






# Thermostructural Qualification of PICA-D for NASA Planetary Science Missions

**Milad Mahzari, Matt Gasch, Suman Muppidi, Keith Peterson**

*NASA Ames Research Center*

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The decision to implement Mars Sample Return will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process.
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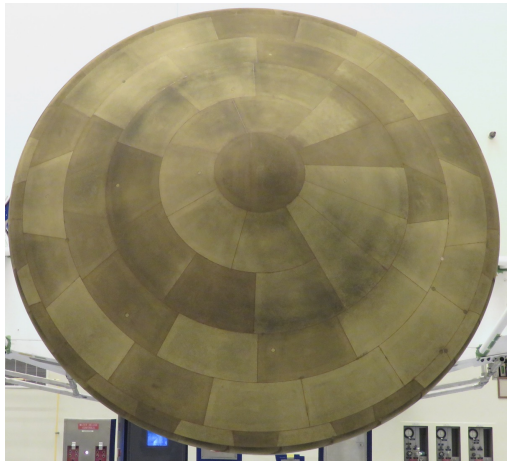
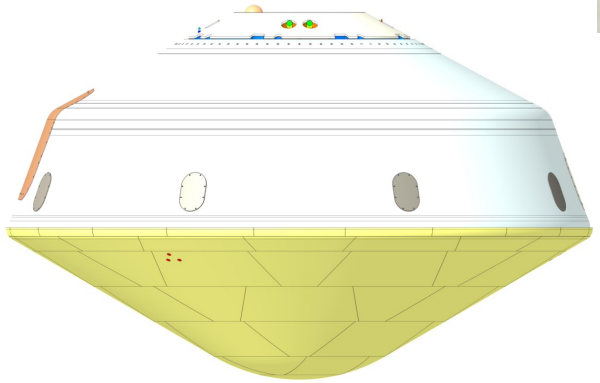
# Introduction

- **PICA-D is the baseline heatshield TPS material for NASA's Dragonfly and SRL missions**
  - PICA-D is the domestic replacement for heritage PICA used on past NASA missions (Stardust, MSL, OSIRIS-Rex, Mars2020)
- **Dragonfly**
  - Relocatable lander at Titan
  - 4.5 m, 60-deg spherecone entry vehicle
  - Peak design heat flux of ~ 300 W/cm$^2$
- **Sample Retrieval Lander (SRL)**
  - Part of the proposed Mars Sample Return campaign
  - 4.65 m, 70-deg spherecone entry vehicle
  - Peak design heat flux of ~ 100 W/cm$^2$
- **Thermostructural analysis has predicted thermally driven compressive failure of PICA-D for both Dragonfly and SRL**
  - Limitations in material property knowledge and analysis techniques drive a desire for qualification testing
- **This talk provides an overview of thermostructural qualification plans to verify PICA-D performance**

Mars2020 Tiled PICA Heatshield

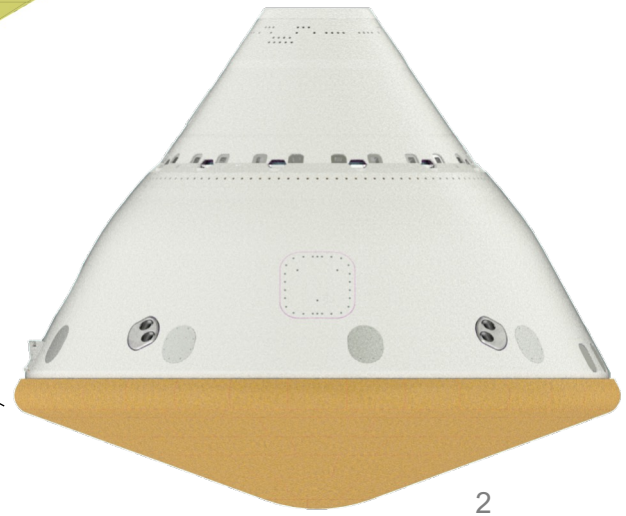


Dragonfly Entry Vehicle



PICA-D Tiles
& RTV Gap Filler

SRL Entry Vehicle



# PICA-D Background and Properties

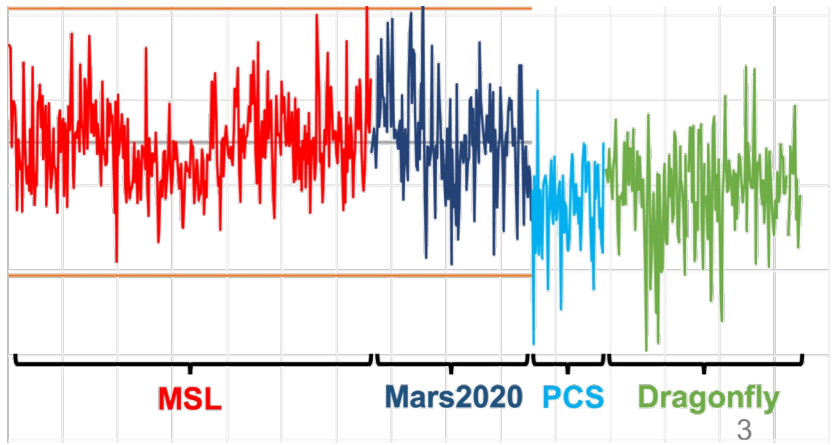
- **PICA has been used as the heatshield TPS material for multiple NASA missions dating back to early 2000s**
  - Precursor Fibers → Fiberform (Carbonized & Cast) → PICA (Phenolic infusion)
  - Different sources of Rayon fibers used. Settled on Sniace Rayon
- **Motivated by the depletion of heritage Rayon source, NASA Ames developed a PICA replacement, called PICA-D**
  - Lyocell was selected as the precursor fiber
  - FMI ended commercial Fiberform line requiring minor changes in Fiberform processing/composition
  - Extended thermal testing showed similar performance to PICA
- **Initial evaluation of PICA-D based on lot acceptance test (LAT) data presents a shift in some mechanical properties**
  - Higher in-plane tension modulus/strength but lower strain-to-failure
  - Very limited data available initially (only RT tension data from LAT)
- **Uncertainties in comparing PICA and PICA-D properties**
  - The only complete source of PICA mechanical properties dates to early developmental billets from Orion ADP era (2007-2009)

