Thermoplastic Development for Exploration Applications (TDEA) Project
Programmatic and Technical Overview

NIAR-NASA Meeting
August 16, 2022

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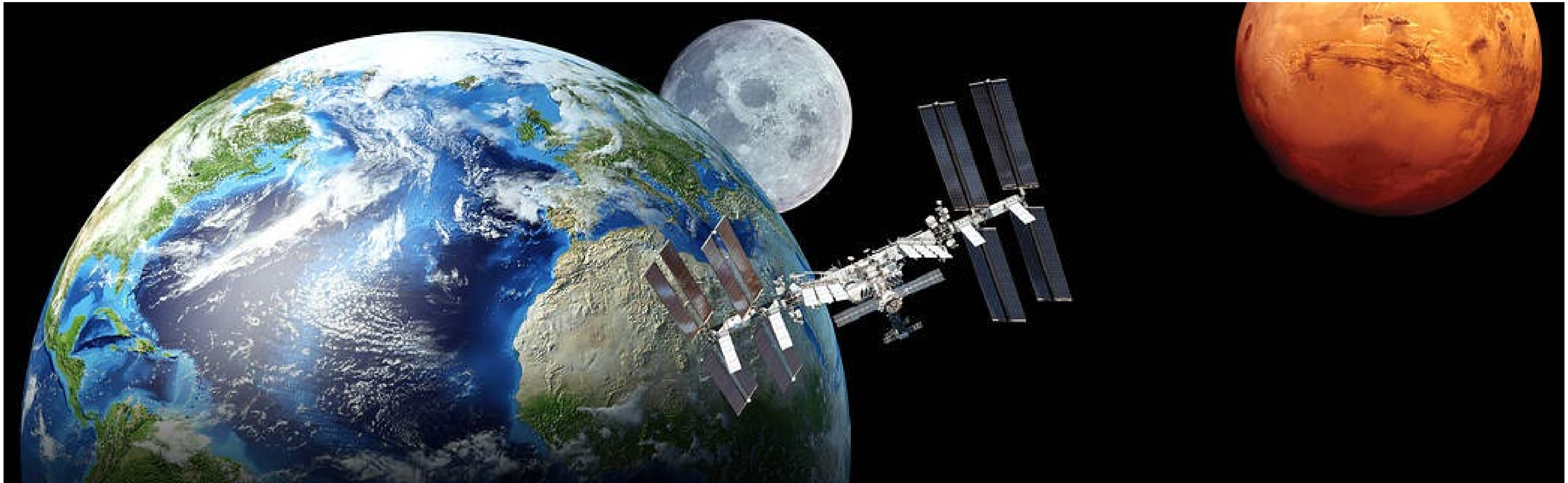
Today's Presentation

- Why is NASA addressing Thermoplastic Composites (TPCs) for space applications?
- What are TDEA plans?
- How will TDEA implement its plans?
- Who is doing this work?
- What are the collaboration opportunities?

TDEA Project Champion's and Team

STMD Administrator: James Reuter
Dir of Technology Maturation: Niki Werkheiser
Program Technologist: John Vickers
Program Element Manager: Martin Annett
Program Manager: John Fikes
Engineering Team: MSFC, GSFC, GRC, and LaRC
Budget: $12.35M   FY21-23



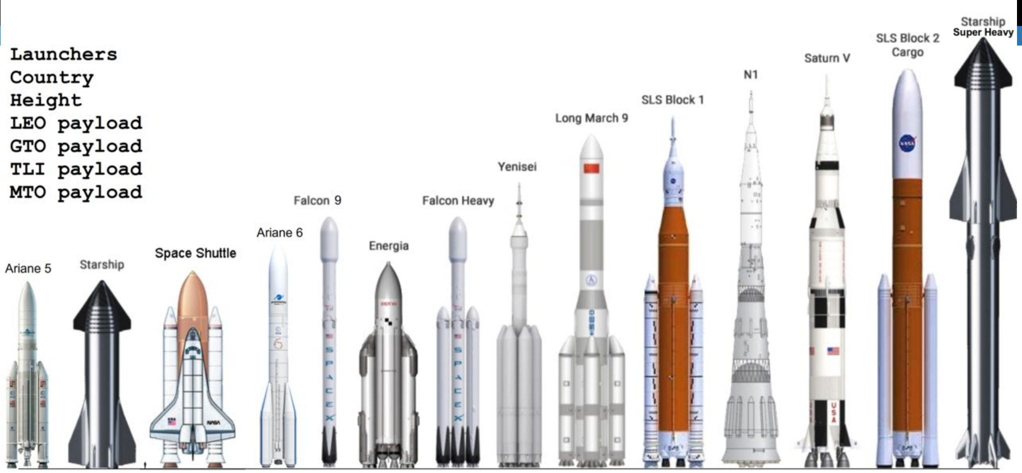
Why TPC?

- **Competitive with thermoset composites for terrestrial built structures**
  - Less complex manufacturing
    - Out-of-Autoclave, Out-of-Oven cure potential
    - Larger structures possible with fewer joints and/or fewer fasteners
  - TPC joining benefits include mass and cost savings
    - Fusion welded, no intermediary materials in the joint, no material discontinuities
      - Factor of Safety requirement potential reduction from 2.0 to 1.5
      - Structure certification requirements may be reduced because there are no bond lines
  - Can leverage aircraft industry lessons for space application
    - Airbus, Fokker, Tencate teaming for Thermoplastic Affordable Primary Aircraft Structure innovation program
    - Boeing and Northrup Grumman have decades of experience with TPC

