Thermal Protection System Technology Maturation and Sustainment in Support of In situ Science Missions: HEEET and PICA

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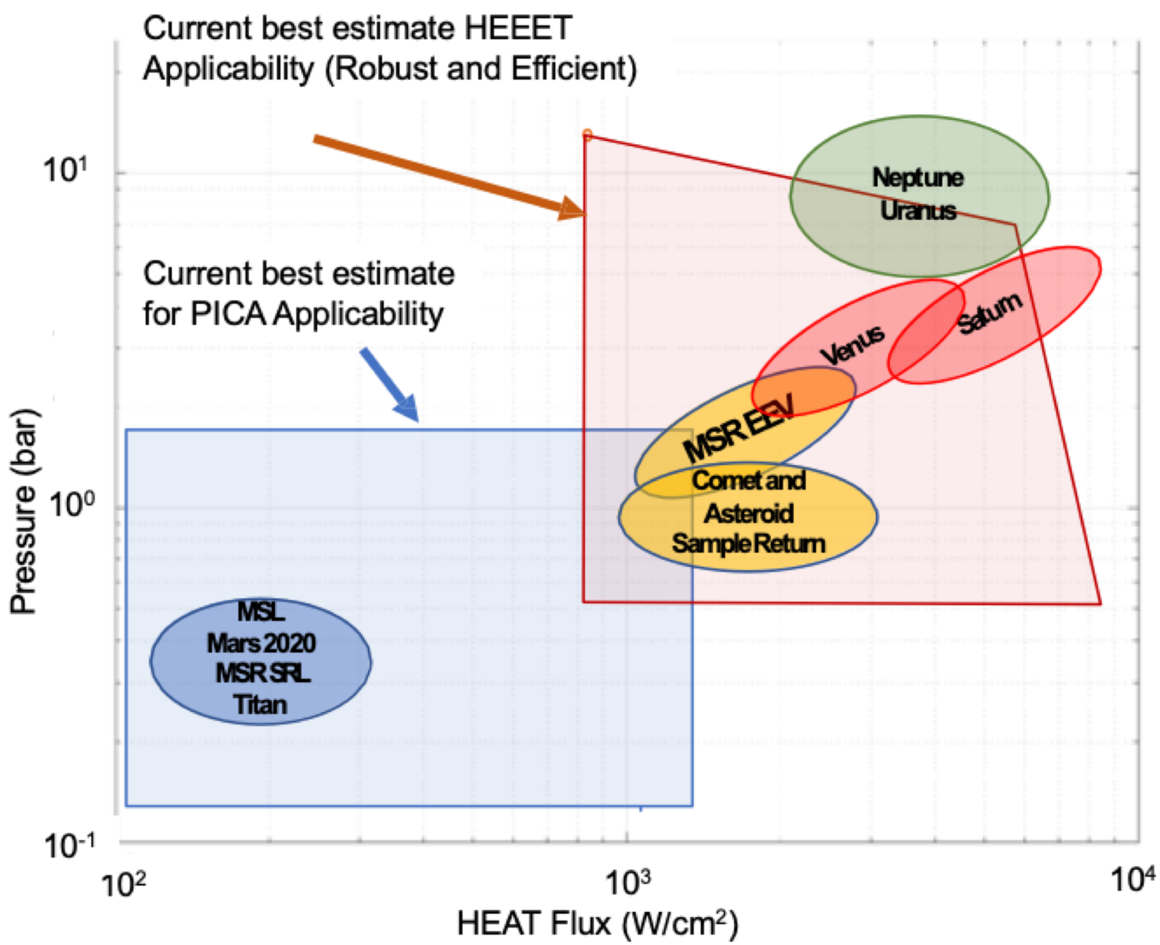
PICA and HEEET Cover Broad Range of Entry Mission Forebody Heatshield Needs



Note: The applicability boundary especially for HEEET is based on limited arc-jet tests. The HEEET acreage material has not failed in any of the tests and so there is some confidence. The heat-shield design (with seam) does carry higher risk at higher conditions due to a) ground test facility test limitations and b) extrapolation.

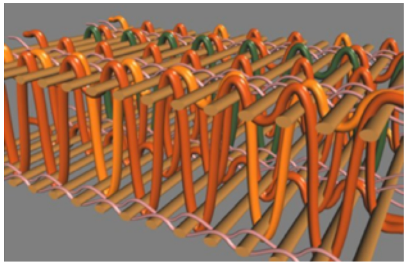
Opportunities for This Community

- HEEET
  - Tool to assist with identification of alternate fiber if needed – HEEET team took sustainability into consideration during development and identified PAN based carbon fibers that are high volume products used in many industries versus Rayon based fibers used previously in Carbon Phenolic that have sustainability challenges – having a tool to predict behavior if a fiber replacement is needed (knowing constituent properties) would enhance the sustainability story

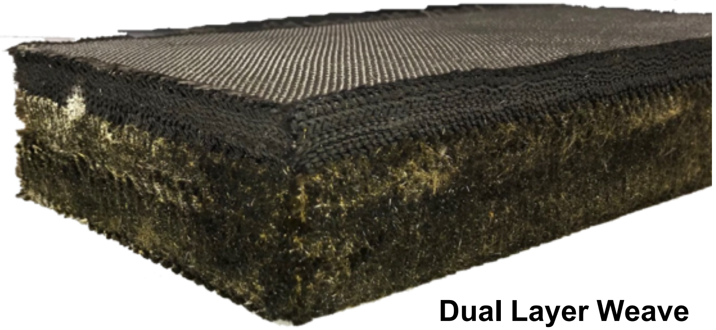
- PICA
  - Understanding enhanced erosion at elevated heat fluxes, pressures and shears
  - Understanding the influence of fiber changes (fiber strength degradation at high temperatures) as a result of exposure on erosion

What is the HEEET Material?