**PICA/PICA-D Timeline**

| Timeline | Mission/ Project | Precursor Type |
|---|---|---|
| Early 2000's | **Stardust** Near Net Shape 0.8m | Liberty rayon |
| 2010 | **Orion CEV ADP** Billets | Multiple sources – settled on Sniace |
| 2012 | **MSL** Billets | Sniace rayon |
| 2016 | **OSIRIS Rex** Near Net Shape 0.8m | Sniace rayon |
| 2018-2019 | **M2020** Billets | Sniace rayon – **source depleted** |
| 2016-2018 | **PICA-D Development** Billets and Near Net Shape | Lyocell - USA, Austria |
| **2019-2021** | **PICA Capability Sustainment (PCS)** | Lyocell - Austria |
| **2021 →** | **Dragonfly / MSR SRL** | Lyocell - USA |

Commercial Fiberform line ended at FMI

**PICA/PICA-D In-Plane Strain to Failure (Tension)**



# Model Prediction of PICA-D Failure

- **Finite Element Method (FEM) tools predict in-plane compressive failure in near-surface layers of PICA-D for both Dragonfly and SRL**
  - Driven by thermal stresses induced by PICA-D's higher IP modulus and CTE
  - Analysis done using a mix of measured and estimated PICA-D properties
  - Models indicate a minimum dimension for this failure mode to occur (not expected in small arcjet coupons)
- **MSL analysis did not reveal this failure mode**
  - Likely influenced by inaccurate properties and model fidelity
  - MSL FEM predicted other failure modes that were addressed through thermostructural testing
- **Limitations of FEM in predicting TPS response**
  - Uncertainties in high-temperature char properties
  - Current FEM models predict failure using traditional linear definition, but the material has significant plastic strain capability beyond its elastic ultimate strength

**Final verification of material performance must be achieved through a thermostructural test**

Coefficient of Thermal Expansion (CTE)

Modulus

Temperature Change

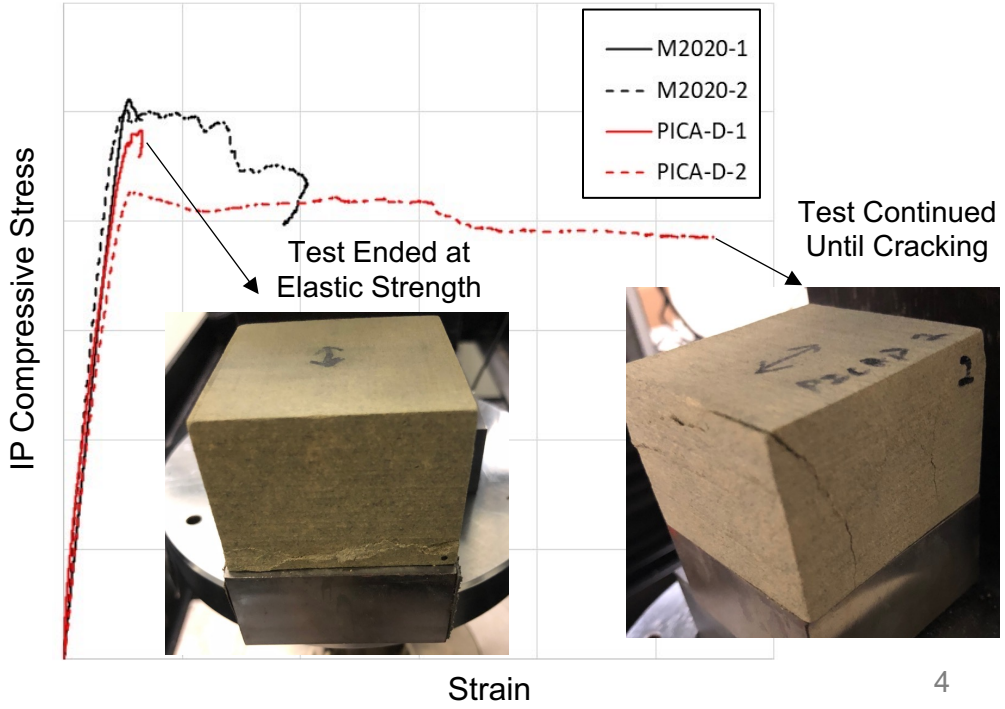
$$\sigma = E\gamma\Delta T/(1-\nu)$$

Poisson's Ratio

Compressive stress generated in the surface layer of a material due to internal constraint when it is suddenly subjected to a temperature change

Young, W., Budynas, R.. *Roark's Formulas for Stress and Strain,* Chapter 16.6, McGraw-Hill, 2002.