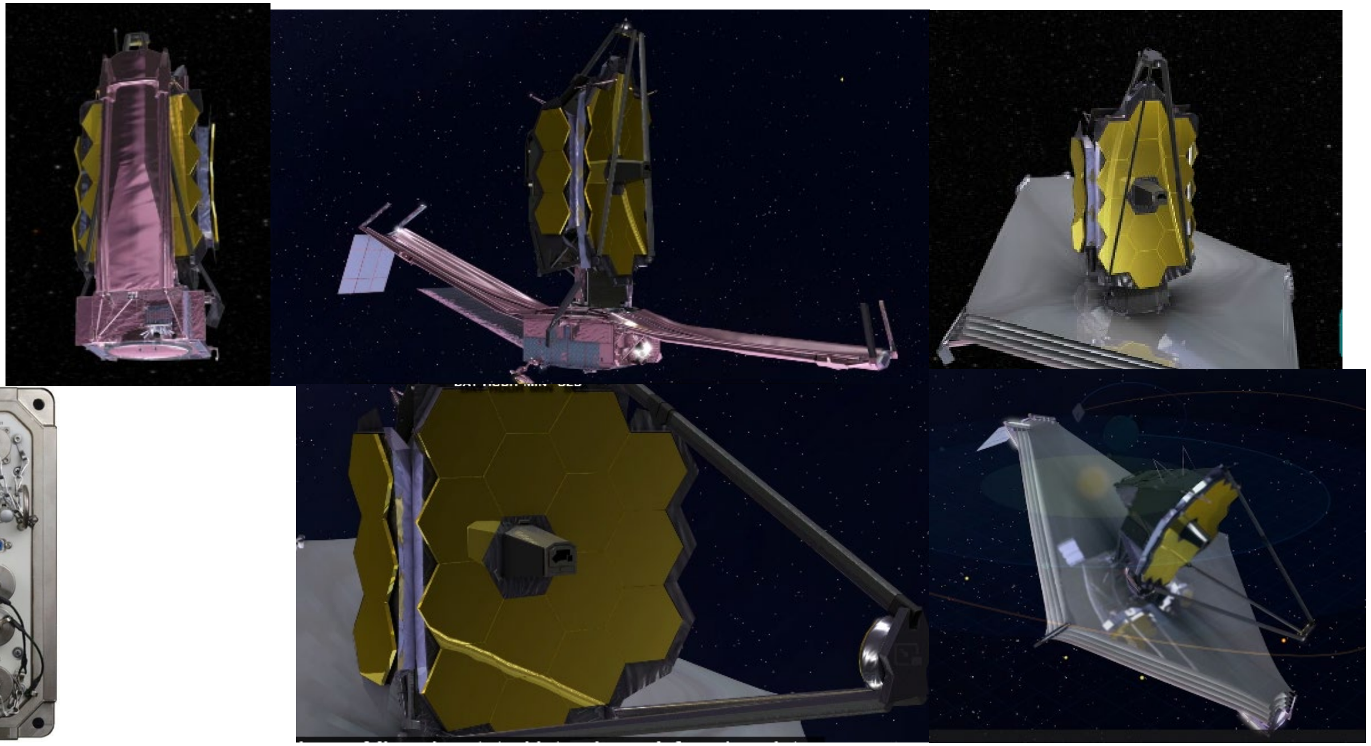
Gulfstream G650 TPC Rudder

Why TPC?

- Current launch systems are mass and volume limited
  - Missions fit within capability at great complexity and cost



- TPC may enable large-structure on-orbit manufacturing
  - NASA is already advancing in-space manufacturing with TP on ISS



AM on ISS: Acrylonitrile butadiene styrene (ABS) thermoplastics made on ISS starting in 2014

TDEA Objectives

Goal:

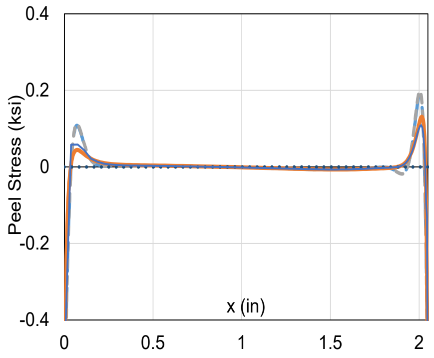
Advance NASA's thermoplastic composites capabilities by developing structurally efficient joining solutions for large-scale space structures and applications to support NASA's future exploration missions.

Objectives:

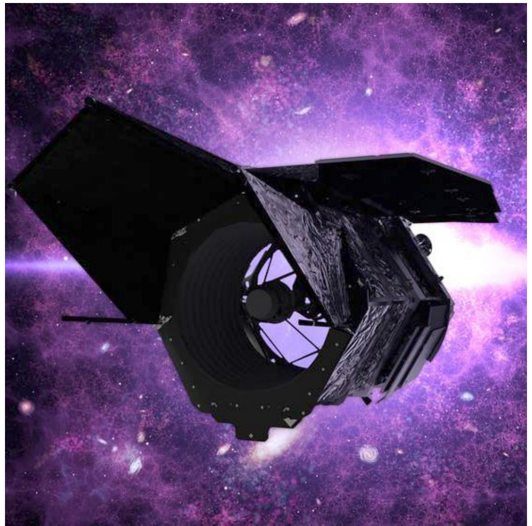
- Evaluate thermoplastic composite material systems for space structures and on-orbit applications.
- Assess the current design, analysis, and manufacture capability of commercially available TPC material systems space structures and on-orbit applications.
- Develop NASA's in-house TPC design, processing and manufacturing capabilities relevant to space structures.
- Develop and understand TPC joining technique(s) relevant to space environments and applicable to unitized and/or reconfigurable composite structures.
- Advance analysis capabilities for process and structural modeling of thermoplastic composites acreage and joints.
- Rapidly mature the most promising TPC processing technologies and associated design and analysis capabilities to enable infusion in future NASA missions.

Space Environment and joining are key focus areas

Will tapered joints be a problem?

