Space Technology Mission Directorate
Game Changing Development Program — Composite Technologies for Exploration (CTE)

John Fikes  | FY19 Annual Review Presentation | September 2019
CTE Technology Overview

- **Technology Goal**
  - The CTE project will develop and demonstrate critical composites technologies with a focus on weight-saving, performance-enhancing bonded joint technology for Space Launch System (SLS)-scale composite hardware to support future NASA exploration missions.

- **Technical Capabilities**
  - Improve the analytical capabilities required to predict failure modes in composite structures.
  - Support SLS payload adapter by maturing composite bonded joint technology and analytical tools to enable risk reduction.

- **Exploration & Science Impact**
  - Lighter weight structures; improved material predictive capabilities; improved bonded joint failure load and mode predictions to help reduce knockdown factors and improve predictability and reliability.
  - Increase confidence of all bonded joint composite structures.
  - Applicable to SLS joints and structures; Lunar Lander structures and joints.
Mission Infusion & Partnerships

➢ Contributing partners and/or stakeholders
  ▪ HEOMD – SLS
  ▪ OCE/NESC is helping capture CTE data for future project usage
    ▪ Composite Bonded Joint Design, Analysis and Test data is being captured through the NESC Polymer Matrix Composite Community of Practice.

➢ Infusion/transition plan
  ▪ HEOMD – SLS
    ▪ Longitudinal bonded joints baselined by SLS Payload Adapter to reduce weight and manufacturing time.
  ▪ SLS Block Upgrades
    ▪ Circumferential bonded joints provide lighter weight structures for greater performance and increased payload capability.
  ▪ Lunar Lander structures and joints.
  ▪ Composite Bonded Joint Design and Analysis through the NESC PMC Community of Practice.
CTE Technology Goals & Project Objectives

<table>
<thead>
<tr>
<th>Technology Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal #1</td>
</tr>
<tr>
<td>Goal #2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Project Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Configuration</td>
</tr>
<tr>
<td>Model Predictions</td>
</tr>
</tbody>
</table>
## Key Performance Parameters

Composite Technologies for Exploration (CTE)

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>State of the Art (SOA)</th>
<th>Threshold Value</th>
<th>Project Goal</th>
<th>Estimated Current Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure Prediction</td>
<td>±25% of mean</td>
<td>±15% of mean</td>
<td>±5 of mean</td>
<td>See #1 in Notes</td>
</tr>
<tr>
<td>Risk Reduction Factor</td>
<td>2.0</td>
<td>1.8</td>
<td>1.4</td>
<td>SOA</td>
</tr>
<tr>
<td>Part Count</td>
<td>100%</td>
<td>75%</td>
<td>50%</td>
<td>2% (4)</td>
</tr>
<tr>
<td>Weight</td>
<td>100%</td>
<td>85%</td>
<td>75%</td>
<td>15% (4)</td>
</tr>
</tbody>
</table>

**Notes:**

1. Current failure prediction: L-Joint, sub-element predictions: Pre-Testing ±9% and Post-Test ± 5%. L-Joint, large-panel predictions: Pre-Test ±11.0%, Post-Test (measured imperfections and loading imperfections): ±2%

2. With a 2.0 FS in the CTE L-joint design, the team demonstrated a FS of 2.9 and 2.4 (undamaged and damaged, respectively) in the large scale panel tests. The next step would have been to redesign the joint for a FS of 1.8 and 1.4 and do additional testing which team did not do due to FY19 budget cut.

3. State of art is a metal bolted joint in primary load path for 8.4 M diameter scale structure. Weight associated with metal/bolted joints (e.g., 3 lb/ft metal bolted joint) was used to estimate weight per linear foot bond line savings. Savings calculated by analysis.

4. Estimated current values were derived using the CTE point design longitudinal bonded joint with a highly loaded structure.
## CTE Technical Assessment

<table>
<thead>
<tr>
<th>Technical Elements</th>
<th>TRL</th>
<th>AD²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Entry</td>
<td>Current¹</td>
</tr>
<tr>
<td>Composite L- Joints– Analysis</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Composite L- Joints– NDE</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Composite L- Joints– Design</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Composite C- Joints - Analysis</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Composite C- Joints - NDE</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

¹Date of last TA was 8/20/2019

²AD²
# CTE Technical Assessment

<table>
<thead>
<tr>
<th>Technical Elements</th>
<th>MRL</th>
<th>AD²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite Longitudinal Joints – Manufacturing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Entry</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Current¹</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Exit</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Composite Circumferential Joints - Manufacturing</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Entry</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Current</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

¹Date of last TA was 8/20/2019
CTE Technical Approach

➢ Project plans to accomplish objectives

- Develop and validate high-fidelity analysis tools/modeling and analysis standards for the prediction of failure and residual strength of composite bonded joints.

- Design, fabricate, and test a light-weight bonded joint concept for SLS Payload Adapter.