**Compression Testing of Virgin PICA-D Shows Significant Non-linear Strain Capability Beyond its Elastic Ultimate Strength**



# Overview of Risk Mitigation Plans

## Four-pronged approach to address the PICA-D thermostructural risk and verify material performance

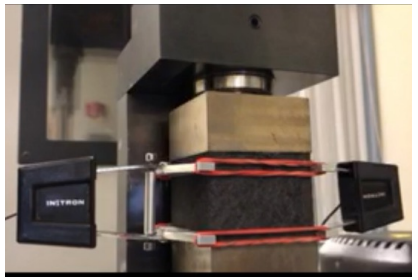
- **PICA-D Mechanical Property Testing**
- **Enhancements to FEM Analysis**
- **Thermostructural Verification Test**
  - Acreage PICA-D
  - Gap Fillers, Repairs, defects
- **Maturing and Testing Backup TPS Materials**

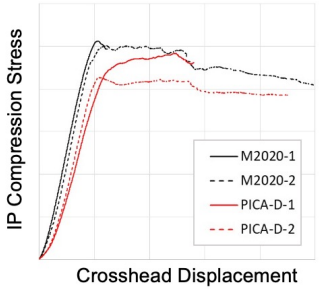
Table 1: Virgin PICA-D Test Matrix

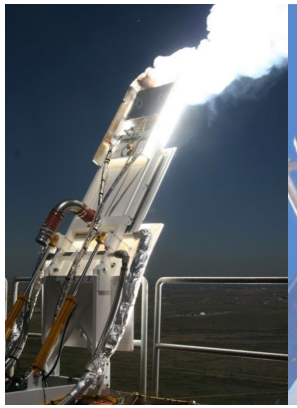
| Coupon Test Description--Virgin PICA-D | -175C | 22C | 288C | Fiber Direction | Relevant ASTM Spec |
|---|---|---|---|---|---|
| Tension | 6 | 3 | 2 | In-Plane (L) | D-1623 |
| Tension | 6 | 3 | 2 | In-Plane (W) | D-1623 |
| Tension | | | | | |
| Compression | | | | | |
| Compression | | | | | |
| Compression | | | | | |
| Shear | | | | | |
| Shear | | | | | |
| Shear | | | | | |
| Four Point Flexure | | | | | |
| Four Point Flexure | | | | | |
| Thermal Expansion | | | | | |
| Thermal Expansion | | | | | |
| Thermal Expansion | | | | | |
| Thermal Expansion | | | | | |
| Thermal Expansion | | | | | |
| Thermal Expansion | | | | | |
| Restrained Thermal Growth | | | | | |
| Restrained Thermal Growth | | | | | |
| Total Virgin PICA-D C | | | | | |

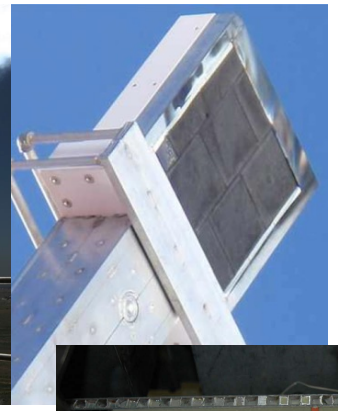
Table 3: Charred PICA-D Test Matrix

| Coupon Test Description Charred PICA-D | 288C | 850C | 2200C | Fiber Direction | Relevant ASTM Spec |
|---|---|---|---|---|---|
| Tension | 2 | 2 | 3 | In-Plane (L) | D-1623 |
| Tension | - | 2 | 3 | In-Plane (W) | D-1623 |
| Tension | 2 | 3 | 2 | Through Thickness | D-1623 |
| Compression | 2 | 2 | 3 | In-Plane (L) | D-1621 |
| Compression | 2 | 2 | 3 | In-Plane (W) | D-1621 |
| Compression | 2 | 3 | 2 | Through Thickness | D-1621 |
| Shear | 3 | 6 | 3 | In-Plane | C-273 |
| Shear | 2 | 2 | 2 | Through Thickness (L) | C-273 |
| Shear | 2 | 2 | 2 | Through Thickness (W) | C-273 |
| Four Point Flexure | 2 | 3 | 2 | In-Plane (L) | D-7264 |
| Four Point Flexure | 2 | 3 | 2 | In-Plane (W) | D-7264 |
| Thermal Expansion | 3 | | | In-Plane (L) | E-228 |
| Thermal Expansion | 3 | | | In-Plane (W) | E-228 |
| Thermal Expansion | 3 | | | Through Thickness | E-228 |
| Total Charred PICA-D Coupons Needed | | | | 87 | |