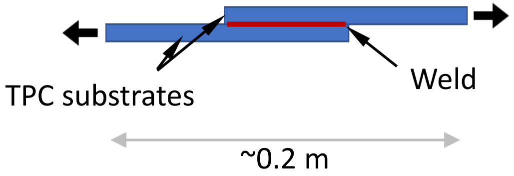


Roman Space Telescope (RST)



TDEA Technology Roadmap

Welded joint pathfinder
Foundational developments



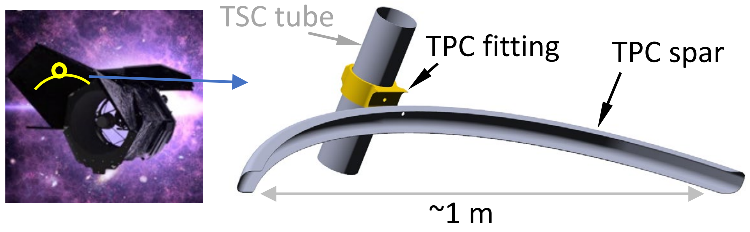
What?

- Coupon scale, **single welded interface**
- Develop analysis approaches for welded joints trade studies
- Fabricate and test joints with nominal conditions, and conditions relevant to in-space applications (e.g., off-nominal thermal history, lunar dust contamination)

Why?

- Seek in-house capabilities for TPC welding relevant to space applications
- Simple generic configuration to leverage existing data

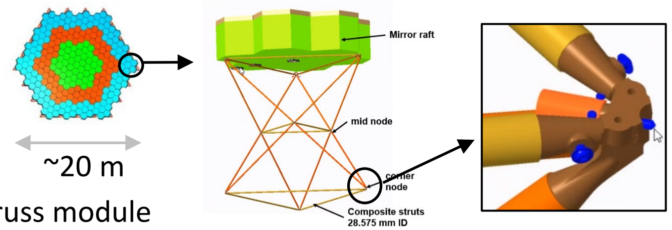
Roman Space Telescope (RST) support beam
Confidence building application



- Moderate-scale, **single spar and fitting**
- Terrestrially manufactured and assembled spacecraft structure
- Evaluate approaches that reduce cost through reduced part count and complexity compared with the RST baseline design

- Knowledge gap in application of TPCs to low-production-volume applications
- How can processes unique to TPCs (e.g., welding, additive) enable better designs?

Developments for in-space all-TPC truss assembly
Game Changing application

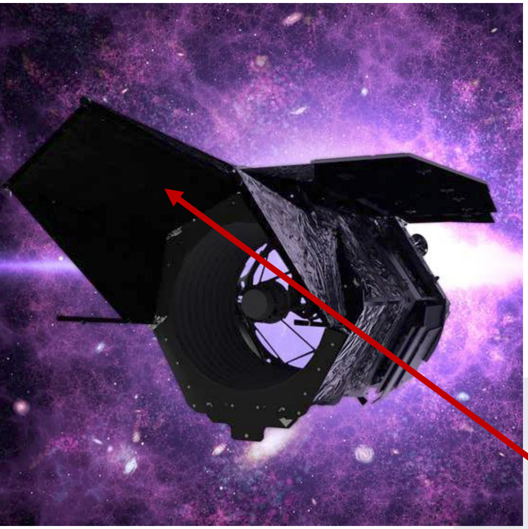


TriTruss module
(notional truss application)

- Large-scale, **multiple spars and fittings**
- Terrestrial manufacturing and in-space assembly (ISA)
- Identify relevant welded joint design requirements, and establish a TDEA Point Design
- Demonstrate through the building block approach

- Challenges remain for TPCs use in ISA/OSAM
- Develop deep understanding of considerations for TPC joining in-space

