis (trigger finger).

(10) Starting the laser system is a three-step process. First, the main unit is activated at the unit control panel or at the remote (can be attached to operator's belt). Second, he/she makes any necessary adjustments based on criteria for the substance being cleaned. Third, the handheld unit is activated at the trigger. The trigger must remain depressed for operation, turning off the laser when the trigger is released. There is an emergency stop (red button) on the handheld unit that will shut down the main system when activated.

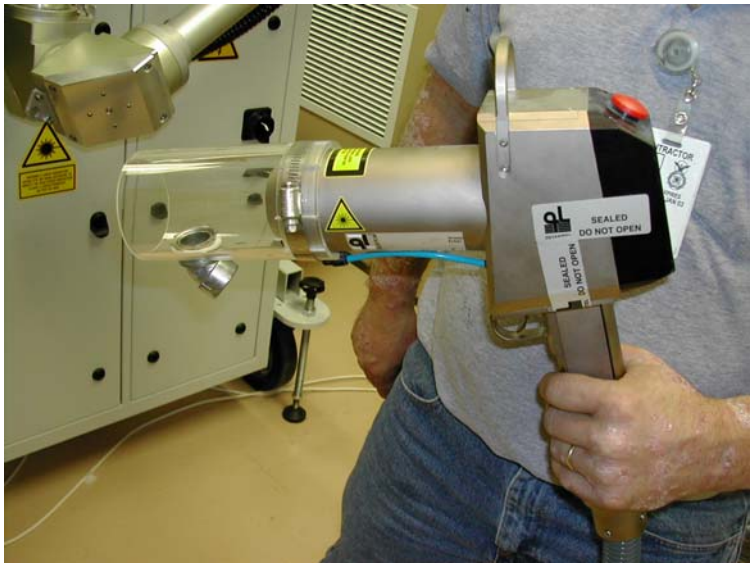

Figure 9: 40 watt- nozzle end was an addition of the operator as capture vent.
The ventilation hose is not attached.

Figure 10: 40 watt- operator's preferred position for using this unit.

Figure 11: Quantel 40watt main system with the handheld unit resting on top. There is a remote to turn on the main system, then activate the handheld unit with the trigger. Note- no hanger or holster to secure the handheld unit.

3. RESULTS

a. *Tool/System*:

(1) The National Institute for Occupational Safety and Health (NIOSH) published a critical review of epidemiological evidence for work related musculoskeletal disorders in 1997, *"Musculoskeletal Disorders and Workplace Factors"*. NIOSH concluded that there is a substantial body of credible epidemiological research providing strong evidence of an association between musculoskeletal disorder and certain work-related physical factors. The risk of each exposure depends on a variety of factors such as the frequency, duration, and intensity of physical workplace exposures. In 1986, Rothman defined "causality in the relationship between workplace risk factors and musculoskeletal disorders as an event, condition, or characteristic that plays an essential role in producing an occurrence of the disease" (NIOSH). The goal for the ergonomist is to apply this evidence in a manner that prevents work-related musculoskeletal disorders.

(2) As noted earlier, awkward postures of the shoulder, repetitive motion with up/down motion of the shoulder while maintaining arm abduction were noted with the use of the 120 watt system pistol shaped handheld unit. Repetitive motion is required with the use of the 40 watt system as well. This motion may take place at the wrist (flexion/extension), the shoulder

(internal/external rotation) or the low back (trunk rotation). Again, the arm activity is associated with awkward postures at the wrist (ulnar deviation to tilt tool), or at the shoulder (abduction to tilt tool). These factors present a potential risk for musculoskeletal disorders of the neck, shoulder and/or wrist/hand as noted by the research reviewed by NIOSH.

(3) There is evidence for a causal relationship between highly repetitive work and neck and neck/shoulder musculoskeletal disorders. Most of the epidemiological studies reviewed by NIOSH defined "repetitive work" for the neck as work activities that involved continuous arm or hand movements that affect the neck/shoulder musculature and generate loads on the neck/shoulder area. There is strong evidence that working groups with high levels of static contraction, prolonged static loads, or extreme working postures involving the neck/shoulder muscles are at increased risk for neck/shoulder musculoskeletal disorders. There is evidence for a positive association between highly repetitive work and shoulder musculoskeletal disorders involving combined exposure to repetition with awkward shoulder postures or static shoulder loads. NIOSH also noted evidence for a relationship between repeated or sustained shoulder postures with greater than 60 degrees of flexion or abduction and shoulder musculoskeletal disorders. The evidence for specific shoulder postures is strongest where there is combined exposure to several physical factors like holding a tool while working overhead.

(4) Carpal Tunnel Syndrome (CTS) is probably the first musculoskeletal disorder one thinks of when referring to the wrist or hand. Due to the repetitive motion at the wrist with the use of the 40 watt handheld unit, and the force required to support and manipulate the 4.5-pound unit, the operator may be at risk for carpal tunnel syndrome. There is evidence of a positive association between highly repetitive work alone or in combination with other factors and CTS. There is also evidence of a positive association between forceful work and CTS. There is insufficient evidence of an association between CTS and extreme postures; however, NIOSH noted laboratory-based studies of extreme postural factors supporting a positive association with CTS. There is evidence of a positive association between work involving hand/wrist vibration and CTS. The strongest evidence of a positive association is between exposure to a combination of risk factors (e.g., force and repetition, force and posture) and CTS. Based on the epidemiological studies reviewed by NIOSH, they concluded that exposure to a combination of the job factors studied (repetition, force, posture, etc.) increases the risk for CTS. These factors are present in the manner and position in which the handheld lasers were used in the laboratory. Epidemiological surveillance data, both nationally and internationally, have also consistently indicated that the highest rates of CTS occur in occupations and job tasks with intensive manual exertion such as meatpackers, poultry processors, and automobile assembly workers (NIOSH).

(5) Other hand musculoskeletal disorders can occur with high repetition, force and posture. These could include tendonitis or tenosynovitis at the thumb (DeQuervain's disease) or at the index finger (Trigger Finger). Due to the sustained hold of the trigger with a wide diameter handle on either unit while supporting and manipulating the unit, the operator may be at risk for tendonitis. There is evidence of an association between any single factor (repetition, force, and posture) and hand/wrist tendonitis, based on currently available epidemiological data. There is strong evidence that job tasks that require a combination of risk factors (e.g., highly repetitious, forceful hand/wrist exertions) increase risk for hand/wrist tendonitis.

(6) The low back may be at risk for musculoskeletal disorder in the de-painting process depending on the workstation configuration and/or method employed. NIOSH concluded there is strong evidence that low-back disorders are associated with work-related lifting and forceful movements and evidence that work-related awkward postures are associated with low-back disorders. Risk is likely related to speed or changes and degree of deviation from neutral position.

4. DISCUSSION

a. *General Guidelines*

(1) In developing the *Level I Ergonomics Methodology Guide for Maintenance and Inspection Work Areas* 1997, recommendations for hand tool criteria were included. This document can be obtained at https://www.afms.mil/ergo/ under the "publications" button. *The Occupational Ergonomics Handbook*, edited by Waldemar Karwowski and William Marras, was also referenced.

(2) The Occupational Safety and Health Administration (OSHA) standard that applies to hand tools, although it is not specific to lasers, is 29CFR 1926.300. This pertains to the following: maintenance of tools in a safe condition, tool guards, point of operation guarding, danger zone, personal protective equipment, on-off controls, and constant pressure switch.

(3) The following are general guidelines for the workstation-tool-worker interface. The main concept for protecting the worker from work-related musculoskeletal disorders is: “bend the tool not the worker”.

(4) In general, the hands should be at elbow height while working. The work surface height may need to be adjusted for the worker, or the worker’s location may need to be adjusted to meet the work surface height. Maximum speed for manual jobs occurs when arms are at one’s side and elbows are bent to right angles.

(5) Work surfaces may need to be angled to match the tool, or the tool may need to be angled to match the workstation in order to keep the workers body in the most neutral postures possible. A vertical surface at elbow height to the worker matches well with pistol grip tools that allow the worker to use a power grip. If the vertical surface were at knuckle height, an in-line tool would be appropriate to allow the worker to use a power grip. If the vertical surface were at shoulder height, it would be better to raise the worker to meet the surface (scissor lift, platform ladder) so the worker can position to the work surface appropriately for the tool being used. A horizontal surface at elbow height to the worker would match well with an in-line tool. If the horizontal surface were at knuckle height, a pistol grip would be more appropriate.

Poor design Better design

Poor design Better design

Figure 12: Work surface-tool-worker interface

(6) Major issues to be considered when developing or selecting a hand tool include: designing the tool for the task, flexibility to be useful in a variety of work situations, tool should encourage neutral and comfortable body postures, the tool should not require excessive forces, and the tool should not expose the user to hard edges, excessive vibration, impact, or torque. Essentially, the hand tool selection should consider how the particular task and workstation relate to the capabilities and limitations of the human operator.

(7) Power hand tools should be well balanced with all the attachments installed, with the hand tool center of gravity aligned with the center of the grasping hand so that the operator does not have to overcome moments by rotating the hand or wrist. Generally the hand tool and its attachments should not exceed 5 pounds, however experienced hand-tool operators have

indicated a preference for tools that weigh approximately 2 to 4 pounds (Karwowski, Marras). Cables and hoses should be minimized as much as possible. Attachment of these lines should be located to keep the tool balanced and minimize interference and drag. Swivel attachments and flexible tubing may improve handling.

(8) The handle/grip diameter of 1.25-2.0" is a general rule, with span for including a trigger of 2.5-3.5", however, Petrofsky found that a maximum grip force is achieved at approximately 2.0-2.4" (5-6cm) (Karwowski, Marras). This can vary with hand size, with large handed operators having a maximum grip force at approximately 2.4" and small-handed operators having a maximum grip force at approximately 2.0". The handle should be smooth, compressible and provide a friction grip surface. Handles should not be bare metal because it reduces the friction between the hand and the surface, increasing the muscular force required to grasp the tool. Rubberized insulating surfaces are preferred. The handle length should be long enough to allow adequate contact between the hand and the handle, without digging into the palm, but not so long that it interferes with the motion at the wrist, elbow or shoulder. Generally this means a length of approximately 4", but a length of 5" may be preferable if gloves are to be worn, for power grip tools. The handle shape should not have any sharp edges or abrupt curves, avoiding channels for individual triggers. A tool that must be directed in a particular manner could have a subtle discontinuity (flat area) in the handle to indicate direction or a flare towards the bottom to decrease hand slipping downward. Full handgrip force required to use the tool should not exceed 8 pounds. The tool should be right or left hand user friendly to allow operator to use either hand, providing rest breaks for each hand.

(9) Triggers and buttons should be positioned to allow activation without causing isolated stress at fingers or thumbs. Extended length triggers distribute the force of squeezing the trigger and grasping the handle to several fingers to reduce the stress at the index finger. The trigger length recommendation is 1.5"-2.25". The recommended trigger width is 0.5-1.0" to allow the entire finger pad to contact the trigger. The depth should be approximately 0.12-0.37" to limit finger extension. The force required to activate the trigger should be minimal, less than 1 pound. The operator should be able to easily sense actuation and release of the trigger.

5. RECOMMENDATIONS

a. *Workstation Design*

(1) The workstation and operating environments have not been fully defined, yet tool recommendations are partially dependent upon how they will be implemented. Because the work environment may be variable, flexibility will be important for implementation of a handheld laser cleaning system.

(2) In a fixed location such as a depot, an overhead suspension system for supporting handheld tools during use could be considered. Permanent or portable scaffolding frames to allow workers to position themselves appropriate to the work area on the aircraft should also be considered. Because the area to be cleaned may be located in unusual places, stair ladders with appropriate railings, and/or power lift platforms with appropriate railing and safety features should be considered in order to align the worker with the work.

(3) If the product to be cleaned is removed from the aircraft, support frames that can clamp the piece in place, and position it at a height and angle appropriate to the user and the tool would be appropriate. Providing proper mats for cushioning the lower extremities during prolonged standing is important. Sit/Stand stools that allow the worker to change position may be a consideration if they will be working in one area for prolonged periods of time.

(4) In a deployed environment, equipment would be similar, but may have to be more portable such as portable stair ladders, suspension frames (hoist), and A frames. The goal continues to be that of protecting the worker from injury and work related musculoskeletal disorders, while maintaining effective work strategies.

Figure 13: A simple A-Frame for mounting work

Figure 14: Height adjustable work surface-
scissor lift

Figure 15: Suspension Systems

Figure 16: Scaffolding

Figure 17: Platform rolling ladder

Figure 18: Scissor lift work platform

b. *Tool/System Design*

(1) <u>120 watt Cleanlaser System</u>

Problems: Pistol shape
Solution: This shape is fine if it is employed at a vertical workstation that is waist level to worker or horizontal surface that is at knuckle height to worker. This is functional in the contact method (nozzle rests on surface) and free-style method (no tool-surface contact) of cleaning. This could entail removing parts from the aircraft and securing them in a frame at appropriate heights and angles for the individual worker or providing appropriate height adjustable platforms to position the worker appropriately to the surface being cleaned. If the work surface is the actual aircraft and has contours to contend with, the use of the pistol shape may lead to awkward postures. To allow flexibility for use in a variety of work situations, an articulating handle that can be fixed at various angles on an in-line or 90 degree tool could be adjusted to complement the angle or contour of the work surface (Figure 19). If the work surface is vertical, the tool can be positioned in a pistol shape. If the surface is contoured or more horizontal, the tool could be angled to allow the nozzle to rest on the work surface

(provided it was equipped with wheels or guide) while the operator moved it forward/backward. Resting the nozzle would provide a counter balance point because the center of gravity of the tool could be too far forward for unsupported operation. A second attachable handle would help balance the tool and provide a second point of control for the operator. An articulating handle may not be technically possible, so a 90 degree two handle style could still be considered (Figure 20). This would be an option when the tool can rest on the work surface, or during free-style cleaning with the work surface angled appropriately to height to allow more neutral postures for the worker.

(2) **Problems**: Weight of pistol shaped tool is imbalanced with hoses attached. The hoses are difficult to manage due to posterior placement.
Solution: Tool redesign so attachment of lines maintains center of gravity in line with operators fist to balance pistol shaped tool. Weight balance needs to be considered if an alternative shaped tool is designed with ventilation and fiber-optic lines as well. Management of the hoses could be improved with relocating attachments at the bottom of the tool, or with flexible hosing or swivel attachments so that the hoses can hang under the operators arm rather than over the shoulder. Another option to consider would be a suspension system to support the hose lines. A permanent overhead suspension system may work well in a depot. Or an articulating arm could be added to the main body of the unit, to suspend the hoses from the handheld unit for the operator. This may work while the operator is on ground level and close to the unit, but if the worker is on a raised platform or working in tight spaces, the angle of pull could increase the torque at the operator's hand. A portable frame (hoist) could be employed in a deployed environment; but the same issue would apply and it could also present other hazards (tripping, head clearance). A tool belt with loops to support hoses close to the body but away from the feet could be helpful but relies on operator compliance. So the best option is likely redesign with the hoses attached towards the bottom of the tool, with the weight well balanced with flexible lines and swivel attachments.

(3) **Problem**: The handle diameter is large and the button trigger is small and may be slipped off easily.
Solution: The recommended button width is 0.5-1.0" to allow the entire finger pad to contact the trigger. The handle/grip diameter of 1.25-2.0" is a general rule, with span for including a trigger of 2.5-3.5". Petrofsky found that a maximum grip force is achieved at approximately 2.0-2.4" (5-6cm) (Karwowski, Marras).

(4) **Problem**: When the operator activates the handheld unit, he/she depresses the one button trigger on the handheld unit while pressing the "start" (green) button with the opposite hand on the handheld unit. For a left hand user, this means reaching across the body and unit to press the green button. A right hand user would reach across the body, but would not have to reach over the unit.
Solution: Relocate the green "start" button to a centerline position so reach is equal for right or left hand users.

(5) **Problem**: When the unit is not in use, the handheld unit is not secured.
Solution: Add a hook, holster or pocket on the main body of the system to store the handheld unit.

(6) 40 watt Quantel System

Problems: Pistol shape
Solution: This shape is fine if it is employed at a vertical workstation that is waist level to worker or horizontal surface that is at knuckle height to worker. This could entail removing parts from the aircraft and securing them in a frame at appropriate heights and angles for the individual worker or providing appropriate height adjustable platforms to position the worker appropriately to the surface being cleaned. If the work surface is the actual aircraft and has contours to contend with, the use of the pistol shape may lead to awkward postures. To allow flexibility for use in a variety of work situations, an articulating handle that can be fixed at various angles on an in-line or 90 degree tool could be adjusted to complement the angle or contour of the work surface (Figure 19). If the work surface is vertical, the tool can be positioned in a pistol shape. If the surface is contoured or more horizontal, the tool could be angled to allow the nozzle to rest on the work surface (provided it was equipped with wheels or guide) while the operator moved it forward/backward. Resting the nozzle would provide a counter balance point because the center of gravity of the tool could be too far forward for unsupported operation. A second attachable handle would help balance the tool and provide a second point of control for the operator. An articulating handle may not be technically possible, so a 90 degree two handle style could still be considered (Figure 20). This could be an option when the tool can rest on the work surface or during free-style cleaning provided the work surface is angled appropriately to height.

(7) **Problems**: The weight of the tool is 4.5 pounds with the hoses attached. Although this is less than 5 pounds, experienced hand-tool operators have indicated a preference for tools that weigh approximately 2 to 4 pounds. Also, the smooth aluminum material increases the grip forces necessary to support the tool.
Solutions: Reduce the weight of the tool and improve the friction coefficient through design and material selection. A plastic material may achieve both. A second handle could be considered so the tool can be supported with 2 hands, therefore distributing the weight. Another option is to use a suspension device. A permanent overhead suspension system may work well in a depot. Or an articulating arm could be added to the main body of the unit, to suspend the hoses from the handheld unit for the operator when he/she is in close proximity to the main unit. A portable frame (hoist) could be employed in a deployed environment; however, this could cause other hazards (tripping, head clearance). Either may not be employable when the operator must work from an elevated platform or in tight spaces. So, the better option would still be tool redesign.

(8) **Problems**: The smooth aluminum surface, sharp edges at the palmar surface of the hand, large diameter handle and single trigger.
Solutions: Improve the friction coefficient through design and material selection. A plastic material or a rubberized handle would address this. Reduce the handle size and remove sharp edges. The handle/grip diameter of 1.25-2.0” is a general rule, with span for including a trigger of 2.5-3.5” to allow activation without causing isolated stress at fingers or thumbs. Petrofsky found that a maximum grip force is achieved at approximately 2.0-2.4” (5-6cm) (Karwowski, Marras). The trigger length recommendation is 1.5”-2.25” to distribute the force of squeezing the trigger and grasping the handle to several fingers. The recommended trigger width is 0.5-1.0” to allow the entire finger pad to contact the trigger.

(9) **Problems**: This handheld system requires repetitive sweeping motions side/side or up/down.
Solutions: System redesign with sequential firing laser beams to reduce the repetitive sweeping motions. Another option would be to mechanize the handheld so that the head of the unit rotates to sweep the beam; however, this could lead to adding further weight and increasing grip forces to support the moving parts. So, beam redesign would appear to be the best option, if this is within the manufacturer's ability.

(10) **Problems**: Requires significant skill to maintain 80-85 mm distance between cleaning surface and laser exit.
Solution: Consider a guide attachment to the front end of the nozzle to be used when cleaning uniform surfaces. The freestyle method may still be the best option for unusual surfaces like seams and sharp angles.

(11) **Problems**: No built in ventilation/vacuum system for collection of fumes and particulate. The operator modified ventilation system also acts as a handle, placing his hand very close to the laser exit.
Solution: Tool redesign to incorporate a vacuum system without increasing tool weight with consideration for hose placement, weight balance and ease of managing hose lines: flexible hoses, swivel attachments, hose location.

Figure 19: Example of articulating tool, screwdriver

Figure 20: Example of 90 degree tool, buffer

Figure 21: Example of pistol grip tool, with 2-finger trigger, appropriate diameter and length, smooth surface.

c. *Work Organization*

(1) The operating environment has not been well defined at this time. It has been estimated that the handheld laser units would not be used in excess of 2-4 hours per day. The task is somewhat visually demanding, in that the operator is visually assessing substance removal throughout the cleaning process with the handheld unit, but the operator is not making precise determinations. The laboratory operator has employed a work/rest cycle of 30 min work/10 min rest with the tool use. The operator changes tasks through out the workday, so he estimates that 50% of his day is spent operating the handheld units.

(2) Jobs where long-duration physically or perceptually demanding tasks are done without breaks (unloading a conveyor) usually have a high work/rest cycle. Jobs with many tasks in a variety of effort levels (cafeteria attendant) can be patterned to have low work/rest ratios by alternating between tasks of different effort levels (Kodak Co). A rest phase may not have to be a cessation of all activity, but a period of doing light activity.

(3) When implementing the handheld laser technology into the work environment, the job demand considerations should include a work/rest cycle by providing multiple tasks at variable levels of effort that can be performed at various times during the workday, allowing worker self-paced operations as feasible. Stretching breaks should be included in the workday. The AFRL laboratory operator has managed well with a 30min/10min work rest cycle, while limiting overall tool use to 4 hours per day. Job rotation may be another strategy employed by training more than one technician on the handheld laser technology.

d. *Other Health/Safety Concerns*

(1) Body Mechanics Instruction should be provided to the operators during initial training and annually thereafter. Proper work technique is important to preventing musculoskeletal disorders. Video training tools are available, but it is also advisable to have the unit safety officer include base level Public Health or Rehabilitative Services in a training plan for body mechanics specific to the work environment and this tool's application.

(2) Vibration of the hand tool may need to be reconsidered if there are increases in the velocities of the current vacuum systems. During trial use, the investigator noted no significant vibration. However, AFRL is conducting air-sampling studies that may indicate a need to increase vacuum system velocity. If this were to be necessary, vibration at the hand tool would need to be considered when determining methods for controlling inhalation hazards.

6. CONCLUSION

a. *Summary*

(1) This report does not imply AFIOH endorsement of this particular method of de-painting nor the tools assessed in this process. Appropriate application is to be determined through a thorough Occupational Health Risk Assessment regarding laser use in regards to the DoDI 605.11 Protection of DoD Personnel from Exposure to Radiofrequency Radiation and the AFOSH 48-139 Laser Radiation Protection Program by AFRL. This ergonomic evaluation is just one aspect of that assessment. Provided this method were determined to be an appropriate de-painting method and the item manager approves its use, the general recommendation would be to employ it in controlled settings, such as the depots, before considering deployment to the field.

(2) The primary recommendation for both tools under consideration would be tool re-design. An articulating handle would provide a great deal of flexibility in application for cleaning/de-painting aircraft and parts. However, a design engineer may determine an articulating handle on a handheld laser is not technically feasible due to ventilation and laser requirements. In which case, the pistol shape may be the best option. In either instant, the tool should be redesigned to address weight, balance, diameter, trigger, sharp edges, and hose

attachment issues. Attention to the work environment will need to be emphasized so that the work can be positioned appropriately to the worker, or the worker can be positioned to the work for use of the tool in the most neutral postures possible to prevent musculoskeletal disorders.

(3) It would also be beneficial for the manufacturer of the 40 watt system to consider methods for reducing the repetitive wrist motions, such as a synchronized laser firing system.

(4) Training for proper body mechanics in the work environment cannot be over emphasized. Proper technique can be a key factor in preventing work related musculoskeletal disorders.

(5) It would be beneficial to include bioenvironmental engineering in the planning and fielding of this technology at their depots. They could assist in potential hazard identification and prevention, and establishment of training and standards of operations specific to their worksite. Further ergonomic consultation may be appropriate when this new technology is fielded.

(6) We greatly appreciate the cooperation of the AFRL staff during this assessment. If you have any questions concerning this report, please contact me at DSN 240-6116.

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Attachments:
1. Tool Worksheet
2. Video Resources
3. References

Distribution:
Carolyn Macola, Maj, USAF, HQ AFMC
Stefan Susta, Contr, SAIC
Gerard Mongelli, Contr, HQ AFMC

Hand Tool Evaluation Worksheet

Table A.3
Hand Tool/Power Tool Evaluation Worksheet

Date:	**Evaluator:**
Job:	**Type:**
Manufacturer:	**Model Number:**
Model Name:	**Price:**

Category	Parameter	Measure	Meets Criteria Yes	Meets Criteria No	N/A
General	Handiness	Tool should be easily used with either the left or right hand.			
	Repetition	Tool should minimize repetitive movements.			
	Ease of Use	Tool should be easy to use.			
	Ease of Maintenance	Tool should be easy to maintain.			
Grip Angle	Wrist and Arm Posture	Handle angle and location should allow a straight wrist and neutral arm position while the tool is being used.			
	Back and Neck Posture	Handle angle and location should allow the user to see the work without having to tilt or bend the head or back.			
Force Requirements	Activation Forces	**Full hand** grip forces required to use tool should be less than 8 lb. (3.6 kg.)			
		Fingertip grip force required to use tool should be less than 2 lb.(0.91 kg.)			
	Two hand activation	Tool should allow two hands when applied forces are high or when additional control is needed.			
	Tool Weight	Tool (and associated cables/hoses) should weigh less than 5 lb. (2.3 kg.) or be mechanically supported.			
	Tool Balance	Tool's center of gravity should be close to or at the grip location.			
	Cable/Hose Attachment	Cables and hoses should be attached to minimize interference and drag.			
	Handle Surface	Grip surfaces should be high friction and slip-resistant.			
		Grip surfaces should be compressible.			
	Handle Shape	There should be no hard/sharp edges or abrupt curves that the contact user's hand or body. Avoid ridges or channels for individual fingers.			
	Handle for Torquing Tools	For torquing tools, the handle should be long enough to prevent grip forces above 8 lb. (3.6 kg.)			

Comments:

Table A.3
Hand Tool/Power Tool Evaluation Worksheet (Cont'd.)

Date:	**Evaluator:**
Job:	**Type:**
Manufacturer:	**Model Number:**
Model Name:	**Price:**

Category	Parameter	Measure	Meets Criteria Yes	Meets Criteria No	N/A
Force Requirements Cont'd	Trigger Force	Force required to activate the trigger should be insignificant (considerably less than 1 lb. or 0.5 kg.)			
	Trigger Function	Tool should avoid continuous activation of a trigger.			
	Connection Force	Force required to connect/disconnect the power tool should be insignificant.			
	Spring Release (Plier-Type Tools)	Plier-type tools should have a spring release mechanism. The spring tension should be minimal.			
Handle Size	Grip Diameter	Grip Diameter for a full hand grip tool should be between 1-1.5" (2.5-3.8 cm.).			
		Grip Diameter for a fingertip grip tool should be between 0.25-0.5" (0.6-1.3 cm.).			
		It should also be possible to increase the diameter of the handle if needed.			
	Handle Span on Plier-Type Tools	Plier-type tools should have a span of less than 3" (7.6 cm.).			
	Total Grip Length	4" (10.2 cm.) minimum, 5" (12.7 cm.) preferred			
Trigger/ Buttons	Trigger/ Button Location	Triggers and buttons should be positioned to prevent extension of fingers or the thumb.			
	Trigger/ Button Shape	Trigger should have large smooth curves. No hard edges or points (particularly at the end of the trigger).			
	Trigger Length	1.5" (3.8 cm.) minimum, 2-2.5" (5.1-6.4 cm.) preferred			
	Trigger Width	0.5-1.0" (1.3-2.5 cm.).			
	Trigger Ridge Depth	0.125" - 0.375" (0.318-0.953 cm.)			
	Trigger Range of Movement	Trigger should have a small range of movement.			

Comments:

Atch 1 (2 of 3)

Table A.3
Hand Tool/Power Tool Evaluation Worksheet (Cont'd.)

Date:	**Evaluator:**
Job:	**Type:**
Manufacturer:	**Model Number:**
Model Name:	**Price:**

Category	Parameter	Measure	Meets Criteria Yes	Meets Criteria No	N/A
Misc.	Heat Conduction	Tool handle should be coated or rubberized (tool handles should not be bare metal)			
	Routing of Air Exhaust	Air powered tools should not blow cold air on hands.			
	Torque/ Impact	Tool should not expose the user to excessive torque or impact.			
	Vibration	Tool should not expose the user to excessive vibration.			

Comments:

Level I Ergonomics Methodology Guide for Maintenance and Inspection Work Areas, Appendix 5, January 1997, Pacific Environmental Services, INC.