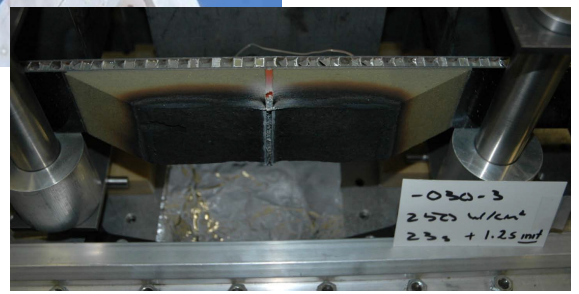




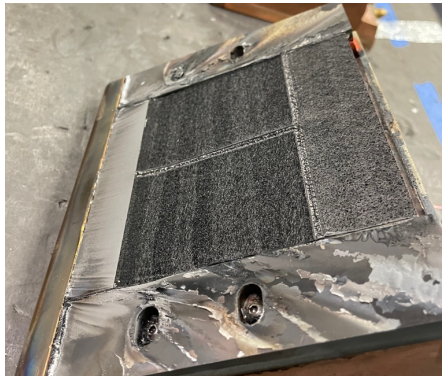


Solar Tower Testing of PICA (Orion ADP)




Laser Flexure Testing of PICA at LHMEL (MSL)

Arcjet Test of Conformal PICA



Mechanical Test of Conformal PICA



# Mechanical Property Testing

The only initial source of data was FMI's LAT measurements on virgin tension coupons

**Phase 0: High-priority compression and CTE testing at Ames and Kratos**

- IP compression testing showed virgin and Fiberform compression properties are in family with heritage PICA
- IP CTE measurements showed PICA-D has higher char CTE at elevated temperatures

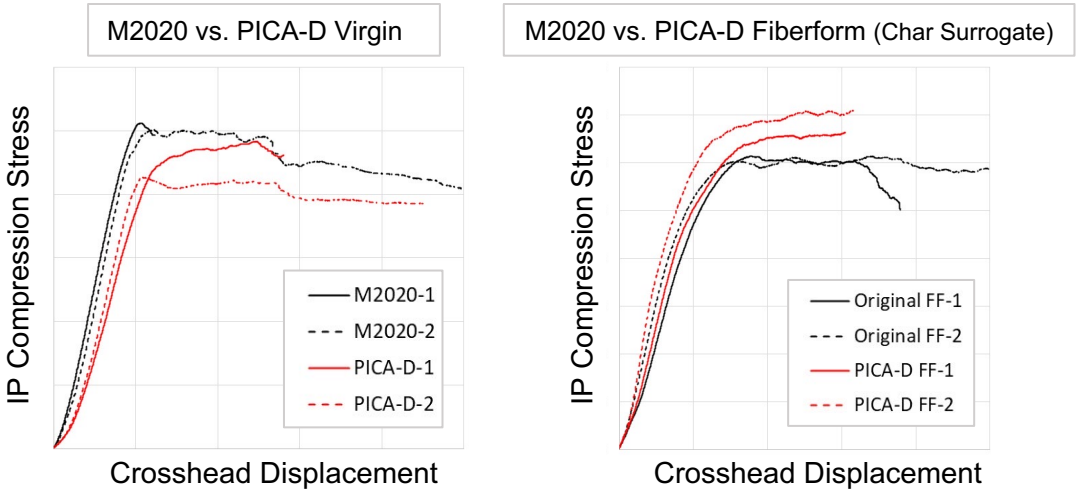
**Phase 1: Subset of full test matrix at Lockheed**

- Focused on IP testing of virgin and char coupons
- CT scanning of PICA-D char coupons tested to different strain levels to evaluate material plastic capability

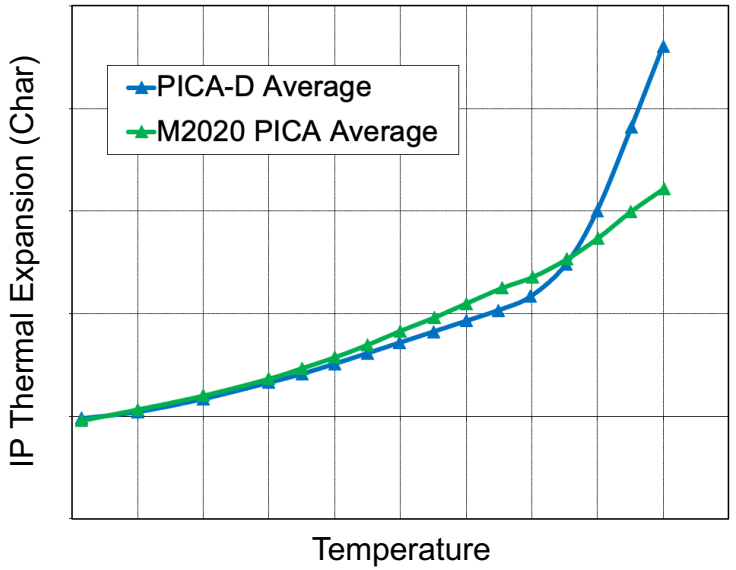
**Phase 2: Full test matrix at Kratos SRE**

- Complete set of properties at multiple temperatures
  - Total of 224 coupons sampled from 6 Dragonfly billets
  - Limited Mars2020 PICA testing for comparison
- Restrained Thermal Growth (RTG) testing to complement initial CTE results

