Environmentally-Preferred and Improved (Rapid) Laser Coating Removal Process for the Safe Removal of Coatings from Composite Substrates

ESTCP Project WP-201709

Dwight Maness
AFLCMC/RO

Final Debrief

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Environmentally Preferred and Improved (Rapid) Laser Coating Removal Process for the Safe Removal of Coatings from Composite Substrates

## 6. AUTHOR(S)
- Dwight Maness, Connor Eviston, Randall Straw, Jesse Holdaway: AFLCMC/RO
- Bryan Pavlich: University of Dayton Research Institute
- Marylee Dunphy, Hannah Easton, Natasha Voevodin: UDRI
- Mike Rigney: Southwest Research Institute
- Andy Strat: Titan Robotics

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## 14. ABSTRACT
Technical objectives of this project:

- Validate and qualify 1 kW nano-pulsed fiber (NPF) laser for thin advanced composites coated with traditional and non-traditional military paint colors such as gloss white.

- The outcome of the qualification will be to implement the NPF laser system in a full production robotic laser coating removal system for the RQ-4 and C-130 weapon systems at Warner Robins Air Logistics Complex (ALC).

## 15. SUBJECT TERMS
- Environmentally Preferred, Improved (Rapid) Laser Coating Removal Process
- Safe Removal, Coatings, Composite Substrates

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## 19. NAME OF RESPONSIBLE PERSON
Connor Eviston

## 19b. TELEPHONE NUMBER (Include area code)
937-255-7730 (administrative POC)
Project Team

- Dwight Maness (AFLCMC/RO)
- Connor Eviston (AFLCMC/RO)
- Randall Straw (AFLCMC/EZPT)
- Jesse Holdaway* (AFLCMC/EZP)
- Bryan Pavlich (University of Dayton Research Institute)
- Marylee Dunphy (UDRI)
- Hannah Easton (UDRI)
- Natasha Voevodin (UDRI)
- Mike Rigney (Southwest Research Institute)
- Andy Strat (Titan Robotics)

* No longer with AFLCMC/EZP
Technical Objectives

- Validate and qualify 1 kW nano-pulsed fiber (NPF) laser for thin advanced composites coated with traditional and non-traditional military paint colors such as gloss white.

- The outcome of the qualification will be to implement the NPF laser system in a full production robotic laser coating removal system for the RQ-4 and C-130 weapon systems at Warner Robins Air Logistics Complex (ALC) (concept shown right).
Technical Approach

- Conduct Optimization Testing on metallic substrates at Southwest Research Institute (SwRI) using 1kW NPF laser with polygon scanner
- Conduct Optimization Testing on composite panels (representative of RQ-4 and C-130 materials) at SwRI
- Conduct Screening Testing on metallic and composite substrates
  - Closed loop (automated) laser de-paint conducted at SwRI
  - Mechanical material evaluations conducted at University of Dayton Research Institute
- Obtain Airworthiness approval through AWB 1015 process
- Develop and install robotic laser coating removal system at Robins ALC

Note: there were personnel, contractor, and scope changes throughout the execution of this project
Project Execution

♦ May 2017 – Contract awarded to UDRI

♦ Sep 2017 to Mar 2018 – Metallic Optimization Testing was conducted at SwRI using 1kW NPF laser with polygon scanner; lead to need for new scanner due to physical size

♦ Mar to Jun 2018 – Equipment shipped through UDRI (Dayton, Oh) for repairs, then on to Titan Robotics (Pittsburgh, PA) and set up

♦ Jun to Oct 2018 – Scanner selection testing conducted at Titan Robotics; resulted in down-selection to galvanometer scanner to enable demonstration and integration into full-production system

♦ Oct 2018 to Jun 2019 – Open-loop optimization testing was conducted at Titan Robotics on metallic panels, followed by on composite panels

♦ Jun 2019 to Jan 2020 – Evaluation (mechanical testing) of metallic and composite panels for laser damage was conducted at UDRI

♦ Jan to Mar 2020 – Deliberation and decision made to not proceed

Project did not reach demonstration as results were not favorable for qualification / implementation
● Southwest Research Institute conducted preliminary optimization testing on metallic substrates using polygon scanner
  ♦ White coating was removed well
  ♦ Good coating removal rates were acceptable
  ♦ However, scanner was physically too large for envisaged robotic laser coating removal system use
Summary of Work to Last IPR (Cont.)

