

# 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



## Technology Goals

<b>Goal #1</b>	Develop and validate high-fidelity analysis tools and standards for predicting failure and residual strength of composite bonded joints.
<b>Goal #2</b>	Develop and demonstrate an analytical tailoring approach that enables the reduction of the baseline 2.0 safety factor for composite discontinuities.

## Project Objectives

<b>Joint Configuration</b>	Identify low mass bonded joints for light-weight composite launch structures.
<b>Model Predictions</b>	Establish modeling capabilities that enable failure predictions with low engineering uncertainty.

# CTE Performance



## Key Performance Parameters

### Composite Technologies for Exploration (CTE)

Performance Parameter	State of the Art (SOA)	Threshold Value	Project Goal	Estimated Current Value
Failure Prediction <sup>(1)</sup>	±25% of mean	±15% of mean	±5 of mean.	See #1 in Notes
Risk Reduction Factor <sup>(2)</sup>	2.0	1.8	1.4	SOA
Part Count <sup>(3)</sup>	100%	75%	50%	2% <sup>(4)</sup>
Weight <sup>(3)</sup>	100%	85%	75%	15% <sup>(4)</sup>

#### 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



Technical Elements	TRL			AD <sup>2</sup>	
	Entry	Current <sup>1</sup>	Exit	Entry	Current
Composite L- Joints– Analysis	3	5	5	6	5
Composite L- Joints– NDE	4	5	5	5	5
Composite L- Joints– Design	4	5	5	6	5
Composite C- Joints - Analysis	2	3	3	8	7
Composite C- Joints - NDE	2	3	2	8	8

<sup>1</sup>Date of last TA was 8/20/2019

# CTE Technical Assessment



Technical Elements	MRL			AD <sup>2</sup>	
	Entry	Current <sup>1</sup>	Exit	Entry	Current
<b>Composite Longitudinal Joints– Manufacturing</b>	4	<b>5</b>	5	6	<b>5</b>
<b>Composite Circumferential Joints - Manufacturing</b>	2	<b>4</b>	3	8	<b>8</b>

<sup>1</sup>Date of last TA was **8/20/2019**

# CTE Technical Approach



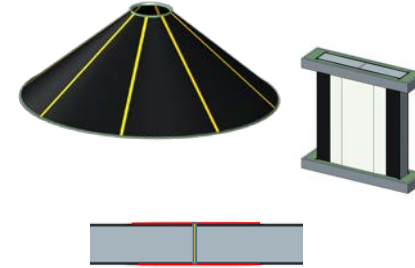
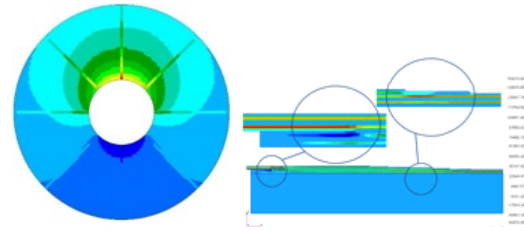
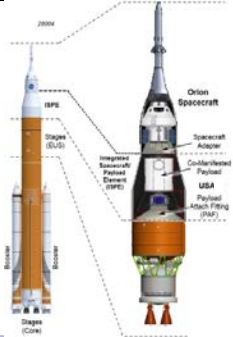
## ➤ Project plans to accomplish objectives

- 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

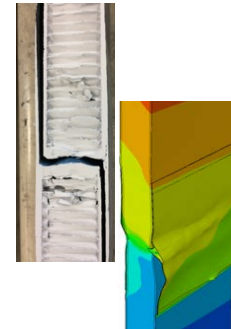
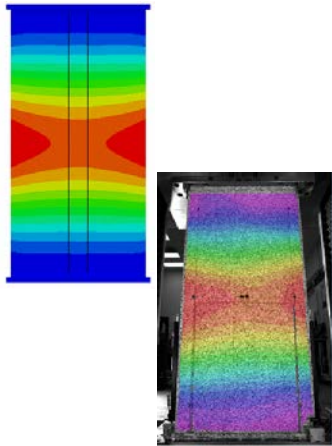


Size and Loading Requirements

Material Characterization Test and Selection

Preliminary/Detailed Joint Analysis

Preliminary/Detailed Joint Analysis



Scale-Up, Large Panel Tests

Sub-element Tests and Post-Test Analysis

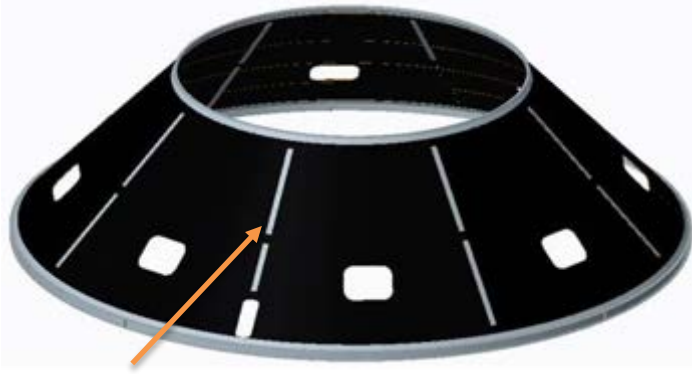
Joint Manufacturing and Process Development

Large-Scale Post-Test Analysis and Correlation



# Technical Status

## SLS Payload Adapter Longitudinal Bonded Joint Preliminary Design and Analysis Accomplishments



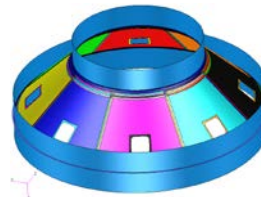
Longitudinal Bonded Joint

- CTE team presented preliminary longitudinal bonded joint sizing to PLA team on August 26<sup>th</sup>
- 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

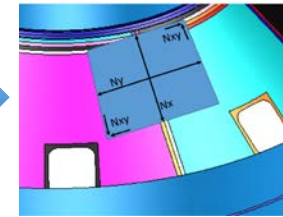
### CTE bonded joint sizing process used for PLA for longitudinal bonded joint sizing

LC	g Load	Angle	0.1 psi
1	A	0.0	Burst
2	A	0.0	Crush
3	A	22.5	Burst
4	A	22.5	Crush
5	B	0.0	Burst
6	B	0.0	Crush
7	B	22.5	Burst
8	B	22.5	Crush
9	C	0.0	Burst
10	C	0.0	Crush
11	C	22.5	Burst
12	C	22.5	Crush

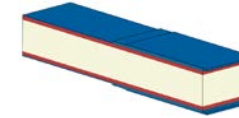
12 PLA load cases applied to sizing FEM



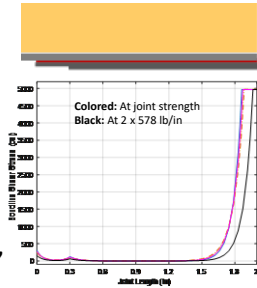
PLA Sizing Model



PLA Joint Line Loads Nx, Ny, Nxy



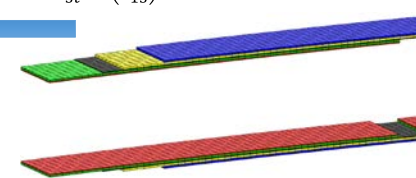
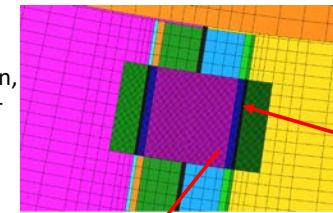
Preliminary Joint Sizing Using A4EI, HyperSizer, and Rapid FEA



Part	Loc	LC	MS						
			σ1	σ2	σ3	τ12	τ13	τ23	*FC 165
Facesheet Ply 9	Outer	06 @ 0 deg	10.8	10.9	21.9	86.2	11.4	10.9	10.0
		09 @ 180 deg	26.3	23.9	78.2	119.6	17.0	15.9	15.0
	Inner	06 @ 0 deg	10.6	11.0	31.2	33.4	15.8	16.8	13.9
		09 @ 180 deg	25.8	22.3	71.8	60.0	21.5	23.4	19.2
Facesheet Ply 8	Outer	06 @ 270 deg	81.5	27.5	83.0	138.4	32.5	76.1	31.0
		06 @ 0 deg	16.5	33.5	10.6	21.4	14.7	3.3	8.7
	Inner	09 @ 180 deg	37.6	9.4	29.9	35.1	21.5	5.5	13.0
		06 @ 270 deg	151.8	91.5	39.3	45.5	42.8	14.8	30.8
Inner	06 @ 0 deg	15.6	33.1	15.7	9.1	19.3	4.9	11.9	
	09 @ 180 deg	37.5	9.0	35.0	16.1	26.5	10.7	16.6	
Inner	06 @ 270 deg	22.0	319.3	50.5	23.1	32.3	8.6	28.1	