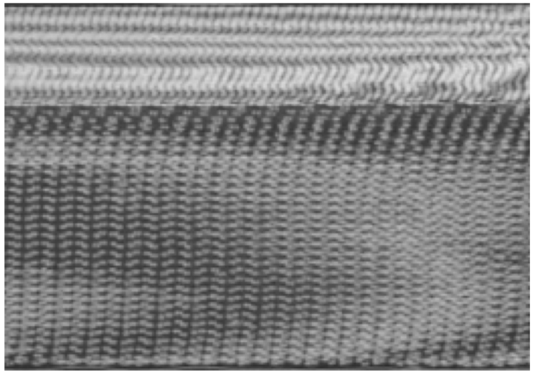
- Mid-density 3D woven dual layer carbon phenolic
  - 3D layer to layer weave
  - Dual Layer:
    - OML Layer = Recession Layer (RL) – manages recession
      - Higher density all carbon fiber weave, exposed to entry environment
    - IML Layer = Insulation Layer (IL) – manages heat load
      - Lower density, lower thermal conductivity, blended carbon/phenolic yarn
    - 2 layers are integrally woven together,
      - mechanically interlocked (not bonded)
  - Woven material has medium density phenolic resin infusion
    - Higher phenolic loading than PICA
    - Open porosity



3D Weave



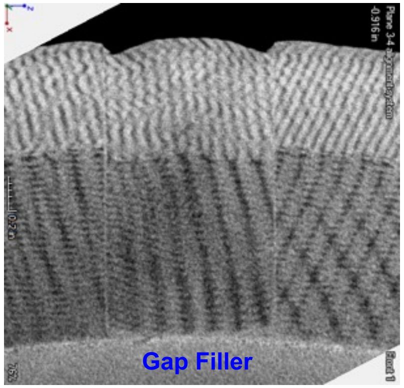
Dual Layer Weave



CT Scan HEEET Weave

Seams in the HEEET Architecture

- A tiled heatshield design is required due to weaving width limitations
  - Results in seams between tiles – **the most challenging part of HEEET development**
- The HEEET project has baselined a gap filler between tiles to perform two primary functions:
  - Provide structural relief for all load cases by increasing compliance in the joint
  - Provide an aerothermally robust joint
- Two factors inherent to the HEEET material and its mission applications drive requirements at the seams in the system.
  - Aerothermal environments for HEEET mission architectures require unsupported adhesive joint widths be minimized to prevent failure at the seam
    - IHF 3” nozzle testing at ~3500 W/cm^2 and 5 atm suggest joints ≤ 0.010” are required
  - HEEET in-plane modulus is high
    - As the carrier structure deflects, the HEEET architecture must have sufficient compliance to maintain compatibility with the carrier without inducing excessive stress in the system



HEEET Manufacturing Overview

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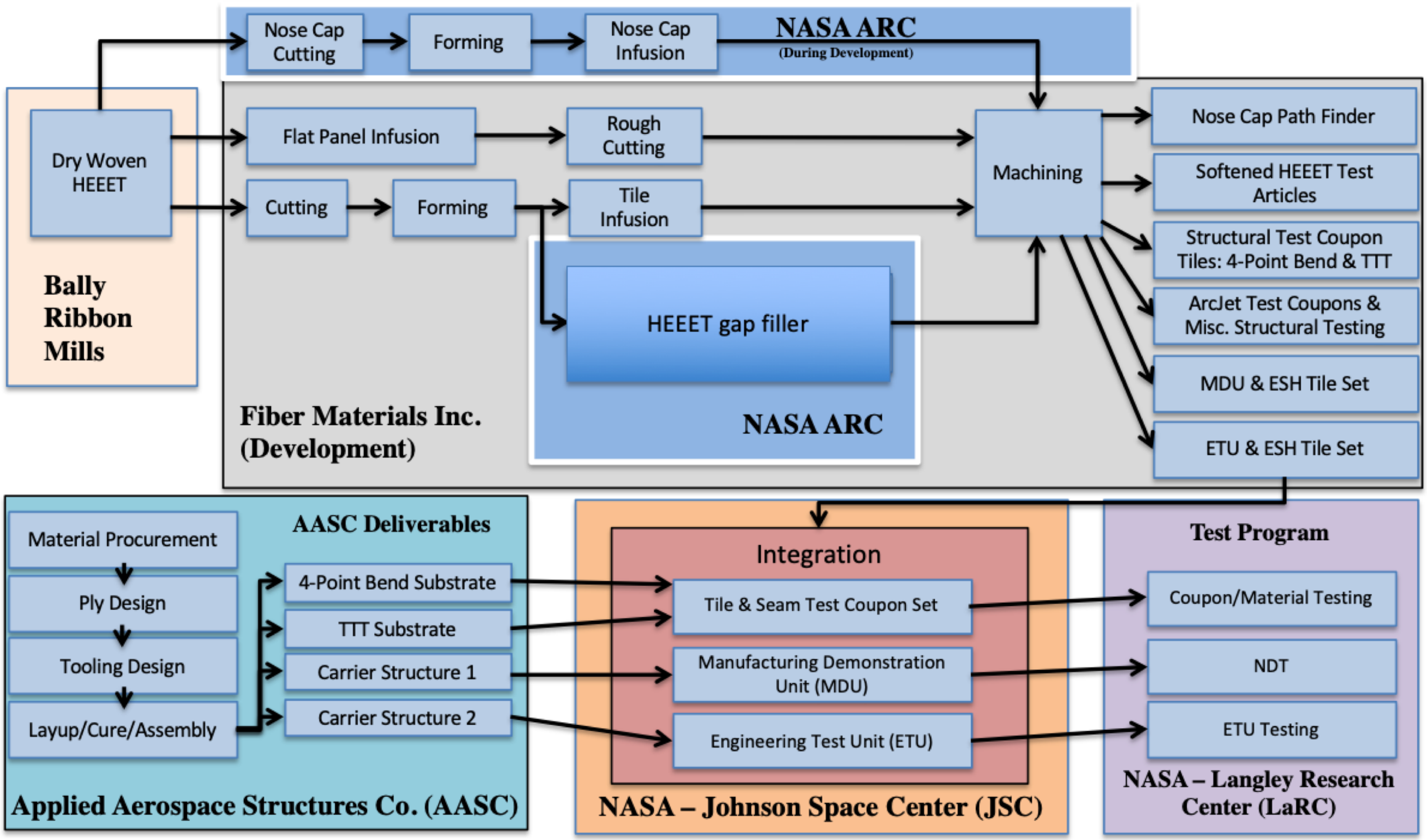