- Equipment shipped through UDRI, repairs made
- Equipment set up at Titan Robotics Laboratory style
- Selected scanner: ScanLab IntelliWELD galvanometer
Optimization Testing on Metallic Substrates at Titan Robotics

♦ Laser System (enclosed, laboratory scale)

- 1 kW NPF Laser: IPG Model YLPN-100-30X100-1000 with controls
- Linear axis rail for sweep speed up to 200mm/s
- Vacuum system for removal of ablated particles
- ScanLab Intelliweld 30 Scanner used for optimization test
Optimization Testing on Metallic Substrate Results

- 1 kW NPF Laser with the IntelliWELD galvanometer scanner
  - setting that produced the fastest removal rate (0.79 ft²mils/min), while remaining under 300°F limit, does not exceed removal rate of 6 kW system at Hill AFB (8.71 ft²mils/min)
  - does not perform well on white coatings (high temperatures, low removal rates)
OPTIMIZATION TESTING ON COMPOSITES
TITAN ROBOTICS
Optimization Testing on Composites

Test Articles – Composite Panel Fabrication

- Panels were constructed at Aviation Equipment Processing, CA
- Six thermocouples (30 gauge, type T) embedded under topmost ply
- Sandwich panel with honeycomb core using materials found on C-130 and RQ-4 aircraft
  - Skin laminate materials:
    - M46J fiber with 7714A resin to ACS-MRS-5002
    - T650 fiber with F584 resin to STM22-817 Type 1 Class 2
    - 285K/120 fiberglass with 7714 resin to STM-22-912
  - Adhesive: Scotch-Weld AF 163-2M Film, red at 9.5mils
  - Core materials:
    - HD183 1/8” cell size, 1/2” thickness
    - HD343 3/16” cell size, 1/2” thickness
## Optimization Testing on Composites

### Test Articles – Composite Panel Coatings

- Coating application was performed at UDRI
  - Surface sealer (select panels): CA 8620 HS PU
  - Primer: MIL-PRF-23377 Type I Class C2
  - Top coats:
    - MIL-PRF-85285, Type IV Class H gray top coat (color 36173)
    - MIL-PRF-85285, Type IV Class H white top coat (color 27925)

<table>
<thead>
<tr>
<th>Panel ID</th>
<th>Surface Preparation</th>
<th>Coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>RQ-4 Representative</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M46J_T_0_G_NPF_1,2</td>
<td>Light sand and alcohol wipe</td>
<td>Gray</td>
</tr>
<tr>
<td>M46J_T_S_G_NPF_1,2</td>
<td>Light sand and alcohol wipe, Surface sealer</td>
<td>Gray</td>
</tr>
<tr>
<td>M46J_T_0_GT_NPF_1,2</td>
<td>Light sand and alcohol wipe</td>
<td>Gray Thick</td>
</tr>
<tr>
<td>M46J_T_0_W_NPF_1,2</td>
<td>Light sand and alcohol wipe</td>
<td>White</td>
</tr>
<tr>
<td>C-130 J Representative</td>
<td></td>
<td></td>
</tr>
<tr>
<td>285K_T_0_G_NPF_1,2</td>
<td>Light sand and alcohol wipe</td>
<td>Gray</td>
</tr>
<tr>
<td>T650_T_0_G_NPF_1,2</td>
<td>Light sand and alcohol wipe</td>
<td>Gray</td>
</tr>
</tbody>
</table>

- G: primer + gray top coat
- GT: “gray thick”
- W: primer + white top coat

- Indicates panel composite type
- Surface sealer (S) or not (0)
- Thermocouples (T) or no thermocouples (0)
- NPF: laser
- CTL: control
Optimization Testing on Composites at Titan Robotics

Parameter Selection

- “Best” parameter selection criteria
  - Minimal temperature (required to be under 200°F)
  - Visual inspection (no obvious burn marks)
  - Removal rate (estimated on minimum number of passes required to remove coating)

Recommended Parameters

<table>
<thead>
<tr>
<th>Pulse Duration (ns)</th>
<th>Pulse Energy (mJ)</th>
<th>Pulse Rate (kHz)</th>
<th>Scan Speed (m/s)</th>
<th>Panel Speed (m/s)</th>
<th>Line Spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>100</td>
<td>2.5</td>
<td>1.5</td>
<td>0.006</td>
<td>1.25</td>
</tr>
</tbody>
</table>

