3D Printing Heat Shields: An overview of the AMTPS Project

NASA Advisory Council
Technology, Innovation & Engineering Committee Meeting

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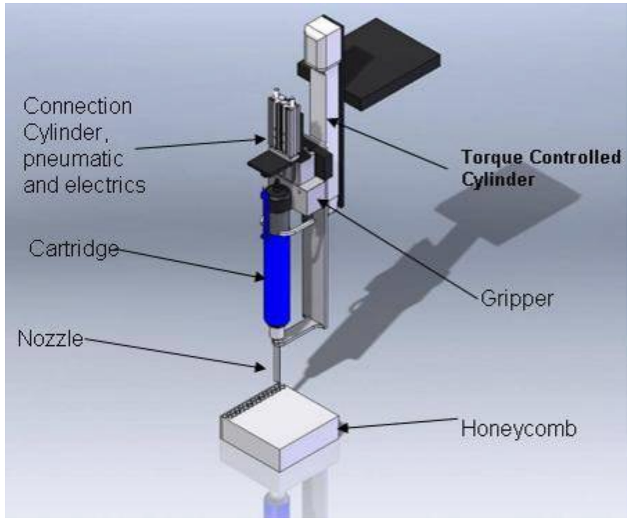
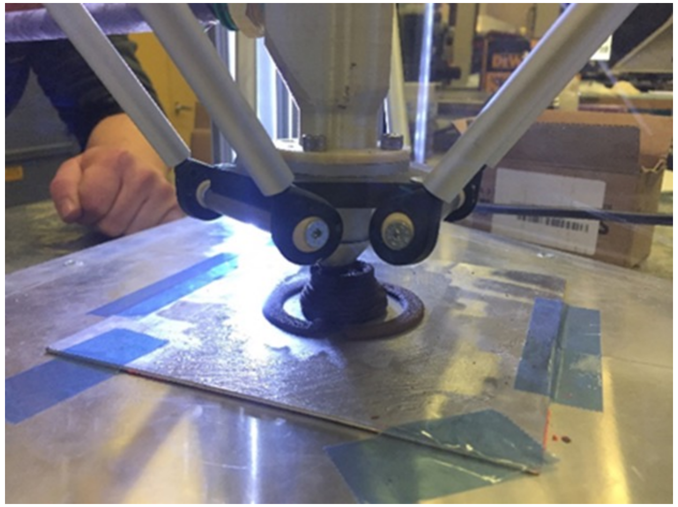
5/16/23

Additive Manufacturing of Thermal Protection Systems

- **2007 – 2009:** Explored automation for TPS
  - TPS Advanced Development Project developed automated gunning of honeycomb Avcoat on flat surfaces
- **2018:** AM manufacturing successes, especially in composite structures, led to exploratory efforts in AMTPS with internal funds at JSC, augmented with DOE funding through Oak Ridge National Lab
  - 3D Printed Heat Shields (FY18-FY20 CIF Project)
- **2019 – Present:** NASA continued development both internally & externally
  - AMTPS Early Career Initiative (ECI)
    - $2.5M / 2 years
  - SBIR/STTR Program
    - 11 Phase 1 awards ($150K / 13 months)
    - 4 Phase 2 awards ($750K / 2 years)



Automation explored for honeycomb Avcoat under TPS ADP (2008)


Initial printing trials under JSC CIF project, 3D Printed Heat Shields (2017-2019)

Outline

- Motivation (Why?)
- Approach (How?)
- Technical Work (What?)
  - Material Development
  - Flight Testing
  - Scale Up
- Next Steps

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What is the need?