1m ETU Successfully Built and Inspected by CT Scan

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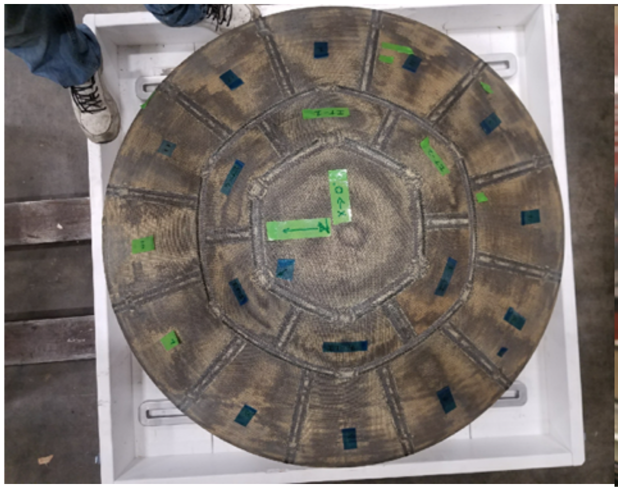
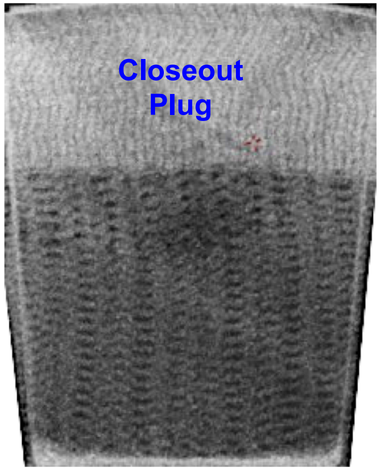
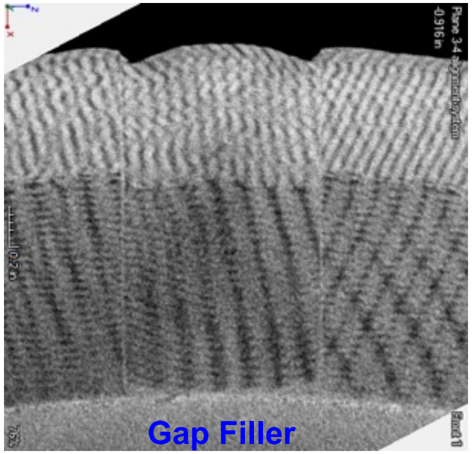
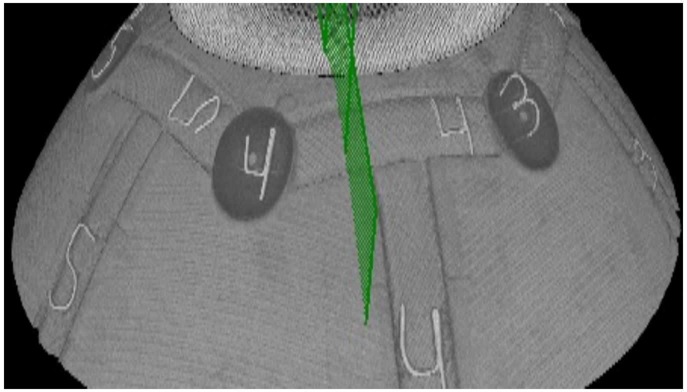








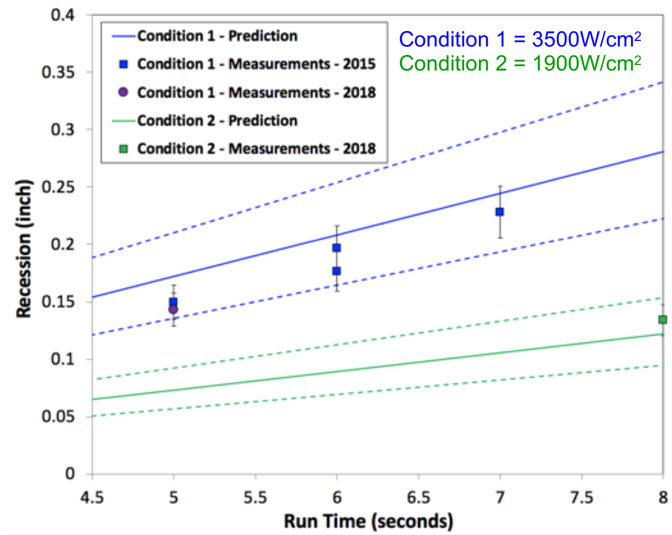
Arcjet Test Campaign

Entry Systems and Technology Division

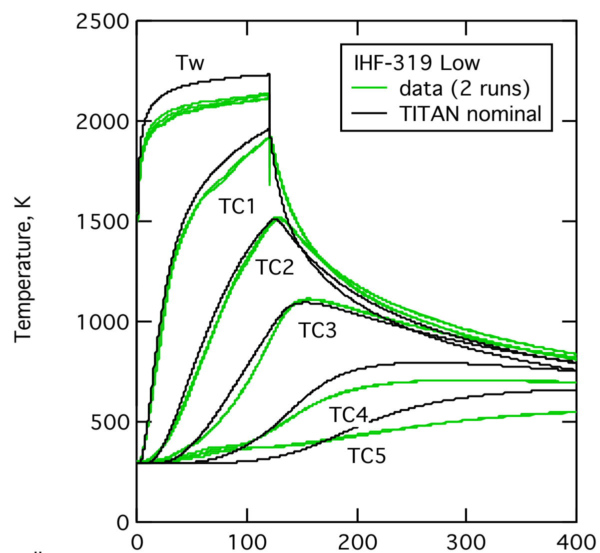
Objectives for aerothermal test campaign:

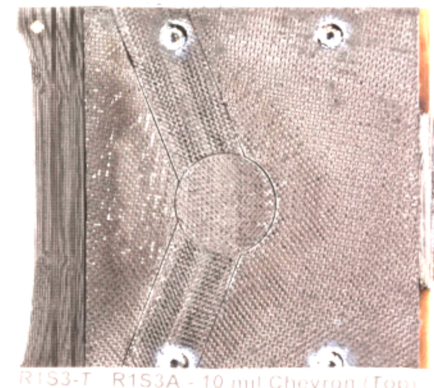
1. Support development and validation of the TPS sizing tools
2. Exercise the system (acreage and seams) under mission relevant conditions to establish system capability
   - Looking for failure modes

- 12 arcjet test series conducted
- >140 coupons tested
- First testing in the IHF 3" nozzle
  - 3500 W/cm² and 5.3 atm
- First NASA testing in AEDC H3 facility
  - 4000 Pa shear
- FIAT code adapted to support dual layer TPS sizing
- New dual layer margins policy developed



IHF 3":
Hot Wall Heat Flux: 3600 W/cm²
Pressure: 5.3 atm

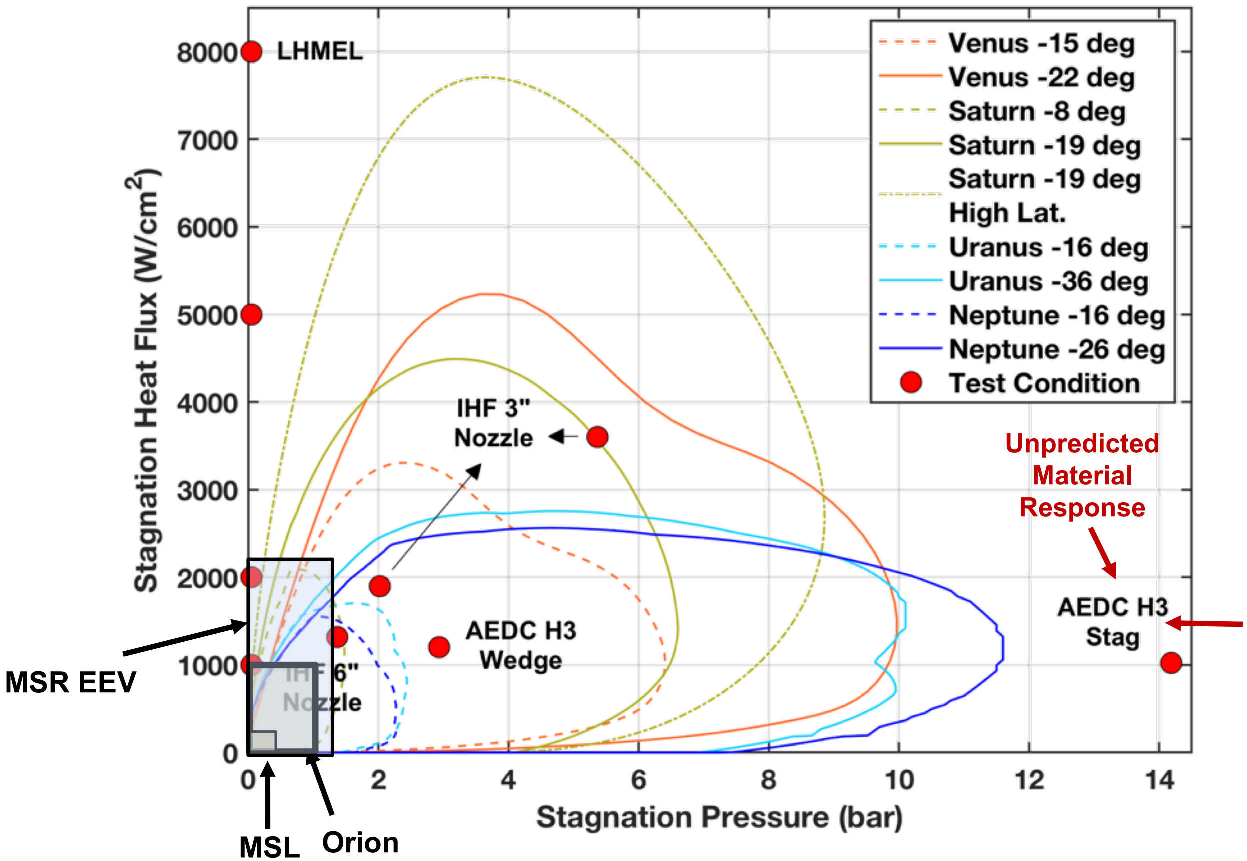




AEDC Shear Testing:
Hot Wall Heat Flux: 1200 W/cm²
Pressure: 2.9 atm
Shear: ~4000Pa

Arcjet Tests and Thermal Response Analysis for Dual-Layer Woven Carbon Phenolic. F. Milos, Y. Chen and M. Mahzari, AIAA 6.2017-3353