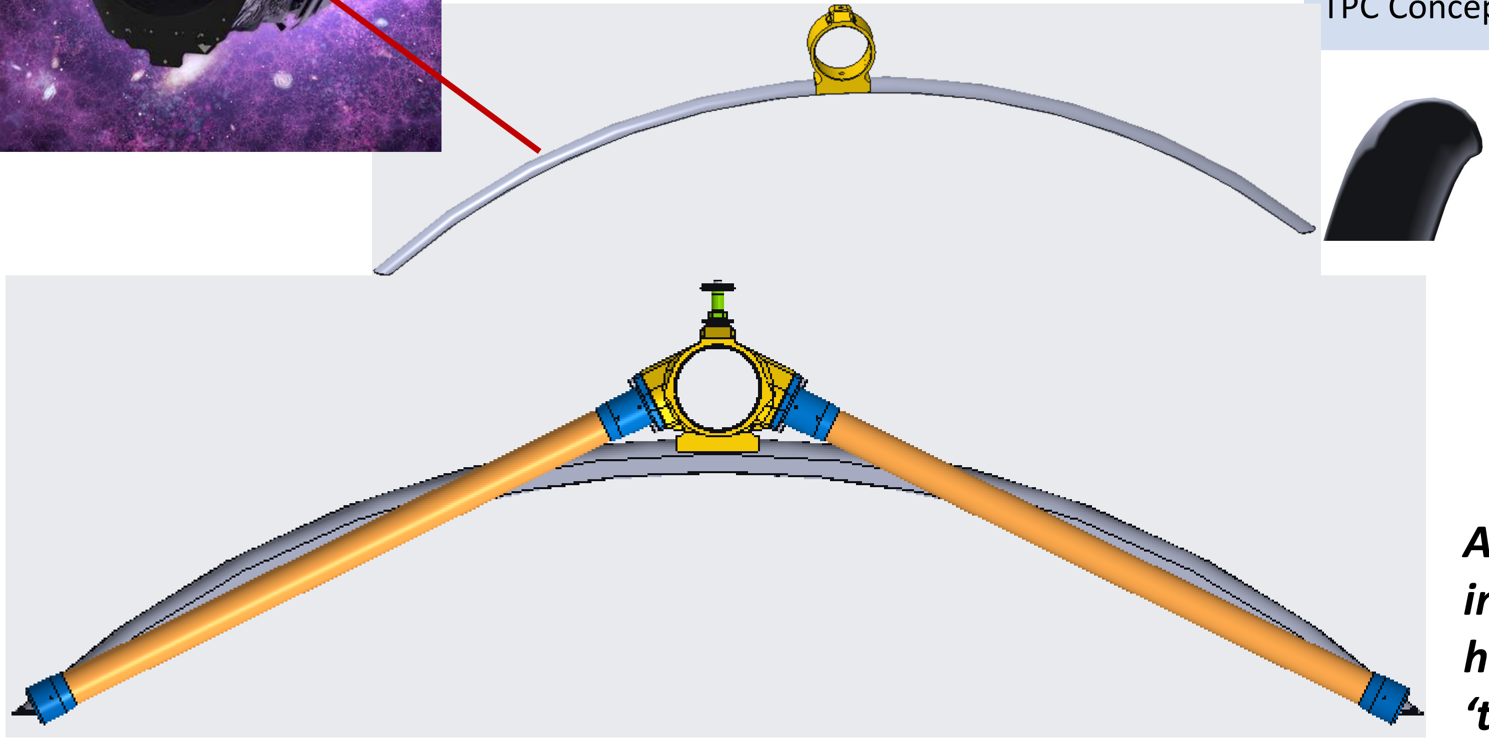
TDEA Application Space



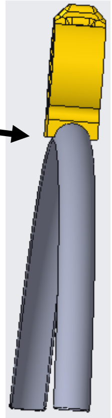
Potential Application Being Considered

RST Deployable Aperture Cover (DAC) Blanket Support

RST Traditional Design vs TPC Concept : Comparison					
Item	Number of Parts	Number of mat'ls	Number of Interfaces	Major Mfg operations	Mass
RST Concept Design	7	4	6	8	1.14 lb
TPC Concept	2	3	1	3	**0.54 lb**



Fused interface between Collar and Beam

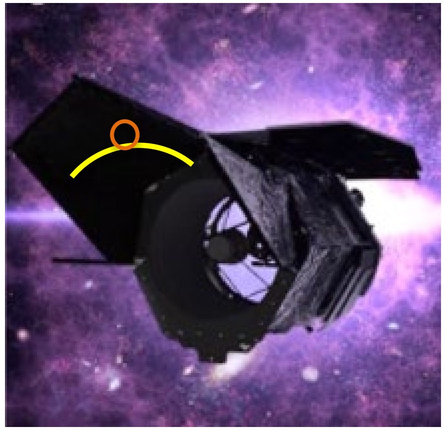


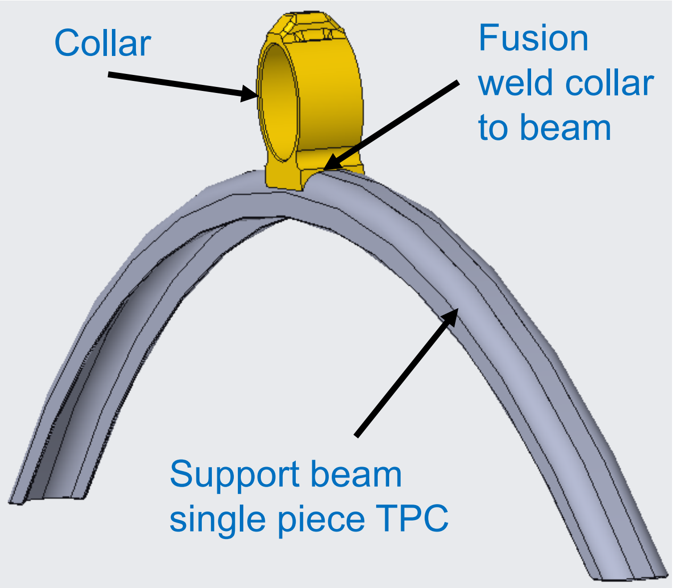
A TPC design with fewer parts, fewer interfaces requiring fewer processes at about half the mass compared to an existing 'traditional' design concept is under evaluation.

TDEA Application Space

Concept TPC Design – Roman Space Telescope (RST) Deployable Aperture Cover Support Beam

- Beam needed to support flexible aperture material during launch and prevent bore sight blockage when deployed.
- RST provided loads that enable the TDEA team to start assessing joint strength requirements





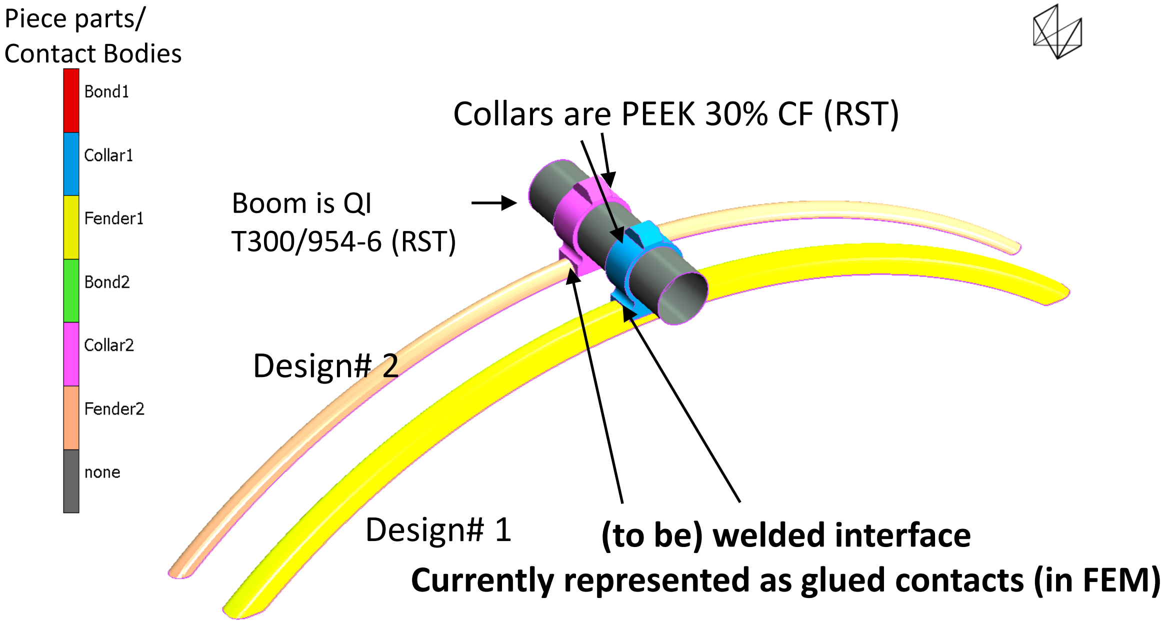
Design Comparison					
Item	Number of Parts	Number of mat'ls	Number of Interfaces	Major Mfg operations	Mass
PDR Design	7	4	6	8	0.517 Kg [1.14 lb]
TPC Option	2	3	1	3	0.331 Kg [0.73 lb]