**In-Plane Compression Testing at Ames**



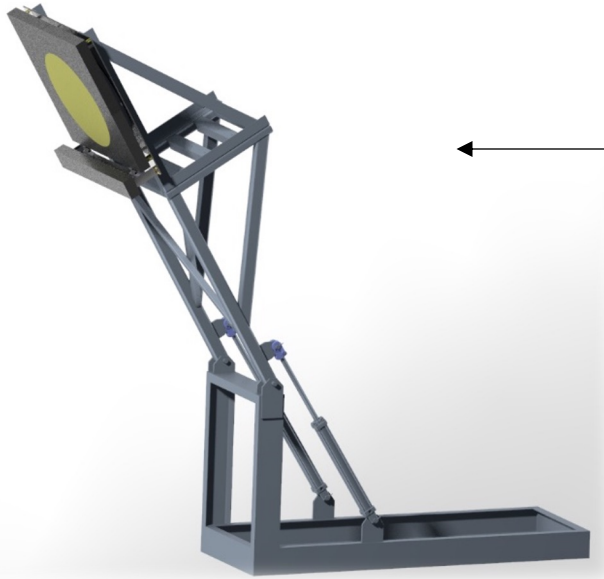

**Thermal Expansion Testing at Kratos**



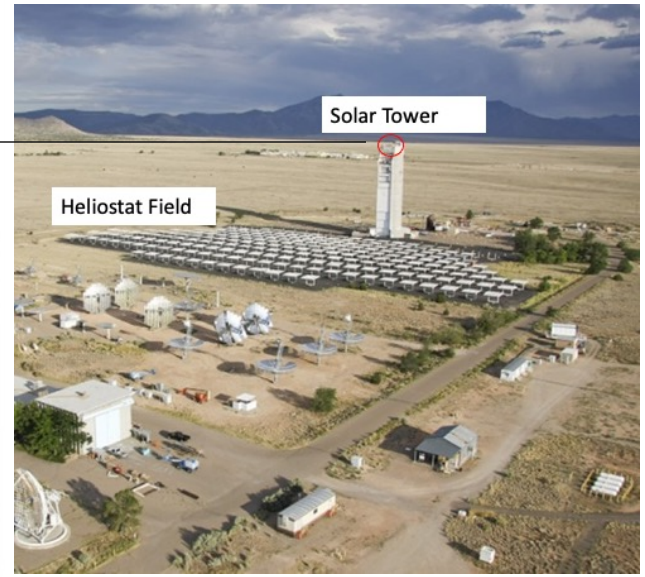
# Solar Tower Testing

- **Objective:** Validate PICA-D performance when subjected to flight relevant thermal-structural load
- **Solar tower test technique**
  - Heat a large article (2-ft diameter) up to ~ 300 W/cm$^2$ by focusing Sun' energy using a heliostat field
  - Apply enforced deflection to a known Radius of Curvature (ROC) using vacuum chuck tooling
  - Advantage over LHMEL: uniform heating of large articles and biaxial loading → uniform in-plane compressive stresses
  - Potential for material combustion at atmospheric pressure is mitigated by $N_2$ knife flow and purge
- **Targeting 3 flight-like heat flux profiles**
  - 100 (SRL), 200, 300 (Dragonfly) W/cm$^2$
- **Vacuum tool ROC:** 250, 350, 500, 950, 1200 inch
  - Based on FEM analysis to match predicted flight stresses, and a desire to chase failure point
- **8 Structural and 3 thermal articles**
  - Bonded to composite
  - Thermal articles contain TC plugs to verify conditions
- **HD/IR Camera, visual inspection, post-test CT scan, laser scan and mechanical tests**

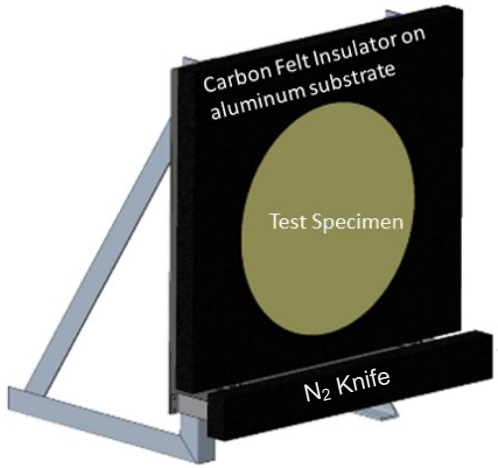
**Test Configuration**



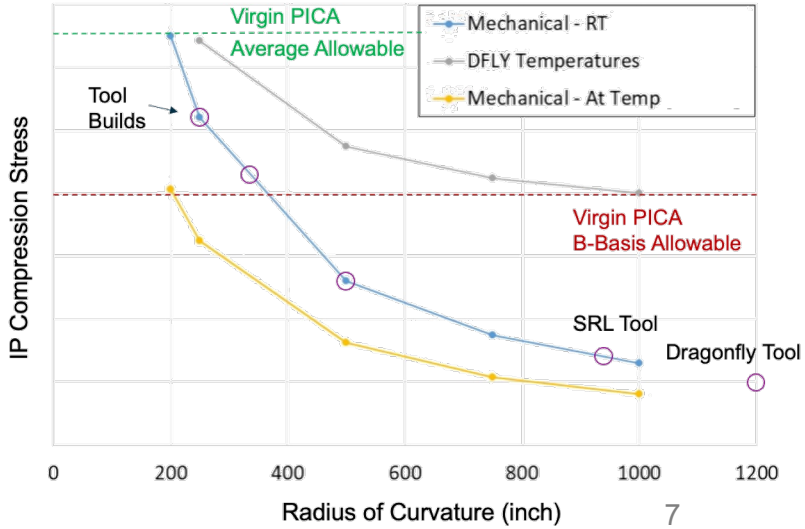
**National Solar Thermal Test Facility (NSTTF)**