- Deliverables include:
  - The design, analysis, fabrication, and test of one or more representative-scale bonded joints.
  - Material equivalency reports.
  - Validated analytical methodologies for the prediction of composite bonded joint behavior and behavior at/near discontinuities.
  - Post-test report to include a proposed strategy and infusion path forward.
Longitudinal Bonded Joint
Structural Analysis and Design
Joint Sizing Process

Size and Loading Requirements
Material Characterization Test and Selection
Preliminary/Detailed Joint Analysis
Preliminary/Detailed Joint Analysis

Large-Scale Post-Test Analysis and Correlation
Scale-Up, Large Panel Tests
Sub-element Tests and Post-Test Analysis
Joint Manufacturing and Process Development
Technical Status
SLS Payload Adapter Longitudinal Bonded Joint
Preliminary Design and Analysis Accomplishments

CTE bonded joint sizing process used for PLA for longitudinal bonded joint sizing

- CTE team presented preliminary longitudinal bonded joint sizing to PLA team on August 26th
- Recommended building block approach future testing of PLA joint with analysis correlation
- PLA team asked CTE team to perform additional analysis of segmented joint design
- CTE team has completed analysis of segmented longitudinal bonded joint design and is updating presentation that will be presented to PLA in a few weeks
Surface preparation automation processes

- Researched and developed surface preparation (atmospheric pressure plasma treatment) automation processes for use on the longitudinal joints
- Recommended approach:
  - Distance between jet and substrate: 0.5 inches
  - Raster (scan) speed: 1 – 6 inches per second

Multi-zone heat blankets evaluation for out-of-oven processing

- Identified key processing limitations in original heater blanket configurations
- Performed cure trials with upgraded multi-zone blankets at various configurations: single-zone heat blankets at full-scale with honeycomb core, multi-zone heat blankets at sub-scale with honeycomb core, and multi-zone heat blankets at sub-scale with foam core.
- Process optimization with upgraded heater blanket resulted in a significant reduction in lead and lag temperatures during cure resulting in a much more uniform cure profile

Draft bonding process specification developed

- Some values remain TBD pending future test results
- Initial process window development coupons have been fabricated and sent to test at NIAR for testing
Bonded joint process window development

- Developed a process window development design of experiments to evaluate process parameters relevant to adhesively bonded joints
  - Ultimate purpose:
    - To establish critical processing parameters that may have a distinct detrimental effect on the quality of the joint
    - To establish a process window box that the joint must be fabricated within to ensure an acceptable bond
- Initial fabrication and testing completed through CTE:
  - Parent laminate panel fabrication and trimming processes
  - Bonding / coupon assembly processes
  - Testing in-work at NIAR (100 coupon tests)
- Draft bonding process specification developed

Design of experiments for critical process parameters of adhesively bonded joints
Technical Status

Design, Analysis, Fabrication, and Testing of Large-Scale Longitudinal Bonded Jointed Concept

CTE team demonstrated scaled-up composite bonded longitudinal joint manufacturing and structural performance (pristine and damaged) by successfully manufacturing and testing two 62” long x 30” wide panels with 62” long x 4.2” wide joints under compressive load conditions.

- Tests showed that composite bonded longitudinal joints are predictable and reliable under buckling load conditions.
- Tests showed that composite bonded longitudinal joints, both pristine and impact-damaged, satisfy design load requirements with 2.9 and 2.4 factors of safety, respectively, and have met fracture critical joint performance requirements.
Pi Preform Accomplishments

• Bally Ribbon Mills (BRM) weaving complete
• Pi-preforms, infused with 5320-1 resin, complete and (6) 50” sections delivered to GSFC.
• Cure process development demonstrating cure of pi-preform complete
• Parts cut to evaluate properties
• Next step to build joint with Pi-Prefoms

3D-Woven C-Channel Accomplishments

• BRM delivered 12” dry preforms to Cornerstone Research Group (CRG)
• CRG Resin Transfer Molded C-Channels
  • NASA evaluations found voids and weave variations that were un-acceptable
  • CRG and BRM varied processing to result in acceptable quality parts. This took 2 iterations of the 12” scaled parts
• BRM delivered (3) 36” dry preforms at the final weave to CRG for scale up evaluations.
• CRG delivered (3) 36” parts for NASA testing
Technical Status
Circumferential Joint Manufacturing Accomplishments

- Test article and test fixture designed and analyzed
- Fabrication of 5 C-Joint sub-element test articles completed
- Test plan completed

C-Joint sub-element test article design

Test fixture design

Tension loading:

Sandwich section fabrication complete

Base plate fabrication complete

Pi-preform ready for bonding
Defect panel was developed in conjunction with BRM, designed to contain characteristic flaws unique to the 3D weaving manufacturing process, most of which are not seen in other production methods.

Panel inspected by NASA Glenn, NASA Marshall, and 3 external vendors: North Coast, NDTS, and R-Con.

All common composites NDE techniques attempted: ultrasound (immersion through transmission and pulse echo, contact phased array pulse echo), infrared thermography, digital radiography, resonance, and mechanical impedance.