Structure Benefits:
36% mass reduction
71% fewer parts
63% fewer assembly operations

Programmatic Benefits:
Developing this concept can give the team experience designing, analyzing manufacturing and welding a part to a relevant application

TDEA Application Space

Roman Space Telescope Collar and Rib Design and Analysis Update



Design and analysis updates:

- Two rib design options are being investigated
- A single fender design to replace two tubes and two bolted joints (RST baseline design)
- FEM: 202k solid elements (dominantly 8-noded hex)
- FEA Results:
  - 25 Hz first mode frequency requirement is not being met
  - Design 2 is dropped and design 1 to be modified to meet frequency requirement, followed by stress analysis under DLL

Ribs/Fenders Materials: Assumed Toray TC1225/T700GC
QI smeared properties calculated and used in FEA (Lamina properties from NCAM with some guess values for missing properties)


NIAR | Wichita State University | National Institute for Aviation Research

Report No: CAM-RP-2019-036 Rev N/C
Report Date: February 21, 2020

NCAMP — National Center for Advanced Materials Performance

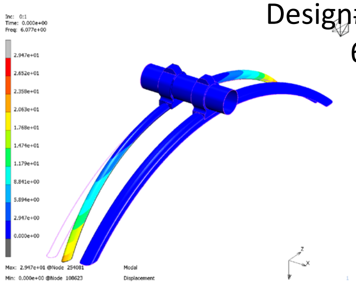
Medium Toughness PAEK thermoplastics
Toray (Formerly TenCate) Cetex® TC1225
(LM PAEK) T700GC 12K T1E Unidirectional Tape
145 gsm 34% RC
Qualification Material Property Data Report

NCAMP Project Number: NPN 061701

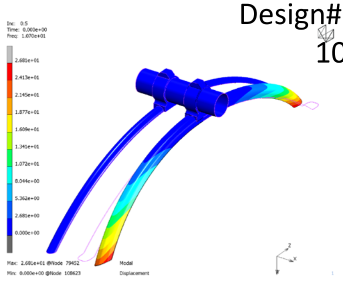
NCAMP Test Report Number: CAM-RP-2019-036 Rev N/C