Atch 1 (3 of 3)

Resources for Ergonomic Training Videos

This list does not imply endorsement by DoD or the USAF.

1. Black Mountain Safety & Health- vendor. www.safety-video-bmsh.com

2. National Safety Compliance- vendor. www.osha-safety-training.net

3. The Richardson Company- vendor. www.rctm.com

4. Training ABC.com- vendor. http://trainingabc.com/ergonomics.htm

5. Washington State Department of Labor and Industries- Video lending library. www.lni.wa.gov

Atch 2

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Atch 3

Appendix F
Health And Safety Plan

SAFETY PLAN

FOR THE

PORTABLE LASER COATING REMOVAL SYSTEM

DATE: 6/15/04

TABLE OF CONTENTS

1. INTRODUCTION 1
1.1. PURPOSE 1
1.2. SCOPE 1
1.3. LASER THEORY 2
1.3.1. Types of Lasers 2
1.3.2. Classes of Lasers 3
1.3.3. Laser Coating Removal Mechanism 4
2. LASER SAFETY PROGRAM RESPONSIBILITIES 5
2.1. SECRETARY OF THE AIR FORCE 5
2.2. AIR STAFF 6
2.3. HQ AIR FORCE MATERIAL COMMAND (AFMC) 6
2.4. MEDICAL TREATMENT FACILITY (MTF) COMMANDER 8
2.5. DIRECTOR OF SAFETY (SE) 8
2.6. UNIT COMMANDER 9
2.7. UNIT SAFETY OFFICER OR DESIGNATED LASER SAFETY OFFICER (LSO) 9
2.8. WORKPLACE SUPERVISORS 10
2.9. INDIVIDUAL / OPERATOR 10
3. LASER HAZARDS 11
3.1. LASER RADIATION HAZARD EVALUATION 11
3.1.1. Laser Radiation Hazard Evaluation Tools 12
3.1.2. Operating Environment 13
3.1.3. Beam Hazards 13
3.1.4. Non-Beam Hazards 14
4. LASER SAFETY 17
4.1. CONTROL MEASURES 17
4.2. OPERATING ENVIRONMENT CONTROL 19
4.2.1. Enclosed Environment 20
4.2.2. Shielded Environment 20
4.2.3. Open Environment (Unshielded) 21
4.3. PERSONAL PROTECTIVE EQUIPMENT 22
4.3.1. Eye Protection 22
4.3.2. Respiratory Protection 24
4.3.3. Skin Protection 24
4.3.4. Hearing Protection 24
4.4. LASER HAZARD WARNING SIGN AND LABELS 25
4.4.1. Laser Equipment Labels 25
4.4.2. Warning Signs 25
4.4.3. Warning Lights 26
4.3. SERVICE, REPAIR, AND MODIFICATION OF LASER SYSTEMS 26
4.4. ADDITIONAL SAFETY GUIDELINES 26
4.5. LASER SAFETY "LESSONS LEARNED" 27
5. TRAINING AND CERTIFICATION 28

6. MEDICAL SURVEILLANCE 29
7. ACCIDENT / INCIDENT INVESTIGATION 30
8. REFERENCES 32

1. INTRODUCTION

1.1. Purpose

The purpose of this safety plan is to provide guidance for safely operating portable handheld lasers, used for the purpose coating removal on aircraft and/or aircraft components. The manual is designed to achieve a safe environment for users, visitors, and workers in potentially hazardous areas. This is a general series document, intended for use with maintenance/repair/overhaul manuals or engineering documents, laser technical manuals, the Air Force Occupational Safety and Health (AFOSH) Standard 48-139 *Laser Radiation Protection Program*, and Technical Order (T.O.) 1-1-8 *Application and Removal of Organic Coatings.* Additionally, a T.O. supplement that specifically addresses laser coatings removal is currently under development.

The primary objectives of this safety plan are to provide guidance to the laser safety approval authorities and to enable safe laser coating removal operations. The establishment of standard safety procedures will ensure that no laser radiation in excess of the maximum permissible exposure (MPE) reaches the human eye or skin as a result of the operation of portable handheld laser systems. In particular, this safety plan is designed to address and manage against the risk of laser injury, electrical shock, fire, and exposure to hazardous chemicals, which may be present during coating removal operations.

1.2. Scope

This document lays out a plan for ensuring the safe operation of portable laser systems that are designed to remove organic coatings at both Intermediate and Depot Levels. This safety plan applies to lasers that operate at wavelengths between 808 and 10,600 nanometers (nm), and places an emphasis on Class IV lasers. The responsibility of this safety plan lies with Air Force Materiel Command Depot Maintenance and Modernization (AFMC/LGPE) until final insertion and transfer to organizations that will maintain and coordinate the T.O. and safety plan. All organizations using this plan are invited to submit recommendations, changes, corrections, or deletions in accordance with each individual activity procedure. All submissions shall be directed to:

AFMC/LGPE,
Attn: Gerard Mongelli (Contractor)
mongellg@ctc.com; Tel. 937-426-2057

1.3. Laser Theory

In 1958 two scientists, Schawlow and Townes, from Bell Labs calculated the conditions to produce a narrow, intense beam of coherent light. This discovery was given the acronym LASER, which stands for Light Amplification by Stimulated emission of Radiation. Normal atomic radiation of light occurs in random directions and times producing incoherent light. An example of this incoherent atomic radiation is in fluorescent or neon lights. These scientists developed a method for generating light that occurs at a single, or very limited, frequency and time, producing a coherent light beam. These light beams can travel over long distances and still maintain their size and direction. The ability of these lasers to generate discrete wavelengths, coupled with the optical power that they are capable of generating, make them of interest as a predictable light source for many high precision applications. Today, lasers are used in a wide range of applications in medicine, manufacturing, construction, surveying, consumer electronics, scientific instrumentation and military systems.

The coherent light beam from a laser is produced by a series of atomic events. In a laser, the atoms or molecules of an active source, such as ruby or garnet crystals or gas, liquid, or other substances, are excited so that more atoms are at higher energy levels than are at lower energy levels. Reflective surfaces are used to reflect this energy back and forth, allowing it to build up during each passage. If a photon whose frequency corresponds to the energy difference between the excited and ground states strikes an excited atom, the atom is stimulated to emit a second photon of the same (or a proportional) frequency, in phase with and in the same direction as the bombarding photon. This process is called stimulated emission. The bombarding photon and the emitted photon may then each strike other excited atoms, stimulating further emission of photons, all of the same frequency and phase. This process produces a sudden burst of coherent radiation as all the atoms discharge in a rapid chain reaction.

All lasers have three basic physical components: an active medium, an energy source, and a resonant cavity. Each of these components is responsible for a different part of the laser process. The active medium provides the source of light and radiation, the energy source provides the stimulation, and the resonant cavity enables amplification and emission. Refer to individual laser technical manuals for detailed information on subsystem, i.e. beam delivery method, controls, and support equipment.

1.3.1. Types of Lasers

Lasers are commonly designated by the type of lasing material that is employed. The various types of lasers are:

- **Solid-state lasers**. These lasers have a lasing material that is distributed in a solid matrix such as ruby or Neodymium:Yttrium-Aluminum Garnet "Nd:YAG". The Nd:YAG laser emits infrared light at 1,064 nm. The laser beams of Nd:YAG lasers can be delivered via fiber optical cable.

- **Gas lasers**. Helium, helium-neon, argon, and carbon dioxide (CO_2) are the most common gas lasers with a visible output of visible red light. CO_2 lasers emit energy in the far-infrared spectrum (10,600 nm). A CO_2 laser 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 be delivered using mirrors inside an umbilical arm.

- **Excimer lasers**. These lasers use reactive gases, such as chlorine and fluorine, mixed with inert gases such as argon, krypton, or xenon. When electrically stimulated, a pseudo molecule (dimer) is produced. When lased, the dimer produces light in the ultraviolet range. The laser beams of excimer lasers can be delivered via fiber optical cable.

- **Dye lasers**. These lasers use complex organic dyes, such as rhodamine 6G, in liquid solution or suspension as lasing media. They are tunable over a broad range of wavelengths. The laser beams of dye lasers can be delivered via fiber optical cable.

- **Semiconductor lasers**. These lasers, commonly called diode lasers, are usually very compact and very efficient. The diode lasers that are used for coating removal operations can be delivered via fiber optic cables at wavelengths of 808 or 940 nm.

1.3.2. Classes of Lasers

Lasers are classified according to their potential to cause biological damage. The parameters that are used for classification are laser output energy (power), radiation wavelengths, exposure duration, and cross-sectional area of the laser beam at the point of interest. Lasers are also classified in accordance with the accessible emission limit (AEL), which is the maximum accessible level of laser radiation allowed within a particular laser class.

The American National Standards Institute (ANSI) Standard Z136.1-2000 is used to signify the level of hazards in a laser system and the extent of safety controls that are required. Under this standard lasers are classified according to the following criteria.

(1) **Class 1** lasers cannot, under normal operating procedures, produce damaging radiation levels. These lasers can be labeled, but are exempt from the requirements of the Laser Safety Program. There is a very low risk of injury and eye protection is not required.

(2) **Class 2** lasers are low power lasers or laser systems in the visible range (400-700 nm wavelength) that may be viewed directly under carefully controlled conditions. These lasers do not normally present a hazard, but may present some hazards if viewed directly for long periods of time.

(3) **Class 3** lasers are medium power lasers that require control measures to prevent viewing of the direct beam. Control measures emphasize preventing exposure of the eye to the primary reflected beam.

(4) **Class 3a** lasers are normally not considered hazardous is viewed for momentary periods with the unaided eye. However, these lasers may present a hazard if viewed using collecting optics.

(5) **Class 3b** lasers can produce a hazard if viewed directly. This includes intrabeam viewing or specular reflections. This class laser can produce a hazardous diffuse reflection.

(6) **Class 4** lasers are high power lasers that produce a hazard not only from direct or specular reflections, but also from a diffuse reflection. These lasers may also produce fire and skin hazards.

1.3.3. Laser Coating Removal Mechanism

The laser coating removal mechanism varies depending on laser beam characteristics and delivery methods. The two basic laser coating removal mechanisms are Thermal Decomposition and Ablation.

(1) **Thermal Decomposition:** Constant wave or continuous wave lasers vaporize thin layers of the coating system. This process uses thermal energy to remove layers of paint from the substrate surface. Constant 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, constant wave lasers require extensive training, controls, and diagnostics to safely remove paint. *Figure 1* provides an illustration of this coating removal mechanism.

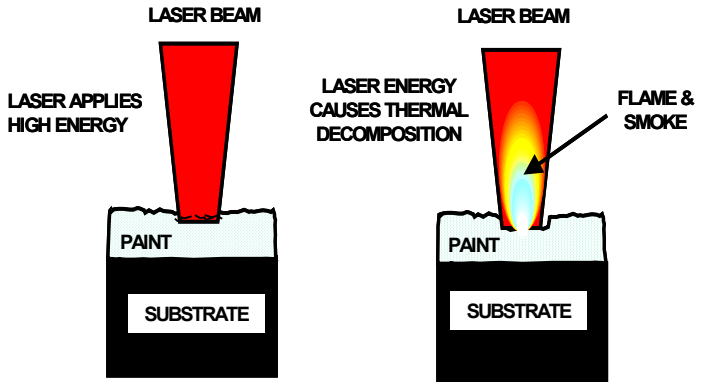

Figure 1. Illustration of Laser Thermal Decomposition Mechanism

(2) **Ablation:** Laser ablation can be achieved using pulsed lasers that create bursts of high intensity energy. One advantage of this, when compared to the constant wave laser coating removal process, is that the removal can occur at lower

average temperatures. The ablation process is a mechanical process. A thin layer of coating is vaporized and converted into plasma, which creates 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. These characteristics include power, wavelength, pulse width, pulse frequency, beam profile, and operating parameters. *Figure 2* provides an illustration of the laser ablation mechanism.

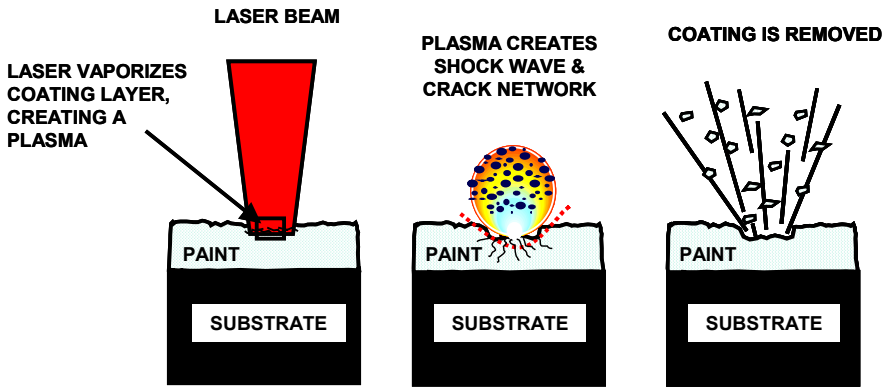

Figure 2. Illustration of Laser Ablation Mechanism

2. LASER SAFETY PROGRAM RESPONSIBILITIES

Responsibility for the Laser Safety Program is shared by many organizations and individuals within the Air Force (AF). Those responsible include the Secretary of the Air Force (SAF), Air Staff, Headquarters Air Force Materiel Command (HQ AFMC), Medical Treatment Facility (MTF) Commander, Unit Safety Officers or designated Laser Safety Officers (LSO), workplace supervisors, and the individual operators. The specific responsibilities for each of these organizations and individuals are detailed in this section.

2.1. Secretary of the Air Force

2.1.1. Assistant Secretary of the Air Force (Acquisition) (SAF/AQ)

The SAF/AQ addresses the issues of health and safety throughout the Research, Development, Test, and Evaluation (RDT&E) cycle. They obtain measured personnel hazards for all lasers along with the AF labs, Single Managers (SM), and program Execution Officers. This office also ensures that life-cycle controls are placed on the laser for compliance with accountability and/or disposal requirements. Specifically the SAF/AQ:

- Ensures that AF labs, SM, and program Execution Officers address the issues of health and safety early and throughout the RDT&E cycle.
- Obtains measured personnel hazard data for all lasers at the earliest possible time in the RDT&E cycle for inclusion into applicable T.O.s
- Ensures that the AF development program incorporates the requirements of the U.S. Code of Federal Regulations (CFR) (21 CFR 1040.10 and 1040.11) into the

early design stages of laser systems. If full compliance with 21 CFR is not possible because of operational needs, the SAF/AQ ensures that the laser is properly exempted from these requirements in accordance with Food and Drug Administration (FDA) Exemption No. 76 EL-01-DOD (see DoDI 6055.11 and paragraphs 1.2 and 1.3 of this standard).

- Ensures that life-cycle controls are placed on the laser for compliance with accountability and/or disposal requirements of the exemption.

2.1.2. Deputy Assistant Secretary of the Air Force for Environmental Quality (SAF/MIQ)

The SAF/MIQ provides oversight for all AF policies related to Environmental, Safety and Occupational Health (ESOH).

2.2. Air Staff

2.2.1 Surgeon General (SG)

The SG is responsible for the:

- Establishment of AF policy for the control of laser radiation hazards
- Establishment of laser radiation personnel exposure standards and criteria
- Approval authority for waivers of protection standards and control procedures.

2.2.2. Air Force Safety Center (HQ AFSC)

The HQ AFSC:
Implements standards approved by USAF/SG for safety programs associated with hazardous laser radiation exposure

- Implements safety standards for non-biological hazards of laser systems and equipment, e.g. electrocution, toxic gases, etc..

2.2.3 Air Force Inspection Agency (HQ AFIA)

HQ AFIA implements programs to assess compliance with the requirement of safety standards.

2.3. Air Force Materiel Command (HQ AFMC)

The HQ AFMC has responsibility for:

- Plans, programs, and budgets for research and development relating to the health and safety of laser radiation, laser protective devices, laser technologies, and laser control measures.
- Develops and implements policies and procedures to ensure that required personnel hazard data for lasers is measured at the earliest possible time in the acquisition cycle and is made available to the appropriate agency.

- Coordinates with HQ AFMC/SG to ensure technical orders, handbooks, and similar publications contain those health procedures and precautions needed to prevent the exposure of personnel to laser radiation in excess of this standard.

2.3.1. Air Force Research Laboratory (AFRL):

AFRL has responsibility under this plan to:

- Conduct research on the biological effects of laser radiation.
- Maintain technical expertise in laser technology and new developments, which may affect laser safety in AF operations.
- Work with other AFMC laboratories and other services to evaluate laser radiation safety issues and resolve operational problems.
- Coordinate the development and approval of laser eye protection (LEP) for AF use.

2.3.2. Human System Center (HSC) Air Force Institute for Occupation Health (AFIOH):

The AFIOH will:

- Provide information to commands, during contingency and peacetime operations, on the adequacy of laser radiation protective devices, materials, and engineering control measures
- Serve as the Headquarters USAF/SG technical center for all issues concerning laser safety, in accordance with AFOSH Std. 48-139.
- Provide professional advice and guidance applicable to laser radiation exposure control and medical surveillance
- Determine acceptable atmospheric attenuation coefficients for use in laser hazard assessments
- Maintain a repository on the characteristics of operational and commercial lasers, and laser radiation protective devices used within the AF
- Maintain an official repository of overexposure investigations to laser radiation

2.3.3. HSC Institute of Aerospace Medicine (IASM):

The responsibility of IASM is to:

- Provide consultative examinations in ophthalmology and dermatology for AF personnel. All other consultations must have approval from HSC/CC
- Develop methods to evaluate occupational injuries from lasers
- Recommend medical surveillance requirements
- USAF School of Aerospace Medicine, Department of Bioenvironmental Engineering (USAFSAM/BE), in conjunction

with the AFIOH, provides formal training for medical personnel on laser safety.

2.4. Medical Treatment Facility (MTF) Commander

The MTF Commander develops policies and procedures to implement the occupational health and safety aspects.

2.4.1. Bioenvironmental Engineering Squadron/Flight (BE)

The BE or designated Base Radiation Safety Officer will:

- Implement and conduct a base laser safety program
- Conduct laser health hazard evaluations when notified of new operations, equipment changes, or any modifications that may alter personnel hazards.
- Determine the laser class, exposure limits, hazard distances and zones
- Recommend engineering controls, posting requirements, and personal protective equipment
- Document the hazard evaluation in the appropriate facility case file
- Report and evaluate suspected overexposures and prepare reports
- Provide laser safety training and information to designated unit safety officers/laser safety officer and other personnel as necessary.

2.4.2. Public Health (PH):

PH has responsibility to:

- Oversee medical surveillance requirements
- Initiate investigations of suspected or actual laser radiation overexposure
- Prepare and distributes Occupational Illness/Injury Report and additional documentation as appropriate for all incidents of personnel overexposure to laser radiation
- Ensure medical follow-up examinations are conducted for persons identified as having been overexposed to laser radiation.

2.5. Director of Safety (SE)

The SE will:

- Review and recommends policies and procedures to prevent mishaps from associated non-radiation laser hazards
- Periodically evaluate procedures and inspects facilities to ensure compliance with safety requirements
- Investigate incidents related to laser ancillary hazards.

2.6. Unit Commander

The Unit Commander is responsible to:

- In cooperation with BE, develop policies, procedures and/or instructions necessary to meet standard
- Assign qualified and trained workers to adjust, maintain, or operate laser equipment.

2.7. Unit Safety Officer or designated Laser Safety Officer (LSO)

The LSO assists the Unit Commander in developing policies, procedures and/or instructions necessary to meet this standard at the unit level. Specifically the LSO will:

- Monitor and enforce the control of laser hazards
- Classify or verify the classification of the lasers used at the each activity
- Evaluate the hazards of laser work areas
- Ensure that prescribed control measures are in effect. If necessary, recommend and approve alternate control measures
- Establish a nominal hazard zone (NHZ)
- Approve Standard Operating Procedures (SOPs) and other procedures that are part of the requirements for control measures
- Make recommendations for personal protective equipment (PPE) to include eyewear, clothing, and barriers
- Approve warning signs and equipment labels
- Approve laser installation and modification of facilities and laser equipment prior to use
- Ensure adequate training is provided for all laser personnel
- Report all suspected laser overexposures to the Unit Commander
- Act as a single point of contact for the unit on laser radiation matters and maintains active liaison with BE, PH, and SE personnel
- Coordinate laser radiation activities with command and supervisory personnel
- Oversee all unit actions needed to minimize laser hazard radiation hazards to personnel
- Conduct initial and annual laser safety training
- Ensure any corrective actions are completed in a timely manner

2.8. Workplace Supervisors

The responsibility of workplace supervisors is to:

- Assist the Unit Safety Officer / LSO in maintaining safe and healthy work environment

- Make sure that all personnel complete any training required to operate the laser safely and provides a list of employees assigned to work with the lasers to the LSO
- Ensure all employees receive required physical exams
- Promptly report to the Unit Safety Officer/LSO any suspected laser overexposure, any unsafe work condition, and/or changes in laser use which could change any hazard assessment
- Ensure any individual suspected of overexposure to laser radiation received prompt medical care
- Ensure visitors receive proper instruction, personnel protective equipment, when required, and clearance to visit the area
- Ensure that personnel and visitors have been instructed on the hazards of working with the laser and the proper procedures for operating the laser.

2.9. Individual/Operator

The individual operator of the laser system is also responsible to:

- Ensure proper handling and control of laser and laser beam
- Follow procedures for safe work practices given in this standard, equipment T.O.s, manuals, SOPs, and unit OIs, and in BE and SE reports
- Ensure required warning signs, safety devices, and personal protective equipment is functional and properly worn or placed before beginning work
- Assist co-workers in understanding and adhering to laser safety policies and procedures
- Promptly report to his/her supervisor and the Unit Safety Officer/LSO any suspected laser overexposure, any unsafe work condition, and/or changes in the laser use which could change the hazard assessment
- Seek prompt medical attention upon suspected overexposure
- Ensure that any person in the general area of the lasers is properly informed of and protected from all potential laser hazards
- Work only with supervisor approval and after completing proper laser training.

3. LASER HAZARDS

Each installation will organize and implement a laser safety radiation program under the supervision of the base Bio-Environmental Engineering (BEE) Office. Per AFOSH Std. 48-139 and ANSI Z136.1-2000, all installation-level safety plans must include the fundamental aspects of the evaluations of laser and ancillary hazards, safety training and certification, medical surveillance, and accident/incident investigation. These elements are described in the following sections.

3.1. Laser Radiation Hazard Evaluation

In accordance with AFOSH Std. 48-139, a hazard evaluation must be accomplished and appropriate safety precautions taken prior to laser operation/maintenance for all readily accessible lasers used for coating removal. This evaluation shall preferably be lead by the base designated LSO. The LSO shall document the laser specifications in AF Form 2760, Laser Evaluation Form, or equivalent. Many factors influence the total hazard evaluation and, thereby, the application of control measures. Consideration shall be given to the following:

- Laser emission characteristics (i.e., pulsed, continues wave, wavelength, pulse width, pulse repletion rate, beam diameter, beam divergence, etc.)
- The transmission of the laser beam through the atmosphere, depending on the wavelength, altitude, length of beam path, air particulates, climatic conditions, or attenuation.
- Attenuation of intervening materials (i.e., windows, shields, canopies, protective equipment) is highly dependent on the laser wavelength and the angle of incidence.
- The use of optical viewing aids (i.e., binoculars, telescopes, etc.) can significantly increase the eye hazard from radiation. The effects of the magnifying power of the optical device need to be weighed along with transmission losses of the device.
- Targets, protective materials, optical instruments, etc. may disintegrate, causing a hazard from fragments or toxic residues.
- Other hazards associated with lasers (i.e., electrical, etc.- see non-beam hazards) can exist and must be evaluated.
- Evaluate beam path and termination points for specular or diffuse reflection hazards.
- The operating environment in which the laser is used.
- The personnel who may use or be exposed to laser radiation.

Only personnel trained in laser safety, optical engineering, or physics are suited to perform the detailed hazard evaluation computations or the classification determinations of a laser or laser system as outlined in this section. In some instances, the LSO may not possess these qualifications, and may choose to delegate (effect) this responsibility. When this occurs, such evaluations are to be performed only by individuals who, as the result of training or experience, can provide knowledgeable technical assistance. Only

then can the LSO be assured that the calculations and risk determinations will be accomplished correctly. Errors in the analysis could result in the specification of inadequate controls and present potentially hazardous conditions to personnel in the laser area.

3.1.1. Laser Radiation Hazard Evaluation Tools

To assist the LSOs in these complex hazard evaluations, the AF has designated the Optical Radiation Branch of the Air Force Research Laboratory (AFRL/HEDO) at Brooks Air Force Base (AFB) as the lead agency for laser hazard evaluations. AFRL/HEDO works closely with the AFIOH in developing and implementing laser safety policies. Ion addition to providing technical expertise and resources, AFRL/HEDO has developed a Windows-based laser hazard assessment program (LHAZ), which is available from:

AFRL/HEDO
8111 18th Street
Brooks AFB, TX 78235-5215
(http://www.brooks.af.mil/AFRL/HED/HEDO/lhaz.htm)

The latest LHAZ software tool (LHAZ Version 4.0) is consistent with ANSI Standard Z136.1-2000, and derives the necessary safety parameters (i.e. Nominal Ocular Hazard Distance [NOHD] and Optical Density [OD]). Information and updates can be requested by sending an email to laser.safety@brooks.af.mil or by calling 1-800-473-3549. The use of LHAZ software is strongly recommended.

LHAZ must be supplied with the following laser parameters. Detailed definitions can be found in the LHAZ user guide:

- Wavelength
- Output Mode
- Average Power
- Energy Per Pulse
- Pulse Duration
- Pulse Repetition Frequency
- Beam Profile
- Beam Distribution
- Beam Divergence
- Beam Waist Diameter
- Beam Waist Range
- Output Aperture Diameter
- Source Size

3.1.2. Operating Environment

The probability of personnel exposure to hazardous laser radiation will be considered in any work environment. If the possibility exists that unprotected personnel can be exposed to primary or specularly reflected laser radiation, the irradiance or radiant exposure must be determined. This determination must be made at the origin of the laser radiation source or at the extended (i.e. reflected) source of the radiance, if applicable. The LSO is responsible for establishing the Nominal Hazard Zone (NHZ), in accordance with ANSI Std. Z136.1-2000. The LSO, however, may employ additional or equivalent control measures, which are not specifically stated in ANSI Std. Z136.1-2000 to achieve a safe environment. The LSO will assure that consideration is given to direct, reflected and scattered laser radiation in the establishment of boundaries for the laser controlled area.

3.1.3. Beam Hazards

The most prominent safety concern for all lasers is the possibility of eye damage from exposure to the laser beam. The nature of the damage and the threshold level of the type of injury that can occur depend on the beam parameters (wavelength, output power, beam divergence, beam diameter, and exposure duration). The types of eye damage that can occur include thermal burn, acoustic damage, photochemical damage, and other eye and skin hazards.

(1) **Thermal Burn**. The laser light that enters the eye in the visible and near infrared (IR) region is focused on the retina. The types of damage that can result from intercepting a laser beam with the eye are thermal burns, which destroys the retinal tissue. Since retinal tissue does not regenerate, the damage is permanent.

(2) **Acoustic Damage**. Laser pulses of a duration less than 10 microseconds induce a shock wave in the retinal tissue, which causes a rupture of the tissue. This type of damage is called acoustic damage, which affects a greater area of the retina with the threshold energy for this effect being substantially lower. Acoustic damage is a permanent condition resulting in greater damage than a thermal burn.

(3) **Photochemical Damage**. Light below 400 nm is not focused on the retina. This light can be laser output, ultraviolet (UV) light from the pump light, or blue light from a target interaction. ANSI standards only take into account exposure to laser light; therefore, additional precautions must be taken to protect against the UV light from the pump light or the blue light from a target interaction.

(4) **Other Eye/Skin Hazards**. When UV or IR laser light enters the eye, much of the light is absorbed in the lens. Depending on the level of exposure, this can cause thermal burns or the development of cataracts over a period of time. The cornea and conjunctive tissue surrounding the eye can also be damaged by exposure to laser light. Cornea and conjunctive tissue damage usually occurs at greater power levels than damage to the retina; therefore, these issues only become a concern for those wavelengths that do not penetrate the retina. Skin can also suffer from thermal burns and photochemical damage from laser exposure. This type of damage is entirely independent of the coherent nature of the laser light, but is aggravated by the high power density of the lasers.