\*Failure Criteria #165  
Joint, Bonded, Delamination, Peel and Transverse Shear

$$\frac{\sigma_3}{F_{3t}} + \left(\frac{\tau_{13}}{F_{13}}\right)^2 = 1$$



2 Doubler Plies

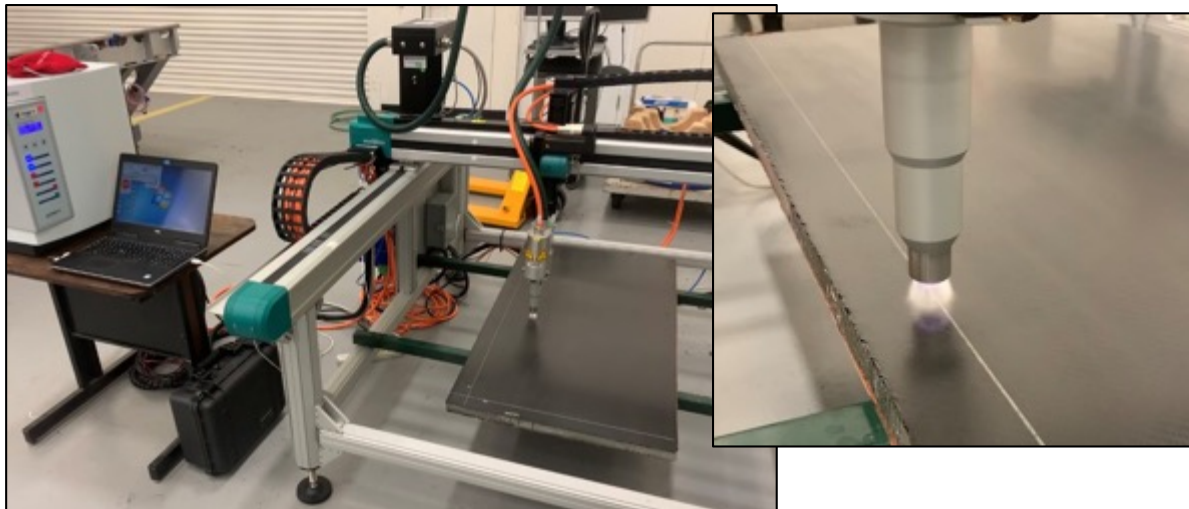
Global/Local Analysis

# Technical Status

## SLS Payload Adapter Longitudinal Bonded Joint Manufacturing Process Development

### 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

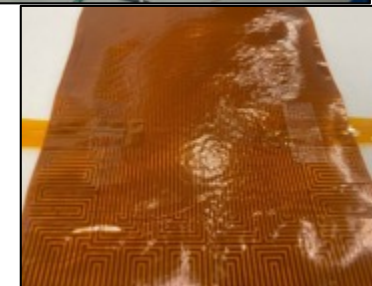
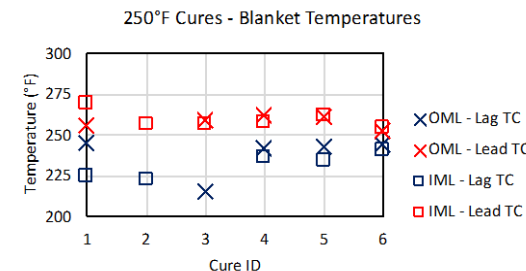
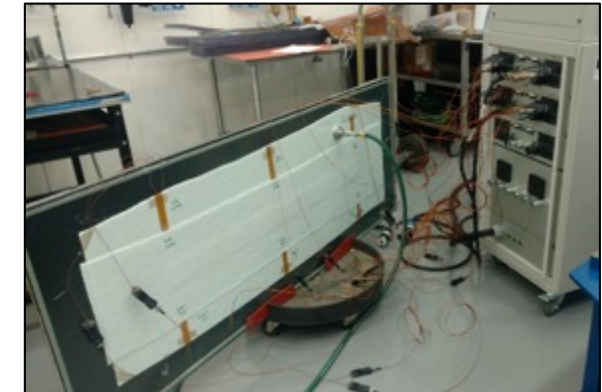


### Draft bonding process specification developed

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

### 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





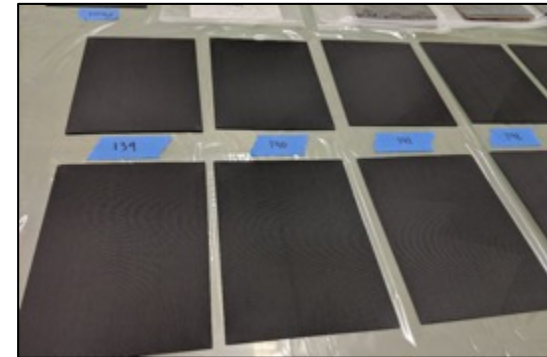
# Technical Status

## SLS Payload Adapter Longitudinal Bonded Joint Manufacturing Process Development

*To establish adequate process controls for bonded joints, processing parameters and critical process controls must be well understood*

### 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



Process Parameters		Adhesive Age (months)	Adhesive Out-time (days)	Laminate Age (months)	Relative Humidity (%)	Prep to Bond Time (days)	Cure Temp. (F)	Plasma Treatment (via APPT)
Tolerances		-0/+1	-0/+3	-0/+1	-5/+5	-0/+3	-10/+10	NA
Levels	Low	<6	<3	<1	<10	0	200	no
	Mid	null	null	null	null	null	250	null
	High	12	30	12	70	10	300	yes

Design of experiments for critical process parameters of adhesively bonded joints

# Technical Status

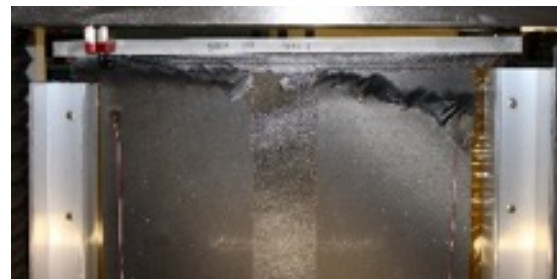
## Design, Analysis, Fabrication, and Testing of Large-Scale Longitudinal Bonded Jointed Concept

*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.*

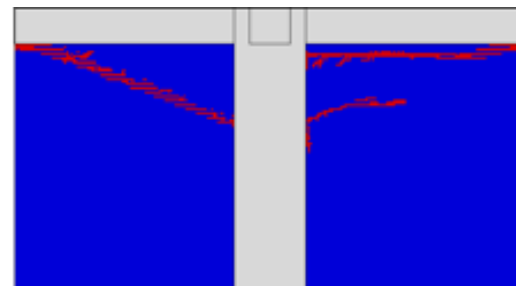
- Tests showed that composite bonded longitudinal joints are **predictable and reliable** under buckling load conditions.
- Tests showed that composite bonded longitudinal joints, both pristine and impact-damaged, **satisfy design load requirements** with 2.9 and 2.4 factors of safety, respectively,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



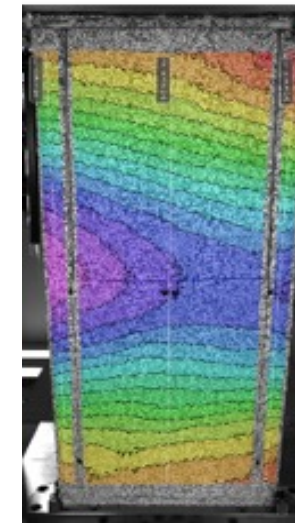
Panel Buckling Test Set-up



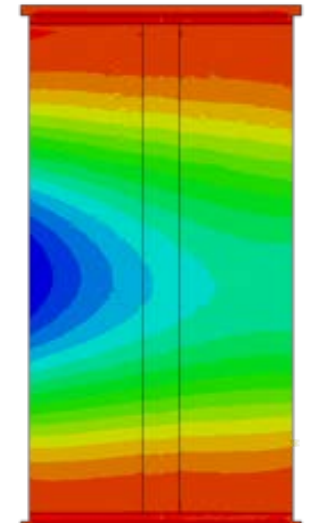
Failure Test



Failure Analysis



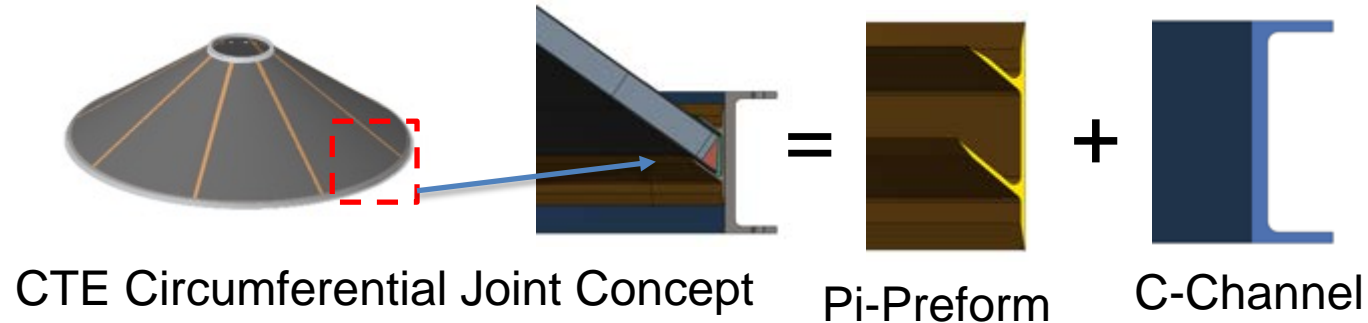
Buckling Test



Buckling Analysis

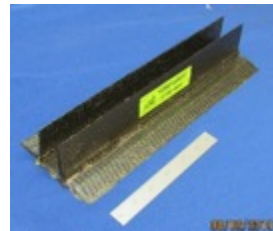
# Technical Status

## Circumferential Joint Manufacturing Accomplishments



### 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-Preforms



Pi-Preform Trial  
(90° orientation)