Report Date: February 21, 2020

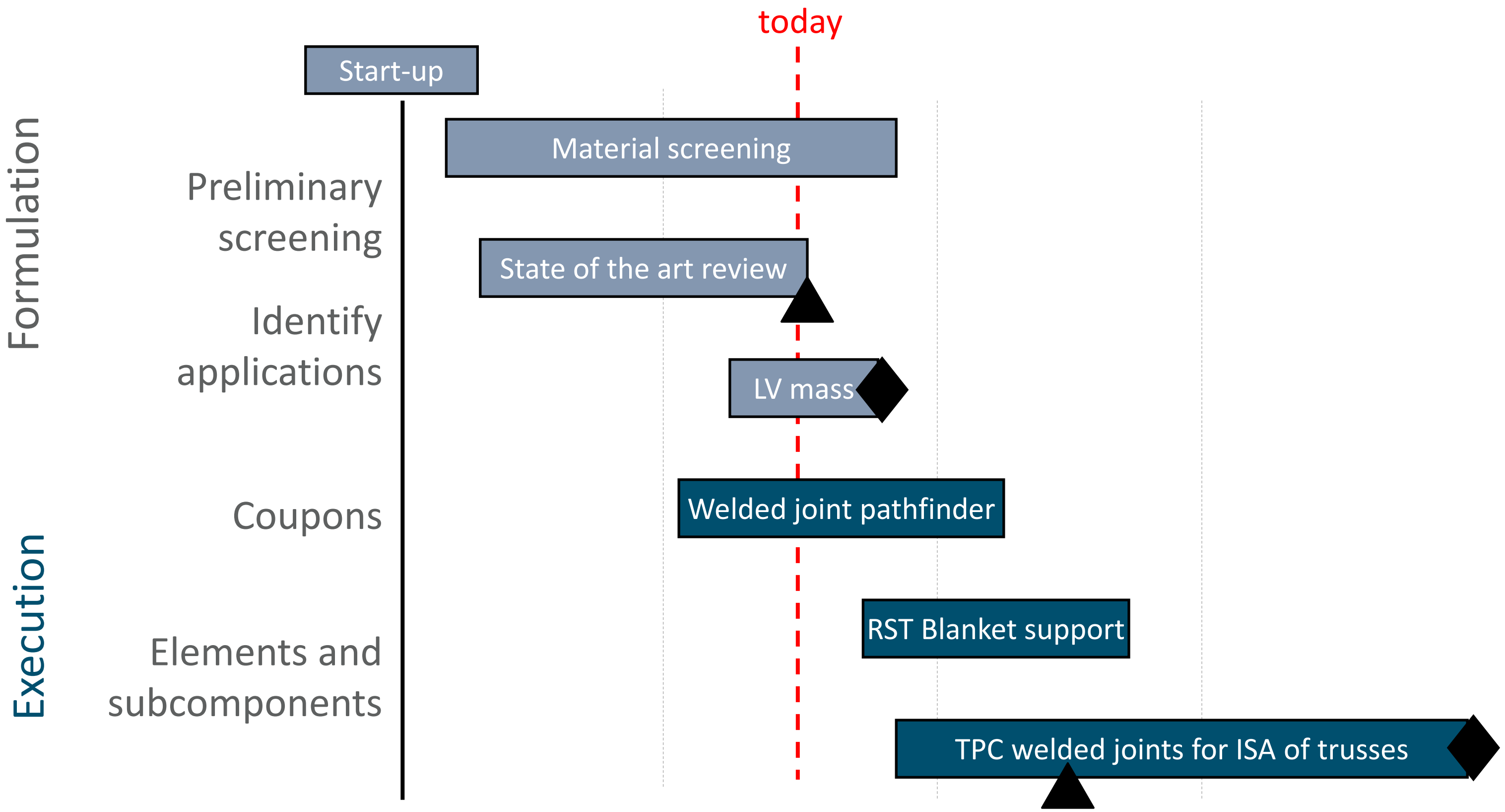
Design#2 First Moe
6.1 Hz



Design#1 First Moe
10.7 Hz



TDEA Planned Activities and Schedule



	FY21	FY22	FY23	FY24
FY21 Budget Request	Worked as part of CTE project	$2M	$3.5M	$5M
Civil servant FTE		9	10	10

TDEA- Materials Data

POCs:
S. Miller (GRC)
A. Bergan (LaRC)
A. Satyanarayana (LaRC)

Collected and organized available material properties for structural analysis:

- Assessment results organized as matrix with property and material system axes:
  - Cells have abbreviated publication reference
  - Gaps are shown as empty cells
- Includes materials procured by TDEA and other promising thermoplastic composite materials
- Significant database exists for room temperature ambient conditions (shown below); very little data for cold temperature conditions (not shown)
- Conducting a similar assessment for process modeling is on-going

TDEA procured materials

Sample from material property gap assessment spreadsheet

	Room temperature, ambient: T=70°F, dry					
Property category	T700/LM PAEK TC1225	AS4/PPS TC1100	AS4/PEEK TC1200	AS4/PEI Ultem	IM7/LM PAEK Victrex AE250	AS4D/PEKK-FC
Lamina elastic constants	NIAR	Toray datasheet	Demuts 1994		NIAR*	HiCAM*, NIAR*, Tijs 2021
Lamina strengths	NIAR	Toray datasheet	Demuts 1994		NIAR*	HiCAM*, NIAR*, Tijs 2021
Lamina CTE			Silverman 1989			Tijs 2021
Interlaminar fracture toughness	HiCAM*, Seneviratne 2021		Fish 1992		NIAR*	HiCAM*, NIAR*, Tijs 2021
Open hole strengths	NIAR	Toray datasheet (partial)			NIAR*	NIAR*
Filled hole strength	NIAR				NIAR*	NIAR*
Single shear bearing strength	NIAR				NIAR*	NIAR*
CAI strength	HiCAM*, NIAR	Toray datasheet (partial)			NIAR*	HiCAM*, NIAR*
Intralaminar fracture toughness						Tijs 2021

Materials Selection

High-performance materials were chosen to gain experience in processing and joining materials across a range of processing temperature and % crystallinity.

PAEK: Polyarylyetherketone: Semi-crystalline material, Data available in NCAMP database.

- TC1225/T700 145 grams per square meter (gsm), 34% Resin Content (RC)

PEEK: Polyetheretherketone: Semi-crystalline material, well characterized the literature.

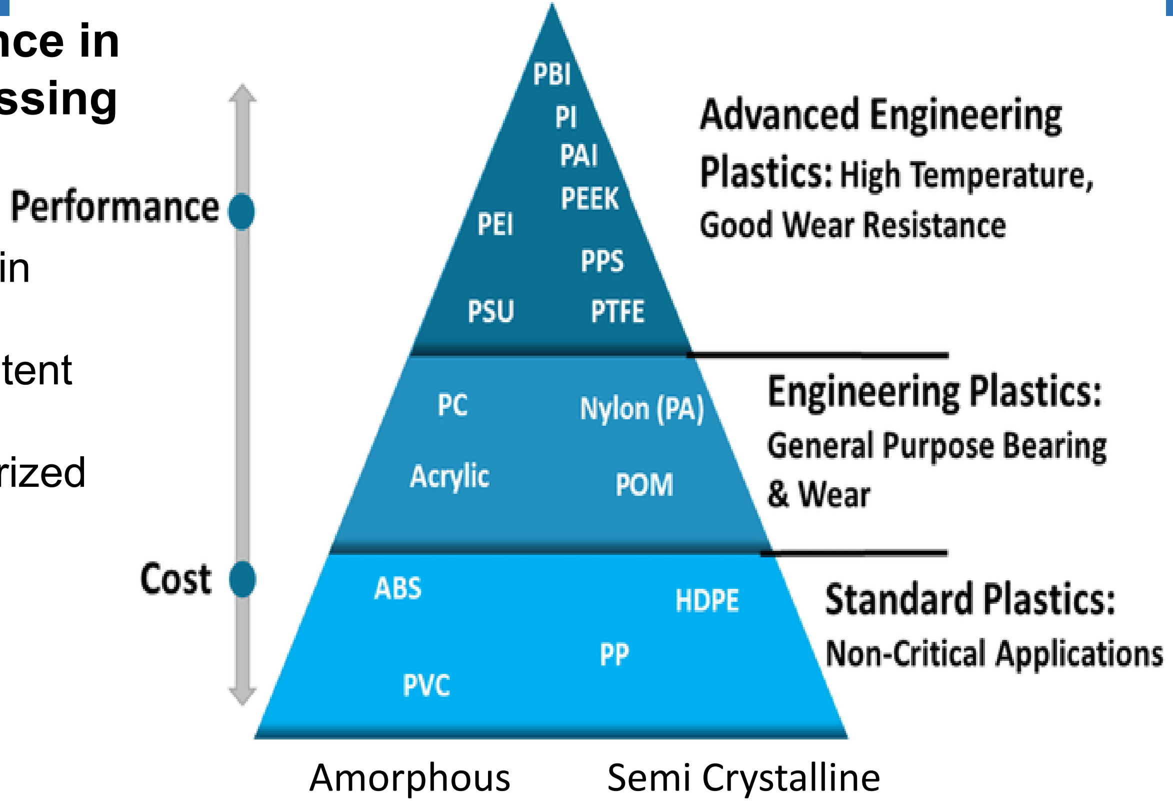
- TC1200/AS4 146 gsm, 34% RC

PPS: Polyphenylenesulfide

- TC1100/AS4 221 gsm, 34% RC
- lower Tg, processing temperature, and mechanicals relative to PAEK/PEEK. Rapid crystallization

PEI: Polyetherimide

- amorphous material, selected to bound the lower % crystallinity and evaluate performance on joining.