HEEET Arcjet Testing Covers Options for Target Destinations

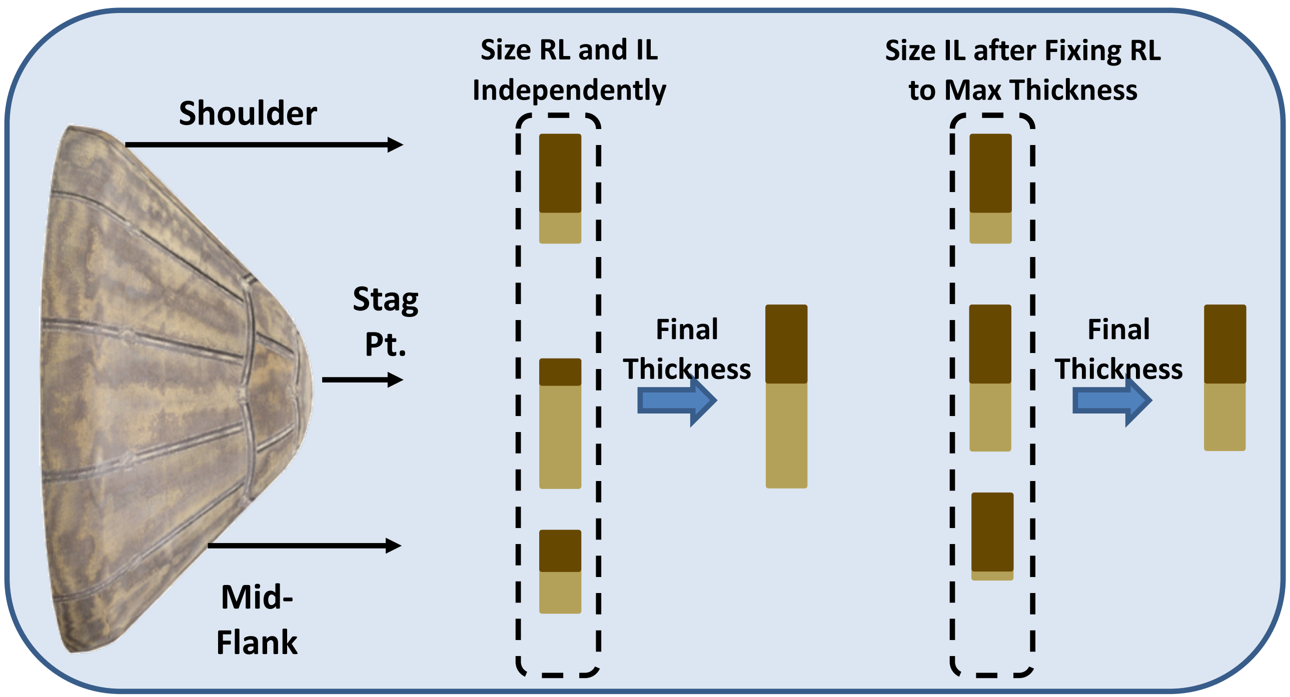


Recession measurement higher than predictions for both HEEET and carbon phenolic at 14 bar – possibly due to non-flight-like geometry and flow through

Limits in ability of ground based test facilities to achieve relevant conditions for some steep and high latitude entries. This issue applies to any TPS concept, not just HEEET.

Dual Layer TPS Sizing

- New constraint at the interface between two layers, beyond typical bondline temperature constraint
  - HEEET insulation layer should not be exposed to flow
- Current HEEET implementation requires uniform TPS thickness for both layers
- Max thickness for each layer may occur at different body points and trajectories
- Sizing RL and IL independently and then stacking max RL thickness from one location on max IL thickness from another location is not mass efficient
  - Excess RL at some locations can serve as insulation
- More mass efficient to size IL after fixing RL to max sized thickness across all locations



Example Sizing from a Venus Reference Mission - 62% reduction in IL thickness, 19% reduction in areal mass

*Sizing and Margin Methodology for Dual-Layer Thermal Protection Systems, Mahzari and Milos, 15th International Planetary Probe Workshop

Final TRL Self Assessment

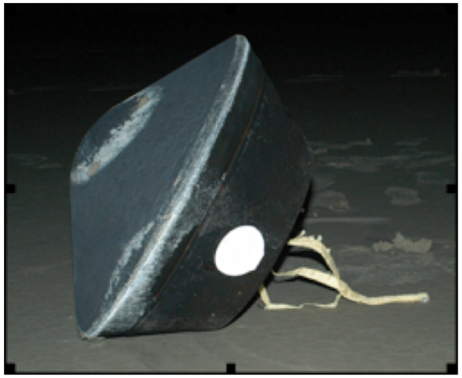
- Have we built high-fidelity prototypes that address scaling issues? Yes
- Have we operated in relevant environments?
  - Aerothermal (arc-jets) Yes
  - Thermostructural (combined loading of flexures at LHMEL) Yes
  - Structural (pressure, thermal-vacuum and point loads on 1 m ETU) Yes
- Have we documented test performance demonstrating agreement with analytic predictions? Yes
- HEEET system is assessed to be at TRL 6
- Limitations
  - Not at TRL 6 for thickness much greater than 2”
  - Not at TRL 6 for applied environments above 5 atm and 3600 W/cm2
  - No mission opportunity (except Jupiter) appears to require these levels
- But don’t just take our word for it - HEEET Independent Review Board (IRB) Assessment:
  - “The IRB concurs […] that the overall objective of achieving TRL 6 has been completed”

Background – PICA

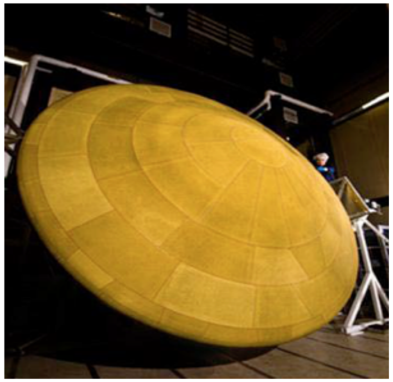
State of the Art Low Density Carbon Phenolic Ablators

Entry Systems and Technology Division

- **Phenolic Impregnated Carbon Ablator (PICA)**
  - First used as forebody single piece heatshield for Stardust
- **Low density coupled with efficient ablative capability at medium-high heat fluxes**
- **Since Stardust-**
  - Under the Orion program PICA was shown to be capable for both ISS and lunar return missions but was not selected as the baseline TPS
  - PICA was transitioned to Mars Science Lab (MSL) post CDR in a tiled configuration when the mission environments went beyond the capabilities of SLA561V
  - OSIRIS-REx sample return capsule as a single piece
  - Mars 2020 – Utilizing last of the “heritage” Sniace rayon based PICA

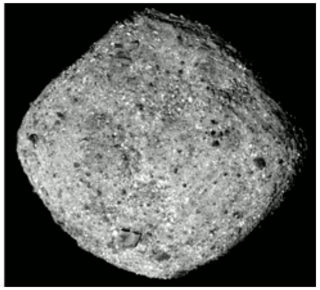


Stardust forebody TPS. (~0.8m diameter)



MSL Heatshield (4.5m diameter)