NOTE: All beam hazards depend on the laser beam characteristics, equipment set-up, operating environment, and laser beam delivery. Beam hazards are unique for each laser and each application. The responsible LSO shall conduct a complete hazard evaluation, determine operating environment/procedures, and personal protective equipment accordingly.

3.1.4. Non-Beam Hazards

Various hazards also exist that are not associated with the laser beam itself. These hazards are related to the equipment that is used to create the laser beam and the use of this equipment.

(1) **Electrical Hazards**. Most lasers contain high-voltage power supplies and large capacitors or capacitor banks that store lethal amounts of electrical energy. The systems that allow access to components at such lethal levels must be interlocked. However, during maintenance and alignment procedures, these components often become exposed or accessible.

(2) **Compressed and Toxic Gases**. Care and attention must be given to handling, storage, marking, and disposition of all compressed gas cylinders. Personnel required to work with compressed gases and gas cylinders shall be trained to have a thorough knowledge of the characteristic of compressed gases, cylinders, valves, and markings.

(3) **Radio Frequencies (RF)**. Some lasers contain RF excited components such as plasma tubes and Q switches. Unshielded and loosely tightened components may allow RF fields to leak from the device and cause exposure to workers. A leakage survey can be obtained from the LSO.

(4) **Ergonomics**. Ergonomic problems can arise from a laser operation by causing awkward or unique arm and wrist positions. If repetitive deviations occur for long periods of time, medical problems such as repetitive strain injuries may occur. The LSO will help the user develop appropriate control measures. For additional information, please contact:

AFIOH/RSHI
Attn: Major Linda Schemm, USAF, BSC
Brooks-City Base, TX
DSN: 240-6116
Commercial: 210-536-6116

(5) **Fumes/Vapors/Laser Generated Air Contaminants (LGAC) from Beam/Target interaction**. Air contaminants may be generated when certain Class 3b and Class 4 laser beams interact with matter. When the target irradiance reaches the given threshold of approximately 10^7 Watts per centimeter squared (W/cm^2), target materials (including plastics, composites, metals, and tissues) may liberate toxic and noxious airborne contaminants. In other words, when laser beams are sufficiently energized to heat up a target, the target may vaporize, creating hazardous fumes or vapors that may need to be captured or exhausted. Particulates should be captured with a vacuum system to avoid air borne contaminants. Appropriate safety protocols and PPE shall be selected, depending on the application, environment, coating types, and laser systems. Note that AFMC/LGPE has conducted air sampling at the demonstration facility to determine the extent of this hazard (see appendix).

(6) **Plasma Emissions**. Interactions between very high power laser beams and target materials may in some cases produce plasmas. The plasma generated may contain hazardous "blue light" and UV emissions that can be an eye and skin hazard. The AFMC/LGPE has collected some data to determine extent of this hazard (see appendix).

(7) **UV and Visible Radiation**. Laser discharge tubes and pump lamps may generate UV and visible radiation. The radiation levels produced may be an eye and skin hazard. The AFMC/LGPE has collected some data to determine extent of this hazard (see appendix).

(8) **Explosion Hazards**. High-pressure arc lamps, filament lamps, and capacitors may explode if they fail during operation; therefore, they must be enclosed in a housing that will withstand the maximum explosion. Laser targets and some optical components also may shatter if heat cannot be dissipated quickly enough. Care must be used to provide adequate mechanical shielding when exposing brittle materials to high intensity lasers. The AFMC/LGPE conducted an explosion and flammability study (see appendix). Lasers shall not be operated around flammable materials.

(9) **Ionizing Radiation (X-rays).** X-rays could be produced from two main sources: high voltage vacuum tubes of laser power supplies and any power supplies which require more than 15 kilovolts.

(10) **Fire Hazards**. Electrical components, gases, and fumes can cause fire hazards. The use of flammables should be avoided, and flame resistant enclosures should be used.

(11) **Hazardous Waste.** Depending on the coating type and substrate, hazardous waste may be generated from the coating removal operations. Proper hazardous waste containment, collection, disposal, and reporting procedures shall be followed.

4. LASER SAFETY

The LSO shall have the responsibility and authority to evaluate, monitor, and enforce the control of laser hazards. This responsibility and authority shall include, but not be limited to, such actions as establishing a NHZ, approving SOPs, avoiding unnecessary or duplicate controls, selecting alternate controls, conducting periodic facility and equipment audits, and providing training. The LSO may, at times, delegate specific responsibilities to a Deputy LSO or other responsible person.

4.1. Control Measures

Control measures shall be devised and used to reduce the possibility of hazardous laser radiation exposure to the eye or skin, and to avoid injury from other hazards associated with the operation of portable handheld laser devices. The engineering controls required for Class 4 by ANSI Std. Z136.1-2000 standards are detailed in Table I.

Table I. Engineering Controls (Class 4 Portable Laser Coating Removal Systems)

ANSI Z136.1-2000 Requirement	Comment
Protective Housing	Shall be used if provided (not applicable for portable laser coating removal systems).
Without Protective Housing	LSO shall establish Alternative Controls: o Laser controlled area o Eye Protection o Barriers, shrouds, beam stops, etc. o Administrative and procedural controls o Education and training
Interlocks on Removable Protective Housings	Shall be used to prevent accidental access to laser radiation in excess of MPE (not applicable for portable laser coating removal systems).
Service Access Panels	Lasers must be 1) interlocked or 2) require a tool for removal and shall have appropriate warning labels.
Key Control	A single master key or electronic code/password is required to start/operate the system
Viewing Portals	Shall be used with proper material selection if provided (not applicable for portable laser coating removal systems).
Collecting Optics (Lenses, Telescopes, Mirrors)	Shall only be used with attenuators, interlocks, filters, etc., to avoid exposure above the MPE (collecting optics shall not be used with portable laser coating removal operations).
Totally Open Beam Path	LSO establishes NHZ, conduct hazard evaluation and ensure correct control measures are implemented.
Limited Open Beam Path	LSO establish NHZ, conduct hazard evaluation in affected zone and ensure correct control measures are implemented.
Enclosed Beam Path	Not applicable for portable laser coating removal systems.
Remote interlock Connector	Interlocks, connected to the main electrical switch, shall be used wherever feasible (entryway, door, etc.) to avoid uncontrolled access and exposure to laser radiation in excess of the MPE.

Table I. Engineering Controls (cont.)

ANSI Z136.1-2000 Requirement	Comment
Beam Stop or Attenuator	Shall be required to prevent access to laser radiation in excess of MPE when the laser output is not required, as in warm up procedures.
Activation Warning System & Emission Delay	Required for portable laser coating removal systems. See *Section 4.4 – Laser Hazard Warning Sign and Labels*.
Class IV Laser Controlled Area	Access control is required for portable laser coating removal systems. See *Section 4.2 - Operating Environment Control*.
Laser Outdoor Controlled Area	Access control is required for portable laser coating removal systems. See *Section 4.2 - Operating Environment Control*.
Temporary Laser Controlled Area	Access control is required for portable laser coating removal systems. See *Section 4.2 - Operating Environment Control*.
Remote Firing and Monitoring	Not applicable for portable, manually operated laser coating removal systems.
Labels	Required for portable laser coating removal systems. See *Section 4.4 – Laser Hazard Warning Sign and Labels*.
Area Posting	Required for portable laser coating removal systems. See *Section 4.4 – Laser Hazard Warning Sign and Labels*.

Laser equipment enclosure and/or laser beam path enclosure is the preferred method of control since the enclosure will isolate or minimize the hazard; however, such beam enclosures severely limit the utility of lasers in coating removal operations. In accordance with ANSI Std. Z136.1 –2000 (Section 4.1), if engineering controls are impractical or inadequate, administrative and procedural controls and protective equipment shall be used. In accordance with ANSI Std. Z136.1 – 2000 (Section 4.1.3.), engineering measures, upon review and approval by the LSO, may be replaced by procedural, administrative, or other alternate engineering controls, which provide equivalent protection. Accordingly, if alternate control measures are instituted, then the personnel directly affected by the measures shall be provided the appropriate laser safety and operational training.

The limits of control measures shall be considered in developing a laser hazard control program. Administrative and procedural controls are listed in Table II.

Table II. Administrative and Procedural Controls (Class 4 Portable Laser Coating Removal Systems)

ANSI Z136.1-2000 Requirement	Comment
Standard Operating Procedures	Required for operating all laser coating removal systems.
Output Emission Limitations	LSO determination.
Education and Training	Required for operating all laser coating removal systems. See *Section 5.0 Training & Certification.*
Authorized personnel	Laser coating removal systems shall only be operated and maintained by authorized personnel.
Alignment Procedures	Required for maintaining/servicing laser coating removal systems. Procedures shall be documented and flowed to avoid accidental exposures in excess of MPE.

Table II. Administrative and Procedural Controls (cont.)

ANSI Z136.1-2000 Requirement	Comment
Protective Equipment	Required for laser coating removal systems. See *Section 4.3. - Personal Protective Equipment*.
Spectators & Demonstrations with the General Public	Shall not be permitted in laser coating removal operations unless: 1) appropriate approval from the supervisor has be obtained, 2) the degree of hazard and avoidance procedures has been explained, and 3) appropriate protective measure are taken.
Service Personnel	Authorized personnel only shall service laser coating removal systems.
Laser Optical Fiber Systems	Optical fibers are considered part of the controlled area. Laser systems shall be properly maintained and services. Laser coating removal systems shall not be operated in the in the event of a fibers breakage, separation, or damage.
Laser Robotic Installations	Not applicable for operating all laser coating removal systems.
Eye Protection	Required for operating all laser coating removal systems. See *Section 4.3.1 – Eye Protection*.
Protective Window	Facility windows (exterior or interior) located inside the NHZ shall provide adequate laser radiation filtration, absorption, blocking or scattering to reduce transmission levels below the MPE.
Protective Barriers and Curtains	Blocking barriers, screens, or curtains shall be sued to block controlled area at levels exceeding the MPE. If protective barriers do not completely enclosed the work area, LSO shall conduct a NHZ analysis and ensure workers outside the controlled area are protected. Barriers shall not support combustion nor release toxic fumes following laser exposure. See *Section 4.2 - Operating Environment Control*.
Skin Protection	LSO shall conduct an evaluation to determine requirement. Engineering controls (shields, etc.), sunscreen creams, and flame retardant gloves and protective clothing shall be considered and implemented if needed. See *Section 4.3. - Personal Protective Equipment*.
Other protective Equipment	Respirators, additional local exhaust ventilation, fire extinguishers, and hearing protection may be required whenever engineering controls cannot provide adequate protection.
Warning Signs and Labels	Required for operating all laser coating removal systems. See *Section 4.4 – Laser Hazard Warning Sign and Labels*.
Service and Repairs	LSO determination. LSO shall require education and safety training appropriate for specific laser systems.
Modifications and Laser Systems	LSO determination. Modified systems may require re-certification, reclassification, and compliance reporting.

4.2. Operating Environment Control

By taking into consideration the laser characteristics and the safety controls listed in Section 4.1, the LSO can establish controlled, safe operating environments. Several possible scenarios are illustrated in the following sections. The field level establishment or implementation of operational environments shall be established, based on field requirements and following a complete hazard evaluation. The LSO is urged to involve personnel from the Public Health, Fire, Safety, and Bio-Environmental Engineering offices.

4.2.1. Enclosed Environment

The general schematic of an enclosed work environment is shown in *Figure 3*. The laser and ancillary equipment are located in an enclosed room with controlled access. The enclosed space, such as a work cell, can only be accessed through designated entry points. Each entry point exhibits an interlock, which, if tripped during laser operation or start-up, either shuts off the laser system, or places the system in a stand-bye mode, whereby the laser is unable to fire until the start-up sequence is re-initiated. This is the safest operational environment as the laser beam is completely contained and personnel outside the enclosed area are protected from laser radiation. Access is controlled through designated entry points. The entry points exhibit flashing lights, which will activate when the laser is in operation. Warning Signs warn entering personnel of the possible danger. During laser operations, the doors are locked to allow only authorized personnel to enter via key. Operators and personnel inside the work area must wear personal protective gear (eye protection, skin protection, etc.) when the laser is in operation.

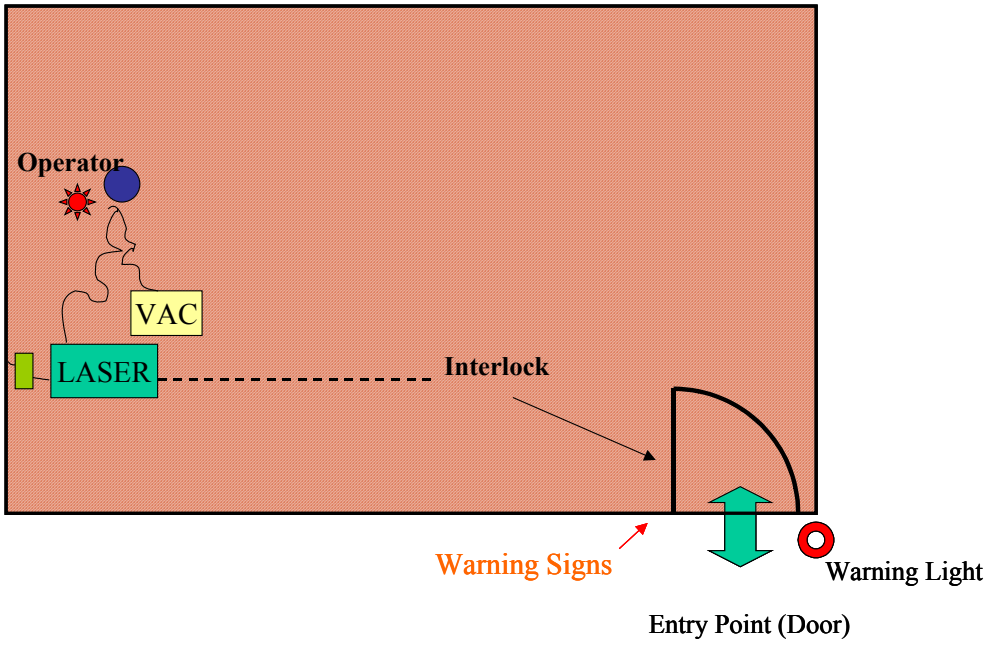

Figure 3. Enclosed Environment Schematic.

4.2.2. Shielded Environment

While an enclosed work-cell (Section 4.2.1) provides the greatest degree of control and safety, such operational requirements also severely limit the (potential) applications of laser coating removal technology. For a large number of applications, work-cells are not a feasible option. Large parts or on-aircraft coating removal, for instance, make enclosed work-cells highly impractical. In these cases, a shielded environment may be used. Blocking barriers, screens, or curtains that block or filter the laser beam should be used to prevent laser light from exiting the area at levels above the MPE level. Operators and

personnel inside the work area must wear personal protective gear (eye protection, skin protection, etc.) when the laser is in operation.

Laser barriers shall be selected to withstand direct and indirect (scattered) laser radiation. Important in the selection of the barrier are the factors of flammability and decomposition products of the barrier material. Barriers shall not support combustion or release toxic materials following laser exposure. Periodically, barriers must be inspected and replaced, if necessary.

In the event where barriers cannot fully contain the work area (i.e. NHZ), the LSO shall conduct a NHZ analysis to assure safety is afforded to all workers outside the shielded area. The LSO may then decide to establish a secured secondary outside perimeter. Signs and warning lights are positioned to warn of hazards inside the shielded area. Access to the laser operating area can be controlled by a safety watch, interlocks connected to the entry points of the curtains/shield, and warning lights and signs. *Figure 4* illustrates a schematic.

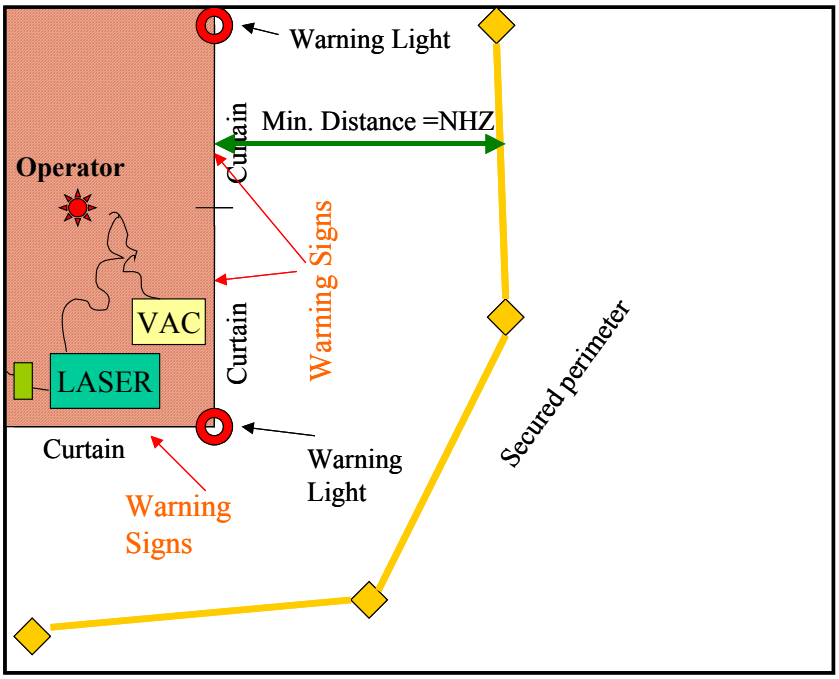

Figure 4. Shielded Environment Schematic

4.2.3. Open Environment (Unshielded)

In applications in which neither a work-cell environment, nor a shielded environment can be created, an open environment may be used. An open environment is the least preferred method of controlling the work environment as it provides the lowest level of safety and maximizes the total area required for operating the laser coating removal system. The open environment does not use shields or barriers, but simply controls the outside perimeter of the NHZ. Warning lights, physical barriers, and warning signs prevent access to the NHZ during laser operation. Operators and personnel inside the

work area must wear personal protective gear (eye protection, skin protection, etc.) when the laser is in operation. Since the NHZ for Class 4 lasers can be very large and the level of protection is limited, this type of environment is not recommended as a permanent work environment. The LSO must complete a full NHZ analysis and implement control procedures to allow laser operation in the environment.

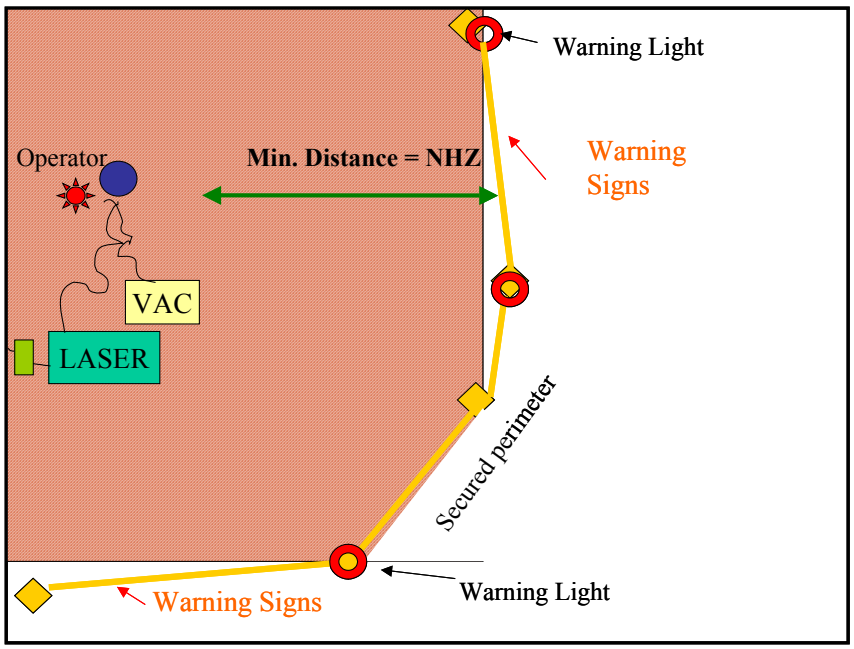

Figure 5. Open Environment Schematic

4.3. Personal Protective Equipment

Engineering controls and physical enclosures of the laser beam path are the preferred method of control since enclosures will isolate or minimize the hazard. However, complete enclosures would severely limit the utility of handheld lasers in coating removal operations. When control measures do not provide adequate means to prevent access to direct or reflected laser beams at levels above the MPE, ANSI Std. Z136.1 –2000 states that it may be necessary to use personal protective equipment. Personal protective equipment has limitations when used as the only control measure with higher-power Class 4 lasers. The protective equipment may not adequately reduce or eliminate the hazard and may be damaged by the incident laser radiation.

4.3.1. Eye Protection

The unprotected human eye is extremely sensitive to laser radiation and can be permanently damaged from direct or reflected beams. The extent of ocular damage is determined by the laser irradiance, exposure duration, and beam size. As laser retinal burns may be painless and the damaging beam sometimes invisible, maximum care should be taken to provide protection for all persons.

As a general rule, protective eyewear should be avoided as primary means against laser radiation. Engineering controls are considered far more important in providing reliable eye safeguard mechanisms. However, many laser coating removal applications make it unfeasible to use engineering controls. Combined with administrative, procedural, and engineering controls, eye protection is a proven tool in avoiding accidents. Careful consideration should be given to selecting the correct type of eyewear. It should be noted that eyewear might also create additional hazards and human error because of reduced visibility or fatigue. Training and strict enforcement of safety procedures are effective in reducing the risk of accidents.

There are two important concepts to consider for eye safety: MPE and NHZ.

(1) MPE is the level of laser radiation to which a person may be exposed without hazardous effect or adverse biological changes in the eye or skin. These levels are determined as a function of laser wavelength, exposure time and pulse repetition and are usually expressed either in terms of radiant exposure in Joules per centimeter squared (J/cm^2) or as irradiance in W/cm^2 for a given wavelength and exposure duration.

(2) NHZ is the physical space in which direct, reflected or scattered laser radiation exceeds the MPE. In practical terms, the entire laser work area should be considered to be within the NHZ because the laser fiber or handpiece can be directed anywhere in the room.

Protective eyewear in the form of goggles, glasses, and shields provides the principal means to ensure against ocular injury, and must be worn at all times during laser operation. Laser safety eyewear (LSE) is designed to reduce the amount of incident light of specific wavelength(s) to safe levels, while transmitting sufficient light for good vision. In accordance with the ANSI Std. Z136 guidelines, each laser requires a specific type of protective eyewear. Some important factors to consider in eyewear are as follows:

(1) The LSE at each laser wavelength shall be specified by the LSO.

(2) As LSE often look alike in style and color, it is important to specifically check both the wavelength and OD imprinted on all LSE prior to laser use.

(3) Color coding of laser handpieces and LSE may help to minimize confusion of laser eyewear.

(4) LSE should not move between laser rooms, nor should they be carried in lab coat pockets between uses.

(5) The integrity of LSE must be inspected regularly since small cracks or loose fitting filters may transmit laser light directly to the eye.

(6) With the enormous expansion of laser use, every facility must formulate and adhere to specific safety policies that appropriately address eye protection.

For AF ground personnel, laser eye protection may be acquired through the supply system or purchased commercially with LSO approval. The AFIOH Radiation Surveillance Division (Brooks City Base) may be contacted to obtain a current list of LSE available commercially and through the military supply system. The LHAZ hazard evaluation tool (Section 3.1.1.) will also recommend appropriate eye protection.

4.3.2. Respiratory Protection

It is recommended that laser operators wear respiratory protection whenever the presence of hazardous air-borne substances is established. Engineering controls alone, such as additional exhaust ventilation, cannot provide adequate respiratory protection. On a case-by case basis, the LSO may require hazardous material exposure testing in accordance with AFOSH Std. 161-8, *Controlling Exposures to Hazardous Materials*, and/or establish a respiratory protection program with the BEs in accordance with AFOSH Std. 48-137 *Respiratory Protection Program*. Careful consideration should be given to respiratory protection when coatings containing heavy metals are removed. The AFMC/LGP collected data at the demonstration facility (see appendix).

4.3.3. Skin Protection

Skin protection can best be achieved through engineering controls that terminate or enclose, the laser radiation. Direct and reflected laser radiation pose a potential danger to the skin. The potential danger exists also for long-term skin damage from UV and blue light exposure (180 nm – 400 nm), particularly for ultraviolet lasers and plasma irradiance generated in the laser-material interaction process. Plasma irradiance levels vary by laser type, the material being removed, and the substrate material. If engineering controls are not sufficient in protecting the skin, then skin covers and/or "sun screen" creams with high Sun Protection Factors (SPFs) are recommended. Most gloves will provide some protection against laser radiation and UV rays. Tightly woven fabrics and opaque gloves provide the best protection. A laboratory jacket or coat provides protection for the arms. Consideration shall be given to flame retardant materials.

4.3.4. Hearing Protection

Noise levels created by the laser coating removal process and ancillary equipment (vacuum, chillers, etc.) may vary, depending on the laser type, parameter settings, coating type, and operational environment. When information indicates that an operator's exposure may equal or exceed an 8-hour time weighted average of 85 decibels, a monitoring program shall be implemented. Representative noise measurements shall be taken and, if needed, a hearing protection program shall be implemented in accordance with Occupational Safety and Health Administration (OSHA) regulation 29 CFR 1910.95

Occupational Noise Exposure, and AFOSH Stds. 48-137 and 48-20 *Hearing Protection Program*.

4.4. Laser Hazard Warning Sign and Labels

4.4.1. Laser Equipment Labels

All laser systems shall be labeled in accordance with 21 CFR 1040.10-1040.11 and military standard MIL-STD-1425A, *Safety Design Requirements for Military Lasers and Associated Support Equipment*.

The following labels (*Figures 6 and 7)* should be permanently affixed to the basic appliance.

Figure 6. Danger - Invisible Laser Radiation Label

Figure 7. Service Cover Label

4.4.2. Warning Signs

Sign dimensions, letter size and color shall be in accordance with American Standard Specification for Accident Prevention Signs, ANSI Std. Z535 series (or latest revision thereof). These signs are available commercially. ANSI Std. Z16.1 –2000 Section 4.7 also provides warning sign requirements and specifications.

Figure 8. Danger-class IV laser-product Warning Sign Label

4.4.3. Warning Lights

In addition to signs, red strobe lights shall be used when the laser is in operation. AC-powered warning lights are preferred over battery operated strobe lights. The LSO shall determine the requirements and approve the equipment prior to use.

4.3. Service, Repair, and Modification of Laser Systems

The LSO shall ascertain whether any changes are required in control measures or whether reclassification is necessary following any service, repair, or modification which may affect the output power or operating characteristics of a laser system so as to make it potentially more hazardous.

4.4. Additional Safety Guidelines

Laser hazards are equipment specific. The manufacturer's technical manual must be consulted. Only a trained, certified laser operator, cognizant of all potential safety hazards, should be allowed to operate the laser. The additional safety guidelines are detailed below, but it does not constitute a comprehensive list. As with all electronic equipment, extreme caution should be exercised in operating electronic equipment especially in potentially hazardous environments. Because of the diversity in potential hazards, the LSO should employ SE, BE, or DEF (Fire Department) to evaluate and address these hazards.

a. Do not wear rings, watches or other metallic apparel when working with electrical equipment.
b. Do not handle electrical equipment when hands or feet are wet or when standing on a wet floor.
c. When working with high voltages, regard all floors as conductive and grounded.
d. Be familiar with electrocution rescue procedures and emergency first aid.
e. Prior to working on electrical equipment, de-energize the power source. Lock and tag the disconnect switch.

f. Check that each capacitor is discharged, shorted and grounded prior to working in the area of the capacitors.
g. Use shock preventing shields, power supply enclosures, and shielded leads in all experimental or temporary high-voltage circuits.

4.5. Laser Safety "Lessons Learned"

According to ANSI Std. Z136.1 – 2000, a review of reported incidents has demonstrated that accidental eye and skin exposures to laser radiation, and accidents related to ancillary hazards of a laser or laser system, are most often associated with personnel involved with the use of these systems under the following conditions.