TDEA will leverage PEKK data from NASA HiCAM project

Material Down-Selection Test Matrix

The tension, compression and fracture toughness of each composite material will be evaluated.

Joining processes and the results of lap shear tests will be considered in the down-selection.

The manufacturing and structural requirements of the TDEA application will guide material selection.

Abbr.	Test	ASTM Standard	Manufacturing Approach	Layup
G1C	Mode I Fracture	D5528	Press	$[0]_{36}$
UNT	Unnotched Laminate Tension	D3039	Press	[45/0/-45/90]2s
UNC	Unnotched Laminate Compression	D6641	Press	[45/0/-45/90]3s
OHT	Open Hole Tension	D5766	Press	[45/0/-45/90]2s
OHC	Open Hole Compression	D6484	Press	[45/0/-45/90]4s
CAI	Compression After Impact	D7136 + D7137	Press	[45/0/-45/90]4s

Conditions: Room Temperature Ambient and Cold Temperature Dry.

Welded Joint Pathfinder Study: Manufacturing Perspective

Objectives

- Develop in-house capability for thermoplastic welding
- Support analysis effort to compare thermoset and thermoplastic composite joint performance

Approach

- Analyze available thermoset and thermoplastic joint data to better quantify current state of the art
- Down-select 1-2 thermoplastic welding techniques to pursue in-house
- Spec (and procure, as funding allows) equipment/systems to enable down-selected welding technique(s)
- Understand key process parameters (via experiment) of down-selected welding technique(s)
- Fabricate thermoplastic joint coupons using down-selected welding technique(s)

Expected Outcomes

- In-house thermoplastic welding capability
- Basic characterization of key process parameters for thermoplastic welding
- Baseline evaluation of thermoplastic joint performance

Looking Forward

- First-hand understanding of thermoplastic welding should help further guide TDEA efforts

Welded Joint Pathfinder Study: Flow Chart

Down-select thermoplastic welding technique(s)
- Most viable candidates: resistive and induction

Spec and procure equipment/systems for thermoplastic welding
- Resistive: relatively straightforward and lowest cost
- Induction: should leverage industry experience to reduce risk/cost

Understand key process parameters for thermoplastic welding
- Resistive: conductive element type, power density, pressure
- Induction: coil type, layup, pressure, rate

Fabricate thermoplastic joint coupons
- Single lap shear: PAEK
- DCB: PAEK

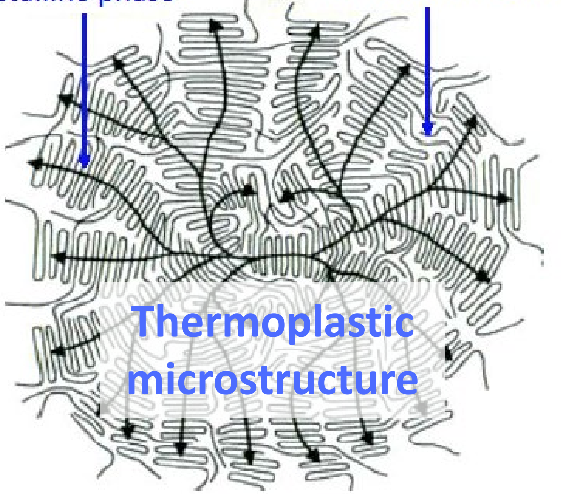
Analyze available data to better quantify joint performance
- CTE (thermoset): lap shear, DCB, ENF
- SLS (thermoset): lap shear, DCB
- MASC (thermoplastic): lap shear, DCB (?)

Resistance Welding and Mechanical Test

PEEK and PEI were selected as materials welding trials.

Qty	Description
	Thermoplastic Resistance Welding Test Matrix (Carbon Fiber Heating Element)
	Resistance Welding Process Development and Final Welding
1	Resistance Welding
	Note - 6 Welds Per Test Method - 5 Test Methods - 2 Material Systems - Total welds - 60
	Weld-Line Photomicrographs
10	Photomicrograph
	Note 1 PM Per Test method Per Material System
	Differential Scanning Calorimetry Inspection
10	Transition Temperatures and Enthalpies of Fusion and Crystallization of Polymers (ASTM D3418)
	Note 1 DSC Per Test Method Per Material System
	ASTM Standard Testing
12	Strength Properties of Double Lap Shear Adhesive Joints (ASTM D3528)
12	Lap Shear Adhesion (ASTM D5868) (45° Ply @ Interface)
12	Lap Shear Adhesion (ASTM D5868) (0° Ply @ Interface)
12	Mode I Interlaminar Fracture Toughness (ASTM D5528)
12	Mode II Interlaminar Fracture Toughness (ASTM D7905)

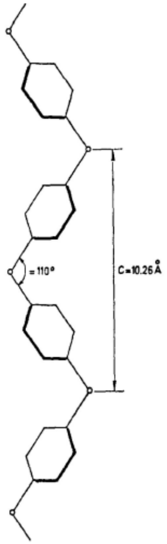
Polypropylene-Sulfide (PPS) Modeling Progress

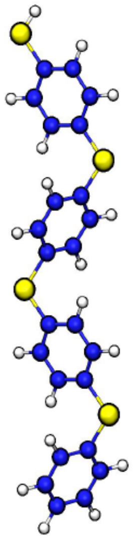


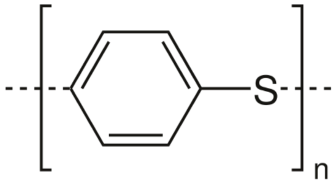
- Developed separate models for crystalline and amorphous phases.
  - Will next use micromechanics to homogenize phases to obtain PPS conductivity based on microstructure.
- Implemented Molecular Dynamics (HOOMD code)
  - Obtain molecular structure for crystalline and amorphous phases.
- Implemented Kinetic Monte Carlo (Boise St. code)
  - Predict charge transport properties.