145°F was not exceeded using these parameters
SCREENING TESTING ON COMPOSITES
UNIVERSITY OF DAYTON RESEARCH INSTITUTE
Screening Testing on Composites

Test Articles – Composite Panels

- Composite sandwich panels identical to those used in optimization, but without thermocouples
- Samples were lased using selected coating removal parameters from composite optimization testing
- Test samples were cut from test panel after lase as shown:
Screening Testing on Composites

Performance Assessment – Coating Removal Rate

- The nominal strip rate while meeting the temperature limit of 145ºF was approximately 0.97 ft²mil/min. (Removal rate of current system at Hill AFB is in order of 8.5 ft²mil/min)

M46J_0_0_G_NPF_1
(M46J composite with single gray stack up)
Screening Testing on Composites

Performance Assessment – Surface Roughness

- Minimal surface roughness is desired for coating re-application purposes
- Testing performed IAW Joint Test Protocol
- Roughness measured by two methods:
  - Using Mitutoyo SJ-210 Stylus, both parallel to and perpendicular to laser scan direction
  - Surface topography image taken by Keyence Microscope
Screening Testing on Composites
Performance Assess. – Surface Roughness (cont.)

- Averages taken and compared to controls

<table>
<thead>
<tr>
<th>Aircraft Representative</th>
<th>Panel ID</th>
<th>Composite</th>
<th>TCs</th>
<th>Surface Sealer?</th>
<th>Coating</th>
<th>Processed?</th>
<th>Surface Roughness (Average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RQ-4</td>
<td>M46J</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Gray</td>
<td>Laser</td>
<td>2.852</td>
</tr>
<tr>
<td></td>
<td>M46J</td>
<td>None</td>
<td>Surface Sealer</td>
<td>Gray</td>
<td>Laser</td>
<td>3.196</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M46J</td>
<td>None</td>
<td>None</td>
<td>Gray Thick</td>
<td>Laser</td>
<td>5.597</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M46J</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Control</td>
<td>1.834</td>
<td></td>
</tr>
<tr>
<td>C-130</td>
<td>285K</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Gray</td>
<td>Laser</td>
<td>2.368</td>
</tr>
<tr>
<td></td>
<td>285K</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Control</td>
<td>1.901</td>
</tr>
<tr>
<td></td>
<td>T650</td>
<td>None</td>
<td>None</td>
<td>Gray</td>
<td>Laser</td>
<td>2.922</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T650</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Control</td>
<td>0.829</td>
<td></td>
</tr>
</tbody>
</table>

Surface Roughness of De-Painted samples greater than their control counterparts
Screening Testing on Composites

Performance Assessment – Adhesion Testing

- Good primer re-adhesion is desired to ensure coating removal method does not inhibit ability to recoat substrate
- Sample re-coated, then adhesion testing performed
  - Patti Adhesion test ASTM D4541 (3 tests per sample)
  - Cross Hatch Tape Adhesion test ASTM D3359 Method B (8 tests per sample)
### Screening Testing on Composites

**Performance Assessment – Adhesion Testing (cont.)**

<table>
<thead>
<tr>
<th>Aircraft Representative</th>
<th>Panel ID</th>
<th>Patti Adhesion (average pull off psig)</th>
<th>Crosshatch Tape Adhesion (Pass:Fail)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Composite</td>
<td>TCs</td>
<td>Surface Sealer</td>
</tr>
<tr>
<td>RQ-4</td>
<td>M46J</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>M46J</td>
<td>None</td>
<td>Surface Sealer</td>
</tr>
<tr>
<td></td>
<td>M46J</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>M46J</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>C-130</td>
<td>285K</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>285K</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>T650</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>T650</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

*De-Painted samples passed more frequently that their control counterparts*
Damage found in all samples except that with Surface Sealer; Determined that temperature testing is not sufficient indicator of damage
Screening Testing on Composites

Performance Assessment – Long Beam Flexure Test

- Performed on 5 specimens cut from each sample panel
- Top Facesheet is the only side that is laser processed
- Results analyzed for ultimate stress, chord modulus and flexural stiffness