- **Key Findings from Industry LEO Commercialization Studies:**
  - Crew and cargo **transportation costs were the major barrier to economic development** of LEO and if not reduced, affect both the commercial LEO destination costs and market demand.
  - Commercial LEO human spaceflight destinations are only **viable with significant U.S. government investment and purchase of services**. NASA is expected to be an anchor tenant.
- **All crew and cargo transport vehicles, to and from LEO, will need thermal protection systems (TPS).**

Sierra Space

Relativity

Firefly

Boeing

Space X

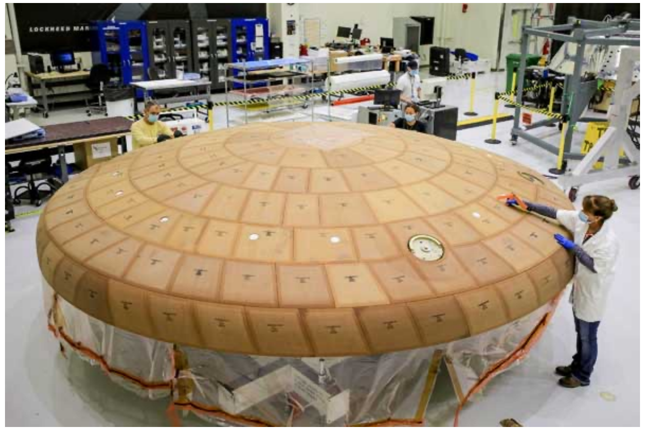
Other EDL companies

Readily Available and Low Cost TPS is Enabler for These Missions.

Why additive manufacturing?

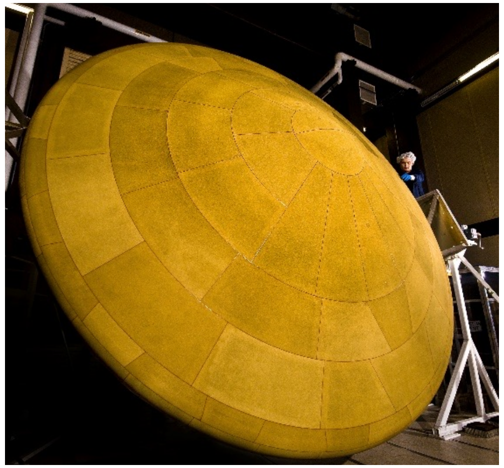
Traditional Approaches

Manual fabrication, bonding in segments, single formulation



Orion

Apollo



Mars Science Laboratory

AMTPS

Automated, monolithic fabrication, graded formulation

Robust Layer
(Transition Layers)
Insulative Layer
3D Printed Structure

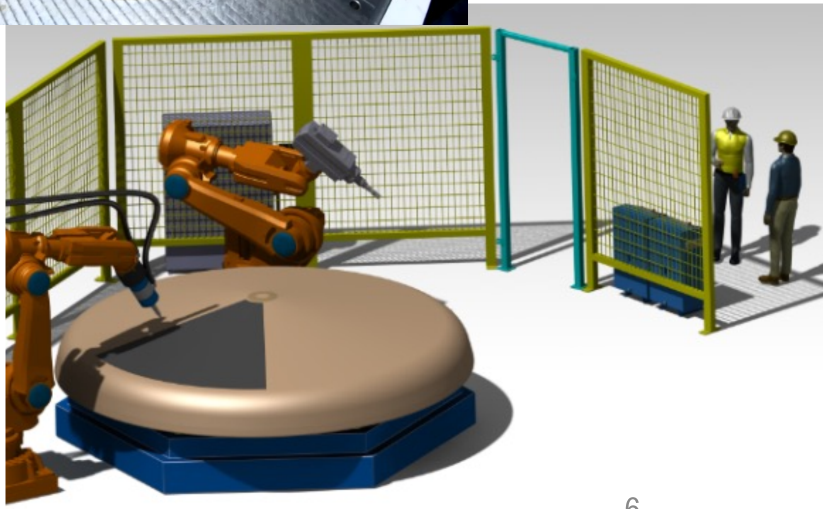


Photo Credits
Left: B. Anthony Stewart/National Geographic/Getty Images, [The Amazing Handmade Tech That Powered Apollo 11's Moon Voyage – HISTORY]
Top right: NASA/Isaac Watson, [Heat Shield Milestone Complete for First Orion Mission with Crew | NASA]
Bot right: NASA/JPL-Caltech/Lockheed Martin, [Large Heat Shield for Mars Science Laboratory – NASA's Mars Exploration Program]