- Unanticipated eye exposure during alignment
- Misaligned optics and upward directed beams
- Available eye protection not used
- Equipment malfunction
- Improper methods of handling high voltage
- Intentional exposure of unprotected personnel
- Operators unfamiliar with laser equipment
- Lack of protection for ancillary hazards
- Improper restoration of equipment following service
- Eyewear worn not appropriate for laser in use
- Unanticipated eye/skin exposure during laser usage
- Inhalation of laser-generated air contaminants and/or viewing laser-generated plasmas
- Ignition of fires of both a facility or personal nature
- Eye or skin injury of photochemical origin
- Failure to follow SOPs

5. TRAINING AND CERTIFICATION

In accordance with AFOSH Std. 48-139, general laser safety training is required for users of readily accessible (i.e., non-interlocked/non-embedded) Class 4 lasers. Users include operators, technicians, engineers, maintenance and service, personnel etc., who work with or around the laser. The unit safety officer/LSO will ensure that the users are knowledgeable of the potential laser and ancillary hazards and the control measures for laser equipment they may have occasion to use. Training should be conducted upon assignment to laser duties with refresher training annually. Additional training in cardiopulmonary resuscitation due to extreme electrical hazards may also be necessary as determined locally.

The level of training will be commensurate with the degree of potential laser hazards. Topics for inclusion in the training program for personnel working on or around laser may include, but are not necessarily limited to the following:

- Fundamentals of laser operation (physical principles, construction, operating instructions, etc.)
- Biological effects of laser radiation
- Relations of specular and diffuse reflections
- Non-radiation hazards of laser (electrical, chemical, reaction by-products, etc.)
- Ionizing radiation hazards (X-rays from power sources and target interactions when applicable)
- Laser and laser system classifications
- Control measures and personnel protective equipment
- Overall management and employee responsibilities
- Medical surveillance practices (if applicable)
- Fire prevention
- BE, or other designated laser safety personnel, will be trained in all the training specified above and the following:
    - Laser terminology
    - Types of lasers including wavelength, pulse shapes, modes, and power/energy
    - Maximum Permissible Exposure (MPE) for eyes and skin
    - Basic hazard evaluations and calculations

New employees and guests may use the laser under the direct supervision of an authorized laser user for a maximum of 30 days before completing training and medical surveillance requirements. The LSO must be notified of these new employees or guest laser users. Laser users must review the Laser Safety Manual, SOP's, and operating and safety instructions furnished by the manufacturer before operating the laser.

6. MEDICAL SURVEILLANCE

In accordance with AFOSH Std. 48-139, medical examination requirements are limited to those that are clearly indicated and are based on known risks of a particular kind of laser radiation. Supervisors are responsible for ensuring personnel who work with Class 4 lasers report upon initial assignment to Public Health (PH). PH will review the individual's medical records and refer them for any required medical surveillance.

Pre and post-employment medical examinations will be performed, i.e. only before an individuals initial assignment to laser duties and as soon as practical subsequent to the actual termination date involving lasers – Permanent Change of Station (PCS), Permanent Change of Address (PCA), retirement, separation). Periodic examinations are not required. Following any suspected laser injury, the pertinent examinations, as determined by an appropriately qualified physician will be performed. AFOSH Std. 48-139, Section 2.5.5 lists the examination requirements.

Other medical exams shall be conducted, by the determination of the LSO, to monitor laser operator exposure to other (non-beam) hazards. This may include hearing examinations (AFOSH Std. 48-19, *Hazardous Noise Program*; and AFOSH Std. 161-20, *Hearing Conservation Program*), hazardous material exposure testing (AFOSH Std. 161-8, *Controlling Exposures to Hazardous Materials*), and respiratory exams (AFOSH Std. 48-137, *Respiratory Protection Program*).

7. ACCIDENT / INCIDENT INVESTIGATION

It is important to recognize the symptoms of laser eye injuries. The following are potential signs of laser eye injury.

(1) Exposure to the invisible CO2 laser beam (10,600 nm) can be detected by a burning pain at the site of exposure on the cornea or sclera.

(2) Exposure to a visible laser beam can be detected by a bright color flash of the emitted wavelength and an after-image of its complementary color.

(3) When the retina is affected, there may be difficulty in detecting blue or green colors secondary to cone damage, and pigmentation of the retina may be detected.

(4) Exposures to the Nd:YAG laser beam (1064 nm) and diode laser beams (typically 808 nm or 940 nm) are especially hazardous and may initially go undetected because the beam is invisible and the retina lacks pain sensory nerves. Photoacoustic retinal damage may be associated with an audible "pop" at the time of exposure. Visual disorientation due to retinal damage may not be apparent to the operator until considerable thermal damage has occurred.

In accordance with AFOSH Std. 48-139, *Laser Radiation Protection Program*, every incident involving an alleged or suspected laser radiation overexposure to personnel will be investigated and documented.

In particular, whenever an alleged or suspected overexposure to laser radiation occurs, the following steps will be taken:

(1) The exposed individual(s) will seek care without delay at the emergency room of the medical facility that provides the unit emergency medical care. The supervisor of the individual will be notified immediately to ensure action is taken to prevent any further injury to their personnel. Medical Care unit will perform a medical examination and start an AF From 190, Occupational Illness Report. The individual will be reexamined within 72 hours.

(2) The supervisor shall notify his unit commander and unit safety officer/LSO who will notify BE. In turn, BE will notify SE, PH, Installation Staff Judge Advocate, and MAJCOM medical authorities immediately. Within 24 hours, BE will also notify the IEAR Radiation Surveillance Division and the Air Force Medical Operations Agency Radiation Protection Division. PH will insure that the AF From 190 is initiated by the attending physician and forwarded to BE.

(3) The unit safety officer/LSO will keep the unit commander and other unit personnel informed of actions being taken or required as part of the medical investigation.

AFOSH Std. 48-139, Section 2.6 and Appendix 1 list the procedures for medical evaluations of personnel following suspected overexposure.

Injuries to personnel from ancillary hazards need to be reported, investigated, and documented in the same manner.

8. REFERENCES

(1) AFI 91-301 - Air Force Occupational and Environmental Safety, Fire Protection, and Health (AFOSH) Program.

(2) AFI 91-302 - Air Force Occupational and Environmental Safety, Fire Protection and Health (AFOSH) Standard.

(3) AFOSH 48-8 - Controlling Exposures to Hazardous Materials.

(4) AFOSH 48-137 - Respiratory Protection Program.

(5) AFOSH 48-139 - Laser Radiation Protection Program.(6) AFOSH 91-31 - Personal Protective Equipment.

(7) AFOSH 91-100 - Aircraft Flight Line – Ground Operations and Activities.

(8) AFOSH 91-501 - Air Force Consolidated Occupational Safety Standard.

(9) MIL-STD-882D - System Safety Program Requirements.

(10) MIL-STD-1425A - Safety Design Requirements for Military Lasers and Associated Support Equipment.

(11) OSHA 21CFR 1040.11 - Performance Standards for Light-Emitting Products - Specific Purpose Laser Products.

(12) OSHA 29CRF 1910.95 - Occupational Noise Exposure.

(13) OSHA 29CFR 1910.132 - Personal Protective Equipment – General Requirements.

(14) OSHA 29CFR 1910.133 - Personal Protective Equipment - Eye and Face Protection.

(15) OSHA 29CFR 1910.134 - Personal Protective Equipment - Respiratory Protection.

(16) OSHA 29CFR 1926.54 - Subpart D, Occupational Health and Environmental Controls - Nonionizing Radiation.

(17) ANSI Publication Z136.1 – Safe Use of Lasers.

(18) ANSI Publication Z535 - Hazard Signs.

Appendix G
Comparative Analysis of Mechanical Properties

AFRL-ML-WP-TR-2005-4190

DESIGN ENGINEERING AND SUPPORT PROGRAM (DESP)

Delivery Order RZ16: Effects On Mechanical Properties From Laser Paint Stripping

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FEBRUARY 2005

Final Report for 01 August 2003 – 28 February 2005

Approved for public release; distribution is unlimited.

STINFO FINAL REPORT

MATERIALS AND MANUFACTURING DIRECTORATE
AIR FORCE RESEARCH LABORATORY
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14. ABSTRACT
The scope of the project was to obtain an understanding of the effects paint removal methods had on the mechanical properties of the substrate used as coverings for military vehicles. The historical data from these methods was compared to the Portable LASER System for Coating Removal (PLSCR) mechanical property test data. The approach taken to compare the different paint removal systems was to use the data from a series of mechanical property tests (tension, fatigue life, fatigue crack growth rate, hardness, and flexure), as described in the Joint Test Protocol (JTP), conducted on the metallic and non-metallic (composite) substrates used in the PLSCR project.

15. SUBJECT TERMS:
Laser paint stripping; Mechanical properties; Fatigue; 2024-T3; Dry Media Blast (DMB); Plastic Media Blast (PMB); 7075-T6; Fatigue crack growth rate; Ultimate tensile strength; Yield tensile strength; Percentage of elongation; Hardness; Flexural strength; Graphite/epoxy; Fiberglass/epoxy; Kevlar/epoxy; Nd YAG laser; CO2 laser; Flashlamp; Abrasive; Wheat starch; Statistical analysis

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TABLE OF CONTENTS

SECTION		PAGE
1	Introduction	1
2	Background	1
3	Literature Survey and Data Comparison	1
4	Statistical Analysis	2
5	Metallic Literature Search Results	2
	5.1 Tensile Results	2
	5.1.1 2024-T3 Bare	4
	5.1.2 2024-T3 Clad	4
	5.1.3 7075-T6 Bare	5
	5.1.4 7075-T6 Clad	5
	5.1.5 Summary	5
	5.2 Fatigue Results	6
	5.2.1 2024-T3 Clad Smooth Fatigue	7
	5.2.2 2024-T3 Clad Notch Fatigue	8
	5.2.3 7075-T6 Bare Smooth Fatigue	8
	5.2.4 7075-T6 Bare Notch Fatigue	8
	5.2.5 7075-T6 Clad Smooth Fatigue	8
	5.2.6 7075-T6 Clad Notch Fatigue	8
	5.2.7 Summary	8
	5.3 Fatigue Crack Growth Rate (FCGR) Testing	9
	5.3.1 FCGR Statistical Analysis	12
	5.3.2 FCGR Data Analysis Using ASTM E647	12
	5.4 Superficial Hardness	15
	5.5 Conclusions/Observations	16
6	Composite Literature Search Results	18
	6.1 Four-Point Flexural Testing	18
	6.2 Summary	19
7	References	21
APPENDICES		
A	Laser Paint Stripping Reference Literature Summary	A-1
B	Tensile Results	B-1
C	Fatigue Results	C-1
D	Fatigue Crack Growth Rate Results	D-1
E	Flexural Strength Results	E-1

LIST OF FIGURES

FIGURE		PAGE
1	2024-T3 Bare Average Tensile Ultimate Strength	3
2	2024-T3 Bare Average Tensile Yield Strength	3
3	2024-T3 Bare Average Elongation	4
4	2024-T3 Clad S-N Smooth Fatigue Results	7
5	2024-T3 Clad S-N Notch Fatigue Results	7
6	Example Plot of FCGR Data	10
7	7075-T6 Clad Fatigue Crack Growth Rate Test Results	11
8	Statistical Representation of FCGR Data for 7075-T6 Clad	14
9	7075-T6 Clad Superficial Hardness Results	15
10	2024-T3 Superficial Hardness Results	16
11	Graphite/Epoxy Flexural Strength Results	19
B1	PLCRS and Reference Data Metallic Al 2024-T3 Clad Ultimate Tensile Strength Results	B-2
B2	PLCRS and Reference Data Metallic Al 2024-T3 Clad Yield Tensile Strength Results	B-3
B3	PLCRS and Reference Data Metallic Al 2024-T3 Clad Elongation Results	B-4
B4	PLCRS and Reference Data Metallic Al 7075-T6 Bare Ultimate Tensile Strength Results	B-5
B5	PLCRS and Reference Data Metallic Al 7075-T6 Bare Yield Tensile Strength Results	B-6
B6	PLCRS and Reference Data Metallic Al 7075-T6 Bare Elongation Results	B-7
B7	PLCRS and Reference Data Metallic Al 7075-T6 Clad Ultimate Tensile Strength Results	B-8
B8	PLCRS and Reference Data Metallic Al 7075-T6 Clad Yield Tensile Strength Results	B-9
B9	PLCRS and Reference Data Metallic Al 7075-T6 Clad Elongation Results	B-10

LIST OF FIGURES (Continued)

FIGURE		PAGE
C1	PLCRS and Reference Data 7075-T6 Bare Smooth Fatigue Results	C-2
C2	PLCRS and Reference Data Metallic Al 7075-T6 Bare Notch Fatigue Results	C-3
C3	PLCRS and Reference Data Metallic Al 7075-T6 Clad Smooth Fatigue Results	C-4
C4	PLCRS and Reference Data Metallic Al 7075-T6 Clad Notch Fatigue Results	C-5
D1	PLCRS Fatigue Crack Growth Rate Metallic Al 7075-T6 Clad Results	D-2
D2	Metallic Al 7075-T6 Clad Fatigue Crack Growth Rate Statistical Analysis at ΔK of 6 and 14	D-3
D3	PLCRS Fatigue Crack Growth Rate Metallic Al 7075-T6 Bare Results	D-4
D2	Metallic Al 7075-T6 Bare Fatigue Crack Growth Rate Statistical Analysis at ΔK of 6 and 14	D-5
E1	PLCRS Flexural Strength Results	E-2
E2	PLCRS and Reference Data Flexural Strength Results	E-3

LIST OF TABLES

TABLE		PAGE
1	Tensile Properties for Various Paint Stripping Methods	6
2	Fatigue Properties	9
3	Statistical Analysis of Fatigue Crack Growth Rate Data Results for PLCRS	13
4	Statistical Analysis of Hardness	15
5	Metallic Matrix for Paint Removal Methods	17
6	Matrix for Composite Flexural Data	20

1. INTRODUCTION

This project, funded under Contract No F42620-00-D-0039, Delivery Order RZ16, evaluated the Portable Laser Coating Removal System (PLCRS) mechanical property tests results compared to the published data of other coating removal systems used by the Department of Defense (DoD). This document was submitted to the Air Force Research Laboratory Materials Laboratory (AFRL/ML). The technical points of contacts at AFRL/MLSC were Mr. Randall Straw and Mr. Thomas Naguy. The Principal Investigators at the University of Dayton Research Institute were Mr. James Coleman and Dr. Peter Sjöblom.

2. BACKGROUND

The processes used to remove coatings from DoD equipment vary from chemical, mechanical, and high intensity light stripping, to hand sanding and scraping. The substrates primarily used on DoD equipment are metallic and composite materials. The Environmental Protection Agency (EPA) requires that the use of hazardous chemicals and materials is held to a minimum. This requirement limits the chemical and mechanical coating removal methods that can release volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) and can produce hazardous waste. The DoD is searching for an environmentally friendly paint removal method to satisfy the environment requirements without decreasing the performance of the substrate material.

3. LITERATURE SURVEY AND DATA COMPARISON

A literature search of 74 published references was conducted on methods commonly used to remove paint from metallic and non-metallic substrates. The references were categorized by substrate and mechanical property data presented. Metallic substrate mechanical properties retrieved from the references were tensile, fatigue, and hardness. No fatigue crack growth data was found in the literature survey. Therefore, no comparison to the data generated in the Portable Laser Coating Removal System (PLCRS) 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. A catalog was created to assist in categorizing the large number of references (Appendix A).

The data gathered were compared to the test results from the (PLCRS) program. Statistical analysis was performed on the test results from the PLCRS program and compared to the literature search data gathered using the same statistical analysis approach when possible. The statistical analysis criterion was established by the Engineering and Technical Services for Joint Group on Pollution Prevention Projects Joint Test Protocol J-00-CR-017 (JTP). The JTP is designed to set the standard for acceptable mechanical tests results used to qualify materials for use in the field.

The paint-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 PLCRS project.

4. STATISTICAL ANALYSIS

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 the (SAS) software package. This software 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.

5. METALLIC LITERATURE SEARCH RESULTS

The primary focus of the metallic substrate literature search was on paint removal testing conducted on aluminum substrates used by the DoD. The JTP requires that four paint removal cycles be performed on the substrate before any mechanical test data is generated. Aluminum 2024-T3 (clad, bare) and 7075-T6 (clad, bare) were the materials selected for the PLCRS project so the data reference search was concentrated on those materials.

5.1 <u>Tensile Results</u>

The PLCRS and reference data tension results are displayed in Fig. 1. Each baseline and paint removal method was evaluated using at least ten replicates. The average tensile ultimate strength (TUS), tensile yield strength (TYS), and elongation (e) are represented in the graphs. The baseline data for the PLCRS and the reference data are the firs bar, plotted in black, in each data set. The bars right of the baseline are the test results after paint removal. Each bar is labeled with the removal method used. The reference from which the data was collected is displayed over the plot.

A statistically significant difference between the baseline and after paint removal is indicated by a '√' mark. A data set without a '√ 'mark indicates no statistical significance between the baseline and after the paint removal. The Metallic Materials Properties Development and Standardization (MMPDS) Handbook 'A' allowable level is also indicated on the charts, where applicable. Although, one cannot direct compare an A design allowable, statistically derived from 300 test results from 10 different lots, to a

mean of a handful of tests, the A allowable for the material form used is plotted in the graphs to give an indication of the relative strength level of the stripped panels.

The Al 2024-T3 bare material tension results are displayed in Figures 1, 2, and 3. The tension results (plots) for the remaining materials are located in Appendix B.

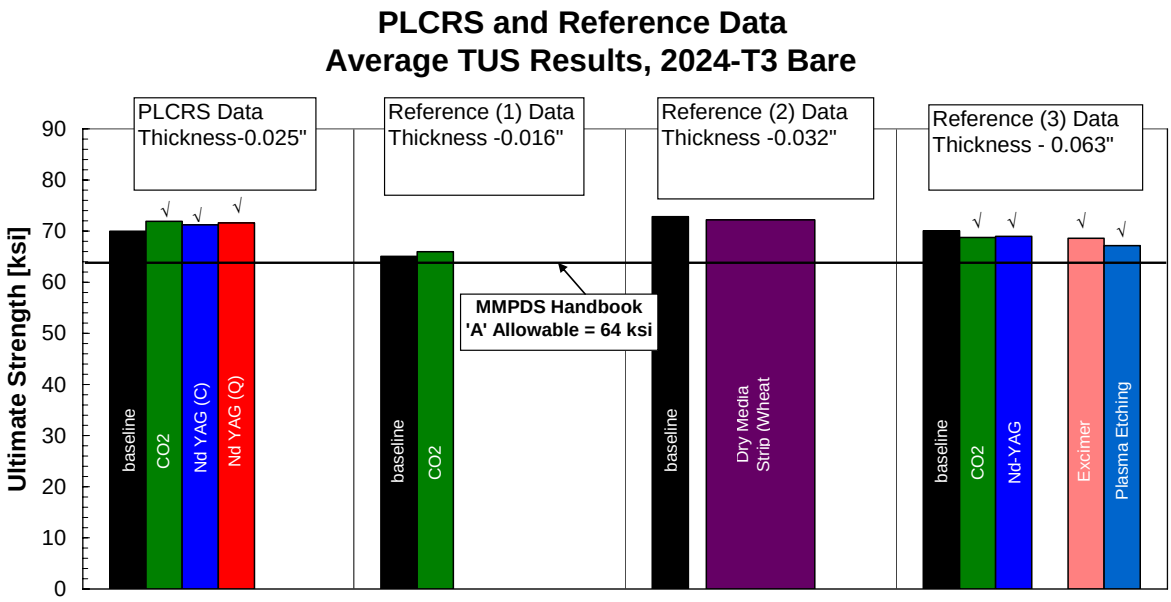

Figure 1. 2024-T3 Bare Average TUS.

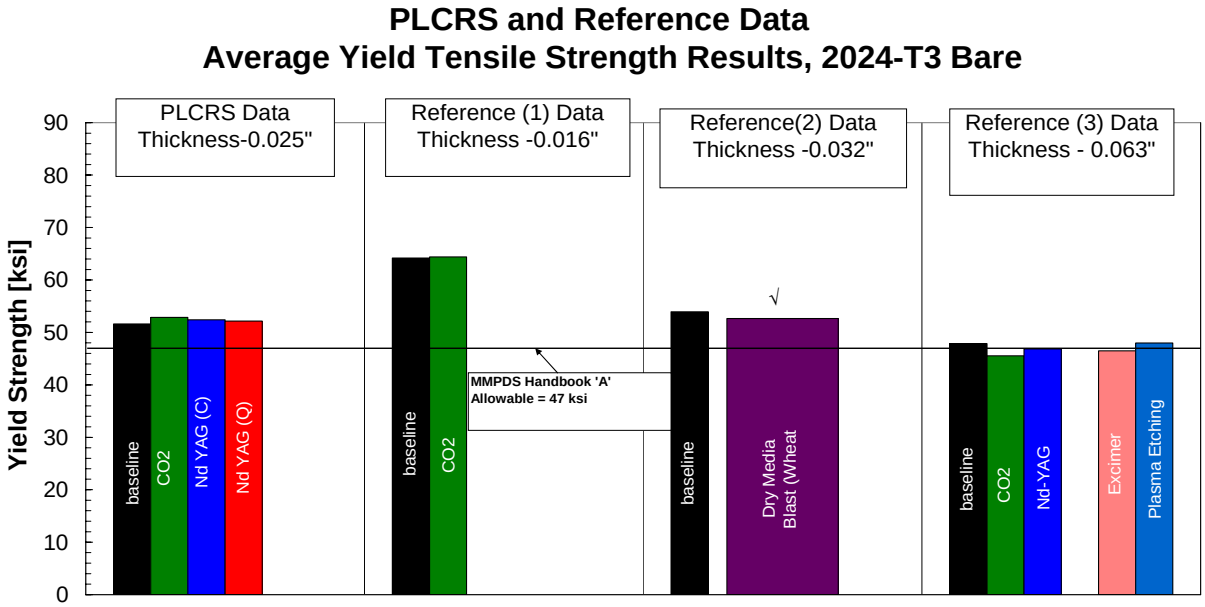

Figure 2. 2024-T3 Bare Average TYS.

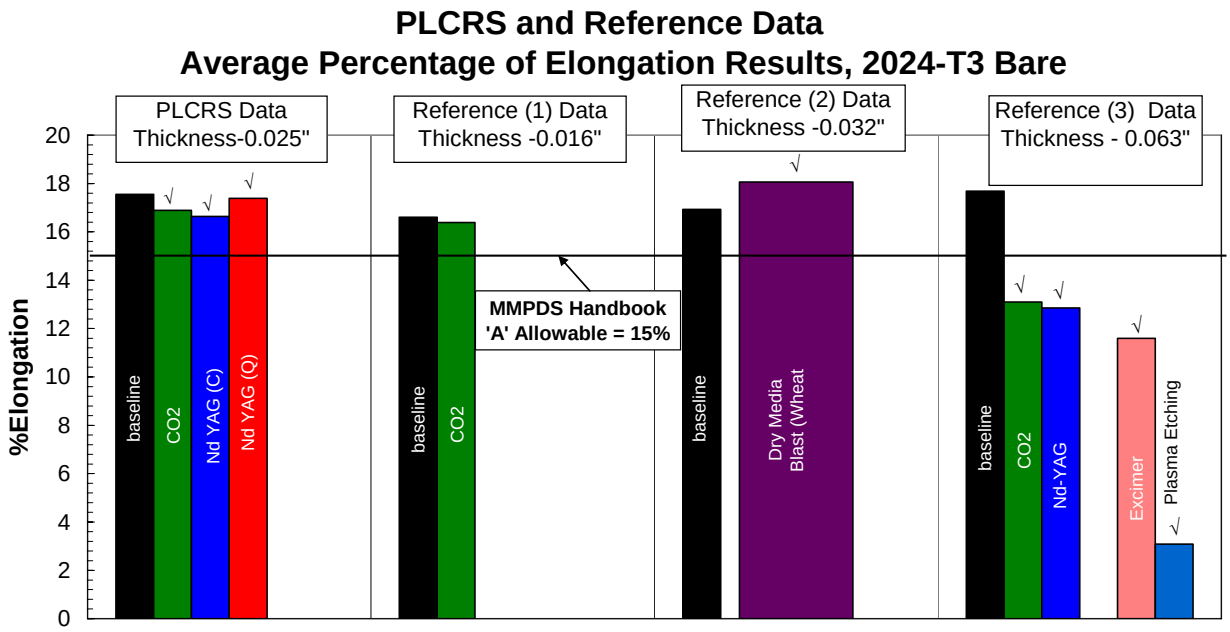

Figure 3. 2024-T3 Bare Average Elongation.

5.1.1 *2024-T3 Bare*

The paint removal method used in reference (2) was a dry media blast (DMB) while reference (1) and (3) use different lasers for removing paint from the substrate.

Strength: The PLCRS tensile properties for Al 2024-T3 bare show a statistically significant increase in ultimate strength compared to the baseline. The same trend can not be found in the reference data. The reference data either depicts a statistically significant decrease, as in reference (3), or no difference as in reference (1) and (2). Reference (2) has a statistical decrease in yield strength.

Percentage of Elongation: The percentage of elongation data from the PLCRS and reference (3) displays a statistically significant decrease when compared to the baselines used in their respective testing. There was no statistical significance difference for the elongation in the reference (1) results. Reference (2) shows a statistical increase in elongation.

5.1.2 *2024-T3 Clad*

Strength: The Al 2024-T3 clad tests results (Figures B1 thru B3 in Appendix B) display a statistically significant increase in TUS for the PLCRS Nd YAG lasers (Clean and Quantel) results; however, there is a statistically significant decrease in strength for

the carbon dioxide (CO_2) laser results. A statistically significant decrease in TYS was seen in the PLCRS CO_2 laser and DMB (2) paint removal methods. The yield strength variation for the other paint removal methods was not statistically significant.

Percentage of Elongation: The elongation for the PLCRS CO_2 and Nd YAG (Quantel) laser and DMB method show statistical difference compared to the baseline data. The PLCRS Nd YAG (Cleanlaser) elongation is statistically significant lower than the baseline data.

5.1.3 *7075-T6 Bare*

Strength: The Al 7075-T6 bare tests results (Figures B4 to B6 in Appendix B) show a statistically significant increase in TUS for the PLCRS CO_2 and Nd YAG (Quantel) laser paint removal methods and a decrease in TUS for the DMB data in reference (2). No difference in TUS using in the PLCRS Nd YAG (Cleanlaser) strength results was observed. The PLCRS laser TYS results show no statistical difference. The DMB (2) yield strength results show a statistical decrease compared to baseline data.

Percentage of Elongation: No statistical significant difference was noted.

5.1.4 *7075-T6 Clad*

Strength: The Al7075-T6 clad test results (Figures B7 to B9 in Appendix B) display an increase in the TUS for the PLCRS laser paint removal methods and a statistical decrease in the DMB (2) paint removal method. The TYS, using PLCRS lasers, did not change, but the DMB paint removal method produced a decrease.

Percentage of Elongation: The elongation results displayed no difference for the PLCRS CO_2 and Nd YAG (Quantel) laser and DMB (2) paint removal methods. The Nd YAG (Cleanlaser) laser paint removal method produced a decrease in elongation.

5.1.5 *Summary*

A summary of the PLCRS tensile results and the reference data is shown in Table 1. The space marked "+" indicates a statistically significant increase in the property, while "-" indicates a decrease. It should be noted, that although there may be a statistically significant difference at the 90% confidence level, there may not be a significant engineering difference. The differences observed are small and 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. It should also be noted that the Laser Stripping Methods showed a lesser, if any, reduction of tensile properties. The Laser Stripping Methods tensile properties are above the MMPDS 'A' allowable.

Table 1. Tensile Properties for Various Paint Stripping Methods

Paint Removal Methods	Al 2024-T3 bare			Al 2024-T3 clad			Al 7075-T6 bare			Al 7075-T6 clad		
	Tension			Tension			Tension			Tension		
Reference	UTS	YTS	%E	UTS	YTS	%E	UTS	YTS	%E	UTS	YTS	%E
(2), DMB (wheat starch)	-	-	NS	-	-	NS	-	-	NS	-	-	NS
(3), Plasma Etching	-	NS	-									
(3), Excimer	-	NS	-									
(1), (3), CO2 Laser	+	NS	+									
(3), Nd YAG	-	NS	-									
PLCRS												
CO2	+	NS	NS	-	-	NS	+	NS	NS	+	NS	NS
Nd YAG (Q)	+	NS	NS	+	NS	NS	+	NS	NS	+	NS	NS
Nd YAG (C)	+	NS	-	+	NS	-	NS	NS	NS	+	NS	-
NS – No Statistically Significant Difference												
- - Statistically Significant Decrease												
+ - Statistically Significant Increase												
- No tabulated reference data found												

5.2 Fatigue Results

An important point to consider when viewing any fatigue data is the inherent scatter in fatigue life for any material and condition. Depending on the stress level, normal scatter in the fatigue life of metallic materials can easily range over a decade in cyclic life, witnessed in the numerous fatigue publications such as the MMPDS handbook. Differences in fatigue life of 20% are well within the norm, particularly when fatigue stresses approach the endurance strength of the material. In general, fatigue data is assumed to follow a log-normal distribution and therefore plotted and analyzed in terms of the log cycles. Thus, differences in cyclic lives of 20% and perhaps even 50%-60%, while statistically significant, may not be as significant from an engineering standpoint. Such debits or variability in fatigue life are generally design specific and best left to the design engineer to ascertain whether slight decreases in life are significant from an engineering standpoint.