More work needs to be done to develop techniques for adequately inspecting 3D weave composites. Despite having knowledge of flaw locations, using state-of-the-art equipment, and having technical experts attempt the techniques, only two setups detected the majority of the flaws (immersion ultrasound and infrared thermography) and both of those have significant limitations on full-scale parts.
## Technical Risk Summary

<table>
<thead>
<tr>
<th>Risk ID</th>
<th>Affinity</th>
<th>Description/Status</th>
<th>Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>M/T</td>
<td>L-Joint Scale-Up</td>
<td>CLOSED</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bonded joint manufacturing processes developed at the laboratory scale may present challenges at full scale. Improving during the remainder of FY19 with demonstration and evaluation of additional out-of-autoclave processes.</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>M/T</td>
<td>C-Joint Manufacturing Scale-Up</td>
<td>↓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Circumferential joint manufacturing developed at the laboratory scale may present challenges at full scale.</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>M/T</td>
<td>C-Joint Assembly Scale-up</td>
<td>↓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Circumferential joint assembly developed at the laboratory scale may present challenges at full-scale.</td>
<td></td>
</tr>
</tbody>
</table>

Updated 09/17/2019
Summary of Education and Public Outreach

- 12/4/2018 - Moon to Mars Day on the Hill (Washington, DC)
- 1/7-11/2019 – 2019 AIAA SciTech (San Diego, Ca)
- 4/18/2019 - NASA Day in Montgomery (Alabama)
- 9/24-26/2019 – Composites and Advanced Materials Expo (CAMX) (Anaheim, CA)

2019 CAMX Special Session

A special session chaired by Sandi Miller on composite bonded joints is occurring at CAMX. Seven papers are being presented by the CTE team members and contract partners.
Due to reduction of FY19 procurement funds from SLS, the project updated FY19 milestones and tasks. FY20 augmentation work was approved to perform additional circumferential joint work.

The CTE analysis team continued to support the SLS PLA team on composite bonded longitudinal joints in FY19. The team presented results of the analysis study to the SLS PLA team on 8/26/2019. Follow-up requests have been completed and a final meeting is being scheduled.

Completed the milestone “Complete Design, Analysis, Fabrication & Testing of Large-Scale Longitudinal Bonded Joint Concept”.

The CTE project will complete the CTE API Milestone “Complete Manufacturing and Test of Circumferential Bonded Joint Concept” on September 24, 2019.

Provided CTE Overview at the Joint Defense Manufacturing Technology Panel. (8/6/2019 at Oak Ridge National Lab, Knoxville, TN)

Presented to NESC Materials working group. (8/20/2019)

CTE TAPR is scheduled at MSFC for November 6, 2019.
## Project Assessment Summary

<table>
<thead>
<tr>
<th>Project</th>
<th>Performance</th>
<th>Comments</th>
</tr>
</thead>
</table>
| Mid Year | ![Yellow](C) ![Yellow](S) ![Green](T) ![Green](P) | **Cost** is yellow due to the decrease of SLS procurement funding for FY19. Cost will trend toward green once decision is made on scope for the remainder of FY19.  
**Schedule** is yellow due to concerns with the first cured 12-in, 3D-woven C-Channel. The CTE team worked with Cornerstone Research Group (CRG) and Bally Ribbon Mills (BRM) on changes to the 3D weave dimensions for the second and third 12-in C-channel preforms and continue to evaluate the Resin Transfer Molding (RTM) process parameters. BRM has delivered the second and third 12-in C-Channel preforms to CRG for RTM (infusion and curing). The cured C-Channels are being evaluated by NASA. Lessons learned from the 12-in C-Channels drive the design of the larger, scaled-up parts. Technical continues to be green.  
**Programmatic** is yellow while options and plans are assessed and a decision is made on scope for the remainder of FY19. SLS Payload Adapter project is currently assessing tasks that the CTE analysis team could support that would positively affect a FY20 structural test article. The CTE project is developing a Change Request (CR) for FY20 augmentation for additional circumferential joint work. |
| Annual | ![Green](C) ![Green](S) ![Green](T) ![Green](P) | Cost – Green  
Schedule – Green  
- The CTE Project submitted a Change Request (CR) that was approved to move schedule completion date from 8/5/2019 to 9/24/2019. The reason for the change request is additional time was needed to manufacture the circumferential bonded joint test coupons and complete the test.  
Technical – Green  
- GSFC fabricated the first C-channel material test coupons. Three test coupons were shipped to NIAR (7/22/2019) and successfully tested.  
- Two circumferential bonded joint sub-elements have been manufactured and will be tested on 9/19/2019.  
Programmatic – Green  
- The CTE analysis team continues to support the SLS PLA team on composite bonded longitudinal joints. The team presented results of the analysis study to the SLS PLA team on 8/26/2019. Follow-up requests are have been completed and a final presentation is being scheduled. |
### Conferences attended

<table>
<thead>
<tr>
<th>Conference Name</th>
<th>Papers/Posters/Panel Discussions</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIAA SciTech</td>
<td>4 Papers</td>
</tr>
<tr>
<td>SAMPE</td>
<td>1 Paper</td>
</tr>
<tr>
<td>NASA &amp; NCAME workshop on “Composites Materials and Manufacturing Technologies for Space Applications</td>
<td>Discussions</td>
</tr>
<tr>
<td>CAMX</td>
<td>7 papers &amp; Composites special session</td>
</tr>
</tbody>
</table>
Circumferential Joint Manufacturing Scale Up

**Risk Statement**
Circumferential joint manufacturing developed at the laboratory scale may present challenges at full scale resulting in a non-conforming composite end ring.

**Approach:** See Below

**Context**
This risk addresses component manufacturing.

1. Component Manufacturing (C-channel) – Mitigate
   a. BRM is weaving 60” straight parts, CTE point design with 6 segments requires a 164” curved part.
      i. BRM has experience weaving curved parts resulting in low fabrication risks; however, curved parts incur increased setup costs.
      ii. A curved weave may result in different mechanical properties. This risk is low as the radius of curvature is gentle and only small fiber angle variation is anticipated.
   b. Larger risk to manufacturing is meeting tolerances on C-Channel bolted interfaces (EUS/USA).