<table>
<thead>
<tr>
<th>Panel IDs</th>
<th>Ultimate Stress</th>
<th>Effective Chord Modulus</th>
<th>Flexural Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>M46J_0_0_GT_NPF_01</td>
<td>Top Facesheet: No Statistical Difference from Control</td>
<td>No Statistical Difference from Control</td>
<td>No Statistical Difference from Control</td>
</tr>
<tr>
<td>M46J_0_S_G_NPF_01</td>
<td>Top Facesheet: No Statistical Difference from Control</td>
<td>No Statistical Difference from Control</td>
<td>No Statistical Difference from Control</td>
</tr>
<tr>
<td>M46J_0_0_G_NPF_01</td>
<td>Top Facesheet: Statistical Difference from Control</td>
<td>No Statistical Difference from Control</td>
<td>No Statistical Difference from Control</td>
</tr>
<tr>
<td>T650_0_0_G_NPF_01</td>
<td>Top Facesheet: Statistical Difference from Control</td>
<td>No Statistical Difference from Control</td>
<td>No Statistical Difference from Control</td>
</tr>
<tr>
<td>285K_0_0_G_NPF_01</td>
<td>Top Facesheet: Statistical Difference from Control</td>
<td>No Statistical Difference from Control</td>
<td>No Statistical Difference from Control</td>
</tr>
</tbody>
</table>

Panel IDs indicate composite material, (lack of) TCs, surface sealer, coating, processing/control

At least one statistical difference found in all samples except that with multiple (4) layers of coating
Screening Testing on Composites

Testing Summary

- De-painted panels were compared to un-painted control panels for a variety of materials properties tests

<table>
<thead>
<tr>
<th>Panel ID</th>
<th>Number of de-paint passes</th>
<th>Surface Roughness (Average)</th>
<th>Patti Adhesion (average pull off psig)</th>
<th>Crosshatch Tape Adhesion (Pass: Fail)</th>
<th>Cross Section</th>
<th>Long Beam Flexure (stat. Diff. From control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M46J_0_0_G_NPF_01</td>
<td>13</td>
<td>2.852</td>
<td>19.2</td>
<td>3:5</td>
<td>Minor surface damage</td>
<td>No statistical difference</td>
</tr>
<tr>
<td>M46J_0_S_G_NPF_01</td>
<td>15</td>
<td>3.196</td>
<td>34.1</td>
<td>8:0</td>
<td>No damage</td>
<td>bottom facesheet effective chord modulus only</td>
</tr>
<tr>
<td>M46J_0_0_GT_NPF_01</td>
<td>&gt;40</td>
<td>5.597</td>
<td>20.7</td>
<td>7:1</td>
<td>damage</td>
<td>Flexural stiffness only</td>
</tr>
<tr>
<td>M46J_0_0_0_CTL_CTL</td>
<td>N/A</td>
<td>1.834</td>
<td>19.0</td>
<td>0:8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>285K_0_0_G_NPF_01</td>
<td>7</td>
<td>2.368</td>
<td>22.6</td>
<td>8:0</td>
<td>damage</td>
<td>Multiple</td>
</tr>
<tr>
<td>285K_0_0_0_CTL_CTL</td>
<td>N/A</td>
<td>1.901</td>
<td>10.6</td>
<td>2:6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>T650_0_0_G_NPF_01</td>
<td>12</td>
<td>2.922</td>
<td>16.3</td>
<td>8:0</td>
<td>damage</td>
<td>Bottom face sheet ultimate stress only</td>
</tr>
<tr>
<td>T650_0_0_0_CTL_CTL</td>
<td>N/A</td>
<td>0.829</td>
<td>15.8</td>
<td>3:5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Panel ID indicates composite material, presence of thermocouples, presence of surface sealer, coating, laser process, and panel number

Surface sealer appeared to protect underlying composite from damage by laser de-paint process, all other composites showed difference from control samples
Performance Assessment - Summary

- Removal of gloss white coating was successful on metallic substrate with polygon scanner (SwRI). An effective and efficient parameter set with selected IntelliWELD galvanometer scanner was not successful with Titan’s efforts on removal of white paint.

- Gray coating removal rates using the 1 kW NSP laser and the polygon scanner (SwRI metallic optimization testing) were equal or greater than the 6 kW continuous wave Robotic Laser Coating Removal System (RLCRS) currently employed at Hill Air Force Base. However, using the selected Intelliweld scanner (Titan optimization testing), coating removal rates were not adequate in comparison to the 6 kW RLCRS (removal rate criteria fair).

- Bulk temperature is not a sufficient indicator that damage to the composite material has or has not occurred.