**Test Fixture**




**FEM Analysis to Inform Tool ROC Selection**



# Closing Thoughts

- **The joint SRL/Dragonfly team is looking forward to the upcoming solar tower test as a key step in the thermostructural qualification of acreage PICA-D**
  - Scheduled for September 8-10
  - Addresses the in-plane compressive failure of acreage PICA-D predicted by FEM models

- **More work ahead for a full verification of PICA-D thermostructural performance**
  - Testing of design features, repair plugs, defects at NSTTF or LHMEL
  - Other mechanical testing (RT 4-point bend tests, cold soak, shock, heatshield TVAC, etc.)
  - Enhancements to the FEM models (updated properties, non-linear capability)

- **Maturing and testing backup TPS materials in the event that solar tower testing shows inadequate PICA-D performance**
  - Conformal PICA (C-PICA-09) is one backup TPS material
  - Backup materials are included in arcjet and solar tower test matrix
  - Solar tower testing of backup TPS materials is scheduled for Sep 29 – Oct 1

# Acknowledgements

PICA-D thermostructural performance has been a key area of interest on both SRL and Dragonfly. Many engineers from NASA Ames, JPL, APL and Lockheed have been involved in evaluating this issue and developing testing and mitigation strategies. The authors would like to acknowledge contributions/feedback/support from:

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**JHU APL**

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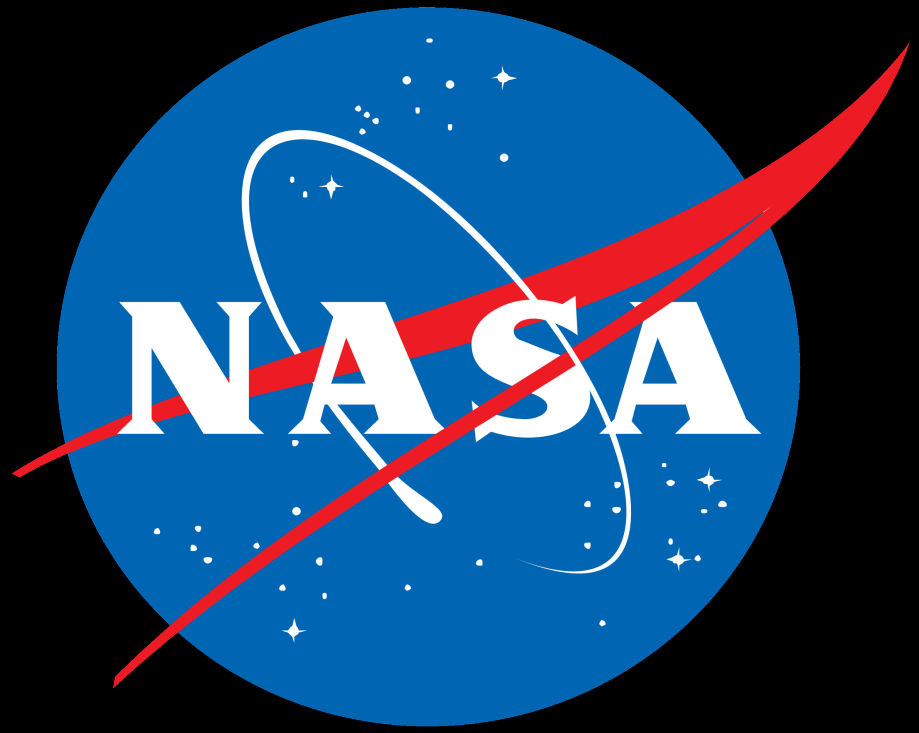
Wayne Dellinger
Ken Hibbard