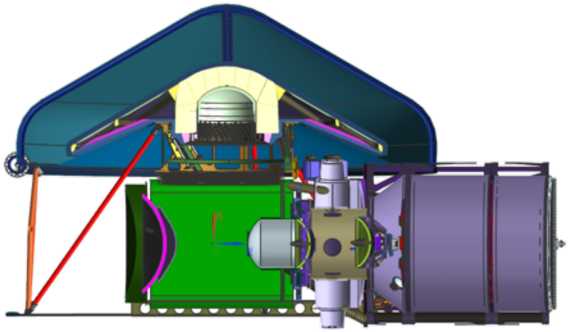
OSIRIS-REx forebody TPS. (~0.8m diameter)



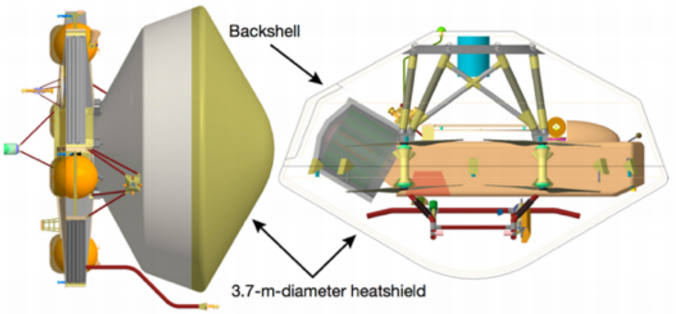
Bennu taken by the OSIRIS-REx spacecraft from a distance of around 50 miles (80 km).

Future Needs for PICA-D*

- Mars Sample Return (MSR) Campaign
  - Sample Retrieval Lander (SRL):
    - Heatshield
  - Earth Entry Vehicle (EEV):
    - Backshell
    - Option for heatshield
- Dragonfly: Heatshield
- Future Discovery and New Frontiers missions:
  - Backshell and Heatshield



MSR EEV



Dragonfly

PICA-D = Domestically (US) manufactured PICA utilizing Lyocell

Challenges with PICA Sustainability

- In 2016 NASA learned that the “heritage” rayon used in PICA was ceasing production, leading to a flight-qualified PICA sustainability concern
  - Rayon precursor for PICA has become obsolete twice since the material was developed and used on Stardust
  - Manufacturing of Rayon is not environmentally friendly (no longer produced in US)
- Lyocell has been identified as a alternative to the rayon based precursor
  - Lyocell production is much more environmentally friendly
  - Lenzing – sister factories in US, Austria and UK able to provide the same Lyocell precursor – multiple supply routes alleviate future sustainability concern

Mission/ Project	Precusror type	Rayon Sustainability	Changes /Updates to PICA
Stardust - Near Net Shape (NNS)	Liberty rayon	US source – production ceased in the 90s	Developing process to fabricate singe piece Near Net Shape (NNS) cast part within the density specification required
Orion - billets	Multiple sources – settled on Sniace	Multiple international sources evaluated	Optimized densification process for billets, tested the bounds of the density specification and the influence on performance / properties
MSL- billets	Sniace rayon	international source – production ceased in ~ 2017	Leveraged Orion data to allow adoption on MSL
OSIRIS Rex - NNS	Sniace rayon	international source – production ceased in ~ 2017	Cast FiberForm preform density spec modified compared to Stardust. Phenolic level adjusted based on lessons learned from Orion/MSL
M2020 - billets	Sniace rayon	international source – production ceased in ~ 2017	Leveraged MSL
PICA-D - billets	Lyocell	Domestic/international sister plants. Greener processing	Orion/MSL density specification range
PICA-D - NNS	Lyocell	Domestic/international sister plants. Greener processing	Leveraged OSIRIS Rex/MSL density specification range

PICA Manufacturing Overview

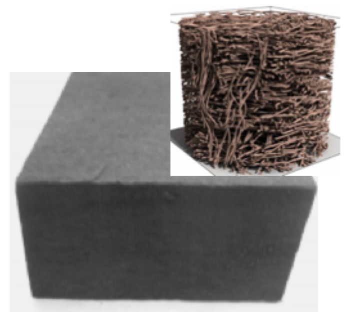
Role of Rayon/Lyocell in PICA Manufacturing

Rayon or Lyocell

Sustainability concern

Conversion to carbon

Near net shape preform



FiberForm® billet preform

Single piece PICA heatshield (< 1.25m max diameter)

Tiled PICA heat shield (> 1.25m max diameter)

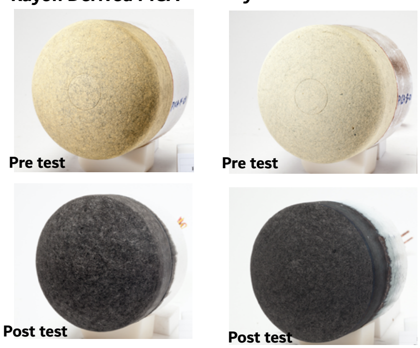
- Chopped, graphitized rayon/Lyocell - based carbon fiber slurry-cast into either block (billet) or single piece heatshield preforms
- Single piece cast heatshields have fiber oriented to optimize (minimize) through-thickness thermal conductivity
- Lightweight phenolic sol-gel matrix is infiltrated into preform

PICA-D Arc Jet Testing

Runs in Air 2017

Pre/Post Test Model Comparison (1550W/cm² condition)

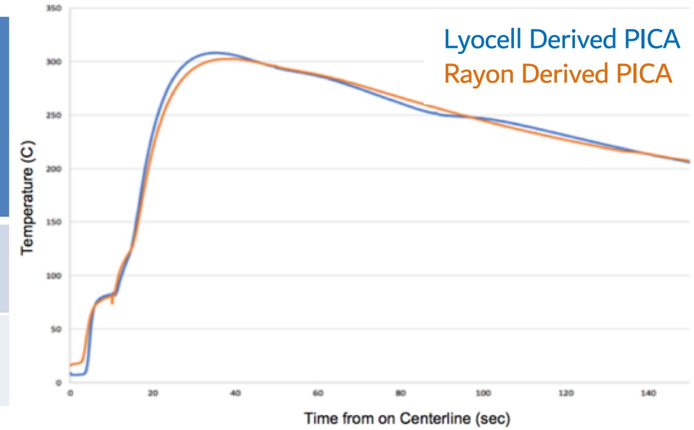
Rayon Derived PICA | Lyocell Derived PICA