CRG Cured 36" C-Channels

### 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

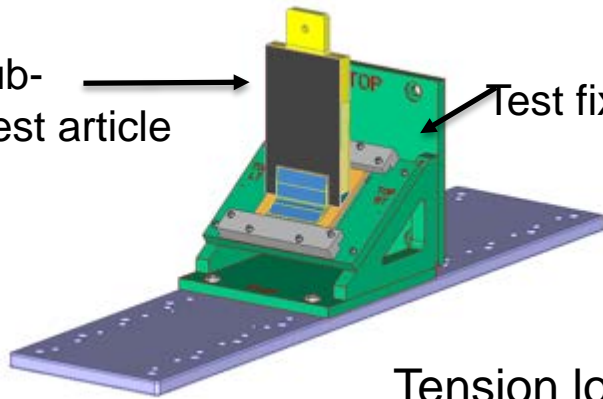
# Technical Status

## Circumferential Joint Manufacturing Accomplishments

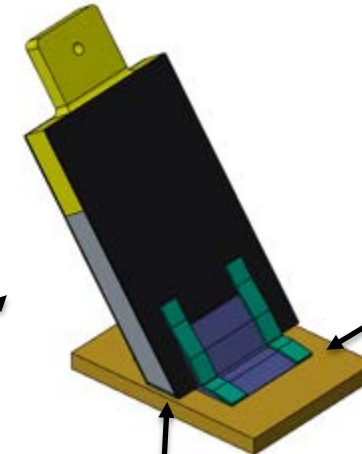
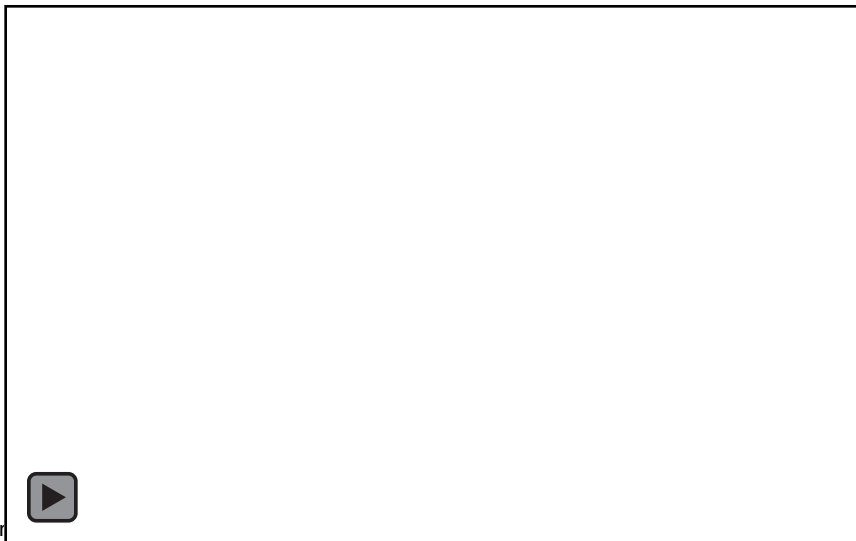


- Test article and test fixture designed and analyzed
- Fabrication of 5 C-Joint sub-element test articles completed
- Test plan completed

C-Joint sub-element test article design



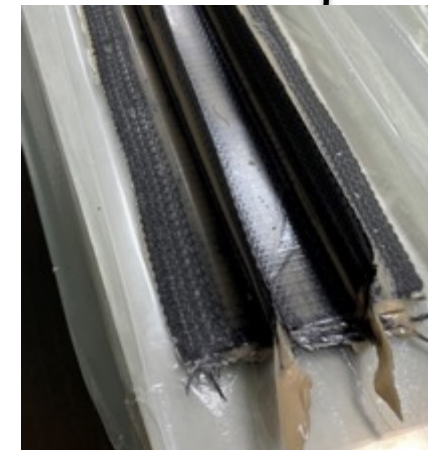
Tension loading:



Base plate fabrication complete



Sandwich section fabrication complete

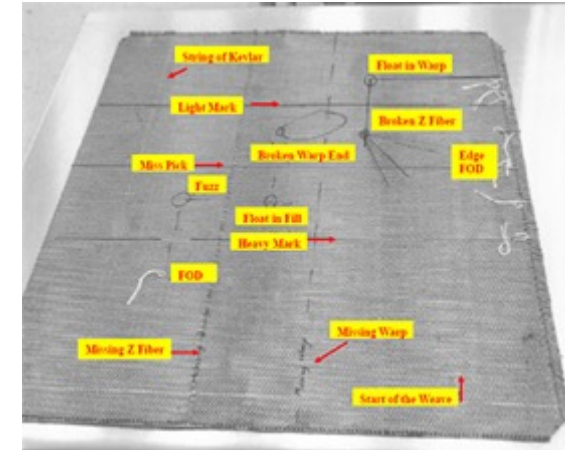


Pi-preform ready for bonding

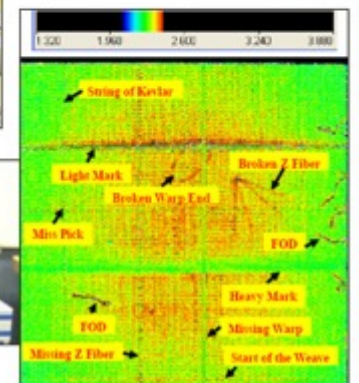
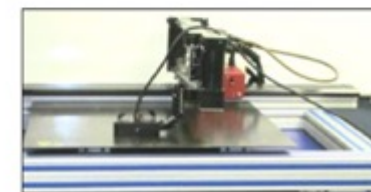
# Technical Status 3D Weave NDE



- 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.**



3D Woven  
Defect Panel  
Approx. 24" x 24"



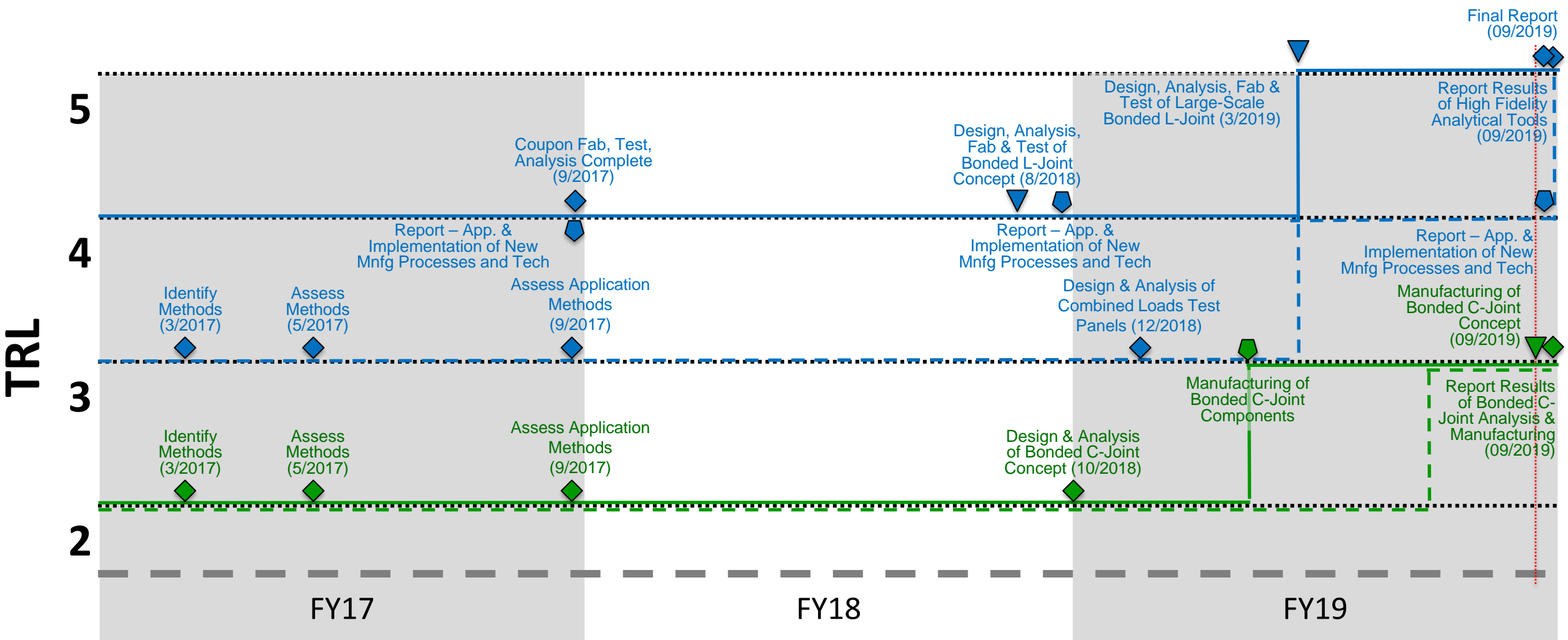
Various inspection equipment.