**Lockheed Martin Space**

Sam Preece
Derek Shannon
Tom Zaccari

## Questions?

National Aeronautics and Space Administration



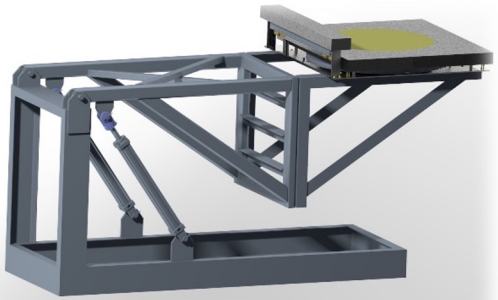

Ames Research Center
Entry Systems and Technology Division

# Solar Tower Testing

## Test Config (-30° to Horizon)



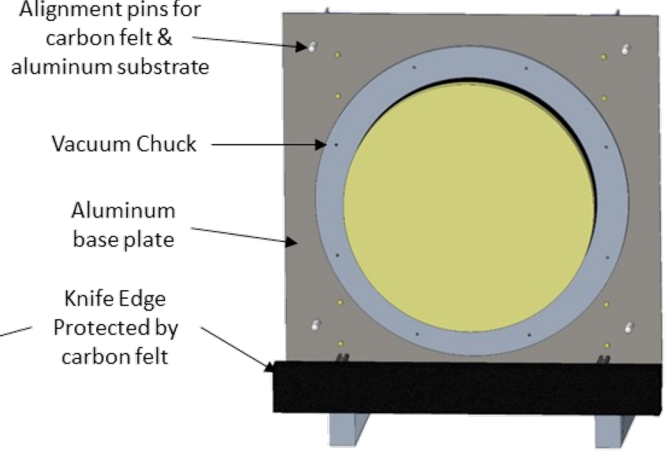
## Installation Config



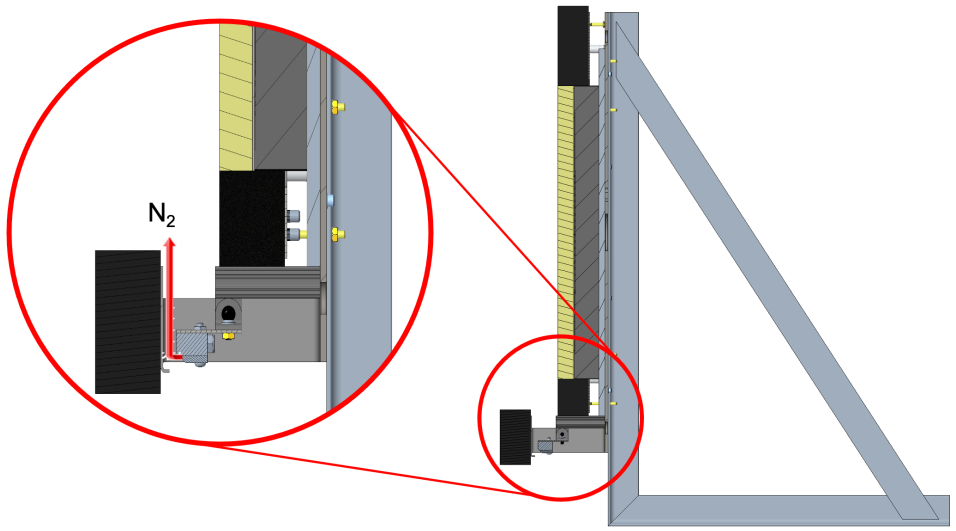
## Test Fixture



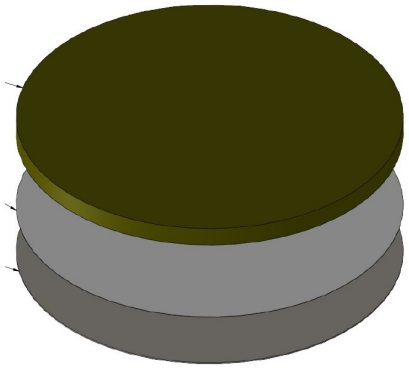

### View without Felt Insulator



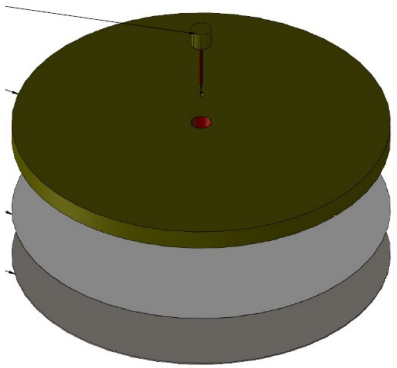

## $N_2$ Knife



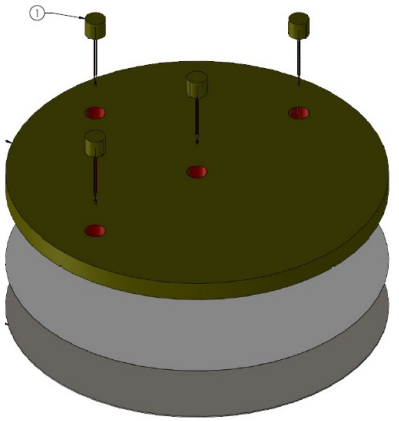

## Test Article



Structural Article



Thermal Article: 1 TC Plug

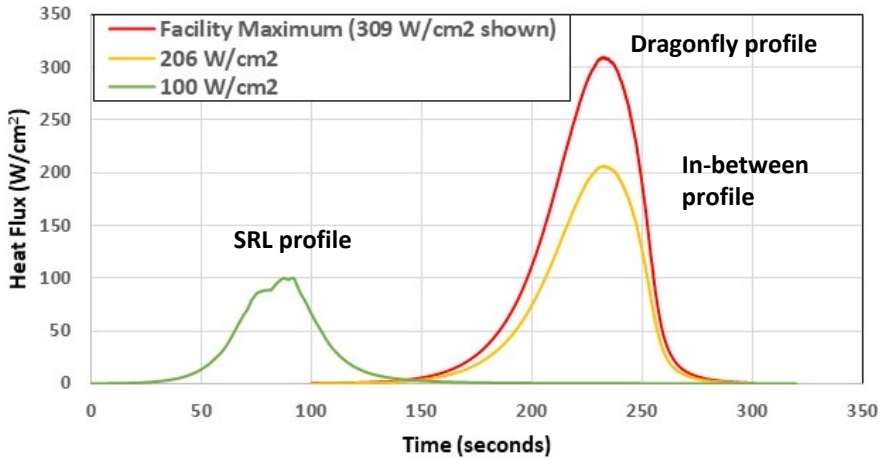


Thermal Article: 4 TC Plugs

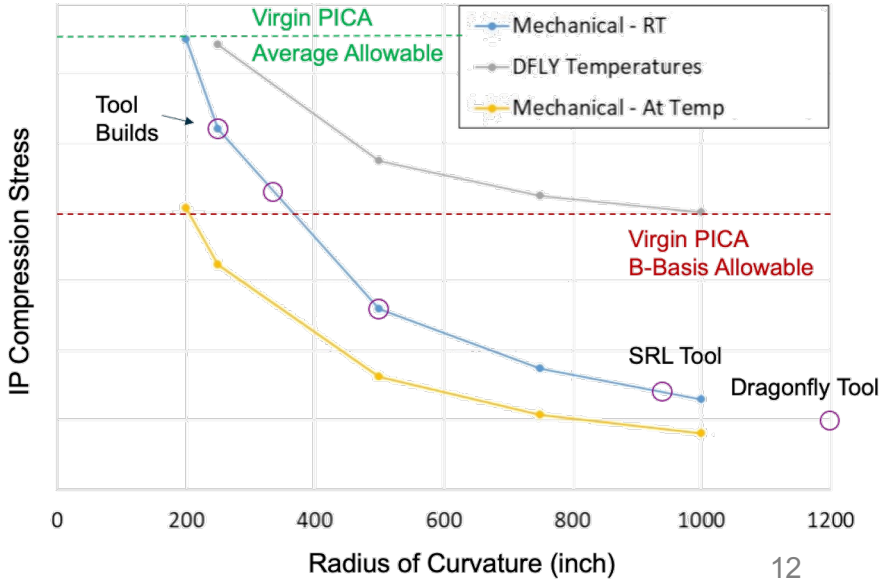
# Solar Tower Test Environments

- Thermal loading
  - Heliostat field focuses Sun's energy on the test article
  - Flight-like profile can be achieved by moving heliostats
  - Targeting 3 conditions: 100, 200 and 300 W/cm$^2$
    - 300 W/cm$^2$ (facility max): Dragonfly design heat flux
    - 100 W/cm$^2$: SRL design heat flux
- Mechanical loading
  - Mechanical load is achieved by conforming PICA-D coupons to a known Radius of Curvature (ROC) using vacuum chuck tooling
  - Tool ROC chosen based on FEM analysis, predicted flight stresses, and a desire to over-test and chase failure modes
  - Five radii of curvature tools to provide known initial deflections and stresses: 250, 350, 500, 950 and 1200 inches
  - 950- and 1200-inch tools represent predicted flight stresses for SRL and Dragonfly respectively