**Status**
- 09/17/2019 – Updated trend to decreasing. Updated planned closure date from 09/01/2019 to 09/01/2020. Process modifications were made to the 4th and 5th 12” C-channels. The lessons learned from the 4th and 5th 12” C-channels were applied to the scaled-up 36” C-channels. Three 36” C-channels were infused and cured at CRG. Some surface pitting was observed; however, there is low porosity through the thickness of the part indicating there is good resin infusion in the complicated preform. GSFC had success with curing of the pi preforms that will be used for representative C-joint assembly testing. See Risk #12 for comments on assembly.

**Mitigation Steps**

<table>
<thead>
<tr>
<th>Mitigation Steps</th>
<th>Dollars to Implement</th>
<th>Trigger/Start Date</th>
<th>Schedule UID</th>
<th>Completion Date</th>
<th>Resulting L/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component- Work with resin transfer molding team to assess scale up issues (12” section)</td>
<td>$0</td>
<td>1/1/2018</td>
<td>4/1/2019</td>
<td>3x4</td>
<td></td>
</tr>
<tr>
<td>Component- Work with resin transfer molding team to assess scale up issues (36” section)</td>
<td></td>
<td>8/1/2019</td>
<td></td>
<td>2x4</td>
<td></td>
</tr>
<tr>
<td>Component – Understand surface pitting with C-channel manufacturing.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component – Understand effects of curved weave for C-channel manufacturing.</td>
<td></td>
<td></td>
<td></td>
<td>1x4</td>
<td></td>
</tr>
</tbody>
</table>
Circumferential Joint Assembly Scale Up

Risk Statement
Circumferential joint assembly processes developed at the laboratory scale may present challenges at full scale resulting in a non-conforming composite end ring.

Approach: See Below

Context
This risk addresses C-joint assembly.
1. C-joint Assembly – Watch
   a. Staggered panel-to-panel and ring segment-to-ring segment joints (CTE point design) scale-up would require hot bonder cure and development of assembly tooling at full-scale:
      i. Oven cure is being used for sub-scale testing rather than heater blankets to reduce (a) confounding variables in test data and (b) schedule risk. Potential risks include (1) oven cure may not represent the potential variation in hot bonder cure temperatures through the part at full-scale and (2) heater blanket design and availability at full-scale.
   b. Aligned panel-to-panel and ring segment-to-ring segment joints scale-up would enable assembly in oven to eliminate need for hot bonder cures and reduce complexity of tooling at full-scale:
      i. Increases risk to panel acreage due to additional oven heat cycle. Minor part deformations and material degradation are possible and would need to be addressed via analysis or test.
      ii. Increases risk of out of tolerance faying surfaces (to EUS and/or USA) and to overall assembly tolerances.

Status
• 09/17/2019 – Updated planned closure date from 09/01/2019 to 09/01/2020. Two representative C-joint sub-element test articles will be tested at MSFC. The test articles include a sandwich panel, prepreg pi preform, and a 3D woven flat panel/baseplate to represent the web of a C-channel. The test articles will be loaded in bending, tension, and compression. Preliminary analysis indicates that both the test article and test fixture should survive the loading of two times the design limit load.

Mitigation Steps

<table>
<thead>
<tr>
<th>Mitigation Steps</th>
<th>Dollars to implement</th>
<th>Trigger/ Start date</th>
<th>Schedule UID</th>
<th>Completion Date</th>
<th>Resulting L/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly- Test a representative sub-element C-joint assembly with the pi preform, representative C-channel baseplate (3D-woven flat panel), and a sandwich panel.</td>
<td></td>
<td></td>
<td></td>
<td>09/18/2019</td>
<td>4x4</td>
</tr>
<tr>
<td>Assembly- Test a representative element C-joint assembly with the pi preform, representative C-channel baseplate (3D-woven flat panel), and a sandwich panel.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3x4</td>
</tr>
</tbody>
</table>
## MRL Exit Assessment Matrix – Composite Longitudinal joint manufacturing