- Delamination and resin-fiber separation was found after laser de-paint in all composite samples inspected (lab test criteria not met) except that with surface sealer. Supports hypothesis that surface sealer or remaining coating can be used to protect composite from laser induced delaminations.
Cost Assessment

- Cost assessment was not performed as project was terminated

Scale-up

- Scale Up from Laboratory to Air Force Implementation was not performed
  - Lab scale coating removal rates did not outperform those attainable by the 6 kW CW laser currently in operation at Hill AFB, UT
  - Material properties test showed damage to resin when de-painting down to substrate material; requires similar process limit as current 6 kW laser operating procedures to leave some coating remaining
Next Steps

- Investigation into the 1 kW NSP laser has been closed as expected benefits were not realized

Technology Transfer

- 1 kW NSP laser is not recommended for technology transfer for aircraft outer mold line de-paint processes as current technology does not allow for faster coating removal rates that the 6 kW continuous wave fiber laser
Key Points

- The 1 kW Nano second pulse fiber laser does not provided a realizable advantage over currently used 6 kW continuous wave fiber laser (Hill AFB)
  - All laser parameters tested lead to damage of the composite resin when all coating was removed, except sample with surface sealer
  - Coating removal rates did not exceed those attainable with the current 6 kW CW system
BACKUP SLIDES
Publications

- No Publications
XX-201709: Environmentally-Preferred and Improved (Rapid) Laser Coating Removal Process for the Safe Removal of Coatings from Composite Substrates

Performers
• Air Force Life Cycle Management Center, Product Support Engineering
• University of Dayton Research Institute (UDRI)
• Southwest Research Institute (SwRI)
• Titan Robotics Inc.

Technology Focus
• 1kW (avg.) nanosecond pulsed fiber laser (1070nm wavelength) for coating removal over C-130 and RQ-4 composite materials

Demonstration Sites
• Laser setting tests were conducted at Titan Robotics, Pittsburgh, PA.
• Material Properties tests were conducted at UDRI, Dayton, OH.

Demonstration Objectives
• Outperform current robotic laser de-paint system (Hill AFB) in removal rate, proximity to composite substrate, and coating variety

Project Progress and Results
• Complete coating removal (to substrate) is not possible without damaging composite epoxy resins or fiber

Implementation
• Implementation is not recommended as continuous wave fiber lasers can perform at an equal or better efficiency
OPTIMIZATION TESTING
SOUTHWEST RESEARCH INSTITUTE (SwRI)
Optimization Testing at SwRI

- 1 kW NPF Laser: IPG Model YLPN-100-30X100-1000
- 60 mm square process fiber

<table>
<thead>
<tr>
<th>Pulse Width</th>
<th>Pulse Rate</th>
<th>Pulse Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>ns</td>
<td>kHz</td>
<td>mJ</td>
</tr>
<tr>
<td>30</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>40</td>
<td>13.3</td>
<td>75</td>
</tr>
<tr>
<td>60</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td>100</td>
</tr>
</tbody>
</table>
Optimization Testing at SwRI

- Polygon Laser Scanner: Lincoln Laser Polytek model
- Effluent extracted to HEPA filter
- Working Distance of 130 mm,
- Scan Width of 49 mm, Swath Length of 75 mm
## Optimization Testing at SwRI

### Performance Objectives

<table>
<thead>
<tr>
<th>Performance Objective</th>
<th>Data Requirement</th>
<th>Success Criteria</th>
<th>Success Criteria Achieved?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quantitative Performance Objectives</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Impact on Substrate</td>
<td>Temperature</td>
<td>Backside $&lt; 300^\circ$F</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Qualitative Performance Objectives</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Impact on Substrate</td>
<td>Visual Inspection</td>
<td>No visual damage to metal substrate</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Although performance parameters were met, Polytek scanner was determined to be too bulky for envisaged robotic laser system concept; equipment returned to UDRI.
EQUIPMENT DAMAGES
UNIVERSITY OF DAYTON RESEARCH INSTITUTE REPAIRS
Damages to Equipment

- Laser was shipped from SwRI to UDRI (Spring 2018)
  - Cosmetic damage to laser housing
  - Corrosion was found inside chiller line fittings
- Repairs were conducted at UDRI
SCANNER SELECTION TESTING
TITAN ROBOTICS
Scanner Selection Testing at Titan Robotics

♦ Laser System (enclosed, laboratory scale)