Streamlined fabrication and integration

AMTPS

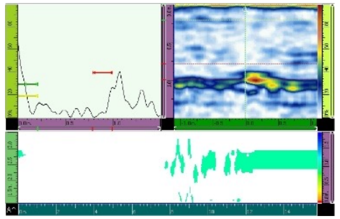
Traditional Block/Tile Approach

Build time: ~months

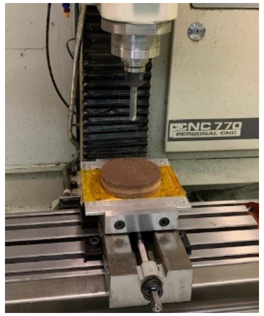
Mix Material & Mold Blocks

Cure Blocks in Oven

Inspect Blocks



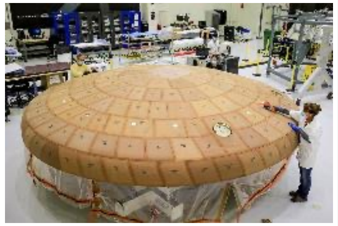
Machine Blocks (IML + OML)



Bond Blocks**

Inspect Bonds

Fill Gaps

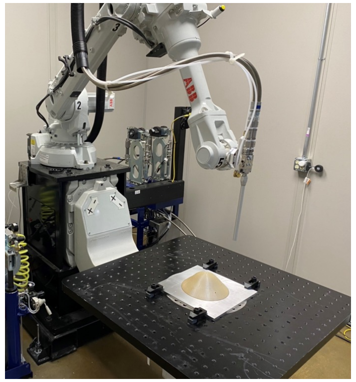


AMTPS Process

Build time: ~weeks

Mix Material

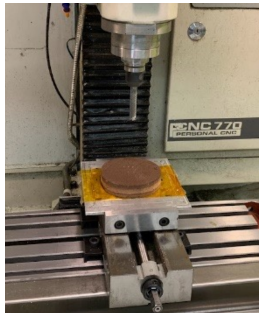
Fixturing**



Printing

Cure and Bond in Oven

Final Machining (OML only)



Inspect & Repair

**Note: Vehicle structure must be available at the noted step

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How to do it?