<table>
<thead>
<tr>
<th>2: Manufacturing Concepts Identified.</th>
<th>3: Manufacturing Proof-Of-Concept Demonstrated.</th>
<th>4: Manufacturing Process in Lab Environment.</th>
<th>5: Prototype components in Production Relevant Environment.</th>
<th>6: System or Subsystem in a Production Relevant Environment.</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Maturity</td>
<td>Top level performance requirements defined. Trade-offs in design options assessed based on experiments. Product lifecycle and technical requirements evaluated.</td>
<td>System characteristics and measures to support required capabilities identified. Form, fit, and function constraints identified and manufacturing capabilities identified for preferred systems concepts.</td>
<td>Lower level performance requirements sufficient to proceed to preliminary design. All enabling/critical technologies and components identified and product lifecycle considered. Evaluation of design key characteristics initiated. Product data required for prototype component manufacturing is available.</td>
<td>System requirements and features are well defined to support preliminary design review. Product data essential for subsystem/system prototyping available, and all enabling/critical components have been prototyped. Preliminary design key characteristics have been identified and addressed in the manufacturing process.</td>
<td>N/A – production modeling not looked at on this project.</td>
</tr>
<tr>
<td>Materials Maturity</td>
<td>Material properties and characteristics identified. N/A</td>
<td>Material properties validated and assessed for basic manufacturability using experiments.</td>
<td>Materials have been manufactured or produced in a prototype environment. Maturation efforts in place to address new material production risks for technology demonstration.</td>
<td>Material properties verified through technology demonstration articles. Preliminary material specifications in place and material properties have been adequately characterized.</td>
<td>N/A – production modeling not looked at on this project.</td>
</tr>
<tr>
<td>Modeling and Simulation</td>
<td>Identification of proposed manufacturing concepts or manufacturability needs based on high-level process flow requirements.</td>
<td>Critical manufacturing processes identified through experimentation.</td>
<td>Production modeling/simulation approaches for process or part are identified/applicable.</td>
<td>Initial models/simulation (prototype or process) developed at the component level and used to determine constraints.</td>
<td>Demonstrated by manufacturing four CTE L-joints on SLS payload adapter (PLA) manufacturing demonstration article (MDA). Have not done in a production ready environment (TRL6).</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>Material and/or process approaches identified.</td>
<td>Critical processes demonstrated and assessed in the laboratory.</td>
<td>Materials and/or process approaches identified.</td>
<td>Manufacturing processes demonstrated in a production relevant environment. Process capability data is available (actual or modeled) from prototype build and process capabilities reqs are refined based on this data.</td>
<td>Rationale</td>
</tr>
<tr>
<td>Functional Elements</td>
<td>System Definition</td>
<td>System Integration</td>
<td>Modeling and Simulation Tools</td>
<td>Capability Validation</td>
<td>Environmental Validation</td>
</tr>
<tr>
<td>---------------------</td>
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<td>-------------------------</td>
</tr>
<tr>
<td>Basic functional elements of technology have been identified.</td>
<td>An apparent engineering design approach has been identified.</td>
<td>System architecture defined in terms of basic functions to be performed.</td>
<td>Operational requirement of functional elements verified through modeling or simulation.</td>
<td>Preliminary performance predictions have been made for basic functional elements.</td>
<td>Critical functional experiments for operational environment are known.</td>
</tr>
<tr>
<td>Operation of functional elements verified through bench-scale tests.</td>
<td>Definition of relevant operational environment defined for basic functional components.</td>
<td>A conceptual design of the integrated system has been created.</td>
<td>Models exist to extend that computer analysis and simulations are possible.</td>
<td>Preliminary system performance measurements have been identified and estimated.</td>
<td>Experimental results demonstrate functionality of basic functions to be performed.</td>
</tr>
<tr>
<td>Subsystem tests in a simulated laboratory environment show element interoperability will function.</td>
<td>System performance metrics and test requirements have been defined for relevant operational environment.</td>
<td>Preliminary functional testing of integrated system completed at laboratory bench-scale.</td>
<td>Modeling shows subsystem interfaces will function at system level to satisfy functional requirements.</td>
<td>System performance metrics verified under simulated use conditions.</td>
<td>Laboratory scale tests indicate components and subsystem interfaces will function in operational environments.</td>
</tr>
<tr>
<td>Functional elements and interfaces understood at engineering scale to provide system design tradeoffs.</td>
<td>Prototypical system testing for the ranges of critical operational environment validates design.</td>
<td>Engineering scale-up challenges understood and resolved for functional system.</td>
<td>Modeling shows subsystem interfaces will function at system level in operational environment.</td>
<td>System and subsystem functional parameters are demonstrated on a bench scale.</td>
<td>System testing in approximate operational environment completed.</td>
</tr>
<tr>
<td>Full-scale engineering design specifications complete and documented.</td>
<td>Full technology system integration demonstrated at an engineering scale.</td>
<td>Performance predictions verified by engineering-scale testing and documented.</td>
<td>Functionality of a high-fidelity engineering design unit demonstrated.</td>
<td>Engineering-scale tests demonstrate functionality over full range of design critical environments.</td>
<td>Full-scale design specifications complete and documented.</td>
</tr>
<tr>
<td>Based on sub-element coupon test results falling above design limit with 2.0 FS and analysis performance in predicting failure load and modes.</td>
<td>Based on testing of sub-element testing and analysis failure load and modes. Mailbox has been set up for testing.</td>
<td>Based on testing of sub-element L-Joint testing and analysis failure load and modes.</td>
<td>Based on analysis of PLA for the PLA, and verified engineering scale.</td>
<td>Based on analysis design of -joints in operational environments and prediction of joint failure load and modes for sub-element test coupons.</td>
<td>Demonstrated scalability of composite bonded longitudinal joint manufacturing and structural performance. Analysis showed we can predict bonding and joint load of large-scale bonded joint. Applied methodology for analysis to the PLA and verified engineering scale.</td>
</tr>
</tbody>
</table>