Recession Comparison

Material	Average centerline recession (1550W/cm² and 1.3 atm)	Average centerline recession (400W/cm² and 0.3atm)	Average centerline recession (220W/cm² and 0.08atm)
Lyocell PICA	4.0mm	6.02mm	3.79mm
Rayon PICA	4.2mm	5.97mm	3.89mm

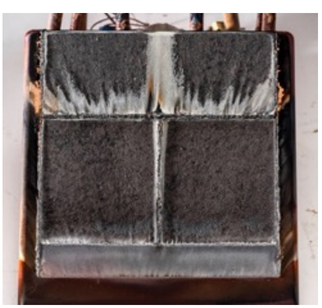
Example in-depth TC Trace @ 1550W/cm²



Run condition very relevant for proposers considering PICA as a forebody or backshell material

Runs in N_2 2018/19

Heat Flux = 140 W/cm², Pressure= 14 kPa



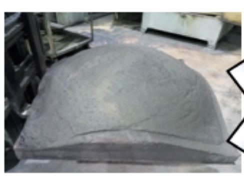
Heat Flux = 260 W/cm², Pressure= 19 kPa

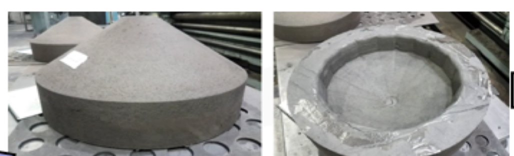
- Previous testing of PICA with RTV seams was only done in air under MSL and Orion programs
- In support of Dragonfly Phase A study, PICA-D built 2 wedge shear models with RTV seams for testing in a nitrogen environment

For a Given Test Condition (Same Run Time) Initial Results Indicate that Recession and In-depth Temperature Between a Lyocell-Derived PICA and a Heritage Rayon-Derived PICA are Comparable, in both Oxygen and Nitrogen.

Lyocell Fiberform/PICA Billet and Near Net Shape Cast Processing

- 9 Fiberform billets manufactured in FY17 to optimize process (Lyocell)
- Additional billets fabricated in FY18 (property and arc jet testing)
- Fabricated 3 net-shaped Fiberform heatshield blanks (OSIRIS REx scale) in FY17
- Fabricated 4 net-shaped ~ 1.5m single piece FiberForm castings (FY18/19)
    - Converted one into 1.4 m PICA heatshield: characterization underway
    - Limited Non Destructive Evaluation (NDE) on the near net shape Fiberform unit to evaluate fiber alignment
- Significant number of lessons learned captured/implemented and substantial risk reduction achieved





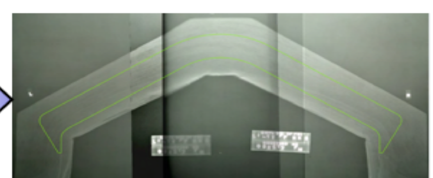
Trimmed prior to infusion

Post-gel

OSIRIS Rex Scale 0.8m

Post-infusion

Trimmed



X-ray (fiber alignment and FOD/void check

Cast unit density coupon cut plan

1.4m heatshield

Extended single piece heatshield manufacturing demonstrated

PICA Summary

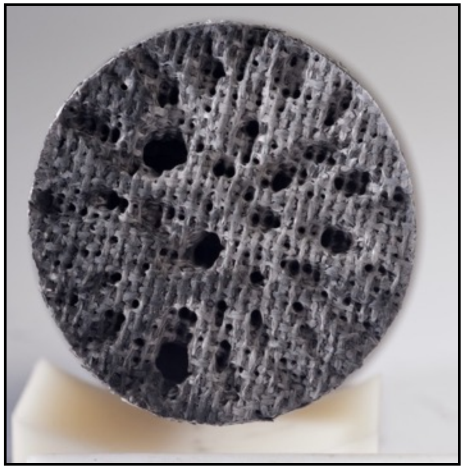
- **PICA has become a workhorse TPS for NASA and sustainment is essential**
- **NASA ARC / FMI are working together to address PICA rayon sustainability concerns**
- **Lyocell Based PICA (PICA-D) was manufactured and limited testing shows it to be a viable replacement for heritage rayon**
- **Scale-up of single piece heatshield manufacturing also demonstrated**
- **Future NASA missions need PICA (SRL, MSR EEV and Dragonfly) and PICA sustainability effort will have a payoff for these missions**
- **Establishing the extended capability of PICA-D will allow Sample Return Missions with higher entry speeds and larger payloads not considered before**

1. Stackpoole, M, Venkatapathy, E. and Violette, S., "Sustaining PICA for future NASA Robotic Science Missions including NF-4 and Discovery," IEEE, Vol. 10.1109/AERO, pp. 1-7, 2018.
2. Matt Gasch[1], Kristina Skokova[2], Mairead Stackpoole[1], Ethiraj Venkatapathy[1], Don Ellerby[1], Frank Milos[1], Keith Peterson[1], Dinesh Prabhu[2], Greg Gonzales[2], Steve Violette[3] and Taylor Franklin[3], "Development of Domestic Lyocelll Based Phenolic Impregnated Carbon Ablator for Future NASA Missions," MS&T 2019. (To be published Oct 2019)

Opportunities for This Community

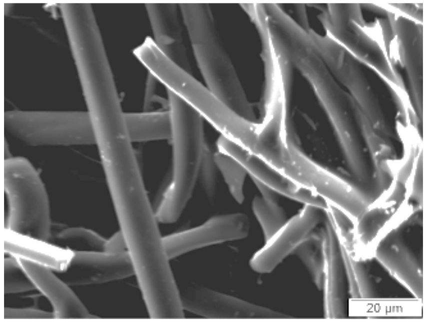
- Failure modes linked to microstructural features
- Influence of test coupon configuration should also be considered