The PLCRS and the reference fatigue data are displayed as bar charts in Figures 4 and 5. The average cycles-to-failure of at least five replicates for each baseline and paint removal method are presented in the graphs. The brackets on each bar represent the observed cycles-to-failure range of the replicates tested at the given stress level. The baseline data for the PLCRS and the reference data is the black bar that appear to the left in each plot. The bars next to the baseline information are the paint removal test results labeled by the removal method. The report reference number is displayed over the bar. A statistical significant difference is indicated by a '√' mark. A data set without a '√'mark indicates no statistical difference at a 90% confidence level.

The 2024-T3 clad material fatigue results are displayed in Figures 4 and 5. The fatigue results for the remaining materials are located in Appendix C (Figures C1 to C3).

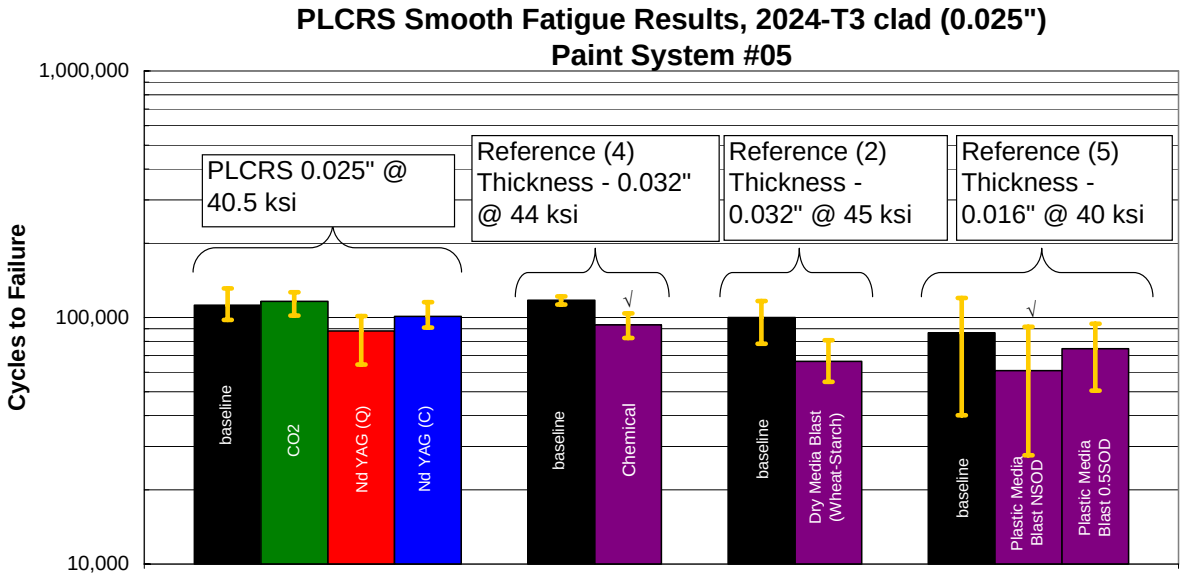

Figure 4. 2024-T3 Clad S-N Smooth Fatigue Results. √ indicate a statistically significant difference.

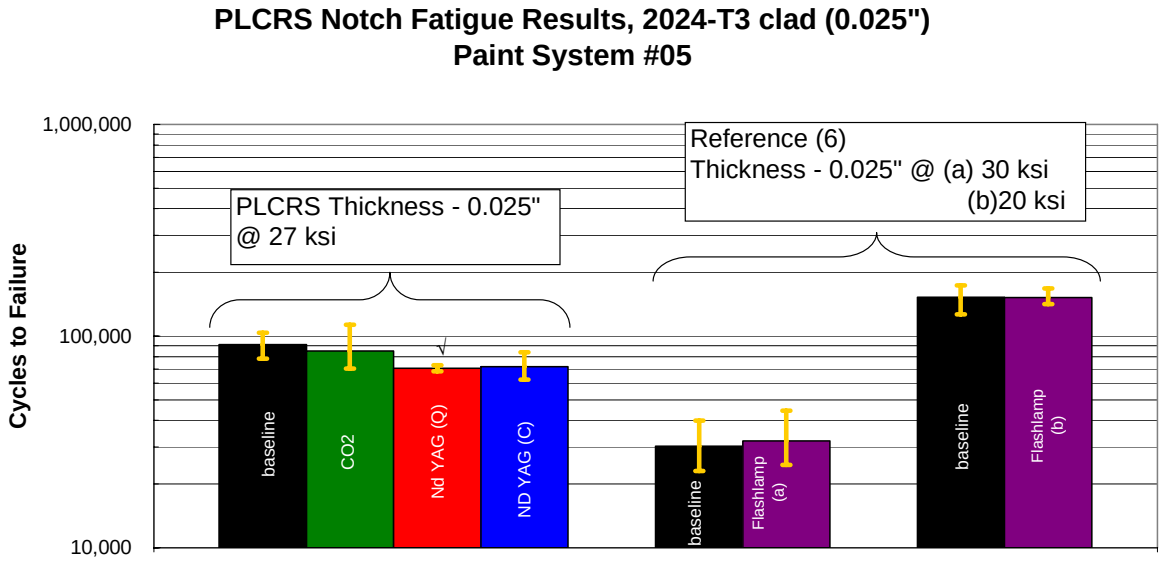

Figure 5. 2024-T3 Clad S-N Notch Fatigue Results. √ indicate a statistical significant difference.

5.2.1 *2024-T3 Clad Smooth Fatigue*

2024-T3 clad smooth fatigue results from the PLCRS program showed no statistically significant difference in fatigue life for the CO_2 and Nd YAG (Cleanlaser)

laser paint removal method. The Nd YAG (Quantel) laser paint and Chemical (reference (4)), and PMB NSOD (reference (5)) removal method showed a statistically significant decrease in fatigue life. Data from reference (2) (DMB) and (5) (PMB) paint removal method displayed no statistically significant difference in fatigue life.

5.2.2 *2024-T3 Clad Notch Fatigue*

The notch fatigue results for 2024-T3 clad from the Nd YAG (Quantel and Cleanlaser) paint removal method showed a statistically significant reduction in fatigue life. The CO_2 and flash lamp paint removal method (reference (6)) showed no statistically significant difference in fatigue life.

5.2.3 *7075-T6 Bare Smooth Fatigue*

The 7075-T6 bare smooth fatigue results (Figure C1 in Appendix C) for the CO_2 laser and DMB paint removal methods showed no statistically significant change in fatigue life. The Nd YAG (Quantel and Cleanlaser) laser paint removal method and chemical paint removal method resulted in a statistically significant shorter fatigue life.

5.2.4 *7075-T6 Bare Notch Fatigue*

7075-T6 bare notch fatigue results (Figure C4 in Appendix C) for the PLCRS project show a statistically significant decrease in fatigue life for the CO_2 and Nd YAG (Quantel and Cleanlaser) laser paint removal methods. No tabulated data was found for 7075-T6 bare notch fatigue in the reference data reports.

5.2.5 *7075-T6 Clad Smooth Fatigue*

7075-T6 clad smooth fatigue results (Figure C3 in Appendix C) showed no statistically significant change in fatigue life for the PLCRS lasers and PMB. Chemical strip and DMB showed a statistically significant decrease in fatigue life.

5.2.6 *7075-T6 Clad Notch Fatigue*

The notch fatigue results for 7075-T6 clad for the Nd YAG (Cleanlaser and Quantel) paint removal method showed a statistically significant reduction in fatigue life. The CO_2 and flash lamp paint removal method (reference (6)) showed no statistically significant difference in fatigue life.

5.2.7 *Summary*

A qualitative summary of the PLCRS fatigue results and the reference data is listed in Table 2. The space marked “+” indicates a statistically significant increase, while “-” indicates a statistically significant decrease. Note that all differences fall well within the normal scatter in fatigue life, approximately one decade. Therefore, the differences are not significant from an engineering standpoint.

Table 2. Fatigue Properties

Paint Removal Methods	2024-T3 Clad		7075-T6 Bare		7075-T6 Clad	
Reference	Smooth	Notch	Smooth	Notch	Smooth	Notch
(4), Chemical	-		-		-	
(2),DMB (Wheat Starch)	-				-	
(5), PMB (Plastic)	-				NS	
(6), Flash lamp		NS		+		+
PLCRS						
CO_2	NS	NS	+	-	NS	NS
Nd YAG (Q)	-	-	-	-	NS	-
Nd YAG (C)	NS	-	-	-	NS	-
NS – No Statistically Significant Difference						
- Statistically Significant Decrease						
+ Statistically Significant Increase						
- No tabulated reference data found						

5.3 Fatigue Crack Growth Rate (FCGR) Testing

Fatigue crack growth rate (FCGR) data aid in determining the life of a component containing cracks, as well as determining inspection intervals for the component. If crack growth rates are increased significantly by a process such as paint removal, the inspection interval may have to be reduced, leading to more frequent inspections. However, if crack growth rates are not significantly affected, the original inspection intervals are presumably still appropriate. As the crack length increases during fatigue cycling, the rate of crack propagation increases (change in crack length/ change in fatigue cycles, or da/dN) due to an increase in the range of stress intensity factor, ΔK, which is a function of both crack length and stress amplitude. The magnitude of ΔK (units of ksi$\sqrt{\text{in}}$) controls the rate of crack propagation and, with the knowledge of the expected fatigue loading and material properties, one can estimate the life of a cracked structure.

The plot in Figure 6 represents typical FCGR data. This sigmoidal shaped curve has three distinct regions: Region 1 (threshold), Region 2 (linear or 'power law' region), and Region 3 (onset of fast fracture). The linear relationship between the logarithm of da/dN and the logarithm of the stress intensity range is generally modeled as a power fit to the actual data and also termed the "Paris Region" after the researcher who first identified this relationship. Data which falls above the curve in Figure 6 indicates a higher crack propagation rate and thus identified as 'Decreased Life'. Conversely, data falling below and to the right of the idealized curve would be have lower propagation rates and thus result in 'Increased Life'.

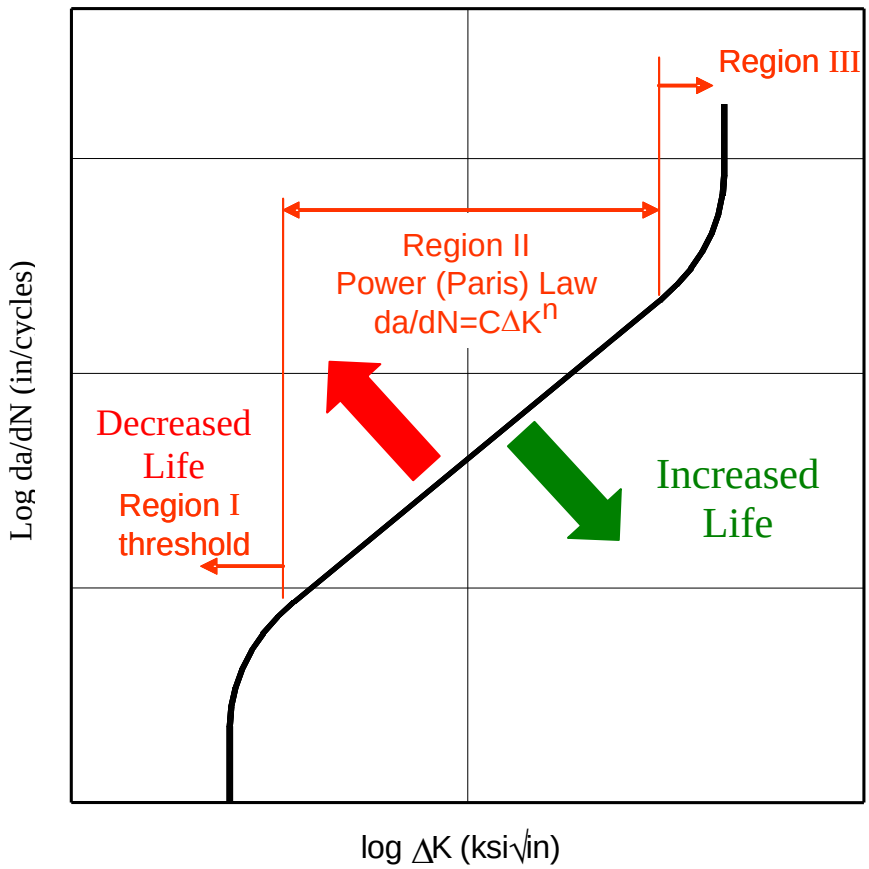

Figure 6. Example Plot of FCGR Data.

This effort evaluated the effect of the various laser paint removal processes on the crack growth rate of the metallic substrates along with baseline (un-stripped) samples. Each baseline and paint removal method had at least four replicates. An example of this for the 2024-T3 substrate is shown in Figure 7. Data for all substrates are further illustrated in Figures D1 to D4 in Appendix D.

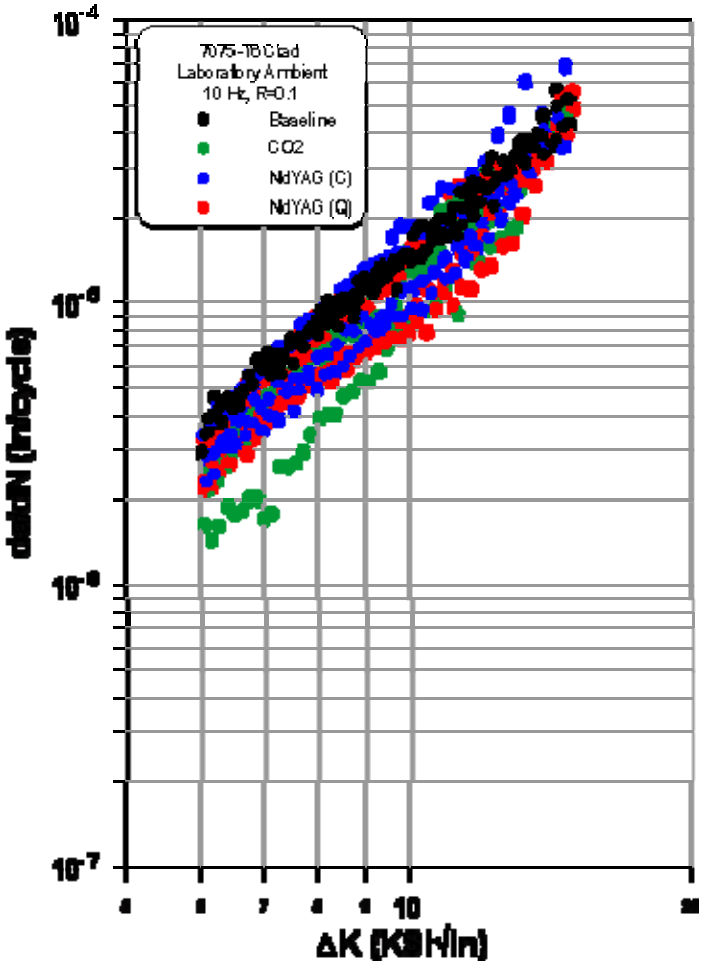

Figure 7. 7075-T6 Clad Fatigue Crack Growth Rate Test Results.

5.3.1 *FCGR Statistical Analysis*

Since any reference FCGR data could not be found in a tabulated format, it is impossible to compare reference paint removal methods with the PLCRS data. The statistical analysis performed on the PLCRS data was accomplished by first modeling the Paris region for each removal technique and substrate and examining the statistical variation in growth rates at a 90% confidence level at two distinct ΔK values: 6 and 14 ksi√in. Table 3 shows the results of this statistical analysis for all of the FCGR tests performed in the PLCRS project. The results of this analysis are further depicted graphically in Figure 8, where the Paris model is shown along with the ± 90% confidence levels. When the confidence levels of a particular data set fall below the baseline curve, a statistically significant decrease in growth rate is noted, beneficially from a life standpoint. Further more, when the confidence intervals are above the baseline, there is a statistical increase in growth rates which corresponds to a decrease in fatigue crack growth life. When the confidence intervals of two data sets overlap, no statistical differences are noted. For the 7075-T6 clad data represented in Figure 8, all the paint strip data at 6 ksi√in fall below the baseline, indicating lower growth rates. At 14 ksi√in, no statistical differences are noted between the stripped data and the baseline with the exception of the Nd YAG (Q) which is statistically lower than baseline.

Reviewing the data shown in Table 3 indicates that from a statistical standpoint, only the 2024-T3 clad data showed a decrease in growth rate resistance (i.e., higher growth rates) over baseline material. The significance of this difference (and all differences) noted in Table 3 from an engineering standpoint is discussed in the following section.

5.3.2 *FCGR Data Analysis using ASTM E647*

It is not unusual for FCGR data to show a large amount of specimen- to-specimen variability. ASTM E 647-00, *Standard Test Method for Measurement of Fatigue Crack Growth Rates*[1], in Section 8.1 states that:

> At crack growth rates greater than 10^{-8} m/cycle, the within-lot variability (neighboring specimens) of d*a*/d*N* at a given ΔK typically can cover about a factor of two. At rates below 10^{-8} m/cycle, the variability in d*a*/d*N* may increase to about a factor of five or more due to increased sensitivity of d*a*/d*N* to small variations in ΔK. This scatter may be increased further by variables such a micro structural difference, residual stresses, changes in crack tip geometry (crack branching) or near tip stress . . .

Furthermore, the standard states:

> … the reproducibility in *da/dN* within a laboratory to average ±27% and range from ±13 to ±50%, depending on laboratory…

[1] Section 3, Metals Test Methods and Analytical Procedures, ASTM International, West Conshohocken, PA.

Table 3. Statistical Analysis of Fatigue Crack Growth Rate Data Results for PLCRS

Material	Paint Removal Method	ΔK ksi-(in)$^{0.5}$	Predicted Value From Model	Lower 90% Confidence Interval	Upper 90% Confidence Interval	Statistical Significance	Predicted Value – Baseline Predicted Value
2024-T3 Clad	**Baseline**	**6**	**-6.163**	**-6.184**	**-6.141**		
		14	**-4.879**	**-4.906**	**-4.852**		
	Q Laser	6	-6.137	-6.146	-6.129		0.0254
		14	-4.664	-4.676	-4.652	-	0.215
	C Laser	6	-6.126	-6.137	-6.114	-	0.0370
		14	-4.689	-4.708	-4.670	-	0.190
	CO_2	6	-6.256	-6.277	-6.235	+	-0.0930
		14	-4.783	-4.813	-4.754	-	0.0961
7075-T6 Clad	**Baseline**	**6**	**-5.366**	**-5.377**	**-5.354**		
		14	**-4.339**	**-4.354**	**-4.324**		
	Q Laser	6	-5.484	-5.508	-5.460	+	-0.118
		14	-4.435	-4.469	-4.402	+	-0.0964
	C Laser	6	-5.447	-5.473	-5.422	+	-0.0818
		14	-4.347	-4.385	-4.309	NS	-0.00786
	CO2	6	-5.584	-5.615	-5.553	+	-0.218
		14	-4.361	-4.411	-4.311	NS	-0.0220
7075-T6 Bare	**Baseline**	**6**	**-5.456**	**-5.474**	**-5.439**		
		14	**-4.259**	**-4.283**	**-4.236**		
	Q Laser	6	-5.552	-5.571	-5.533	+	-0.0955
		14	-4.250	-4.279	-4.222	NS	0.00892
	C Laser	6	-5.671	-5.707	-5.634	+	-0.214
		14	-4.202	-4.255	-4.148	NS	0.0574
	CO2	6	-5.516	-5.539	-5.492	+	-0.0591
		14	-4.244	-4.284	-4.204	NS	0.0153

+ -Statistically significant difference where the laser FCGR data lies below the baseline
- - Statistically significant difference where the laser FCGR data lies above the baseline
NS No statistical significance

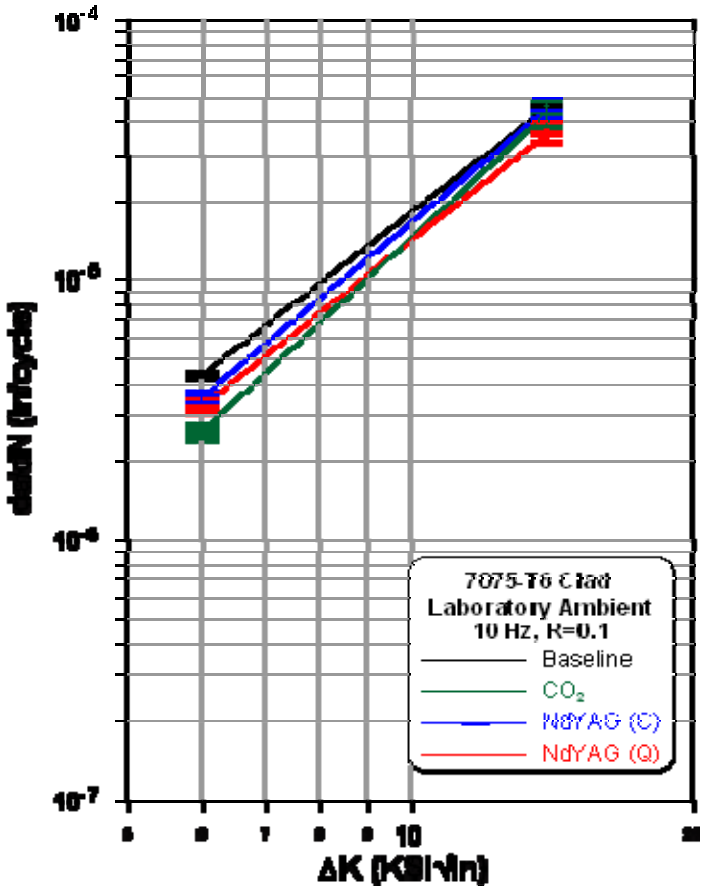

Figure 8. Statistical Representation of FCGR data for 7075-T6 Clad.

Thus the statistical differences shown in Table 3 should thus be viewed with this in mind. The data comparisons are made at the discrete ΔK levels of 6 and 14 ksi√in. The corresponding levels of d*a*/d*N* are in the range of $1x10^{-4}$ to $1x10^{-6}$ in/cyc. Per the ASTM E647 standard, differences within a factor of two to five between data sets can be expected due to specimen-to-specimen variability. Therefore, since the data in Table 3 (shown as log da/dN) does not vary by more than a factor of two, differences from the baseline should be considered expected variability. As none of the data meet this criterion, there does not appear to be significant differences from an engineering standpoint between the baseline and FCGR data for any of the three examined substrates.

5.4 Superficial Hardness

The statistical analysis for the PLCRS hardness for 2024-T3 and 7075-T6 clad are shown in Table 4 and Figures 9 and 10. The statistical significant difference at a 90% simultaneous confidence interval for each paint removal method is indicated by a '√' mark. A data set without a '√ 'mark indicates no difference.

Both YAG lasers decreased the hardness; CO_2 no change for both 7075-T6 and 2024-T3.

Table 4. Statistical Analysis of Hardness

Paint Removal Method	2024-T3	7075-T6
PLCRS	**Superficial Hardness**	**Superficial Hardness**
Baseline	**82.6**	**89.2**
CO_2	82.1	89.5
Nd YAG (Q)	81.5	88.1
Nd YAG (C)	80.9	88.7

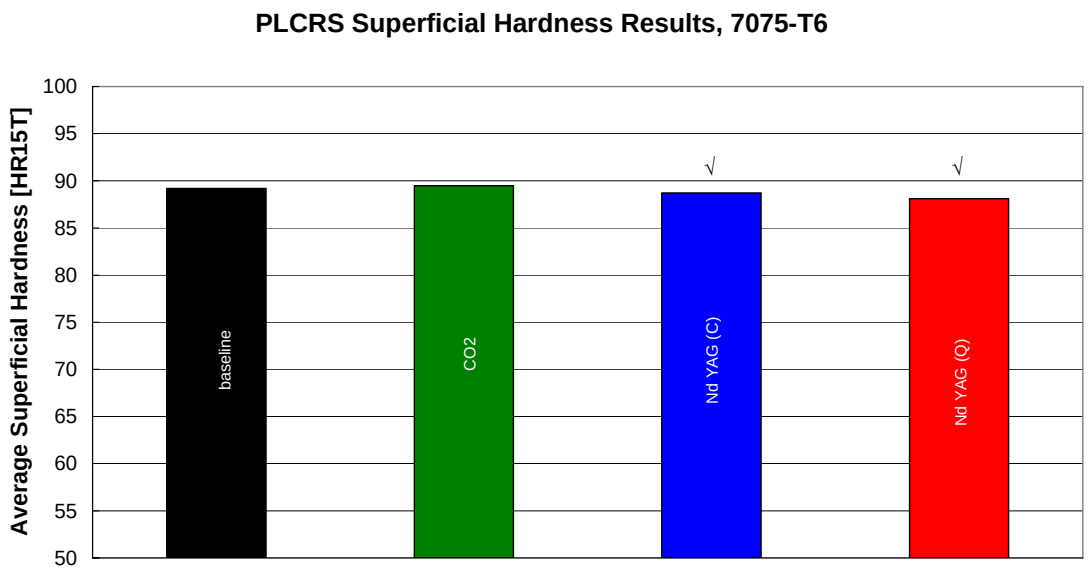

Figure 9. 7075-T6 Clad Superficial Hardness Results.

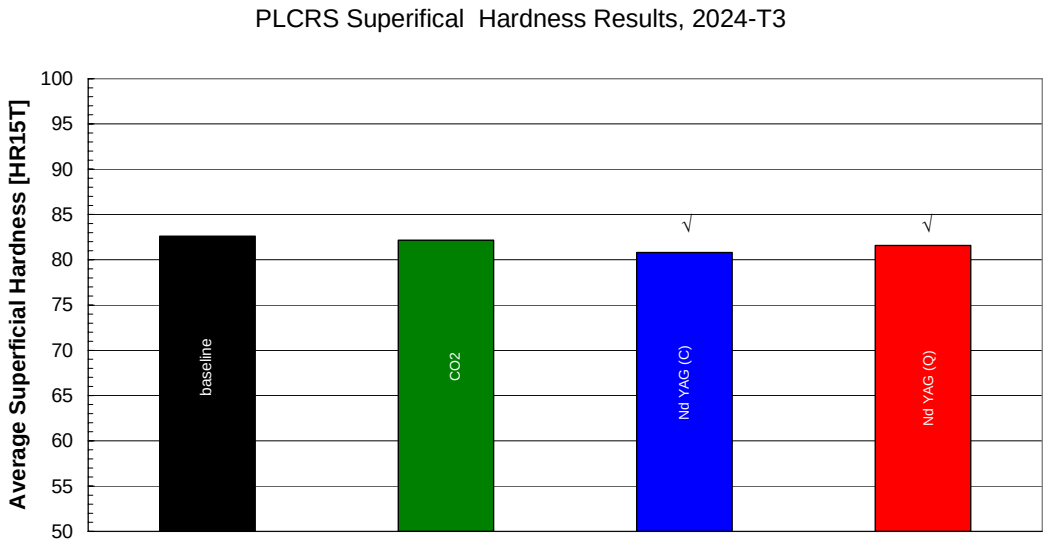

Figure 10. 2024-T3 Superficial Hardness Results. √ indicate a statistical difference at a 90% confidence level.

5.5 Conclusions/Observations

Table 5 summarizes the effects of the paint removal methods on the mechanical properties of the metallic substrates. No conclusive data depict one paint removal method to be better or worse than the others. The statistical significance presented may not represent an engineering significance. Most of the metallic tension mean levels (TUS, TYS, percentage of elongation) are above the 'A' Allowable given in the MMPDS Handbook. The most notable view from this study was how few mechanical property tests data were published on the past paint removal methods.