**AD2 Level 5**

2018 2019
<table>
<thead>
<tr>
<th>Year</th>
<th>TRL</th>
<th>Functional Elements</th>
<th>System Definition</th>
<th>System Integration</th>
<th>Modeling and Simulation Tools</th>
<th>Capability Validation</th>
<th>Environmental Validation</th>
<th>Life Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>2</td>
<td>Technology concept and/or application formulated.</td>
<td>Basic functional elements of technology have been identified.</td>
<td>An apparent engineering design approach has been identified.</td>
<td>System architecture defined in terms of basic functions to be performed.</td>
<td>Operational requirement of functional elements verified through modeling or simulation.</td>
<td>Preliminary performance predictions have been made for basic functional elements.</td>
<td>Critical functional experiments for operational environment are known.</td>
</tr>
<tr>
<td>2019</td>
<td>3</td>
<td>Analytical and experimental critical function and/or characteristic proof-of-concept.</td>
<td>Operation of functional elements verified through bench-scale tests.</td>
<td>Definition of relevant operational environment defined for basic functional components.</td>
<td>A conceptual design of the integrated system has been defined.</td>
<td>Models exist to extent that computer analysis and simulations are possible.</td>
<td>Preliminary system performance measurements have been identified and estimated.</td>
<td>Modeling or experimental results show feasibility of basic functions in expected environments.</td>
</tr>
<tr>
<td>2018</td>
<td>4</td>
<td>Component and/or breadboard validation in laboratory environment.</td>
<td>Subsystem tests in a simulated laboratory environment show subsystem interfaces will function.</td>
<td>System performance metrics and test requirements have been defined for relevant operational environment.</td>
<td>Preliminary functional testing of integrated system completed at laboratory bench scale.</td>
<td>Modeling shows subsystem interfaces will function at system level to satisfy functional requirements.</td>
<td>System performance metrics validated under simulated use conditions.</td>
<td>Laboratory scale tests indicate components and subsystem interfaces will function in operational environments.</td>
</tr>
<tr>
<td>2019</td>
<td>5</td>
<td>Component and/or breadboard validation in relevant environment.</td>
<td>Functional element and interfaces sufficiently understood at engineering-scale to provide system design tradeoffs.</td>
<td>Prototypical system testing for the ranges of critical operational environments validates design.</td>
<td>Engineering scale up challenges understood and resolved for functional system.</td>
<td>Modeling shows subsystem interfaces will function at system level in operational environment.</td>
<td>System and subsystem functional parameters are demonstrated on a bench scale.</td>
<td>Operational needs for all materials properties have been identified.</td>
</tr>
<tr>
<td>2018</td>
<td>6</td>
<td>System/sub-system model or prototype demonstrated in a relevant environment.</td>
<td>Functional elements and interfaces provide optimized system design.</td>
<td>Full-scale engineering design specifications complete and documented.</td>
<td>Full technology system integration demonstrated at an engineering scale.</td>
<td>Performance predictions verified by engineering-scale testing and documented.</td>
<td>Functionality of a high-fidelity engineering design unit demonstrated.</td>
<td>Engineering scale tests demonstrate functionality over full range of design critical environments.</td>
</tr>
<tr>
<td>2019</td>
<td>Rationale</td>
<td>NDE methods used for CTE L-joints are mature and have been demonstrated on numerous flight programs. Techniques are identified and perform well in current configurations. Final system parameters would need to be refined for specific designs.</td>
<td>NDE methods used for CTE L-joints are mature and have been demonstrated on numerous flight programs. Inspection systems and specifications are mature and in use on existing flight projects.</td>
<td>NDE methods used for CTE L-joints are mature and have been demonstrated on numerous flight programs. Inspection systems are in active use on large-scale flight and test articles.</td>
<td>NDE methods used for CTE L-joints are mature and have been demonstrated on numerous flight programs.</td>
<td>NDE methods used for CTE L-joints are mature and have been demonstrated on numerous flight programs. Techniques are identified and perform well in current configurations. Final system parameters would need to be refined for specific designs.</td>
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<td>N/A</td>
</tr>
</tbody>
</table>
# MRL Exit Assessment Matrix – Composite G joint manufacturing

|-----------|------------------|------|------|------|------|------|------|------|------|
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<tr>
<th>TRL</th>
<th>Functional Elements</th>
<th>System Definition</th>
<th>System Integration</th>
<th>Modeling and Simulation Tools</th>
<th>Capability Validation</th>
<th>Environmental Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Technology concept and/or application formulated.</td>
<td>Basic functional elements of technology have been identified.</td>
<td>An apparent engineering design approach has been identified.</td>
<td>System architecture defined in terms of basic functions to be performed.</td>
<td>Operational requirement of functional elements verified through modeling or simulation.</td>
<td>Preliminary performance predictions have been made for basic functional elements.</td>
<td>Critical functional experiments for operational environment are known.</td>
</tr>
<tr>
<td>3. Analytical and experimental critical function and/or characteristic proof-of-concept.</td>
<td>Operation of functional elements verified through bench-scale tests.</td>
<td>Definition of relevant operational environment defined for basic functional components.</td>
<td>A conceptual design of the integrated system has been defined.</td>
<td>Models exist to extent that computer analysis and simulations are possible.</td>
<td>Preliminary system performance measurements have been identified and estimated.</td>
<td>Experimental results demonstrate feasibility of operations for basic functions to be performed.</td>
</tr>
<tr>
<td>4. Component and/or breadboard validation in laboratory environment.</td>
<td>Subsystem tests in a simulated laboratory environment show element interfaces will function.</td>
<td>System performance metrics and test requirements have been defined for relevant operational environment.</td>
<td>Preliminary functional testing of integrated system completed at laboratory bench-scale.</td>
<td>Modeling shows subsystem interfaces will function at system level to satisfy functional requirements.</td>
<td>System performance metrics verified under simulated use conditions.</td>
<td>Laboratory scale tests indicate components and subsystem interfaces will function in operational environments.</td>
</tr>
<tr>
<td>5. Component and/or breadboard validation in relevant environment.</td>
<td>Functional element and interfaces sufficiently understood at engineering scale to provide system design tradeoffs.</td>
<td>Prototypical system testing for the ranges of critical operational environments validates design.</td>
<td>Engineering scale up challenges understood and resolved for functional system.</td>
<td>Modeling shows subsystem interfaces will function at system level in operational environment.</td>
<td>System and subsystem functional parameters are demonstrated on a bench scale.</td>
<td>System testing in approximate operational environment completed.</td>
</tr>
<tr>
<td>6. System/sub-system model or prototype demonstrated in a relevant environment</td>
<td>Functional elements and interfaces provide optimized system design.</td>
<td>Full-scale engineering design specifications complete and documented.</td>
<td>Full technology system integration demonstrated at an engineering scale.</td>
<td>Performance predictions verified by engineering-scale testing and documented.</td>
<td>Functionality of a high-fidelity engineering design unit demonstrated.</td>
<td>Engineering-scale tests demonstrate functionality over full range of design critical environments.</td>
</tr>
</tbody>
</table>