Direct Ink Write (DIW) / Paste Printing

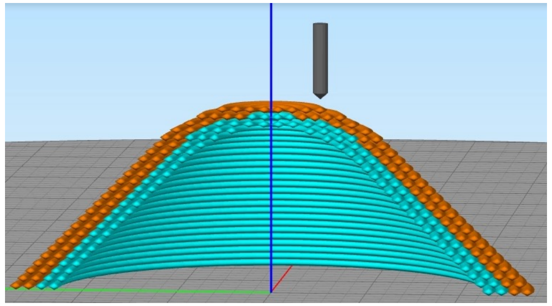
Material Formulation

Strength/CTE Modifiers

Rheology Modifiers

Density Modifiers

Toolpathing

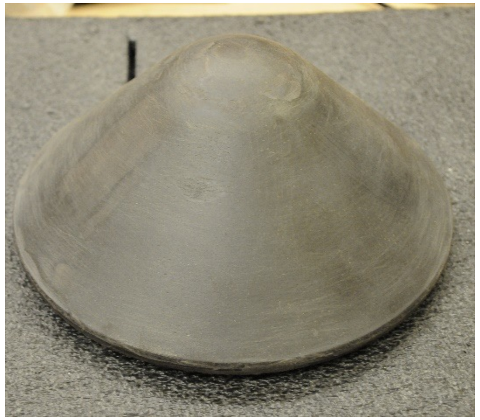


Print

Cure

Near net shape part

Machine OML



Assembly & Integration

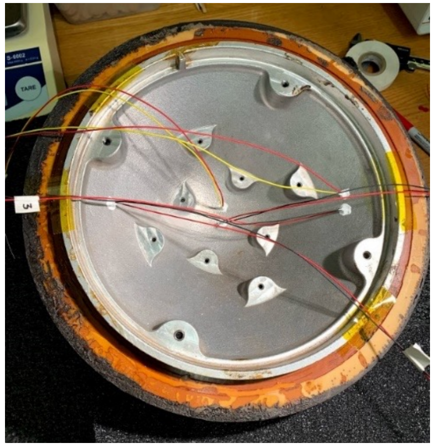


Photo Credit: A. Martin/Univ. of Kentucky

AMTPS Project Goals

AMTPS

Goal: To develop an automated, additive approach for heat shield manufacturing

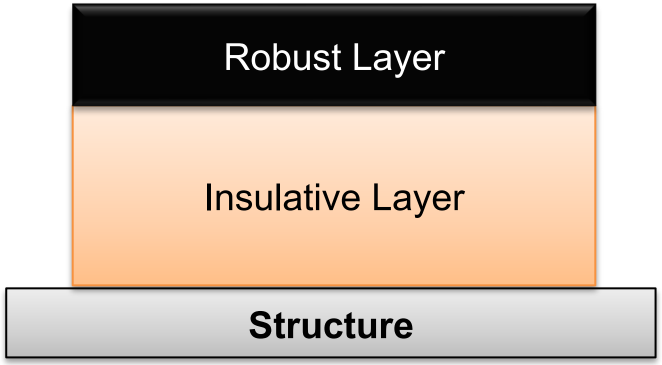
Why? Reduce cost and improve consistency over traditional manufacturing by automating and accelerating production; direct integration onto structure during processing simplifies integration

Internal R&D (pre-cursor project)

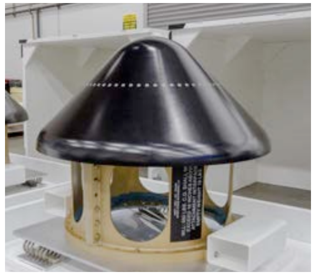
Focus on ablative TPS

Project Deliverables

(1) Develop and characterize a printable, graded TPS architecture



(2) Build and test a mid-scale MDU (up to 1.0m dia.)



(3) Design and build AM capsule for flight testing

FY18-20 | *FY21* | *FY22* | *FY23*

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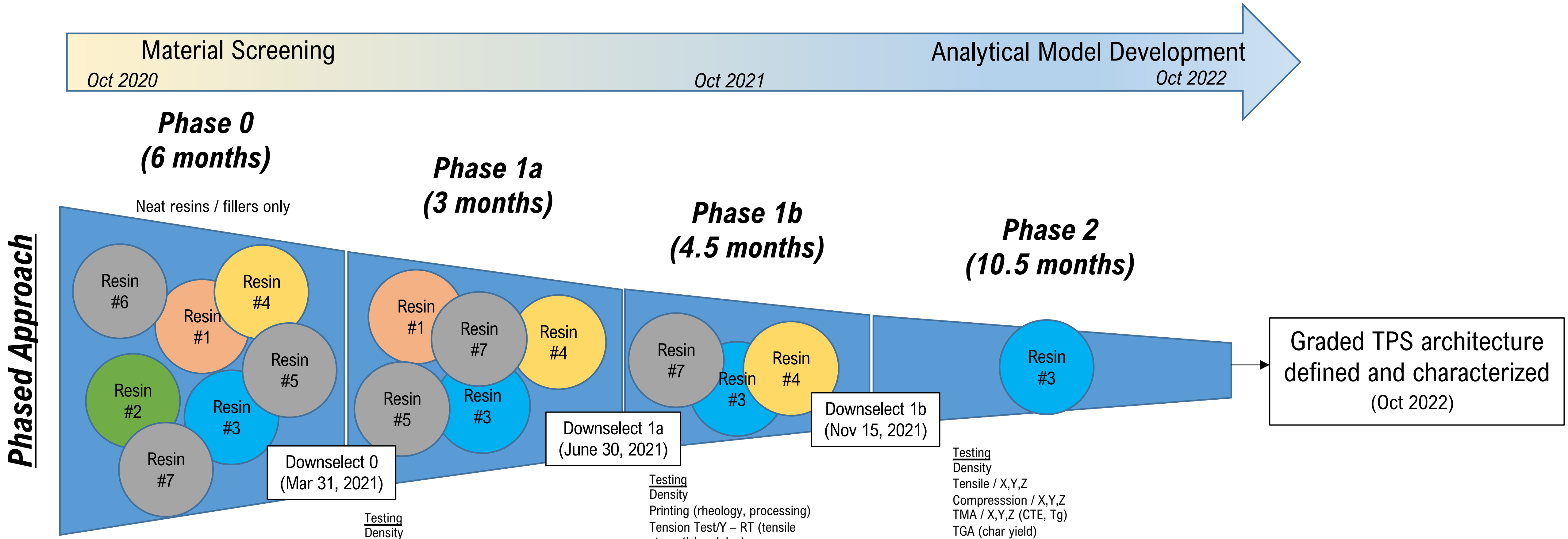
Material development progression