Table 5. 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 F)										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	-
Nd YAG (Q) Laser (AFRL Testing)	+	NS	NS			+	NS	NS	-	-	+	NS	NS	NS	-	+	NS	NS	-	-
Nd YAG (C) 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

6. COMPOSITE LITERATURE SEARCH RESULTS

The primary focus of the composite literature search was on paint removal testing conducted on composite substrates used by the DoD and in the PLCRS project The JTP requires the substrate to be run through four paint removal cycles before any mechanical testing is performed on the substrate. Graphite, fiberglass, and Kevlar epoxy were the materials selected for the PLCRS project, so the reference search focused on these materials. The paint removal methods were PMB, high intensity light (flash lamp), and hand (wet/dry) abrasive.

6.1 Four-Point Flexural Testing

The PLCRS and the reference data flexural results are displayed in bar charts. Each baseline and paint removal method had at least five replicates with the average flexural strength represented in the graphs. The baseline data for the PLCRS and the reference data are represented by the black bar that appears on the left in each data set. The bars next to the baseline information are the paint removal test results labeled by the removal method. The reference number is displayed over the data from which it was extracted and corresponds to the summary chart in Appendix A. A statistically significant difference in the data between the baseline and the paint removal method at a 90% simultaneous confidence interval is indicated by a '√' mark. A data set without a '√ 'mark indicates no statistical difference.

Figure 11 shows the results of the PLCRS graphite/epoxy flexural test and the reference data found for that material. Graphs for the other substrates are in Appendix E. The Nd YAG (Cleanlaser) laser results in Figure 11 shows a decrease in flexural strength in comparison to the baseline data. The reference data shows no statistical change in flexural except in the wet abrasive which showed an increase.

Figure E1 displays the PLCRS flexural strength results for the graphite, fiberglass and Kevlar epoxy laminate tests. The fiberglass results show a decrease in flexural strength for both Nd YAG lasers compared to the baseline. The Kevlar results showed no difference between the Nd YAG lasers.

Figure E2 displays the PLCRS and a PMB reference data graphite/epoxy laminate flexural strength results. Only the four cycles PMB at 38 and 60 psi showed a decrease in strength.

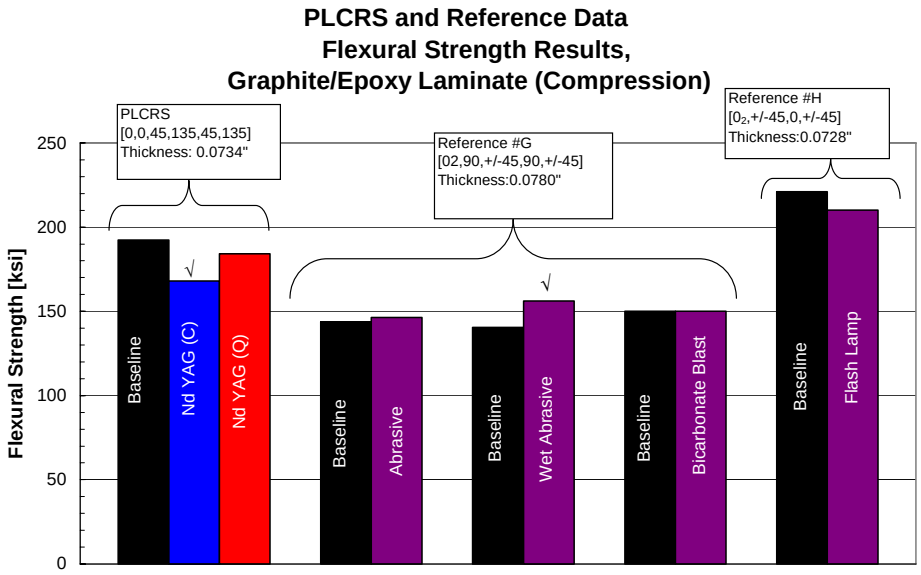

Figure 11. Graphite/Epoxy Flexural Strength Results. √ indicates a statistical significant difference at a 90% confidence level.

A matrix of the PLCRS composite flexural strength results and the reference data is presented in Table 6. The space marked "+" indicates an increase (at a 90% confidence interval) in the flexural strength, while "-" indicates a decrease.

6.2 Summary

The results of tests conducted to compare paint removal methods were inconclusive. The data did not depict one paint removal method to be better or worse than the other methods. Any indicated statistically significant difference may not represent an engineering significance. The most notable finding from this study was how few mechanical property tests data have been published on presented past paint removal methods.

Table 6. Matrix for Composite Flexural Data

Paint Removal Method	Graphite/Epoxy	Fiber Glass/Epoxy	Kevlar/Epoxy
Reference	Flexural Strength	Flexural Strength	Flexural Strength
#H Flash Lamp	NS		
#E PMB (Plastic)	NS		
#G Bicarbonate Blast	NS		
#G Abrasive	NS		
#G Wet Abrasive	+		
PLCRS			
Nd YAG (Q)	NS	-	NS
Nd YAG (C)	-	-	NS
NS – No Statistical Significance			
- - Statistical decrease			
+ - Statistical increase			
- No tabulated reference data found			

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APPENDIX A

LASER PAINT STRIPPING REFERENCE LITERATURE SUMMARY

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APPENDIX B

TENSILE RESULTS

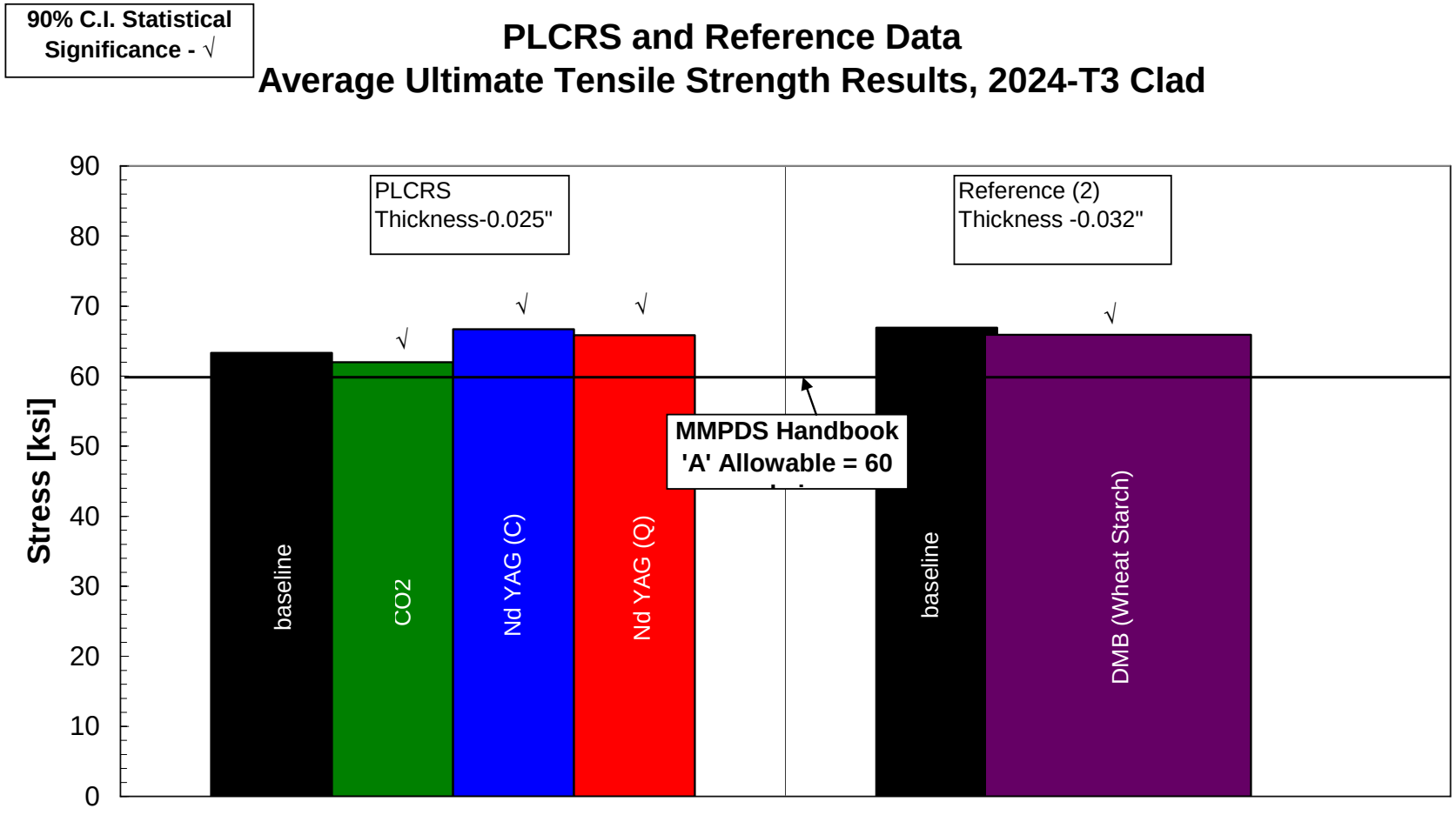

Figure B1. PLCRS and Reference Data Metallic Al 2024-T3 Clad Ultimate Tensile Strength Results.

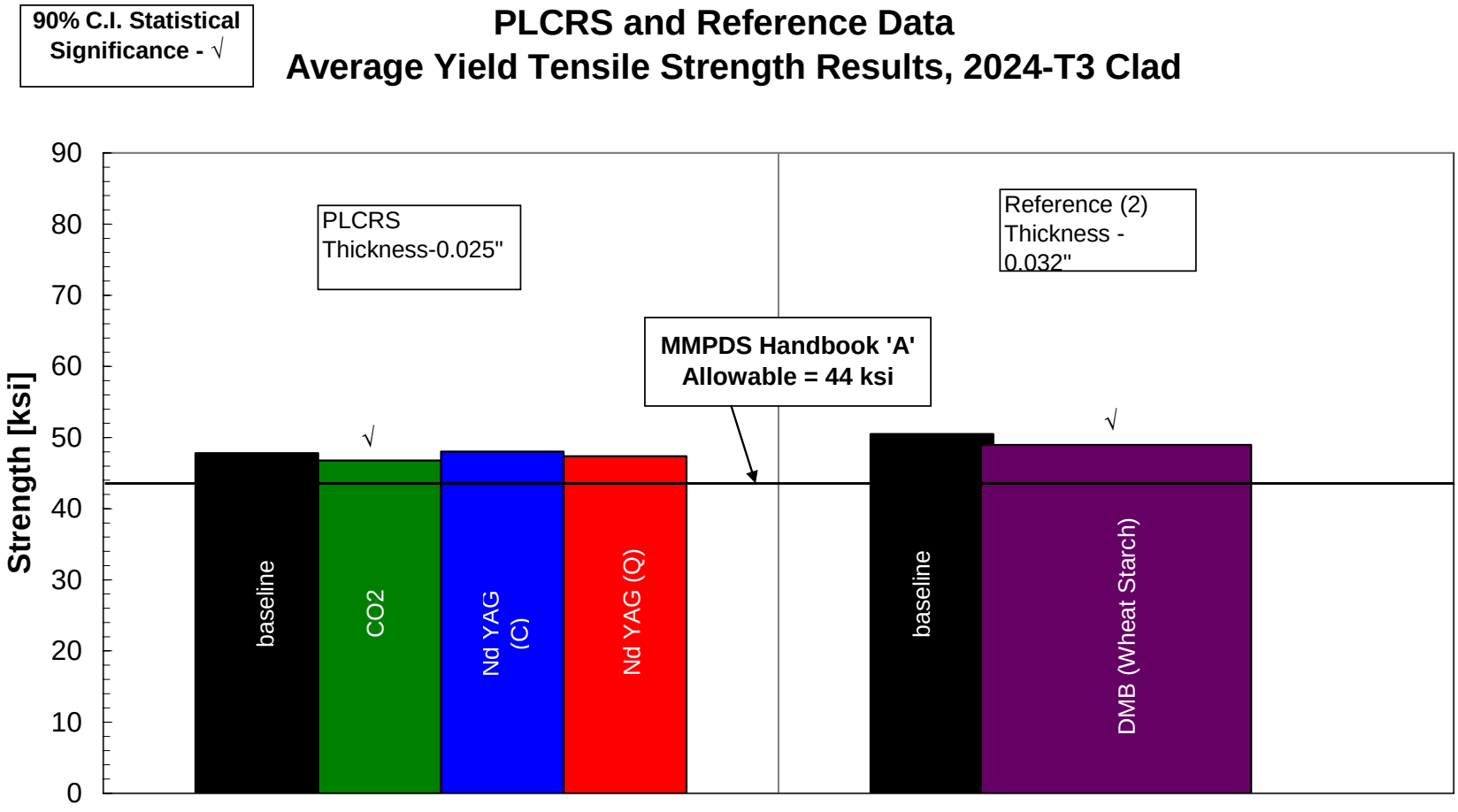

Figure B2. PLCRS and Reference Data Metallic Al2024-T3 Clad Yield Tensile Strength Results.

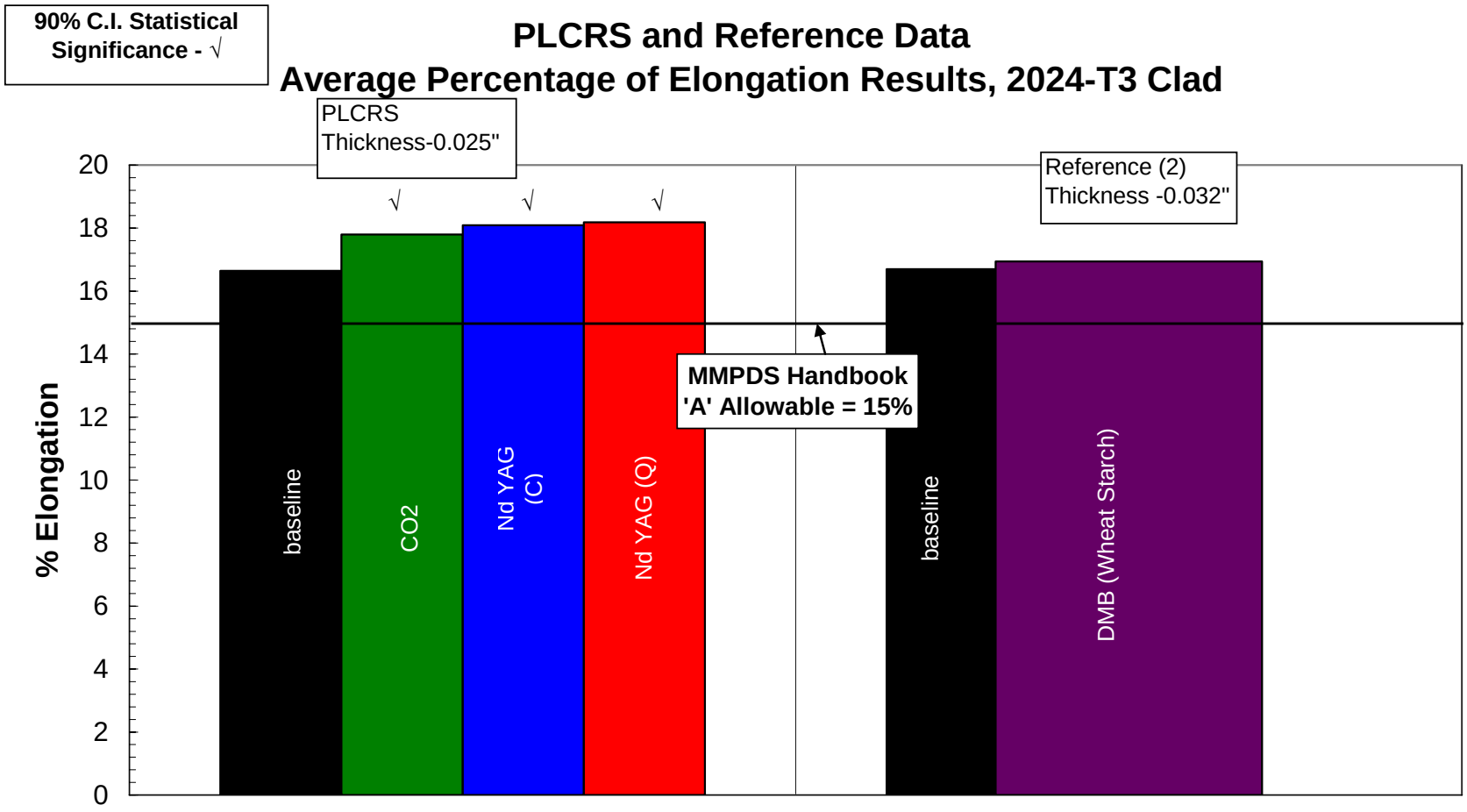

Figure B3. PLCRS and Reference Data Metallic Al2024-T3 Clad Elongation Results.

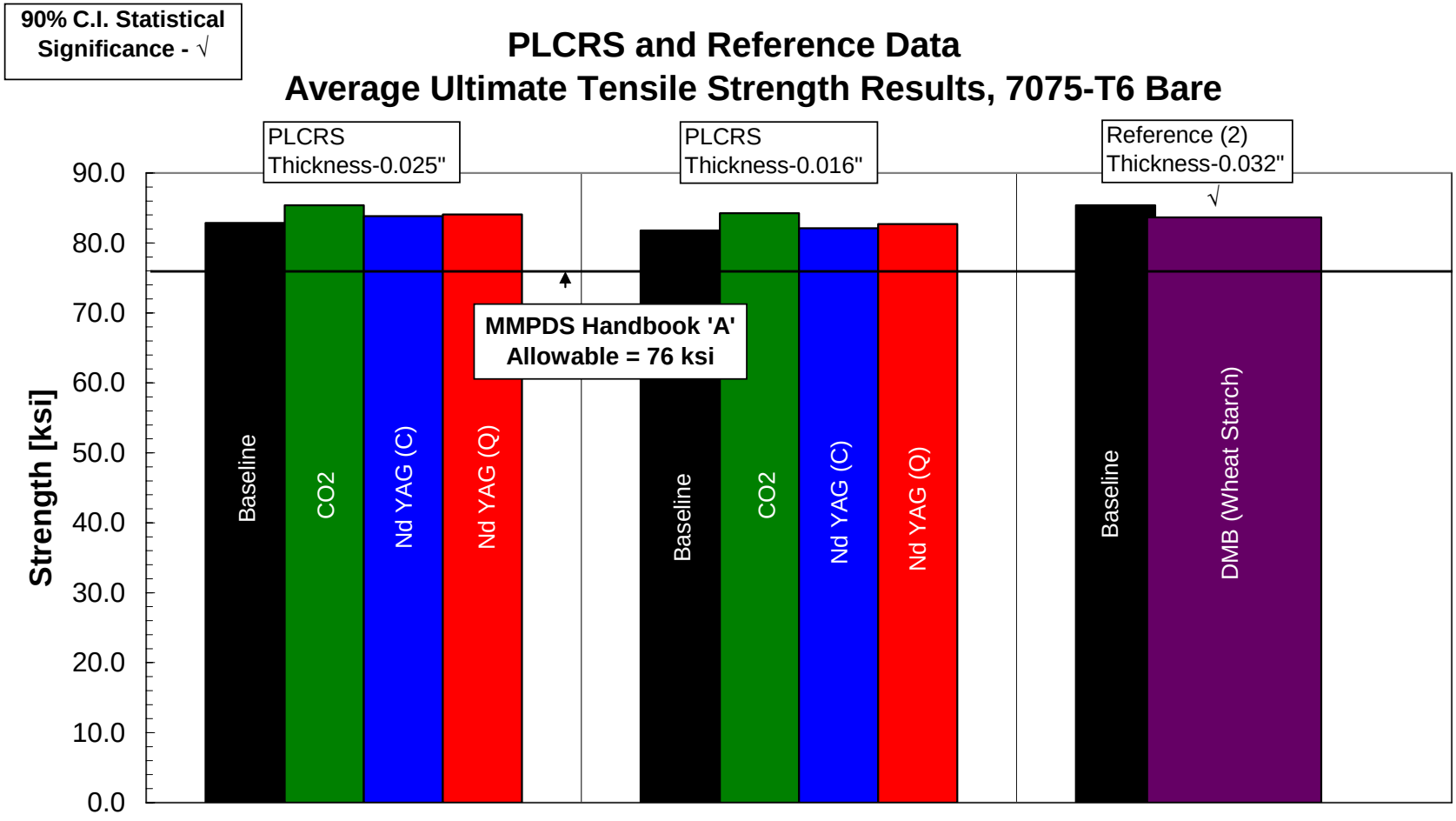

Figure B4. PLCRS and Reference Data Metallic Al7075-T6 Bare Ultimate Tensile Strength Results.

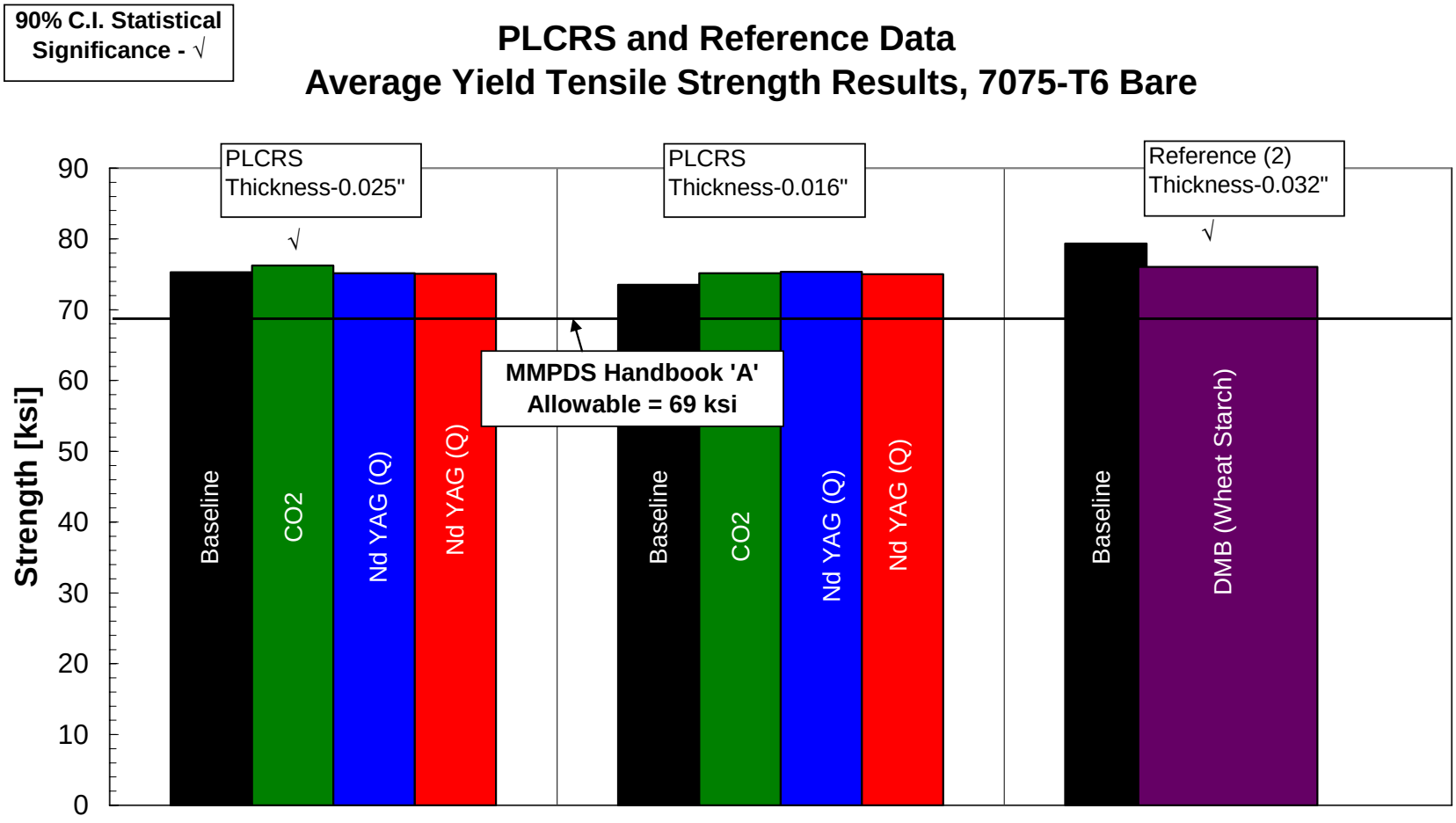

Figure B5. PLCRS and Reference Data Metallic Al7075-T6 Bare Yield Tensile Strength Results.

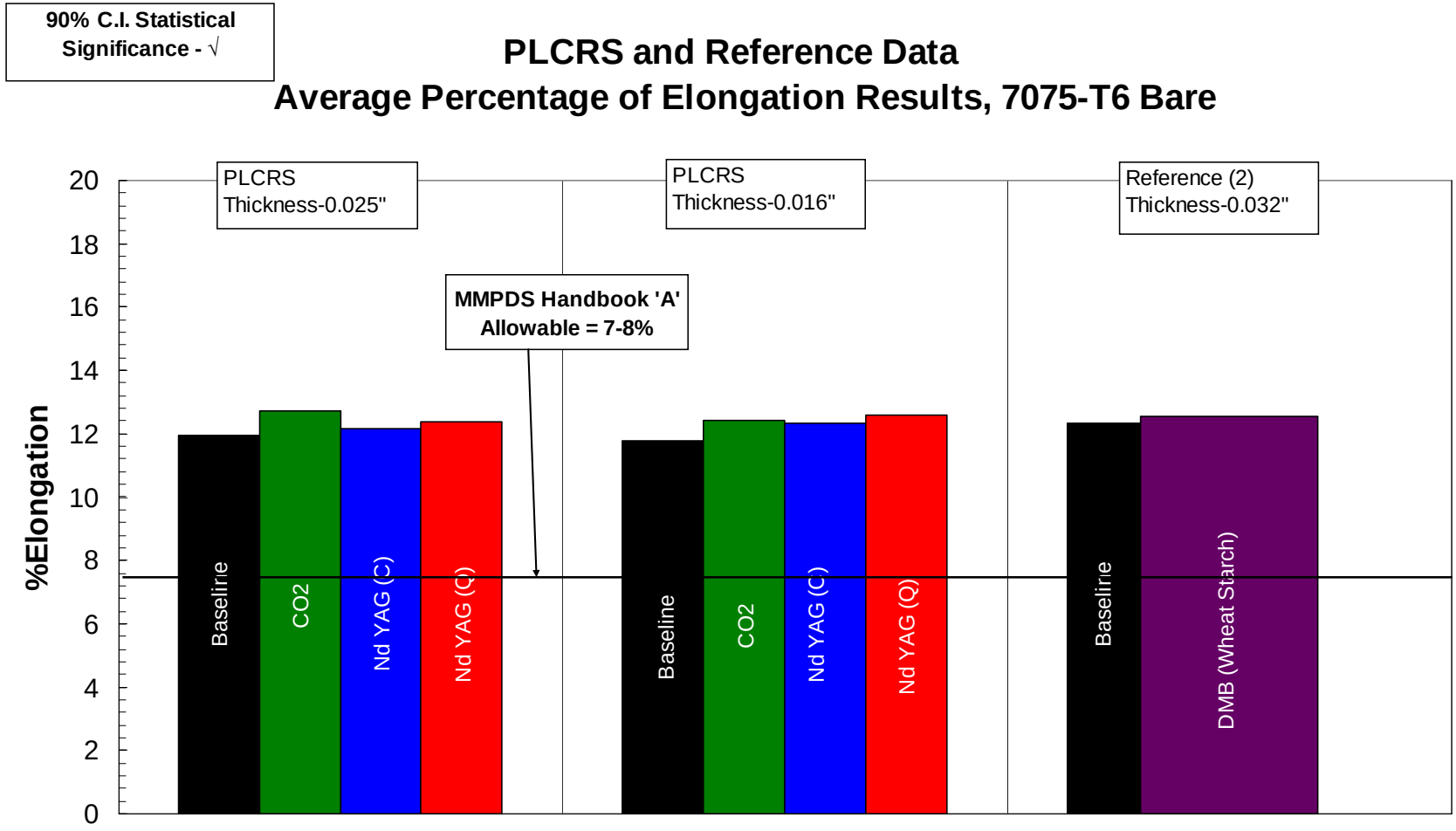

Figure B6. PLCRS and Reference Data Metallic Al7075-T6 Bare Elongation Results.