Rationale

- C-points have been designed and analyzed, but not tested. On the 3D wave, predicting stiffness has been demonstrated (the functional element). We’ve predicted, tested and verified our tools at that basic level based on coupon testing.

Entry/Exit: 2/3
AD2 entry: 8
AD2 Level 7
<table>
<thead>
<tr>
<th>TRL</th>
<th>Functional Elements</th>
<th>System Definition</th>
<th>System Integration</th>
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<th>Environmental Validation</th>
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<tr>
<td>2: Technology concept and/or application formulated.</td>
<td>Basic functional elements of technology have been identified.</td>
<td>An apparent engineering design approach has been identified.</td>
<td>System architecture defined in terms of basic functional components.</td>
<td>Operational requirement of functional elements verified through modeling or simulation.</td>
<td>Preliminary performance predictions have been made for basic functional elements.</td>
<td>Critical functional experiments for operational environment are known.</td>
</tr>
<tr>
<td>3: Analytical and experimental critical function and/or characteristic proof-of-concept.</td>
<td>Operation of functional elements verified through bench-scale tests.</td>
<td>Definition of relevant operational environment defined for basic functional components.</td>
<td>A conceptual design of the integrated system has been defined.</td>
<td>Models exist to extent that computer analyses and simulations are possible.</td>
<td>Preliminary system performance measurements have been identified and estimated.</td>
<td>Modeling or experimental results show feasibility of basic functions in expected environments.</td>
</tr>
<tr>
<td>4: Component and/or breadboard validation in laboratory environment.</td>
<td>Subsystem tests in a simulated laboratory environment show element interfaces will function.</td>
<td>System performance metrics and test requirements have been defined for relevant operational environment.</td>
<td>Preliminary functional testing of integrated system completed at laboratory bench scale.</td>
<td>Modeling shows subsystem interfaces will function at system level to satisfy functional requirements.</td>
<td>System performance metrics verified under simulated use conditions.</td>
<td>Laboratory scale tests indicate components and subsystem interfaces will function in operational environments.</td>
</tr>
<tr>
<td>5: Component and/or breadboard validation in relevant environment.</td>
<td>Functional element and interfaces sufficiently understood at engineering scale to provide system design trades.</td>
<td>Prototypical system testing for the ranges of critical operational environments validates design.</td>
<td>Engineering scale-up challenges understood and resolved for functional system.</td>
<td>Modeling shows subsystem interfaces will function at system level in operational environment.</td>
<td>System and subsystem functional parameters are demonstrated on a bench scale.</td>
<td>Operational needs for all material properties have been identified.</td>
</tr>
<tr>
<td>6: System/sub-system model or prototype demonstrated in a relevant environment</td>
<td>Functional elements and interfaces provide optimized system design.</td>
<td>Full-scale engineering design specifications complete and documented.</td>
<td>Full technology system integration demonstrated at an engineering scale.</td>
<td>Performance predictions verified by engineering scale testing and documented.</td>
<td>Functionality of a high-fidelity engineering design unit demonstrated.</td>
<td>Operational capability of all materials has been demonstrated.</td>
</tr>
</tbody>
</table>

**Rationale**

- **Potential NDE methodologies have not been demonstrated on any CTE C-joint components or assemblies.** Shown in UT and thermography can work in a couple cases, but still needs more development.

- **Potential NDE methodologies have not been demonstrated on any CTE C-joint components or assemblies.** Working with IME and create reliable data but a panel to stand on. We know better what we are looking for.

- **Potential NDE methodologies have not been demonstrated on any CTE C-joint components or assemblies.** Keep at TRL 2. Differences between flat panels and actual structures are too difficult to define for final inspection.

- **Potential NDE methodologies have not been demonstrated on any CTE C-joint components or assemblies.** We have baseline data on a flat panel from 4 or 5 techniques that we can use to move forward.

- **Potential NDE methodologies have not been demonstrated on any CTE C-joint components or assemblies.** Keep at TRL 4 since work so far has only been on flat panels.