# CTE IMS/TRL Alignment



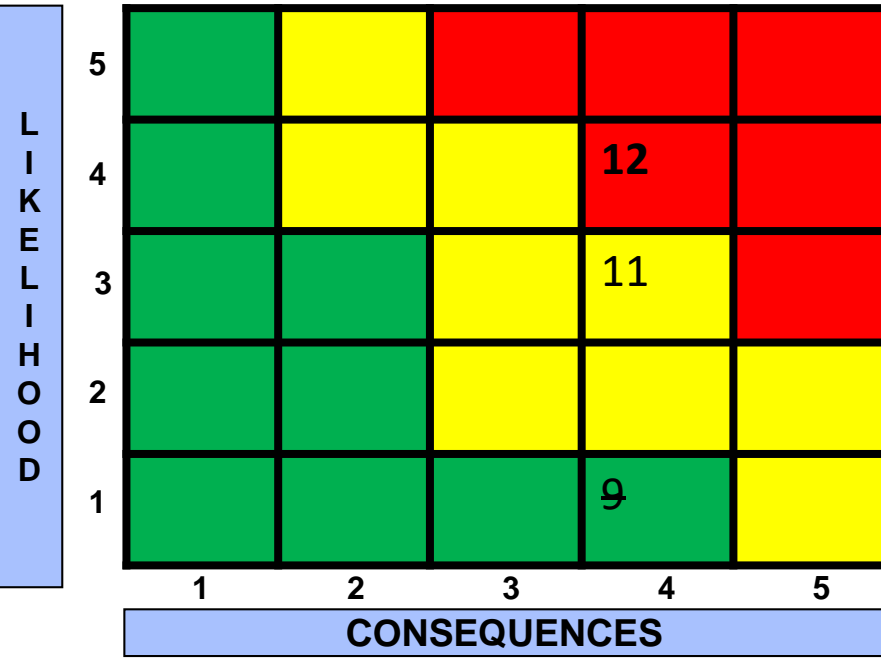
◆ Project Milestone    
 ◆ GCD (Key) Milestone    
 ▼ Controlled Milestone    
 — TRL Progression

— L- Joint Fab    
 — L- Joint Analysis    
 — C- Joint Fab    
 — C- Joint Analysis





# Technical Risk Summary



<b>Criticality</b>	<b>L x C Trend</b>	<b>Approach</b>
High	↓ Decreasing (Improving)	M - Mitigate
Med	↑ Increasing (Worsening)	W - Watch
Low	→ Unchanged	A - Accept
	□ New Since Last Period	R - Research

Risk ID	Affinity	Description/Status	Trend
9	M/T	<b>L-Joint Scale-Up</b> <i>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.</i> <b>CLOSED</b>	
11	M/T	<b>C-Joint Manufacturing Scale-Up</b> <i>Circumferential joint manufacturing developed at the laboratory scale may present challenges at full scale.</i>	↓
12	M/T	<b>C-Joint Assembly Scale-up</b> <i>Circumferential joint assembly developed at the laboratory scale may present challenges at full-scale.</i>	↓

Updated 09/17/2019

# EPO Summary Chart



## ➤ 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)
- 5/20-23/2019 - Society for the Advancement of Material Process Engineering (SAMPE) (Charlotte, NC)
- 9/24-26/2019 – Composites and Advanced Materials Expo (CAMX) (Anaheim, CA)



Mallory Johnston & Tracie Prater at NASA Day in Montgomery, Alabama

## 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.

# Annual Summary



- 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



Project	Performance				Comments
	C	S	T	P	
Mid Year	Yellow	Yellow	Green	Yellow	<p><b>Cost is yellow due to the decrease of SLS procurement funding for FY19.</b> Cost will trend toward green once decision is made on scope for the remainder of FY19.</p> <p><b>Schedule is yellow due to concerns with the first cured 12-in, 3D-woven C-Channel.</b> 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.</p> <p><b>Lessons learned from the 12-in C-Channels drive the design of the larger, scaled-up parts.</b></p> <p><b>Technical continues to be green.</b></p> <p><b>Programmatic is yellow while options and plans are assessed and a decision is made on scope for the remainder of FY19.</b> 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.</p>
Annual	Green	Green	Green	Green	<p>Cost – Green</p> <p>Schedule – Green</p> <ul style="list-style-type: none"> <li>- 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.</li> </ul> <p>Technical – Green</p> <ul style="list-style-type: none"> <li>- GSFC fabricated the first C-channel material test coupons. Three test coupons were shipped to NIAR (7/22/2019) and successfully tested.</li> <li>- Two circumferential bonded joint sub-elements have been manufactured and will be tested on 9/19/2019.</li> </ul> <p>Programmatic – Green</p> <ul style="list-style-type: none"> <li>- 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.</li> </ul>

# EPO Summary Chart



## ➤ Conferences attended

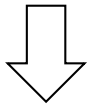
Conference Name	Papers/Posters/Panel Discussions
AIAA SciTech	4 Papers
SAMPE	1 Paper
NASA & NCAME workshop on “Composites Materials and Manufacturing Technologies for Space Applications	Discussions
CAMX	7 papers & Composites special session

# Circumferential Joint Manufacturing Scale Up



**11**

**Trend**



**Criticality**

**Med**

**Current LxC**

3x4

**Affinity Group**

Technical

**Planned Closure**

09/01/2020

**Open Date**

October 2018

**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 4<sup>th</sup> and 5<sup>th</sup> 12” C-channels. The lessons learned from the 4<sup>th</sup> and 5<sup>th</sup> 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.

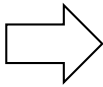
Mitigation Steps	Dollars to implement	Trigger/Start date	Schedule UID	Completion Date	Resulting L/C
Component- Work with resin transfer molding team to assess scale up issues (12” section)	\$0	1/1/2018		4/1/2019	3x4
Component- Work with resin transfer molding team to assess scale up issues (36” section)				8/01/2019	2x4
Component – Understand surface pitting with C-channel manufacturing.					2x4
Component – Understand effects of curved weave for C-channel manufacturing.					1x4

# Circumferential Joint Assembly Scale Up



**12**

**Trend**



**Criticality**

**High**

**Current LxC**

4x4

**Affinity Group**

Technical

**Planned Closure**

09/01/2020

**Open Date**

October 2018

**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

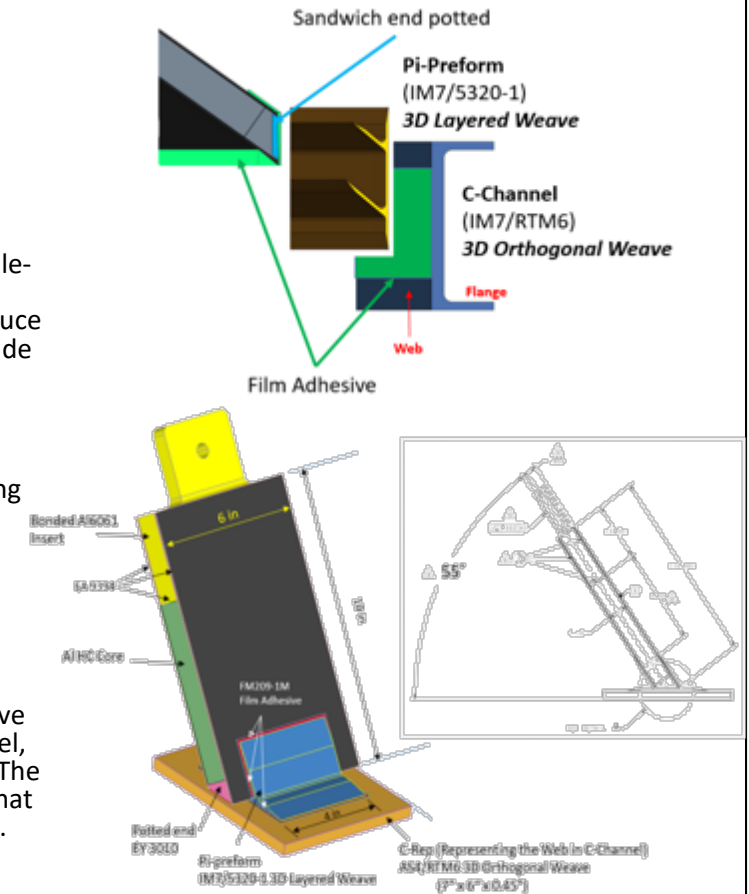
**Context**

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	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
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.		09/18/2019			4x4
Assembly- Test a representative element C-joint assembly with the pi preform, representative C-channel baseplate (3D-woven flat panel), and a sandwich panel.					3x4