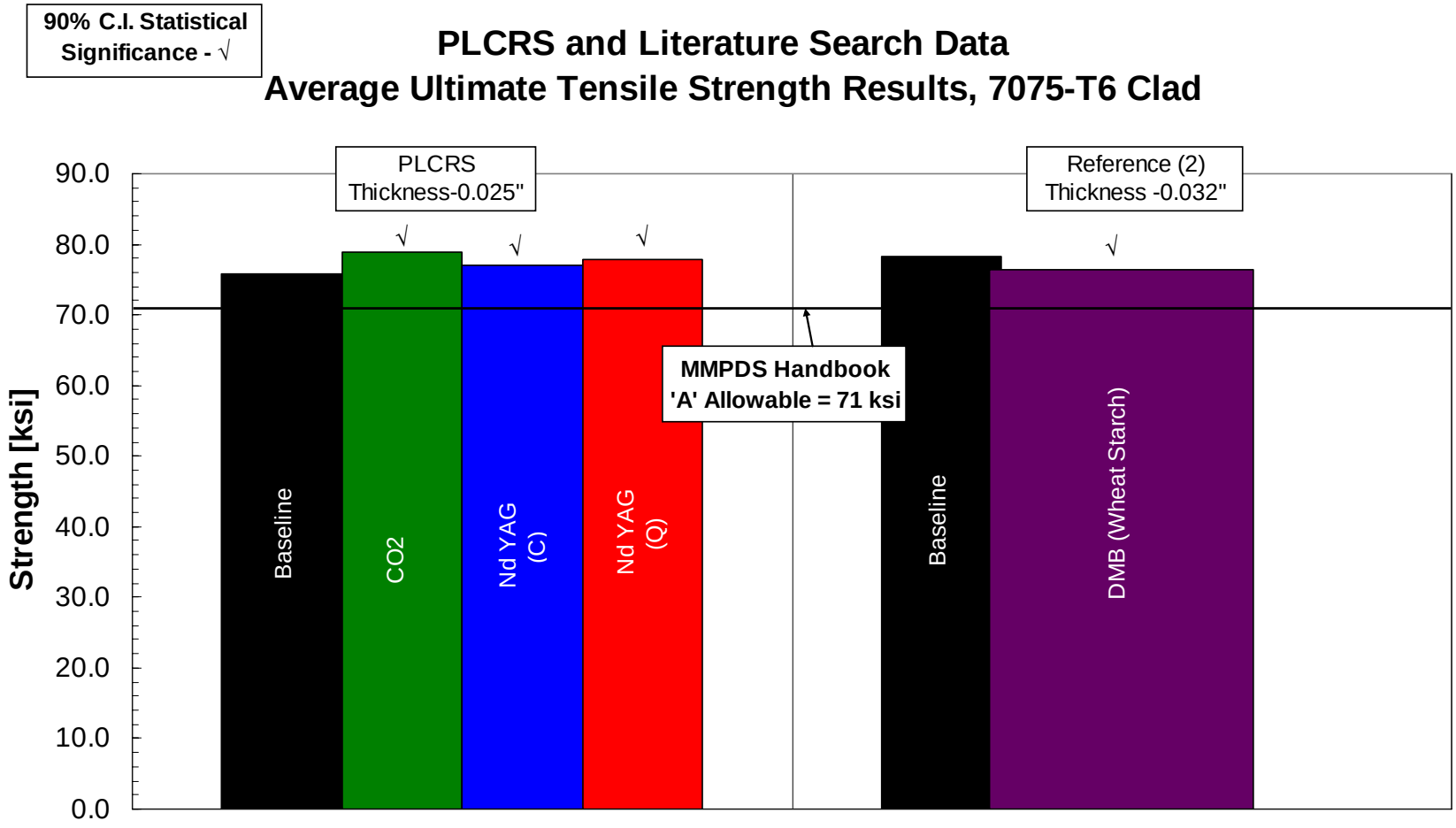

Figure B7. PLCRS and Reference Data Metallic Al7075-T6 Clad Ultimate Tensile Strength Results.

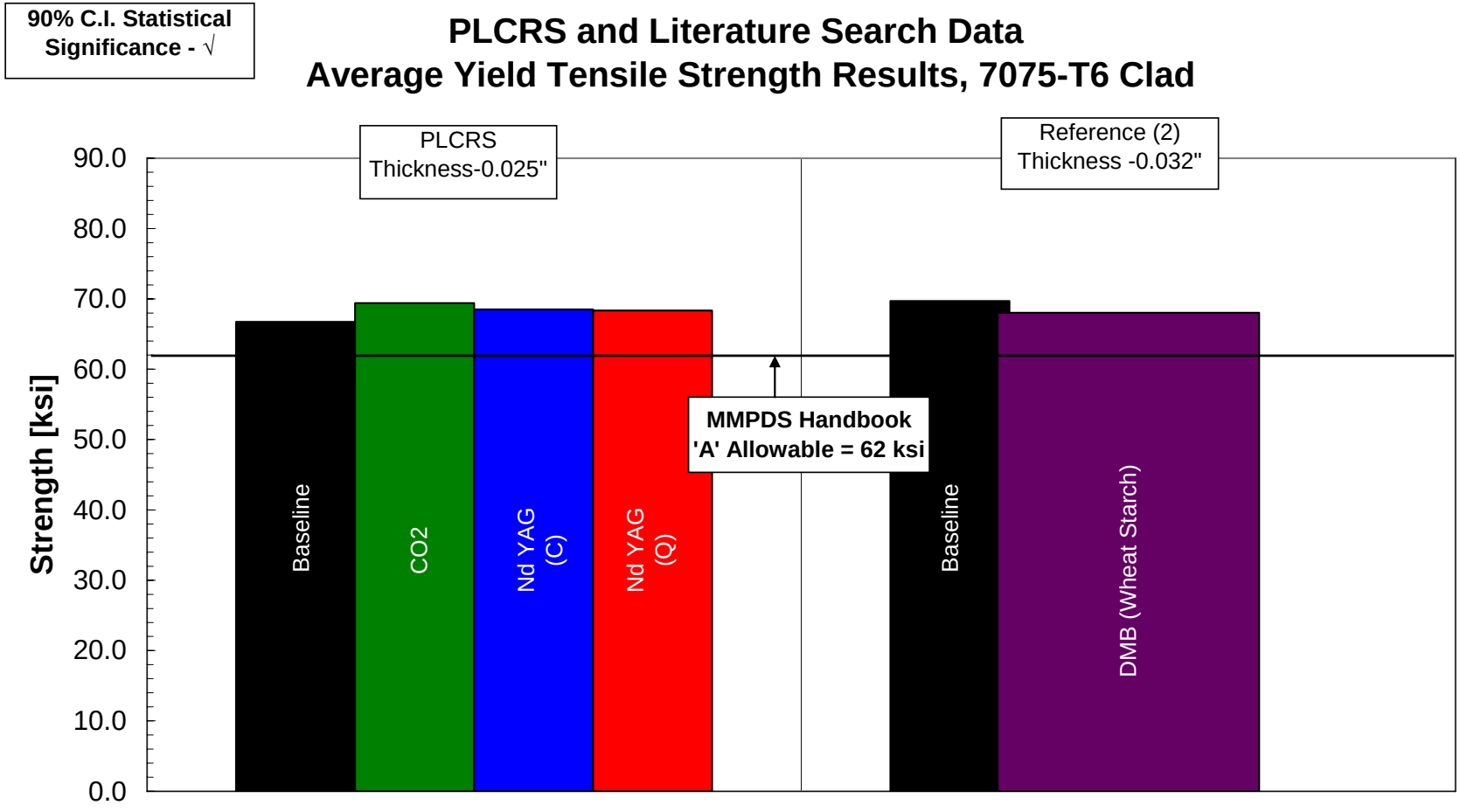

Figure B8. PLCRS and Reference Data Metallic Al7075-T6 Clad Yield Tensile Strength Results.

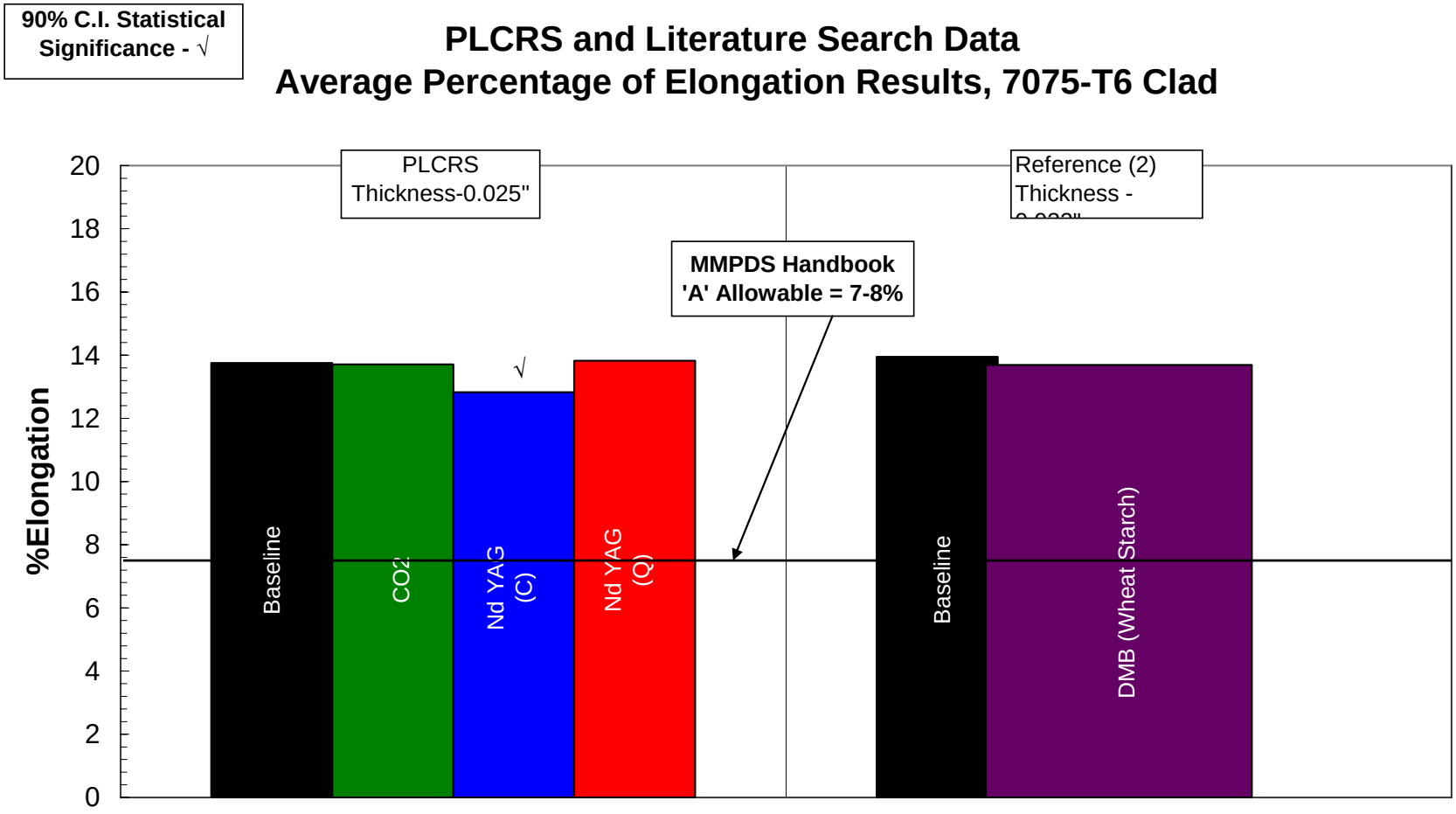

Figure B9. PLCRS and Reference Data Metallic Al7075-T6 Clad Elongation Results.

Reference Data for Tension Testing

Reference (3) - "Mechanical Behavoior of Al 2024 All0y Specimen to Paint Stripping by Laser Radiation and Plasma Ecthing"

		UTS	Std Dev	YTS	Std Dev	%Elog	Std Dev	- Number of sample
Baseline	Al 2024-T3Bare	70.05076		47.86077		17.68		5
TEA-CO2 laser	Al 2024-T3Bare	68.8905		45.54025		16.4		5
CO2 laser	Al 2024-T3Bare	68.74547		45.54025		13.1		5
YAG laser	Al 2024-T3Bare	68.96302		46.84554		12.85		5
Excimer laser	Al 2024-T3Bare	68.60044		46.48296		11.6		5
Plasma etching	Al 2024-T3Bare	67.15011		47.9913		3.08		5

Reference (2) - "Evaluation of Envirostrip for De-painting Thin-Skinned Aluminum Alloys"

		UTS	Std Dev	YTS	Std Dev	%Elog	Std Dev	- Number of sample
Baseline	Al 2024-T3Bare	72.83	0.1	53.94	0.24	16.93	0.44	4
Envirostrip	Al 2024-T3Bare	72.19	0.25	52.67	0.14	18.06	0.49	4
Baseline	Al 2024-T3Clad	66.91	0.38	50.48	0.39	16.70	1.00	4
Envirostrip	Al 2024-T3Clad	65.93	0.25	48.97	0.09	16.94	0.78	4
Baseline	Al 7075-T6Bare	85.41	0.37	79.32	2.23	12.33	0.75	4
Envirostrip	Al 7075-T6Bare	83.65	0.29	76.06	0.31	12.55	0.26	4
Baseline	Al 7075-T6Clad	78.28	0.4	69.68	1.11	13.95	0.64	4
Envirostrip	Al 7075-T6Clad	76.38	0.09	68.03	0.11	13.69	0.54	4

Reference (1) - "Laser Paint Stripping"

		UTS	Std Dev	YTS	Std Dev	%Elog	Std Dev	- Number of sample
Baseline	Al 2024-T3Bare	64960		63590		16.3		
		64750		64400		16.7		
		65470		64390		17		
		65109		63520		16.4		
		65070		65030		11.6		
	Avg.	***65071.8***		***64186***		***15.6***		
	Std Dev.	***262.6808***		***632.163***		***2.252776***		
CO2	Al 2024-T3Bare	66980		65260		15.6		
		65060		63450		16.1		
		64790		62990		17.1		
		67330		65580		16.3		
		65250		64210		18.6		
		64660		63360		16.3		
		64540		63290		15.5		
		66570		64480		16.2		
		67080		65560		16.2		
		67330		65580		16		
	Avg.	***65959***		***64376***		***16.39***		
	Std Dev.	***1193.04***		***1059.929***		***0.890006***		

APPENDIX C

FATIGUE RESULTS

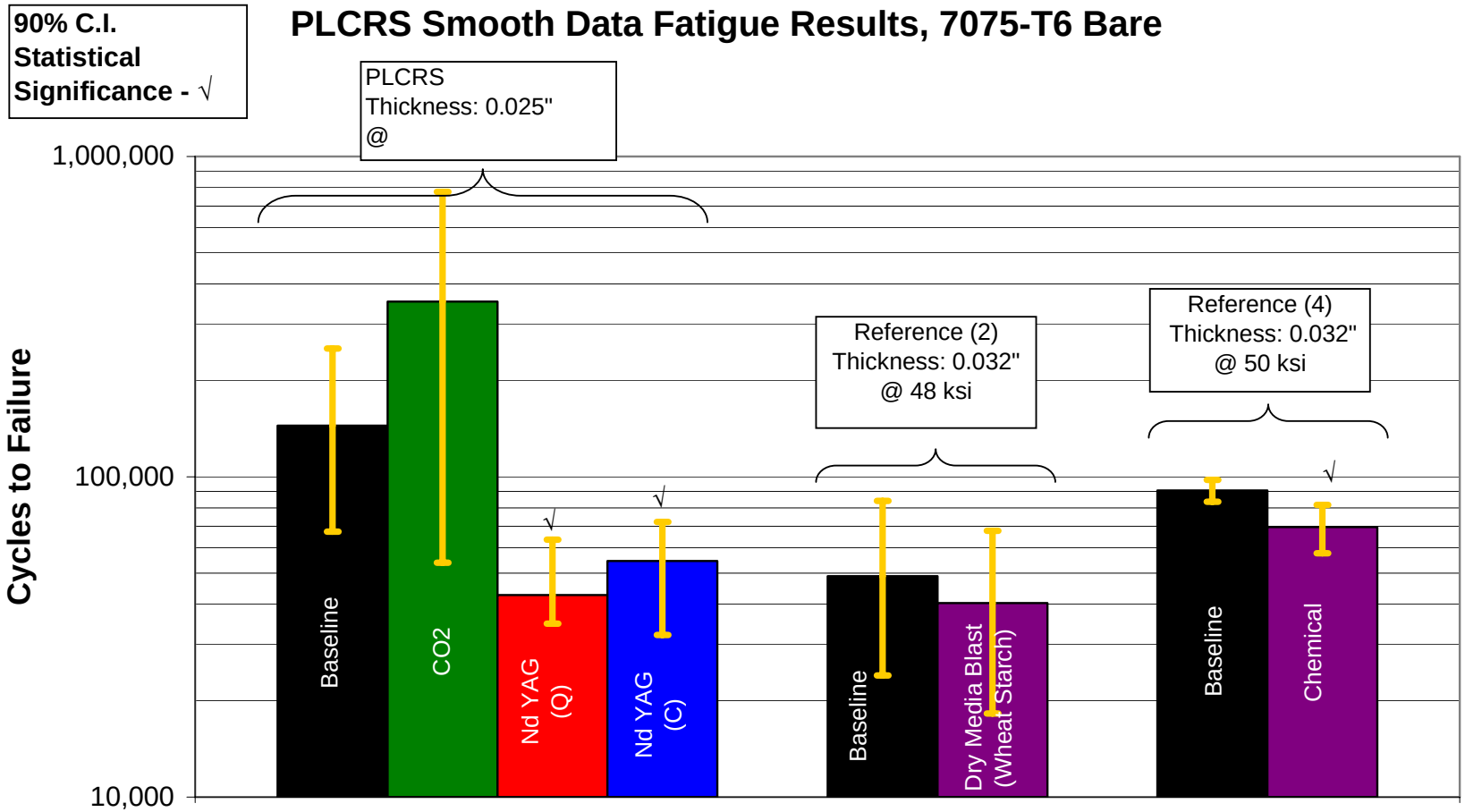

Figure C1. PLCRS and Reference Data 7075-T6 Bare Smooth Fatigue Results. √ indicates a statistical difference at a 90% simultaneous confidence level.

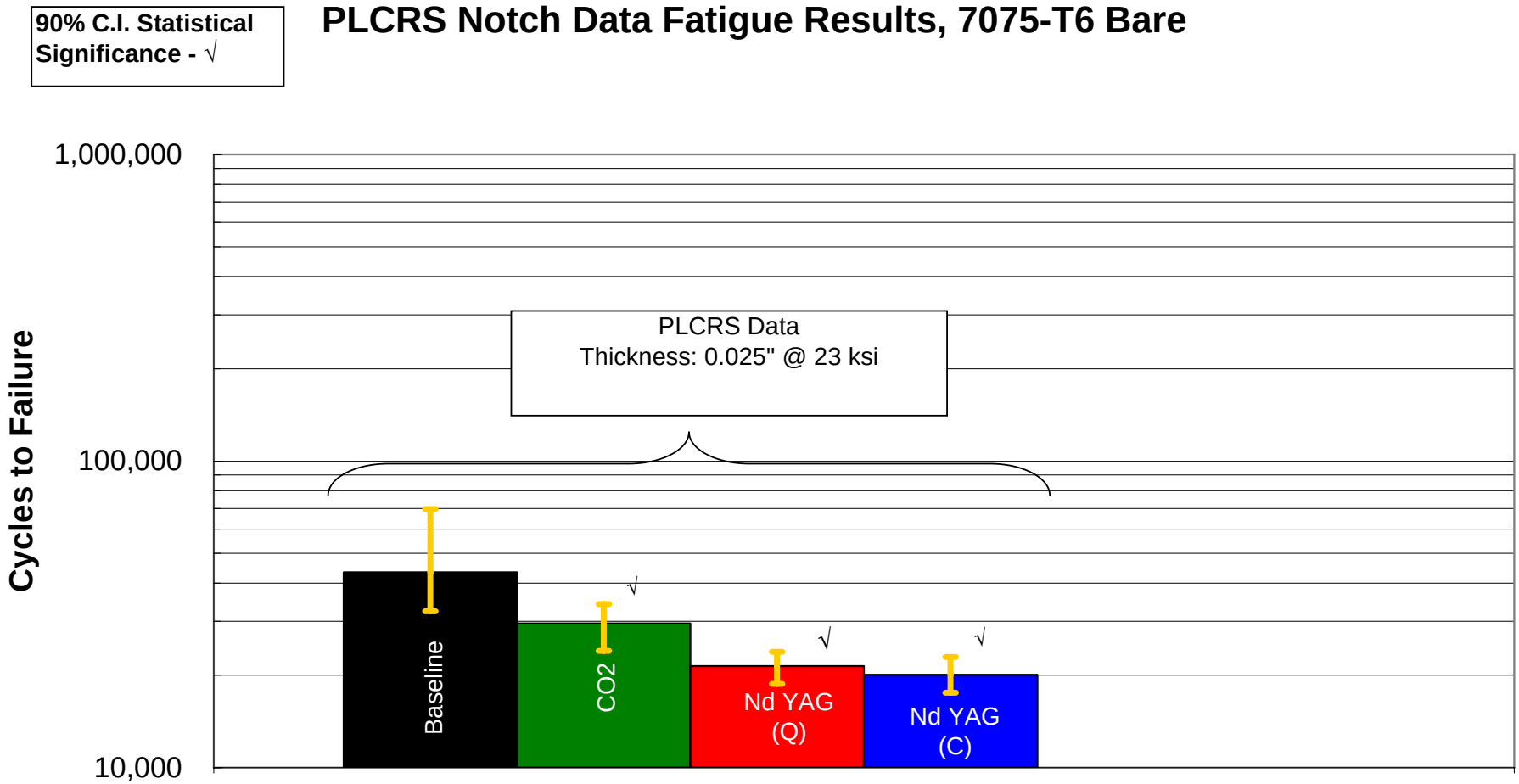

Figure C2. PLCRS and Reference Data Metallic Al7075-T6 Bare Notch Fatigue Results.

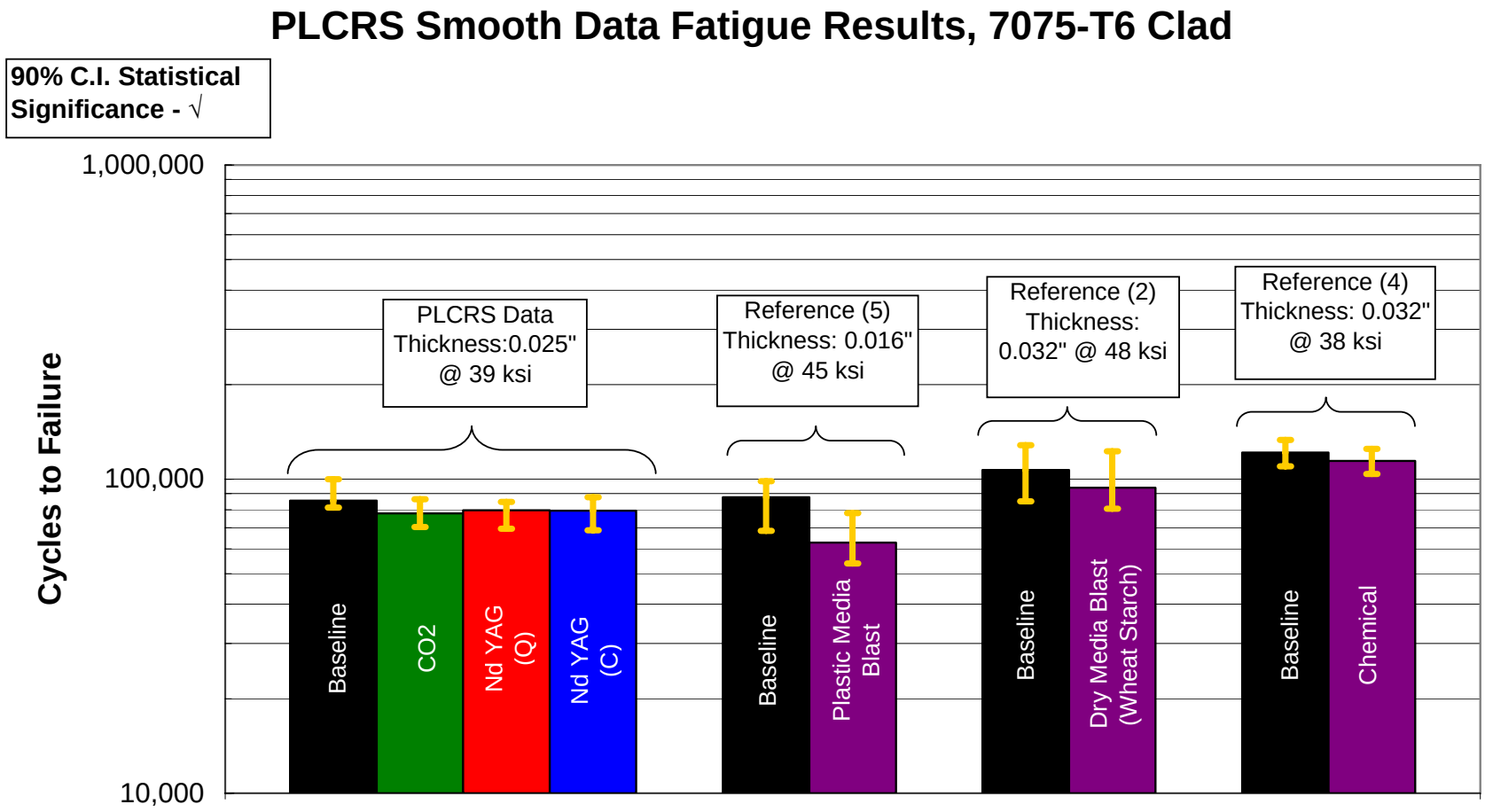

Figure C3. PLCRS and Reference Data Metallic Al7075-T6 Clad Smooth Fatigue Results.

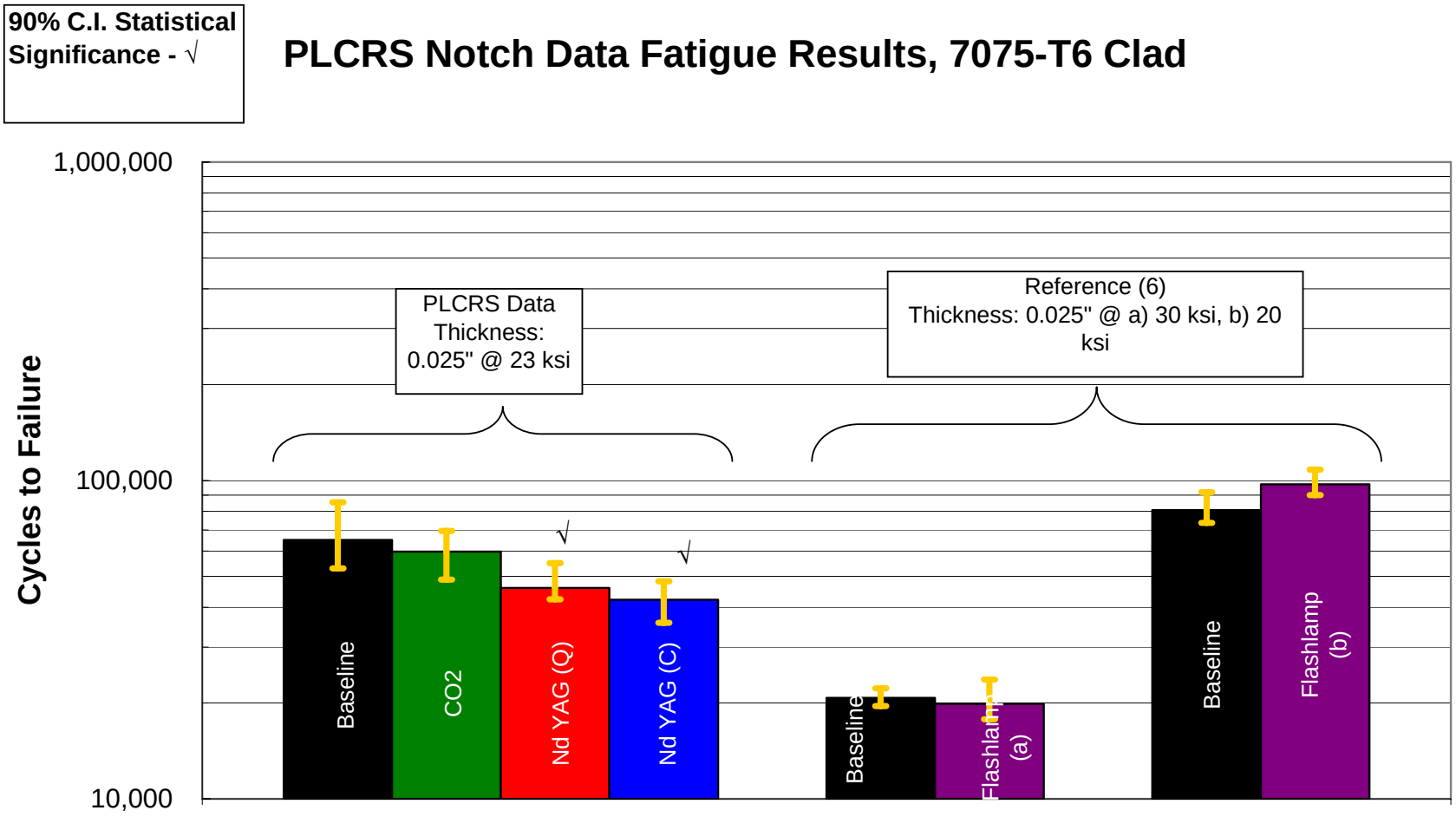

Figure C4. PLCRS and Reference Data Metallic Al7075-T6 Clad Notch Fatigue Results.