- 1 kW NPF Laser: IPG Model YLPN-100-30X100-1000 with controls
- Linear axis rail for sweep speed up to 200mm/s
- 3D scanner with intrinsic functions for focus, scan speed, scan width
- Vacuum system for removal of ablated particles
Scanner Selection Testing at Titan Robotics

- Four scanner set ups tested:
  - ScanLab IntelliWeld with beam shaping optic
  - Scan Lab IntelliWeld with the beam shaping optic removed
  - IPG Mid Power Scanner
  - IPG Mid Power Scanner with replacement f-theta lens

<table>
<thead>
<tr>
<th>Scanner:</th>
<th>IntelliWeld with optic</th>
<th>IntelliWeld without optic</th>
<th>IPG Mid Power</th>
<th>IPG Mid Power with new lens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal Length (mm)</td>
<td>460</td>
<td>460</td>
<td>254</td>
<td>163</td>
</tr>
<tr>
<td>Field Width (cm)</td>
<td>30</td>
<td>30</td>
<td>19</td>
<td>8</td>
</tr>
<tr>
<td>Max Spot Speed (m/s)</td>
<td>9</td>
<td>9</td>
<td>2.5</td>
<td>1.25</td>
</tr>
<tr>
<td>Focus Range (mm)</td>
<td>+/- 70</td>
<td>+/- 70</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Spot Width (mm)</td>
<td>2.49*</td>
<td>2.49</td>
<td>3.03</td>
<td>1.94</td>
</tr>
<tr>
<td>Spot Area (cm²)</td>
<td>*</td>
<td>0.062</td>
<td>0.0915</td>
<td>0.0377</td>
</tr>
<tr>
<td>Beam clipped (%)</td>
<td>8.9</td>
<td>8.9</td>
<td>22.2</td>
<td>22.2</td>
</tr>
</tbody>
</table>

* Beam shaping optic makes an ellipse with one of the axes larger, while maintaining short axis length
### Scanner Selection Testing at Titan Robotics

#### Performance Assessment

<table>
<thead>
<tr>
<th>Parameter Set</th>
<th>IntelliWeld</th>
<th>IPG Mid Power</th>
<th>IPG Mid Power with new lens</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Irradiance (MW/cm²)</td>
<td>Fluence (J/cm²)</td>
<td>Irradiance (MW/cm²)</td>
</tr>
<tr>
<td>T1</td>
<td>24.49</td>
<td>0.74</td>
<td>14.17</td>
</tr>
<tr>
<td>T2</td>
<td>27.54</td>
<td>1.10</td>
<td>15.94</td>
</tr>
<tr>
<td>T3</td>
<td>24.49</td>
<td>1.47</td>
<td>14.17</td>
</tr>
<tr>
<td>T4</td>
<td>14.69</td>
<td>1.47</td>
<td>8.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>IntelliWeld</th>
<th>IPG Mid Power</th>
<th>IPG Mid Power with new lens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Coverage Rate (ft²/min) (no row overlap)</td>
<td>14.473</td>
<td>4.892</td>
<td>1.566</td>
</tr>
</tbody>
</table>

*ScanLab Intelliweld Scanner allowed for fluence and irradiance values while also being capable of a fast coverage rate*
Screening Testing on Composites

Performance Assessment – Coating Removal Rate

- The nominal strip rate while meeting the temperature limit of 145°F was approximately 0.97 ft²mil/min. (Removal rate of current system at Hill AFB is in order of 8.5 ft²mil/min)

<table>
<thead>
<tr>
<th>Panel ID</th>
<th>Number of Passes</th>
</tr>
</thead>
<tbody>
<tr>
<td>RQ-4 Representative</td>
<td></td>
</tr>
<tr>
<td>M46J_0_0_G_NPF_1</td>
<td>13</td>
</tr>
<tr>
<td>M46J_0_S_G_NPF_1</td>
<td>15</td>
</tr>
<tr>
<td>M46J_0_0_GT_NPF_1</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>C-130 J Representative</td>
<td></td>
</tr>
<tr>
<td>285K_0_0_G_NPF_1</td>
<td>7</td>
</tr>
<tr>
<td>T650_0_0_G_NPF_1</td>
<td>12</td>
</tr>
</tbody>
</table>

Coating removal rate is not greater than current capability at Hill AFB, UT, using a 6 kW continuous wave robotic laser coating removal system.