2018 2019

MRL Exit Assessment Matrix – Composite Longitudinal joint manufacturing

Entry/Exit: 4/5  
AD2 entry/exit:  
6/5

	Manufacturing Tech Development	Producibility	Design Maturity	Materials Maturity	Modeling and Simulation	Manufacturing Maturity
2: Manufacturing Concepts Identified.	New manufacturing concepts and potential solutions identified.	N/A	Applications defined. Broad performance goals identified that may drive manufacturing options.	Material properties and characteristics predicted N/A	Initial models developed, if applicable.	Materials and/or process approaches identified.
3: Manufacturing Proof of Concept Demonstrated.	Manufacturing technology concepts identified through experiments/models	Relevant materials/processes evaluated for manufacturability using experiments/models	Top level performance requirements defined. Trade-offs in design options assessed based on experiments. Product lifecycle and technical requirements evaluated.	Material properties validated and assessed for basic manufacturability using experiments.	Identification of proposed manufacturing concepts or producibility needs based on high-level process flow models.	Critical manufacturing processes identified through experimentation.
4: Manufacturing Process in Lab Environment.	Manufacturing Science & Advanced Manufacturing Technology requirements identified.	Initial producibility and manufacturability assessment of preferred systems concepts completed. Results considered in selection of preferred design concepts	System characteristics and measures to support required capabilities identified. Form, fit, and function constraints identified and manufacturing capabilities identified for preferred systems concepts.	Projected materials have been produced in a laboratory environment.	Production modeling/simulation approaches for process or product are identified applicable.	Critical processes demonstrated and assessed in the laboratory.
5: Prototype components in Production Relevant Environment.	Required manufacturing technology development efforts at sufficient maturity for manufacturing prototypes.	Producibility and manufacturability assessments of key technologies and components initiated. Ongoing design trades consider manufacturing processes. Manufacturing processes assessed for capability to test and verify in production.	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.	Materials have been manufactured or produced in a prototype environment. Maturation efforts in place to address new material production risks for technology demonstration.	Initial models/simulation (product or process) developed at the component level and used to determine constraints.	Maturity has been assessed on similar processes in production. Process capability requirements have been identified for pilot line, low and full rate production.
6: System or Subsystem in a Production Relevant Environment	Required manufacturing technology development solutions demonstrated in a production relevant environment.	Producibility assessments and producibility trade studies (performance vs. producibility) of key technologies/components completed. Preliminary designs assessed against manufacturing processes..	System requirements and features are well enough 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.	Material maturity verified through technology demonstration articles. Preliminary material specifications in place and material properties have been adequately characterized.	Initial models/simulation (product or process) developed at the component level and used to determine constraints.	Manufacturing processes demonstrated in a production relevant environment. Process capability data is available (actual or modeled) from prototype build and process capability req'ts are refined based on this data.
Rationale	Demonstrated by manufacturing four CTE L-joints on SLS payload adapter (PLA) manufacturing demonstration article (MDA)	Demonstrated by manufacturing four CTE L-joints on SLS payload adapter (PLA) manufacturing demonstration article (MDA). Additional trades studies done: surface prep, cure techniques (heater blankets)	Demonstrated by manufacturing four CTE L-joints on SLS payload adapter (PLA) manufacturing demonstration article (MDA)	Material maturity verified through NCAMP database. Additional testing on film adhesive + Large scale panel test and material testing.	N/A – production modeling not looked at on this project.	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)

2018 2019

AD2 Level 5



2018 2019

**Current TRL Exit Assessment Matrix – Composite Longitudinal joints - Analysis**

Entry/Exit: 3/5  
AD2 entry: 6

TRL	Functional Elements	System Definition	System Integration	Modeling and Simulation Tools	Capability Validation	Environmental Validation	Life-cycle Design
2: Technology concept and/or application formulated.	Basic functional elements of technology have been identified.	An apparent engineering design approach has been identified.	System architecture defined in terms of basic functions to be performed.	Operational requirement of functional elements verified through modeling or simulation.	Preliminary performance predictions have been made for basic functional elements.	Critical functional experiments for operational environment are known.	N/A
3: Analytical and experimental critical function and/or characteristic proof-of-concept.	Operation of functional elements verified through bench-scale tests.	Definition of relevant operational environment defined for basic functional components.	A conceptual design of the integrated system has been defined.	Models exist to extent that computer analysis and simulations are possible.	Preliminary system performance measurements have been identified and estimated.	Experimental results demonstrate feasibility of operations for basic functions to be performed	N/A
4: Component and/or breadboard validation in laboratory environment.	Subsystem tests in a simulated laboratory environment show element interfaces will function.	System performance metrics and test requirements have been defined for relevant operational environment.	Preliminary functional testing of integrated system completed at laboratory bench-scale.	Modeling shows subsystem interfaces will function at system level to satisfy functional requirements.	System performance metrics verified under simulated use conditions.	Laboratory scale tests indicate components and subsystem interfaces will function in operational environments	Operational needs for all material properties have been identified.
5: Component and/or breadboard validation in relevant environment.	Functional element and interfaces sufficiently understood at engineering-scale to provide system design tradeoffs.	Prototypical system testing for the ranges of critical operational environments validates design.	Engineering scale-up challenges understood and resolved for functional system.	Modeling shows subsystem interfaces will function at system level in operational environment.	<b>System and subsystem functional parameters are demonstrated on a bench scale.</b>	System testing in approximate operational environment completed.	Operational capability of all materials has been demonstrated.
6: System/sub-system model or prototype demonstrated in a relevant environment	Functional elements and interfaces provide optimized system design.	Full-scale engineering design specifications complete and documented.	Full technology system integration demonstrated at an engineering scale.	Performance predictions verified by engineering-scale testing and documented.	Functionality of a high-fidelity engineering design unit demonstrated.	Engineering-scale tests demonstrate functionality over full range of design critical environments	Full-scale design specifications complete and documented.
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.	Based on testing of sub-element testing and analysis for operating relevant loads and temperatures. Models have been set up for whole system and included relevant material data, including data for large scale panel and exercised the model for a full system.	Based on testing of sub-element L-Joint testing and analysis failure load and mode prediction. Applied methodology for analysis to the PLA.	Based on sub-element coupon test results failing above design limit with 2.0 FS and analysis performance in predicting failure load and modes. Demonstrated scaled up composite bonded longitudinal joint manufacturing and structural performance. Analysis showed we can predict buckling and joint failure load/mode of large-scale bonded joint. Applied methodology for analysis to the PLA and verified engineering scale	Sub-element L-joint tested and analyzed under some simulated loading conditions. Demonstrated scaled up composite bonded longitudinal joint manufacturing and structural performance. Analysis showed we can predict buckling and joint failure load/mode of large-scale bonded joint. Applied methodology for analysis to the PLA 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 buckling and joint failure load/mode of large-scale bonded joint. Applied methodology for analysis to the PLA and verified engineering scale Not yet TRL 6: Maybe there are other environments that we didn't consider. We didn't include the vibration/acoustic environment.	Based on CTE project testing to obtain material properties. We have the complete approach. Not fully documented.