7075-T6 Bare Smooth Fatigue Data

Reference (4)

		Average		N - Number of Samples
Control	83,588			
	97,772	90,680	4.957512	12
Chemical	57,671			
	81,641	69,656	4.842959	8

Reference (2)

	Average	Std Dev	Average	Std Dev	
Control	48,937	17,662	4.689637	4.24704	10
Envirostrip	40,300	17,484	4.605305	4.242641	10

7075-T6 Clad Fatigue Data

Smooth

Reference (5)

Control	68,500		
	96,000		
	98,500	87,667	4.942834
PMB	78,000		
	56,700		
	53,900	62,867	4.79842

Reference (2)

	Average	Std Dev	Average	Std Dev	N - Number of Samples
Control	106,900	13,762	5.028978	4.138682	10
Blasted	93,852	14,361	4.972444	4.157185	10

Reference (4)

				N - Number of Samples
Control	109,903			
	133,147	121525	5.084666	12
Chemical	103,928			
	124,872	114400	5.058426	8

Notch

Reference (6)

Control (30 ksi)	20,614		
	19,573		
	20,639		
	22,254	20,770	4.317436
Stripped (30 ksi)	17,811		
	20,000		
	18,134		
	23,727	19,918	4.299246
Control (20 ksi)	91,787		
	78,845		
	78,900		
	73,585	80,779	4.9073
Stripped (20 ksi)	82,389		
	116,427		
	79,536		
	110,634	97,247	4.987874

2024-T3 Clad Fatigue Data

Smooth and Notch

Reference (5)

Control	67,237		
	74,111		
	101,700		
	76,676		
	83,929		
	94,228		
	87,327		
	100,758		
	77,394		
	93,755	86,518	4.937104
PMB	36,584		
	67,527		
	80,355		
	77,450		
	45		
	27,665		
	49,075		
	72,499		
	91,650		
	61,220	56,407	4.751333
PMB	82,998		
	76,923		
	84,479		
	69,337		
	94,511		
	50,500		
	71,024		
	68,562		
	88,300		

Reference (2)

	Cycles	Std Dev	Cycles	Std Dev	N - Number of Samples
Control	100157	10494	5.000681	4.02094106	10
Blast	66500	11281	4.822822	4.052347599	10

Reference (6)

	39,929		
Control (30 ksi)	30,408		
	27,608		
	23,025	30,243	4.48062
	24,666		
Stripped (30 ksi)	30,615		
	44,508		
	28,100	31,972	4.50477
	126,649		
Control (20 ksi)	173,515		
	163,970		
	147,424	152,890	5.18438
	141,938		
Stripped (20 ksi)	168,236		
	153,498		
	143,788	151,865	5.18146

Reference (4)

				N - Number of Samples
Control	112,854			
	121,860	117357	5.069509	12
Chemical	82,601			
	104,007	93304	4.9699	8

APPENDIX D

FATIGUE CRACK GROWTH RATE RESULTS

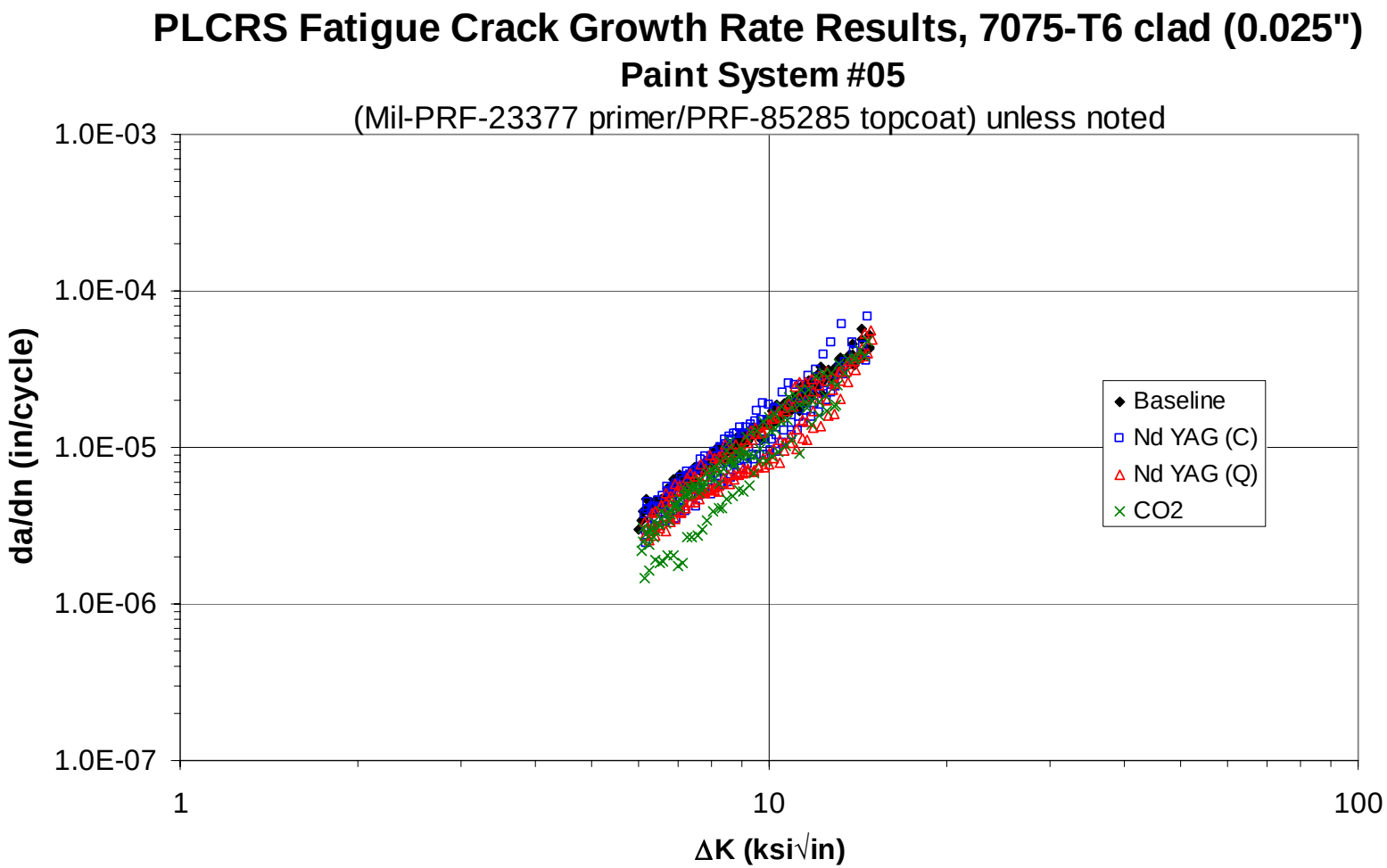

Figure D1. PLCRS Fatigue Crack Growth Rate Metallic Al7075-T6 Clad Results.

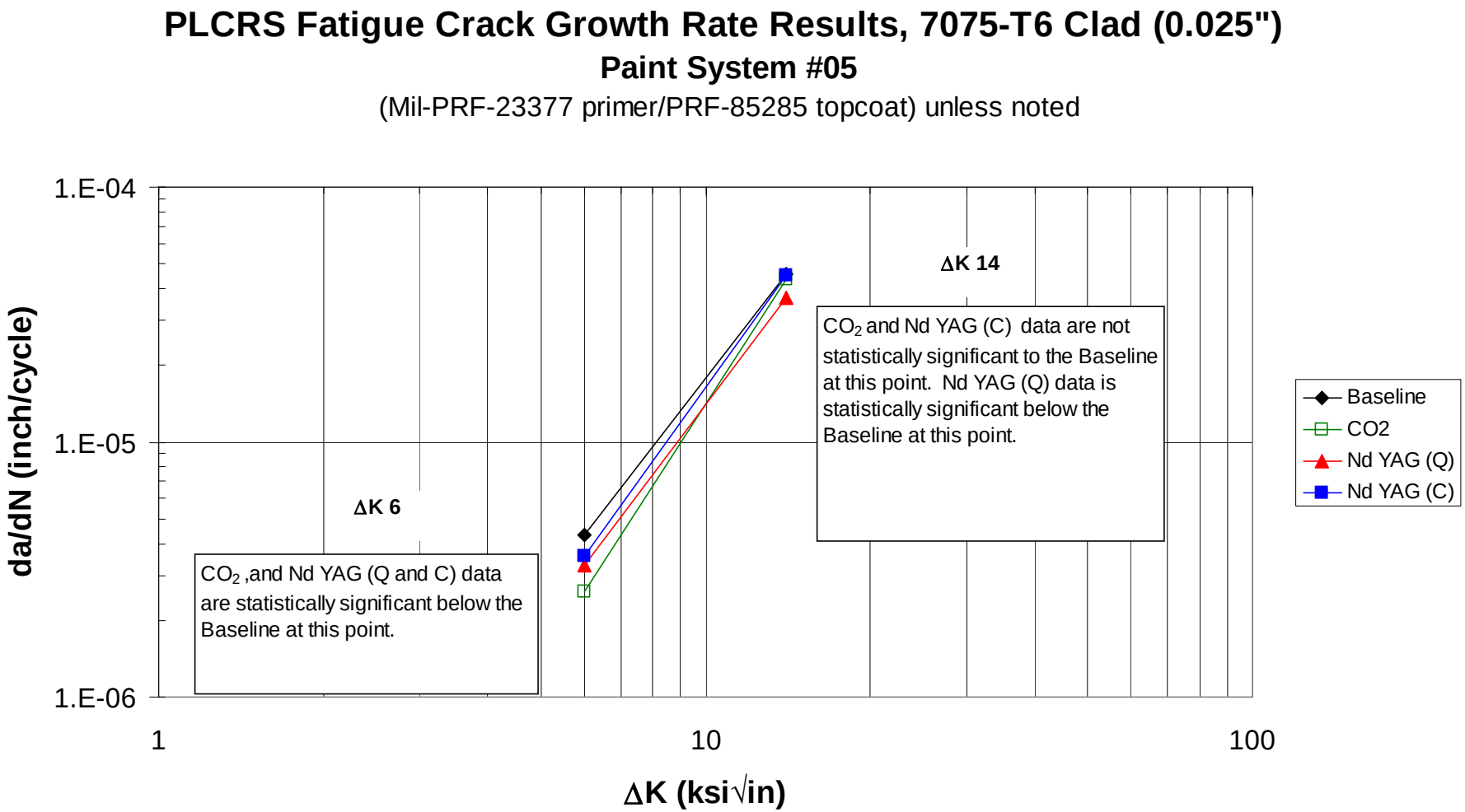

Figure D2. Metallic Al 7075-T6 Clad Fatigue Crack Growth Rate Statistical Analysis at ΔK of 6 and 14.

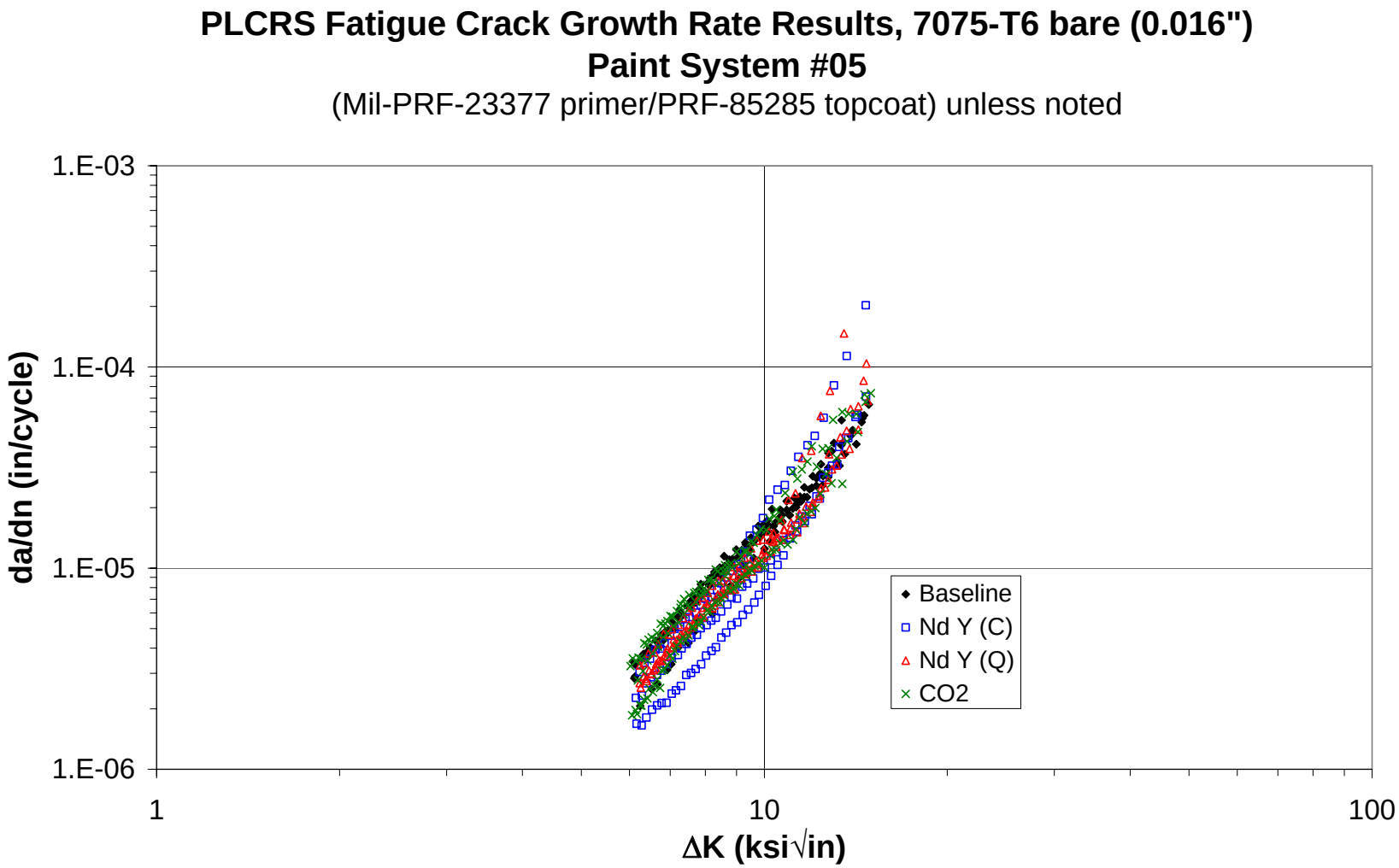

Figure D3. PLCRS Fatigue Crack Growth Rate Metallic Al7075-T6 Bare Results.

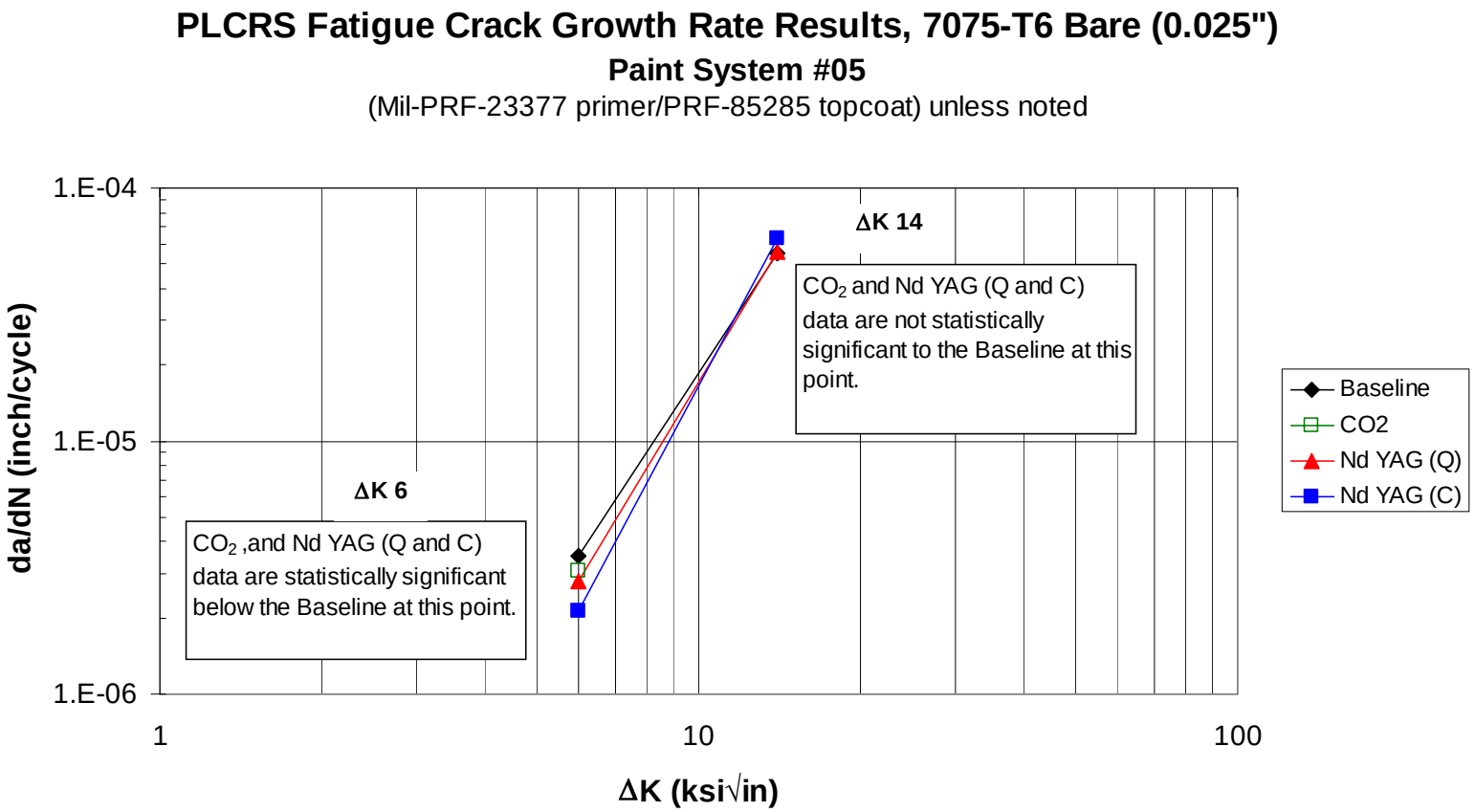

Figure D4. Metallic Al 7075-T6 Bare Fatigue Crack Growth Rate Statistical Analysis at ΔK of 6 and 14.

APPENDIX E

FLEXURAL STRENGTH RESULTS

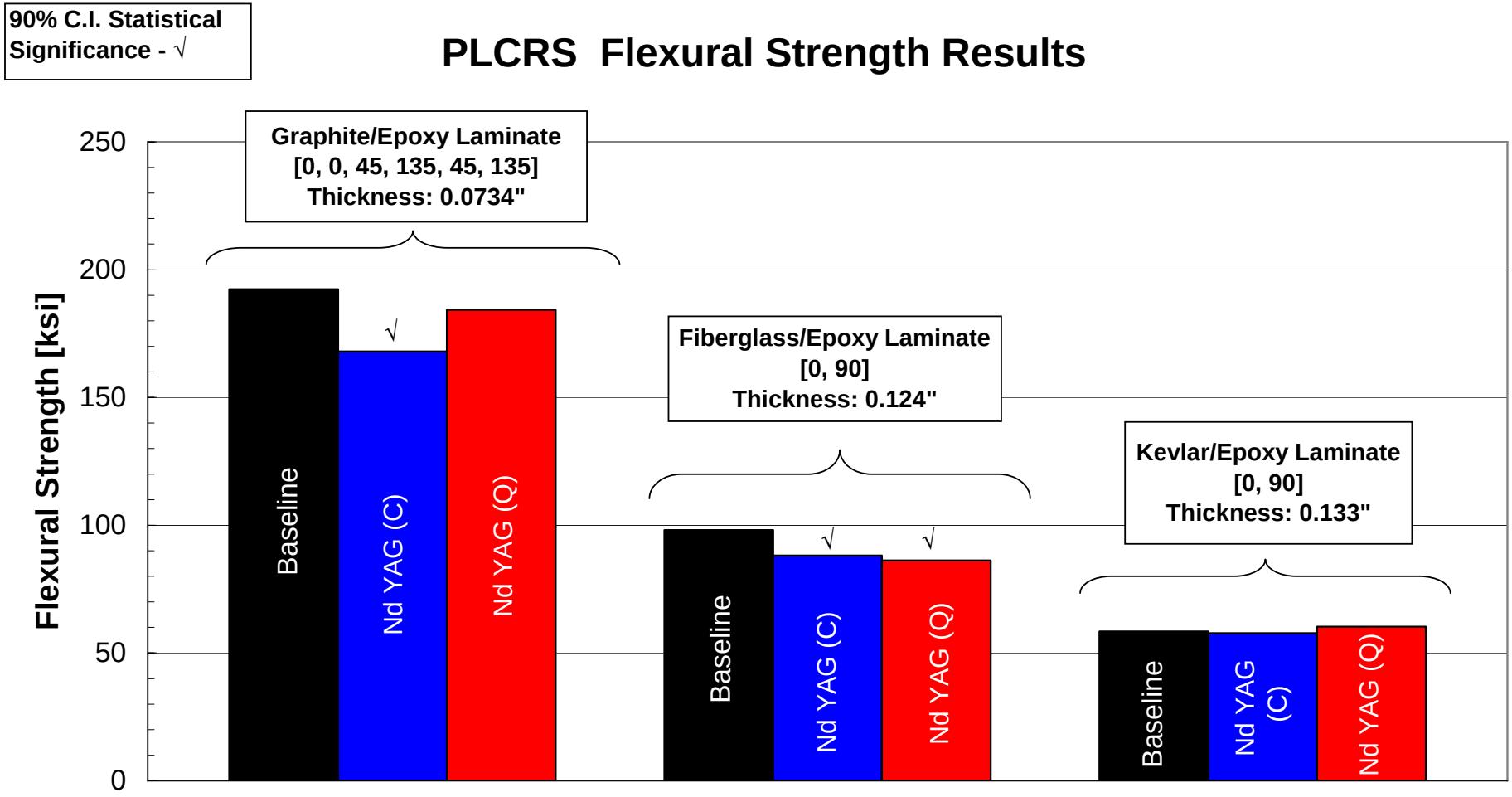

Figure E1. PLCRS Flexural Strength Results.

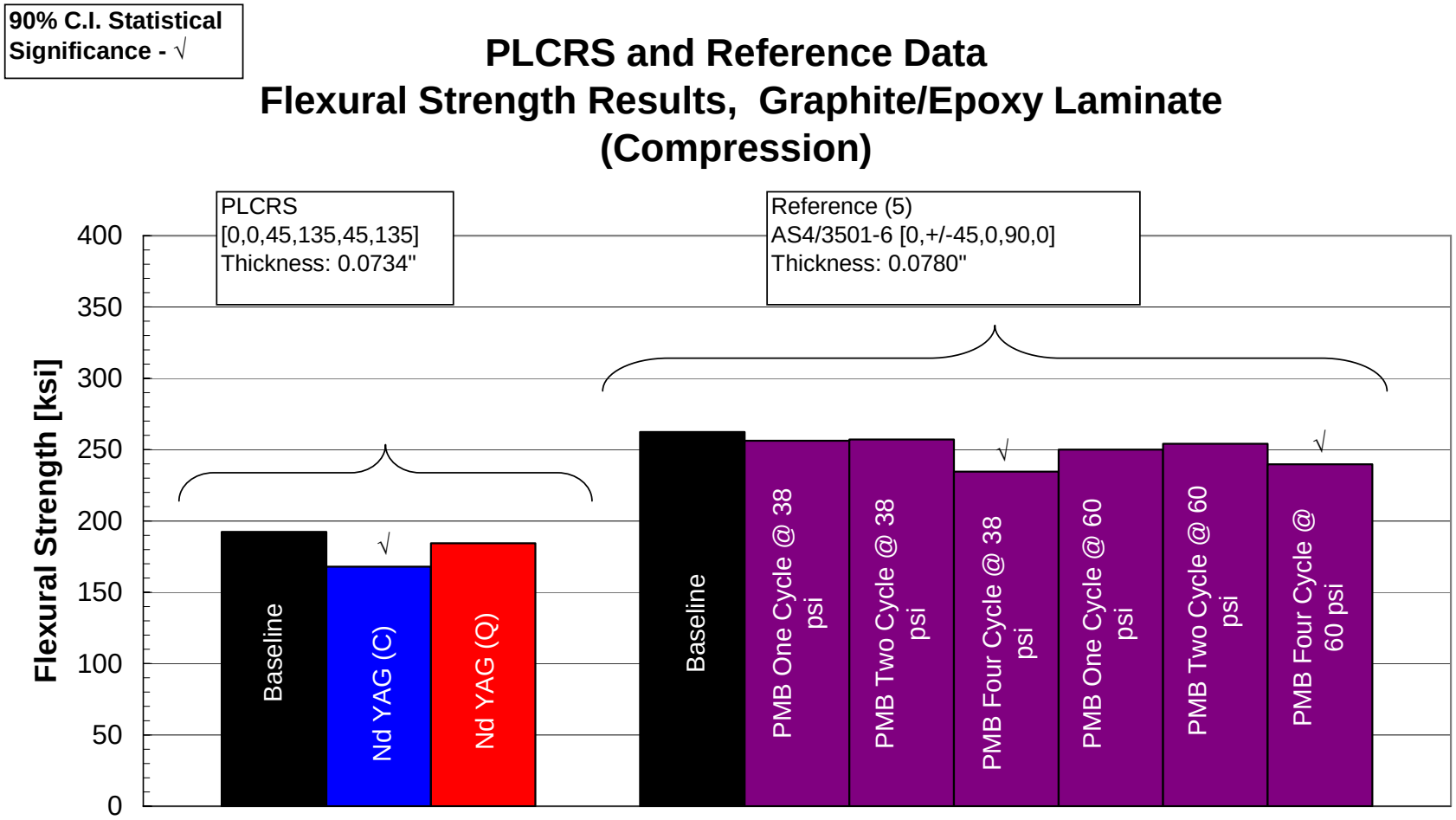

Figure E2. PLCRS and Reference Data Flexural Strength Results.

Reference Data for Flexural Strength

Reference (7)

Wet Abrasive		Average Flexural Strength
Baseline	-	140.4
Substrate	-	156.3

Bicarbonate		Average Flexural Strength
Baseline	-	150.1
Substrate	-	171.4

Abrasive		Average Flexural Strength
Baseline	-	143.7
Substrate	-	146.4

Reference (5)

PMB

	Number of Specimen	Average Strength	Std. Dev.
Baseline	7	161.78	6.87
One @ 38	8	157.15	17.74
One @ 38	6	146.67	13.37
Two @ 38	9	149.60	12.47
Four @ 38	10	158.49	15.39
One @ 60	8	153.91	14.62
Two @ 60	9	144.45	11.37
Four @ 60	7	142.68	9.70

Reference (9)

Flash lamp

	Number of Specimen	Average Strength	Std. Dev.
Baseline	12	221.1	8.0
Substrate	12	210.2	8.0