- **Potential NDE methodologies have not been demonstrated on any CTE C-joint components or assemblies.** Keep at TRL 4.
## Current TRL Exit Assessment Matrix – Composite Longitudinal Joints - Design

<table>
<thead>
<tr>
<th>TRL</th>
<th>Functional Elements</th>
<th>System Definition</th>
<th>System Integration</th>
<th>Modeling and Simulation Tools</th>
<th>Capability Validation</th>
<th>Environmental Validation</th>
<th>Life-cycle Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Technology concept and/or application demonstrated.</td>
<td>Basic functional elements of technology have been identified.</td>
<td>System architecture drafted in forms of basic functional elements.</td>
<td>Operational requirements of functional elements verified through modeling or simulation.</td>
<td>Preliminary performance predictions have been made for basic functional elements.</td>
<td>Critical performance parameters for operability and maintenance have been defined.</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>Analytical and experimental critical function assessment.</td>
<td>Operation of functional elements verified through bench scale tests.</td>
<td>Definition of relevant operational environment defined for basic functional components.</td>
<td>Preliminary performance predictions have been made for relevant operational environments.</td>
<td>Operational performance assessments have been verified and optimized.</td>
<td>Modeling or experimental results show critical functions under operational conditions.</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>Component/subsystem and validation.</td>
<td>Subsystem benches in a simulated laboratory environment shown to function.</td>
<td>System performance metrics and test requirements have been defined for relevant operational environments.</td>
<td>Pre-operational testing of integrated system completed at laboratory bench-scale.</td>
<td>System performance metrics verified under simulated use conditions.</td>
<td>Laboratory scale tests indicate components and subsystem interfaces will function in operational environments.</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>Component/subsystem model or prototype demonstrated in a relevant environment.</td>
<td>Prototypical system testing for the ranges of critical operational environments validates design.</td>
<td>Engineering scale-up challenges understood and resolved for functional system.</td>
<td>Modeling shows subsystem interfaces will function at system level in operational environment.</td>
<td>System and subsystem functional parameters are demonstrated on a bench scale.</td>
<td>System testing in approximate operational environment completed.</td>
<td>N/A</td>
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<td></td>
<td>System/subsystem model or prototype demonstrated in a relevant environment.</td>
<td>Functional elements and interfaces provide optimized system design.</td>
<td>Full-scale engineering design specifications complete and documented.</td>
<td>Full technology system integration demonstrated at an engineering scale.</td>
<td>Performance predictions verified by engineering-scale testing and documented.</td>
<td>Functionality of a high-fidelity engineering design unit demonstrated.</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Rationale</td>
<td>Full-scale engineering design specifications complete and documented.</td>
<td>Full technology system integration demonstrated at an engineering scale.</td>
<td>Performance predictions verified by engineering-scale testing and documented.</td>
<td>Functionality of a high-fidelity engineering design unit demonstrated.</td>
<td>Full-scale engineering design specifications complete and documented.</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Entry/Exit: 4/5**

**AD2 Level 5**

**Rationale**

- Based on sub element coupon test results failing above design limit with 2.0 FS and analysis performance in predicting failure load and modes.
- Design and analysis of L-joints based on system requirements has been verified by developing required test protocols to determine capability of joints. Tests successfully performed and joints failed above design limit load with 2.0 FS. Models have been set up for whole system and included relevant material data, including fatigue for large scale panel and assessed the model for a full system.
- Design and analysis of L-joints demonstrated by testing of sub-element coupons which failed above design limit load with 2.0 FS. Applied methodology for analysis to the P/A.
- Design and analysis of L-joints demonstrated by testing of sub-element coupons which failed above design limit load with 2.0 FS. Demonstrated scaled up composite bonded longitudinal joint manufacturing and structural performance. Analysis showed we can predict bonding and joint failure load/mass of large-scale bonded joint. Applied methodology for analysis to the P/A and verified engineering scale.

Based on analysis design of L-joints in operational environments and prediction of joint failure load and modes for sub element test coupons. Demonstrated scaled up composite bonded longitudinal joint manufacturing and structural performance. Analysis showed we can predict bonding and joint failure load/mass of large-scale bonded joint. Applied methodology for analysis to the P/A and verified engineering scale.

Not yet TRL 6. Maybe there is adverse environment that we didn't consider. We didn't include the vibration/thermal env.
CTE
Provide a brief caption for each description

Caption: Test coupon

Caption: SLS Payload Adapter (PLA) Manufacturing Demonstration Article (MDA) curing a longitudinal composite joint.

Caption: Layup of a longitudinal composite joint panel

Caption: Non Destructive Evaluation of Large Scale Composite Bonded panel.

Caption: Replacing tape on the automated fiber placement machine

Caption: Bally Ribbon Mills machine for 3D weave
Additional Pictures
Panel to panel joints to be bonded

SLS Payload Adapter (PLA) Manufacturing Demonstration Article (MDA) (Sept 2018)
Primary objective: Further develop and demonstrate manufacturing processes at full-scale
Article will not be structurally tested at full-scale
CTE Longitudinal Bonded Joint Panel Manufacturing Process

- Sandwich Panel Assembly Undergoing Gap Filler Injection
- Composite Doubler Following Lay Up and Installation
- Composite Doubler Bag Cure
- Longitudinal Bonded Joint Assemblies Following Doubler Cure