2018 2019  
AD2 Level 5



2018 2019

**Current TRL Exit Assessment Matrix – Composite Longitudinal joints - NDE**

Entry/Exit: 4/5  
Life AD2 entry: 5  
Design

TRL	Functional Elements	System Definition	System Integration	Modeling and Simulation Tools	Capability Validation	Environmental Validation	Life AD2 entry: 5 Design
2: Technology concept and/or application formulated.	Basic functional elements of technology have been identified.	An apparent engineering design approach has been identified.	System architecture defined in terms of basic functions to be performed.	Operational requirement of functional elements verified through modeling or simulation.	Preliminary performance predictions have been made for basic functional elements.	Critical functional experiments for operational environment are known.	N/A
3: Analytical and experimental critical function and/or characteristic proof-of-concept.	Operation of functional elements verified through bench-scale tests.	Definition of relevant operational environment defined for basic functional components.	A conceptual design of the integrated system has been defined.	Models exist to extent that computer analysis and simulations are possible.	Preliminary system performance measurements have been identified and estimated.	Modeling or experimental results show feasibility of basic functions in expected environments.	N/A
4: Component and/or breadboard validation in laboratory environment.	Subsystem tests in a simulated laboratory environment show element interfaces will function.	System performance metrics and test requirements have been defined for relevant operational environment.	Preliminary functional testing of integrated system completed at laboratory bench-scale.	Modeling shows subsystem interfaces will function at system level to satisfy functional requirements.	System performance metrics verified under simulated use conditions.	Laboratory scale tests indicate components and subsystem interfaces will function in operational environments	Operational needs for all material properties have been identified.
5: Component and/or breadboard validation in relevant environment.	Functional element and interfaces sufficiently understood at engineering-scale to provide system design tradeoffs.	Prototypical system testing for the ranges of critical operational environments validates design.	Engineering scale-up challenges understood and resolved for functional system.	Modeling shows subsystem interfaces will function at system level in operational environment.	System and subsystem functional parameters are demonstrated on a bench scale.	System testing in approximate operational environment completed.	Operational capability of all materials has been demonstrated.
6: System/sub-system model or prototype demonstrated in a relevant environment	Functional elements and interfaces provide optimized system design.	Full-scale engineering design specifications complete and documented.	Full technology system integration demonstrated at an engineering scale.	Performance predictions verified by engineering-scale testing and documented.	Functionality of a high-fidelity engineering design unit demonstrated.	Engineering-scale tests demonstrate functionality over full range of design critical environments	Full-scale design specifications complete and documented.
Rationale	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.	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.	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.	NDE methods used for CTE L-joints are mature and have been demonstrated on numerous flight programs. Modeling and historical data support conclusions that identified techniques will perform, but additional testing would be required to verify performance in other configurations.	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.	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.	NDE methods used for CTE L-joints are mature and have been demonstrated on numerous flight programs. Modeling and historical data support conclusions that identified techniques will perform, but additional testing would be required to verify performance in a range of configurations.

2018 2019  
AD2 Level 5



2018 2019

MRL Exit Assessment Matrix – Composite C joint manufacturing

Entry/Exit: 2/3  
AD2 entry: 8  
maturity

	Manufacturing Tech Development	Producibility	Design Maturity	Materials Maturity	Modeling and Simulation	Manu
2: Manufacturing Concepts Identified.	New manufacturing concepts and potential solutions identified.		Applications defined. Broad performance goals identified that may drive manufacturing options.	Material properties and characteristics predicted.	Initial models developed, if applicable.	Materials and/or process approaches identified.
3: Manufacturing Proof of Concept Demonstrated.	Manufacturing technology concepts identified through experiments/models	Relevant materials/processes evaluated for manufacturability using experiments/models	Top level performance requirements defined. Trade-offs in design options assessed based on experiments. Product lifecycle and technical requirements evaluated.	Material properties validated and assessed for basic manufacturability using experiments.	Identification of proposed manufacturing concepts or producibility needs based on high-level process flow models.	Critical manufacturing processes identified through experimentation.
4: Manufacturing Process in Lab Environment.	Manufacturing Science & Advanced Manufacturing Technology requirements identified.	Initial producibility and manufacturability assessment of preferred systems concepts completed. Results considered in selection of preferred design concepts	System characteristics and measures to support required capabilities identified. Form, fit, and function constraints identified and manufacturing capabilities identified for preferred systems concepts.	Projected materials have been produced in a laboratory environment.	Production modeling/simulation approaches for process or product are identified applicable.	Critical processes demonstrated and assessed in the laboratory.
5: Prototype components in Production Relevant Environment.	Required manufacturing technology development efforts at sufficient maturity for manufacturing prototypes.	Producibility and manufacturability assessments of key technologies and components initiated. Ongoing design trades consider manufacturing processes. Manufacturing processes assessed for capability to test and verify in production.	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.	Materials have been manufactured or produced in a prototype environment. Maturation efforts in place to address new material production risks for technology demonstration.	Initial models/simulation (product or process) developed at the component level and used to determine constraints.	Maturity has been assessed on similar processes in production. Process capability requirements have been identified for pilot line, low and full rate production.
6: System or Subsystem in a Production Relevant Environment	Required manufacturing technology development solutions demonstrated in a production relevant environment.	Producibility assessments and producibility trade studies (performance vs. producibility) of key technologies/components completed. Preliminary designs assessed against manufacturing processes..	System requirements and features are well enough 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.	Material maturity verified through technology demonstration articles. Preliminary material specifications in place and material properties have been adequately characterized.	Initial models/simulation (product or process) developed at the component level and used to determine constraints.	Manufacturing processes demonstrated in a production relevant environment. Process capability data is available (actual or modeled) from prototype build and process capability req'ts are refined based on this data.
Rationale	Have not fabricated CTE prototypes yet, but Composite Crew Module (CCM) is a relevant environment for CTE. We have manufactured prototypes: c-channel and pi preform. (test coupon: straight piece for prototype)	3d weave Concept identified but not yet demonstrated; some components have been fabricated, but the CTE application for C-joint is not yet complete. We've manufactured the individual components and assembly - a representative straight Circumferential joint prototype ( the 3d weave flat panel and pi preform )	CTE C-joints are still at a low level of design maturity, pending coupon-level tests and validation of analyses. System characteristics and measures are identified as well as the mitigation capabilities needed for those preferred sys. (the void content, doing the cross sections, the process and making sure during cure the parts consolidate as required and bond as needed). We've done in a lab environment.	Materials have been produced and used on other NASA and ESA projects; yet to be applied to CTE. All components of C joint have been assembled. We have identified risks and are addressing them with application to CTE design (ex: pi preform resin distribution and applying intensifiers)	Cornerstone is modeling springback – one example of process modeling. BRM uses a simulation for the weave. It's been identified and we've used them and iterated and used them at the component level to determine constraints (fiber % and fiber volume)	CCM is the basis for maturation start point for CTE. The CTE C-joint has not been fabricated yet; development work for assembly has not been initiated; critical processes have not been identified. CTE has fab'd the components of the C Joint and working towards assembly and test of the sub assembly

2018 2019

AD2 Level 8



2018 2019

**Current TRL Exit Assessment Matrix – Composite Circumferential joints - Analysis**

Entry/Exit: 2/3  
AD2 entry: 8

TRL	Functional Elements	System Definition	System Integration	Modeling and Simulation Tools	Capability Validation	Environmental Validation	Design
2: Technology concept and/or application formulated.	Basic functional elements of technology have been identified.	An apparent engineering design approach has been identified.	System architecture defined in terms of basic functions to be performed.	Operational requirement of functional elements verified through modeling or simulation.	Preliminary performance predictions have been made for basic functional elements.	Critical functional experiments for operational environment are known.	N/A
3: Analytical and experimental critical function and/or characteristic proof-of-concept.	Operation of functional elements verified through bench-scale tests.	Definition of relevant operational environment defined for basic functional components.	A conceptual design of the integrated system has been defined.	Models exist to extent that computer analysis and simulations are possible.	Preliminary system performance measurements have been identified and estimated.	Experimental results demonstrate feasibility of operations for basic functions to be performed	N/A
4: Component and/or breadboard validation in laboratory environment.	Subsystem tests in a simulated laboratory environment show element interfaces will function.	System performance metrics and test requirements have been defined for relevant operational environment.	Preliminary functional testing of integrated system completed at laboratory bench-scale.	Modeling shows subsystem interfaces will function at system level to satisfy functional requirements.	System performance metrics verified under simulated use conditions.	Laboratory scale tests indicate components and subsystem interfaces will function in operational environments	Operational needs for all material properties have been identified.
5: Component and/or breadboard validation in relevant environment.	Functional element and interfaces sufficiently understood at engineering-scale to provide system design tradeoffs.	Prototypical system testing for the ranges of critical operational environments validates design.	Engineering scale-up challenges understood and resolved for functional system.	Modeling shows subsystem interfaces will function at system level in operational environment.	System and subsystem functional parameters are demonstrated on a bench scale.	System testing in approximate operational environment completed.	Operational capability of all materials has been demonstrated.
6: System/sub-system model or prototype demonstrated in a relevant environment	Functional elements and interfaces provide optimized system design.	Full-scale engineering design specifications complete and documented.	Full technology system integration demonstrated at an engineering scale.	Performance predictions verified by engineering-scale testing and documented.	Functionality of a high-fidelity engineering design unit demonstrated.	Engineering-scale tests demonstrate functionality over full range of design critical environments	Full-scale design specifications complete and documented.
Rationale	C-joints have been designed and analyzed, but not tested. On the 3D weave, predicting stiffness has been demonstrated (the functional element). We've predicted, tested and verified our tools at that basic level based on coupon testing.	Based on analysis and design of C-joints for operational loads, we've done models of the C joint. We've come up with performance matrix (strength or stiff). We have some test requirements and design test coupon. Test matrix has been defined for validating analysis tools.	Conceptual design and analysis has been performed for C-joints. We have a integrated conceptual design and analysis of C-joints. We're developing analysis models and test predictions for our planned sub element test articles to be tested.	Computer models exist and simulations are being performed on C-joints. << Same >>	Preliminary analysis has been performed to assess C-joint performance. Keep at 3 – we have not 'verified'	Modeling and analysis results show feasibility of C-joints. Keep at 3 – test results are not in yet.	C-joints have been designed and analyzed, but not tested. Material properties are known and we know how we need them to behave.