First Set of Charge Transport Simulation Results

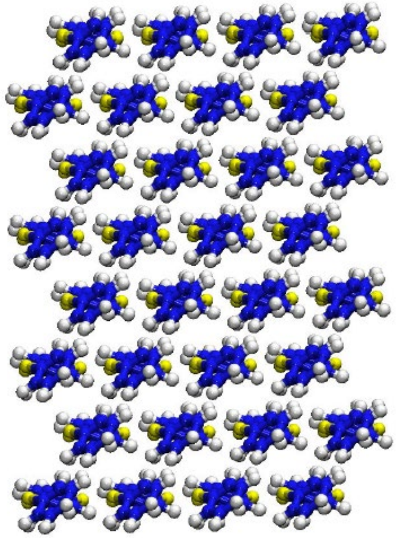
Morphology	Simulation (cm^2/Vs)	Experiment - From literature (cm^2/Vs)
Crystalline	0.48 – 0.66	searching
Amorphous	$2. – 4.\times10^{-6}$	1×10^{-6}







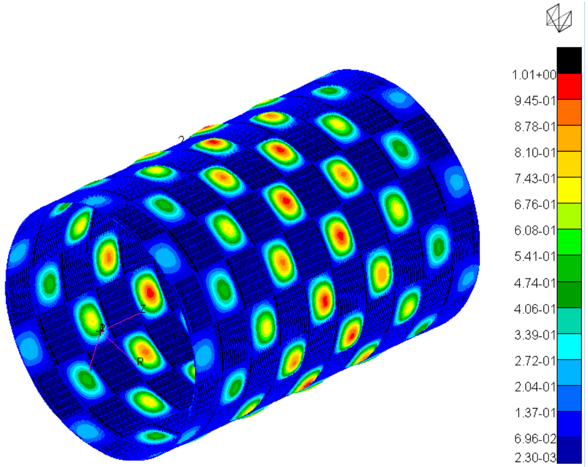
Polypropylene-sulfide (PPS)



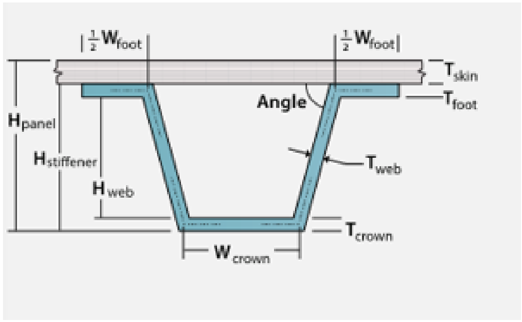
*Courtesy Dr. Brett Bednarcyk

Structural Sizing to Assess Mass Saving Opportunities Enabled By TPCs

- Background:
  - GKN/Fokker have shown that allowing the thermoplastic skin on the Gulfstream G500, G600, and G650 rudders and elevators to post-buckle at 70% of limit load leads to 20% cost and 10% weight savings.
  - Previously, NASA and Collier Research performed an extensive sizing study for the Ares V interstage, including consideration of post-buckled designs using thermoset composite materials.
- Current objective:
  - Perform a material swap on the Ares V hat stiffened panels with thermoplastic material properties and allow the panel to post-buckle at 70% limit load (or some percentage of limit load) to investigate potential weight savings.
- Initial accomplishments:
  - The model has been built including 16 TPC and TSC laminates.
  - Failure criteria for the study have been discussed and chosen in HyperX.
  - Preliminary results of the TPC hat panel construction have been generated.
- Next steps
  - Investigate the extent to which the TPC hat panels can post-buckle due to its higher toughness.
  - Compare acreage mass of each of the candidates.



FEA Buckling Mode Shape



TPC Outreach

- **NASA High-Rate Composite Aircraft Manufacturing (HiCAM) –** Technical Exchanges
- **TDEA Hosted Industry Presentations**
  - **Jessie Pandher, U of South Carolina / McNAIR Center**
    - Induction Welding
  - **Dr. Waruna Seneviratne, Wichita State University / NIAR**
    - ATLAS Capabilities
  - **Dr. Don Kinard, Lockheed Martin**
    - 80s to today, TP Materials Trades in Aircraft
  - **Tony Belcher, Boeing**
    - TP Adhesive Bonding
  - **Arnt Offringa and Bas Tjis, GKN Aerospace/Fokker**
    - TPC Use in GKN/Fokker Parts and Assemblies
    - Design and Modeling and Verification of Welding approach

Takeaways:

- **TPCs are understood for aircraft applications with broad expertise in process modeling, manufacturing, and fusion welding, and are still more limited in those applications than thermosets at this time**
- **Comparatively little information is available for space applications**
- **US Industry and Academia are ready, willing, and able to help**

TDEA: Partnerships

- **Seeking Public Private Partnerships**
- **Target partners, broken down by focus area**

Focus Area	NASA Centers + Partners
Develop NASA's capabilities with respect to automated fiber placement (AFP) processing for thermoplastics.	MSFC
Partner with material supplier(s) to qualify emerging thermoplastic materials for automated fiber placement manufacturing process.	MSFC, GRC, GSFC, Industry
Work with industry and academic partners to develop and qualify advanced thermoplastic joining technique(s) applicable to lightweight structures used on Human Lander System (HLS), launch vehicles, and lunar surface or on-orbit applications.	MSFC, GRC, LaRC, Industry, Academia
Develop process models and advanced analytical tools for structural systems employing thermoplastics joining.	GRC, LaRC, GSFC, Academia
Understand the structural behavior of unitized thermoplastic composite components.	MSFC, LaRC, GSFC, Industry

- **NASA brings engineering talent, funding, and applications**

Questions?