**Targeted Heat Flux Profiles**




**FEM Analysis to Inform Tool ROC Selection**



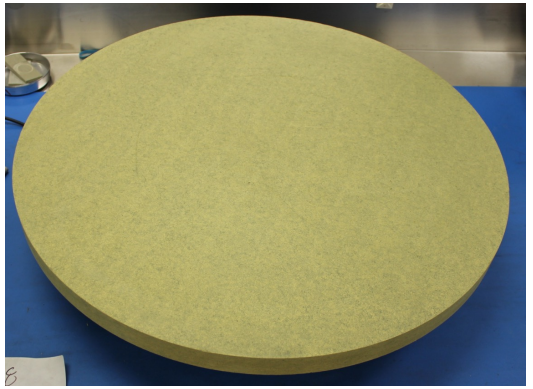
# Test Matrix and Instrumentation

- Test matrix assumptions
  - The high condition can be achieved only around solar noon
  - Test a non-critical article first to verify test technique
  - Test flight-representative ROCs and design heat fluxes first
  - If successful, show increased capability and chase failure point by using tighter ROCs
- Instrumentation and post-test article evaluation
  - TC plugs in thermal panels, pyrometer
  - HD/IR camera
  - Visual inspection
  - Post-test CT scan and laser scan
  - Post-test mechanical tests
- PICA-D solar tower testing scheduled for Sep 8-10

**Preliminary Test Matrix**

| Day | Run | Mat'l | Test Article Type | RoC (in) | Environment ($W/cm^2$) | Time |
|---|---|---|---|---|---|---|
| 1 | 1 | PICA-D | Therm. 1 plug | 1200 | 206 | Morning |
| 1 | 2 | PICA-D | Therm. 4 plug | 1200 | 309 | Solar Noon |
| 1 | 3 | PICA-D | Structural | 1200 | 309 | Solar Noon |
| 1 | 4 | PICA-D | Structural | 950 | 100 | Afternoon |
| 2 | 5 | PICA-D | Therm. 1 plug | 950 | 100 | Morning |
| 2 | 6 | PICA-D | Structural | 500 | 309 | Solar Noon |
| 2 | 7 | PICA-D | Structural | 350 | 309 | Solar Noon |
| 2 | 8 | PICA-D | Structural | 350 | 200 | Afternoon |
| 3 | 9 | PICA-D | Structural | TBC | TBC | Morning |
| 3 | 10 | PICA-D | Structural | TBC | TBC | Solar Noon |
| 3 | 11 | PICA-D | Structural | TBC | TBC | Solar Noon |

**PICA-D Test Article**



**Vacuum Chuck Tools**