2018 2019  
AD2 Level 7



2018 2019

**Current TRL Exit Assessment Matrix – Composite Circumferential joints - NDE**

Entry/Exit: 2/2  
AD2 entry: 8  
Design

TRL	Functional Elements	System Definition	System Integration	Modeling and Simulation Tools	Capability Validation	Environmental Validation	
2: Technology concept and/or application formulated.	Basic functional elements of technology have been identified.	An apparent engineering design approach has been identified.	System architecture defined in terms of basic functions to be performed.	Operational requirement of functional elements verified through modeling or simulation.	Preliminary performance predictions have been made for basic functional elements.	Critical functional experiments for operational environment are known.	N/A
3: Analytical and experimental critical function and/or characteristic proof-of-concept.	Operation of functional elements verified through bench-scale tests.	Definition of relevant operational environment defined for basic functional components.	A conceptual design of the integrated system has been defined.	N/A	Preliminary system performance measurements have been identified and estimated.	Modeling or experimental results show feasibility of basic functions in expected environments.	N/A
4: Component and/or breadboard validation in laboratory environment.	Subsystem tests in a simulated laboratory environment show element interfaces will function.	System performance metrics and test requirements have been defined for relevant operational environment.	Preliminary functional testing of integrated system completed at laboratory bench-scale.	Modeling shows subsystem interfaces will function at system level to satisfy functional requirements.	System performance metrics verified under simulated use conditions.	Laboratory scale tests indicate components and subsystem interfaces will function in operational environments	Operational needs for all material properties have been identified.
5: Component and/or breadboard validation in relevant environment.	Functional element and interfaces sufficiently understood at engineering-scale to provide system design tradeoffs.	Prototypical system testing for the ranges of critical operational environments validates design.	Engineering scale-up challenges understood and resolved for functional system.	Modeling shows subsystem interfaces will function at system level in operational environment.	System and subsystem functional parameters are demonstrated on a bench scale.	System testing in approximate operational environment completed.	Operational capability of all materials has been demonstrated.
6: System/sub-system model or prototype demonstrated in a relevant environment	Functional elements and interfaces provide optimized system design.	Full-scale engineering design specifications complete and documented.	Full technology system integration demonstrated at an engineering scale.	Performance predictions verified by engineering-scale testing and documented.	Functionality of a high-fidelity engineering design unit demonstrated.	Engineering-scale tests demonstrate functionality over full range of design critical environments	Full-scale design specifications complete and documented.
Rationale	Potential NDE methodologies have not been demonstrated on any CTE C-joint components or assemblies. Shown 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 BRM and credible mfg defects and have a panel to start 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.	N/A	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 fwd.	Potential NDE methodologies have not been demonstrated on any CTE C-joint components or assemblies. Keep at TRL 2 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

2018 2019

AD2 Level 8



2018 2019

**Current TRL Exit Assessment Matrix – Composite Longitudinal joints - Design**

Entry/Exit: 4/5  
AD2 entry: 6

TRL	Functional Elements	System Definition	System Integration	Modeling and Simulation Tools	Capability Validation	Environmental Validation	Life-cycle Design
2: Technology concept and/or application formulated.	Basic functional elements of technology have been identified.	An apparent engineering design approach has been identified.	System architecture defined in terms of basic functions to be performed.	Operational requirement of functional elements verified through modeling or simulation.	Preliminary performance predictions have been made for basic functional elements.	Critical functional experiments for operational environment are known.	N/A
3: Analytical and experimental critical function and/or characteristic proof-of-concept.	Operation of functional elements verified through bench-scale tests.	Definition of relevant operational environment defined for basic functional components.	A conceptual design of the integrated system has been defined.	Models exist to extent that computer analysis and simulations are possible.	Preliminary system performance measurements have been identified and estimated.	Modeling or experimental results show feasibility of basic functions in expected environments.	N/A
4: Component and/or breadboard validation in laboratory environment.	Subsystem tests in a simulated laboratory environment show element interfaces will function.	System performance metrics and test requirements have been defined for relevant operational environment.	Preliminary functional testing of integrated system completed at laboratory bench-scale.	Modeling shows subsystem interfaces will function at system level to satisfy functional requirements.	System performance metrics verified under simulated use conditions.	Laboratory scale tests indicate components and subsystem interfaces will function in operational environments	Operational needs for all material properties have been identified.
5: Component and/or breadboard validation in relevant environment.	Functional element and interfaces sufficiently understood at engineering-scale to provide system design tradeoffs.	Prototypical system testing for the ranges of critical operational environments validates design.	Engineering scale-up challenges understood and resolved for functional system.	Modeling shows subsystem interfaces will function at system level in operational environment.	System and subsystem functional parameters are demonstrated on a bench scale.	System testing in approximate operational environment completed.	Operational capability of all materials has been demonstrated.
6: System/sub-system model or prototype demonstrated in a relevant environment	Functional elements and interfaces provide optimized system design.	Full-scale engineering design specifications complete and documented.	Full technology system integration demonstrated at an engineering scale.	Performance predictions verified by engineering-scale testing and documented.	Functionality of a high-fidelity engineering design unit demonstrated.	Engineering-scale tests demonstrate functionality over full range of design critical environments	Full-scale design specifications complete and documented.
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 defining required tests 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 data for large scale panel and exercised 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 PLA.	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 buckling and joint failure load/mode of large-scale bonded joint. Applied methodology for analysis to the PLA and verified engineering scale	Sub-element L-joint designed, analyzed, and tested under simulated loading conditions. Demonstrated scaled up composite bonded longitudinal joint manufacturing and structural performance. Analysis showed we can predict buckling and joint failure load/mode of large-scale bonded joint. Applied methodology for analysis to the PLA 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 buckling and joint failure load/mode of large-scale bonded joint. Applied methodology for analysis to the PLA and verified engineering scale Not yet TRL 6: Maybe there are other environment that we didn't consider. We didn't include the vibration/acoustic env.	Based on CTE project testing to obtain material properties. We have the complete approach. Not fully documented.

2018 2019  
AD2 Level 5

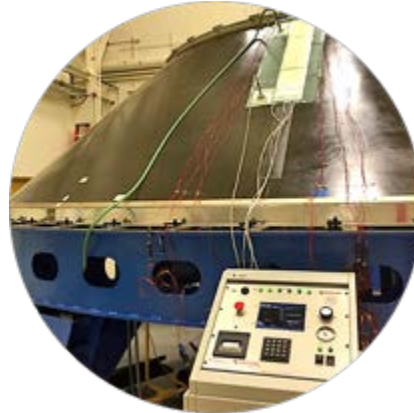
# CTE



Provide a brief caption for each description



Caption: Test coupon



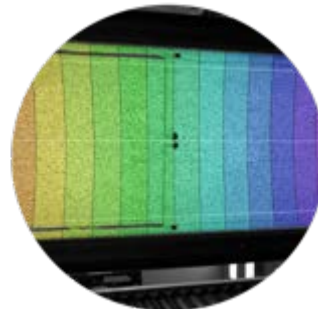
Caption: SLS Payload Adapter (PLA) Manufacturing Demonstration Article (MDA) curing a longitudinal composite joint.