Tunneling failure mode

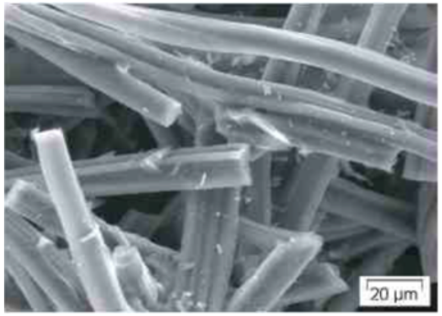


Interstitial size drives flaw/failure
Permeability / scale of porosity

- Changing fiber precursor



Lyocell – smooth and not hollow



Rayon – crenulated and hollow

Carbon Fiber Properties Change with Temperature

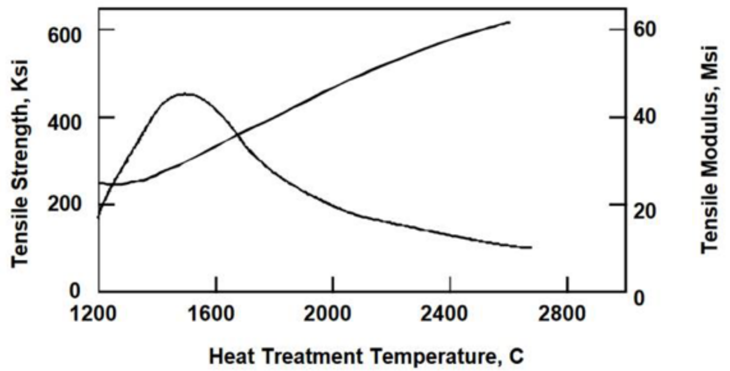
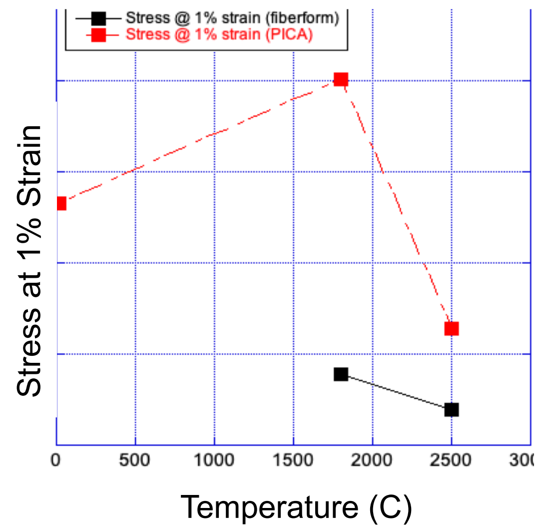
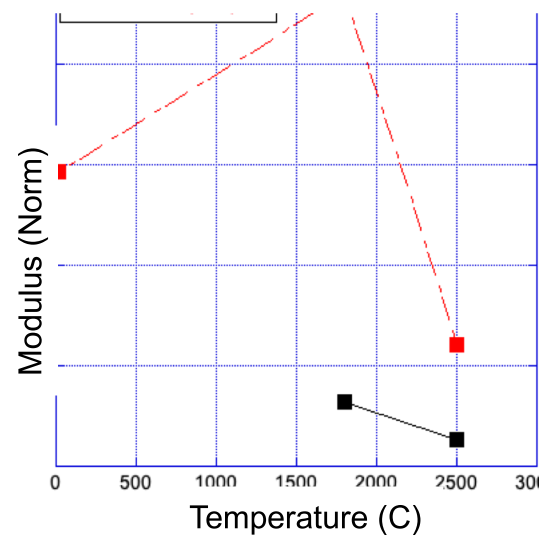


Figure 3-8. Effect of graphitization temperature on fiber properties

From. https://nanoed.tul.cz/pluginfile.php/3599/mod_resource/content/2/Properties-of-fibers.pdf

PICA/Fiberform compression performance degrades at elevated temperatures





- Possibility of increased erosion (recession) of C substrate materials at higher conditions
- Influence of C fiber phase change (or other system changes) with temperature on material performance?
- Kinetics plays a part – lab test vs entry environment

Questions

Entry Systems and Technology Division

HEEET Team

NASA ARC:
- Dave Driver (Retired)
- Marianne Shelley (Retired)
- Ron Chinnapongse (Retired)
- Don Ellerby
- Matt Gasch
- Cole Kazemba
- Milad Mahzari
- Frank Milos
- Owen Nishioka
- Keith Peterson
- Margaret Stackpoole
- Ethiraj Venkatapathy
- Zion Young
- Peter Gage
- Tane Boghozian
- Jose Chavez-garcia
- Greg Gonzales
- Ben Libben
- Ruth Miller
- Grant Palmer
- Dinesh Prabhu
- Joseph Williams
- Alexander Murphy

NASA Facilities:
- Ames:
  - Arcjet Complex
  - STAR Lab
  - EEL
  - Main Shop
- JSC:
  - ES4/Manufacturing
- LaRC
  - James H. Starnes, Jr., Structures and Materials Laboratory
  - Light Alloy Lab
  - Materials Research Lab
  - Model Shop
  - Systems Integration and Test Branch Laboratory

NASA JSC:
- Mike Fowler
- Charles Kellermann

NASA LaRC:
- Carl Poteet
- Scott Splinter
- Sarah Langston
- Kevin Mclain
- Gregory Shanks
- Jacob Tury
- Stewart Walker

HEEET Independent Review Board (IRB)
- Bobby Braun (UC-Boulder, IRB Chair)
- Micheal Amato (GSFC)
- Stan Bouslog (JSC)
- Robin Beck (ARC)
- Anthony Calomino (LaRC)
- Steve Gayle (LaRC)
- Ken Hibbard (APL)
- Pam Hoffman (JPL)
- Joy Huff (KSC)
- Michelle Munk (LaRC)
- Christine Szalai (JPL)

External Partners:
- Bally Ribbon Mills
- Fiber Materials Inc.

External Test Facilities:
- Laser Hardened Materials Evaluation Laboratory (LHMEL)
- Arnold Engineering Development Center (AEDC)
- NTS

External NDE:
- Hadland
- NSI
- VJ Technologies

Carrier Structures:
- AASC

PICA-D Team

NASA ARC:
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- Jose Chavez-Garcia
- Kristina Skokova
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