Caption: Replacing tape on the automated fiber placement machine



Caption: Layup of a longitudinal composite joint panel

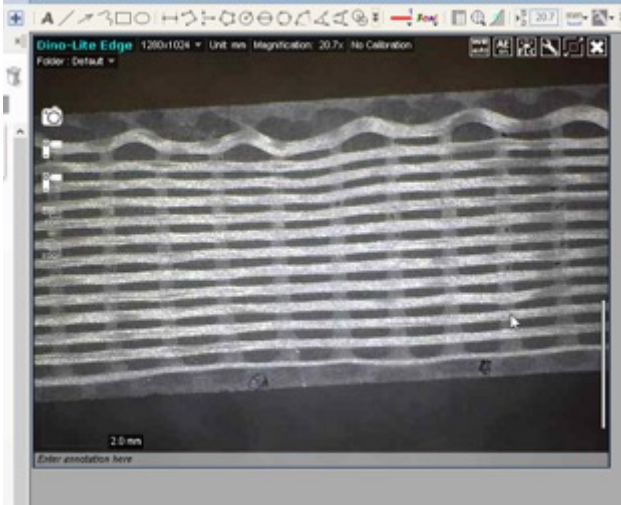
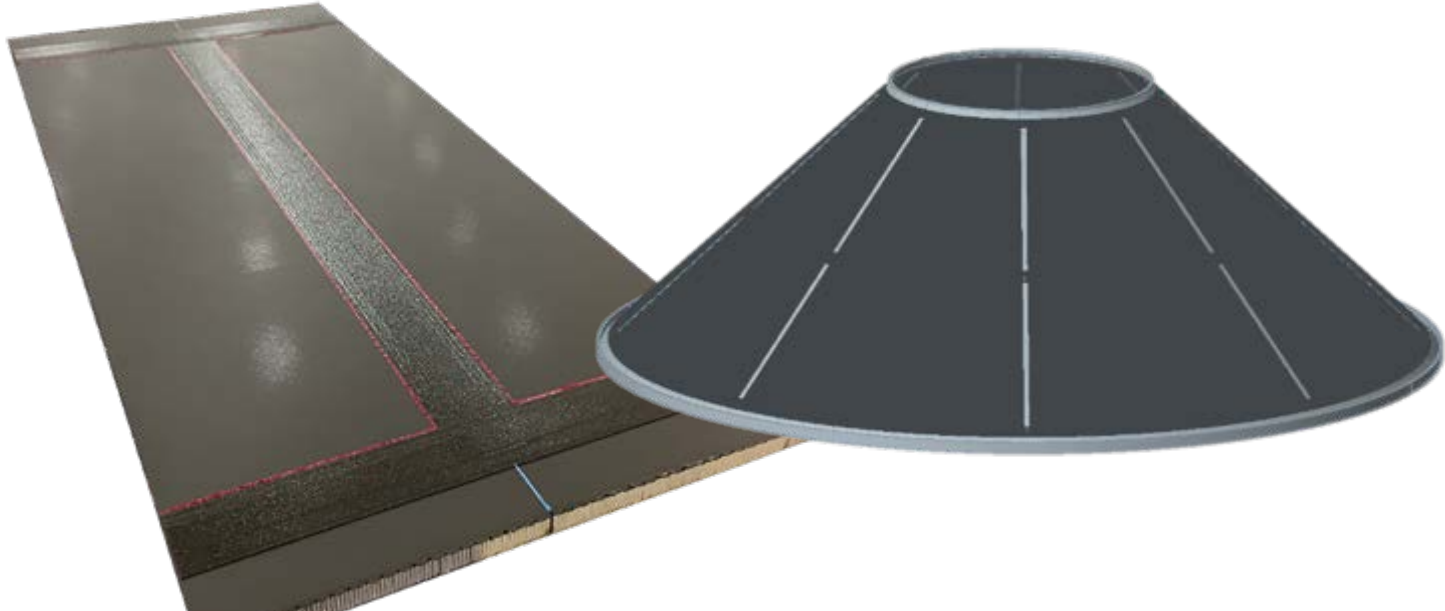
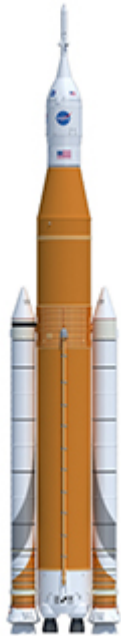


Caption: Non Destructive Evaluation of Large Scale Composite Bonded panel.



Caption: Bally Ribbon Mills machine for 3D weave

# Additional Pictures

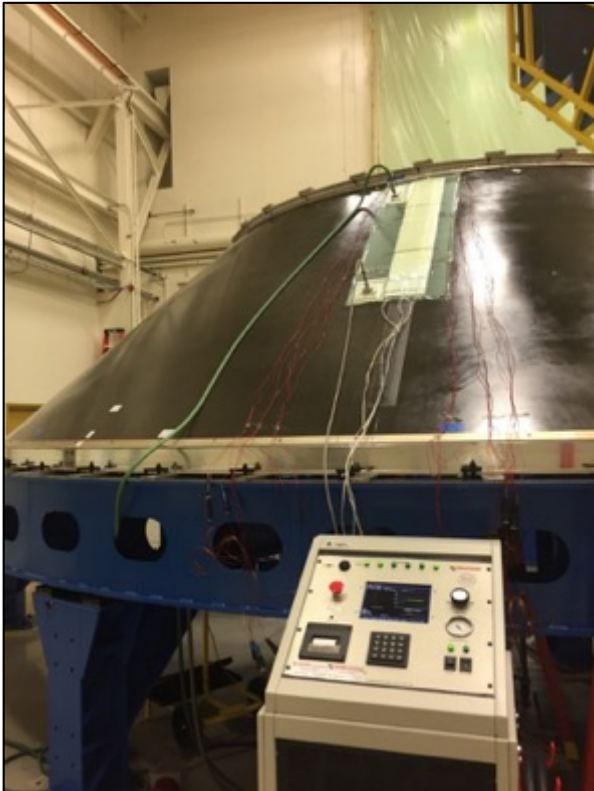
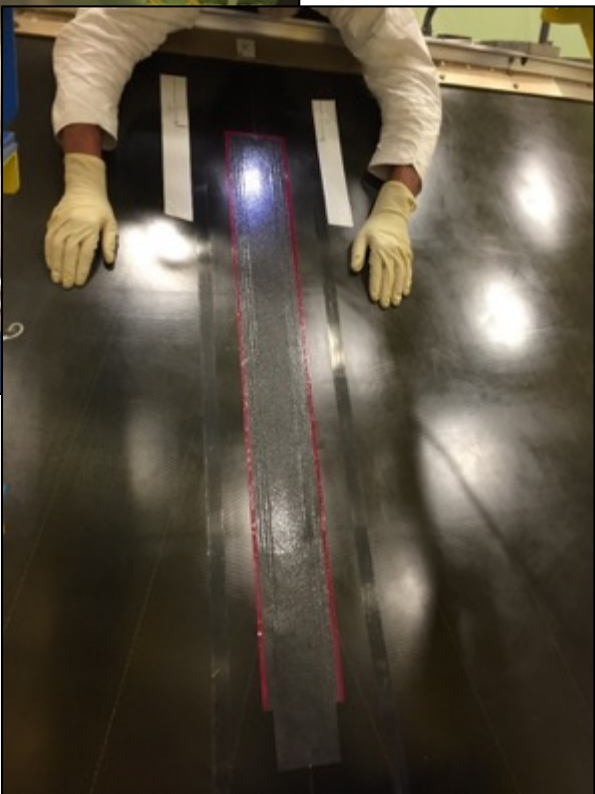


# Additional Pictures

Panel to panel joints to be bonded

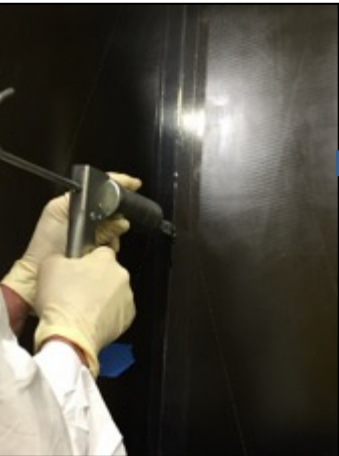
## SLS Payload Adapter (PLA) Manufacturing Demonstration Article (MDA) (Sept 2018)

Primary objective: Further develop and demonstrate manufacturing processes at full-scale  
Article will not be structurally tested at full-scale

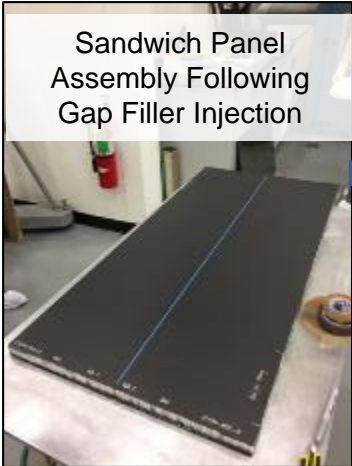


# Additional Pictures

## CTE Longitudinal Bonded Joint Panel Manufacturing Process



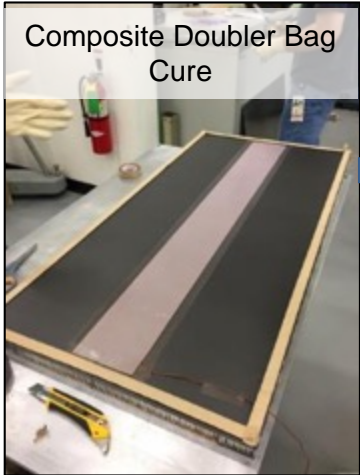
Sandwich Panel Assembly Undergoing Gap Filler Injection



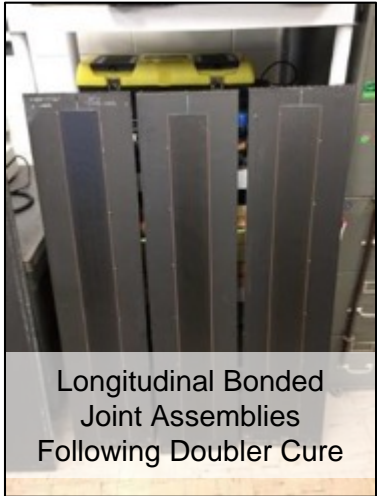
Sandwich Panel Assembly Following Gap Filler Injection



Composite Doubler Following Lay Up and Installation



Composite Doubler Bag Cure



Longitudinal Bonded Joint Assemblies Following Doubler Cure