AMTPS



Phase 0 – Testing
- TGA (char yield, char robustness)
- DSC (Tg, curing behavior)
- TMA (CTE, Tg)
- Manufacturer data (% solids, viscosity, thermal conductivity*)

Phase 1a – Testing
- Density
- Printing (rheology, processing)
- Tension Test/X – RT and elevated (tensile strength/modulus)
- TMA/X,Y,Z (CTE, Tg)
- TGA (char yield)
- Modulated DSC (Cp, curing kinetics)
- DTC (thermal conductivity)
- ICP Torch (ablative performance)

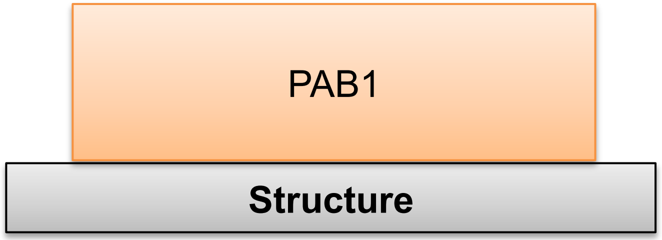
Phase 1b – Testing
- Density
- Printing (rheology, processing)
- Tension Test/Y – RT (tensile strength/modulus)
- Flatwise tension/Z (tensile strength)
- Arcjet (ablative performance)

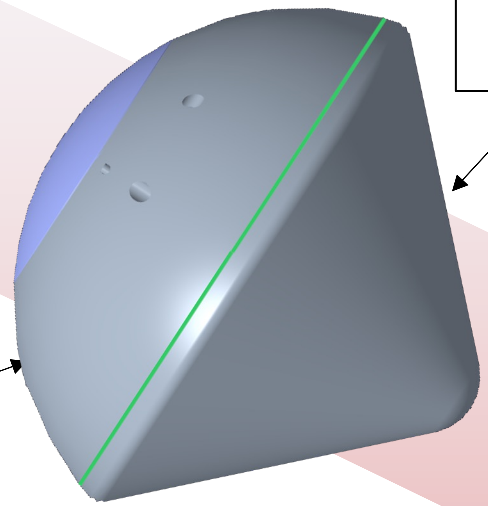
Phase 2 – Testing
- Density
- Tensile / X,Y,Z
- Compresssion / X,Y,Z
- TMA / X,Y,Z (CTE, Tg)
- TGA (char yield)
- Modulated DSC (Cp, curing kinetics)
- Elemental Analysis (composition)
- Heat of Combustion (heats of formation)
- DTC / Z (thermal conductivity)

Two printable TPS material systems

Backshell (PAB1)

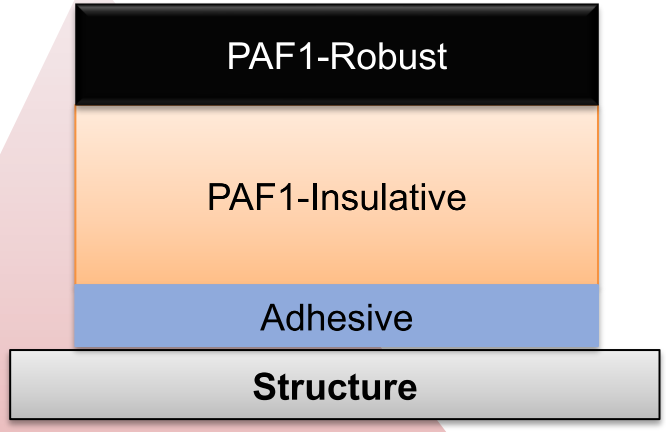
- **P**rintable, Low density **A**blator for **B**ackshell
- Several resin options explored during course of project





Forebody (PAF1)

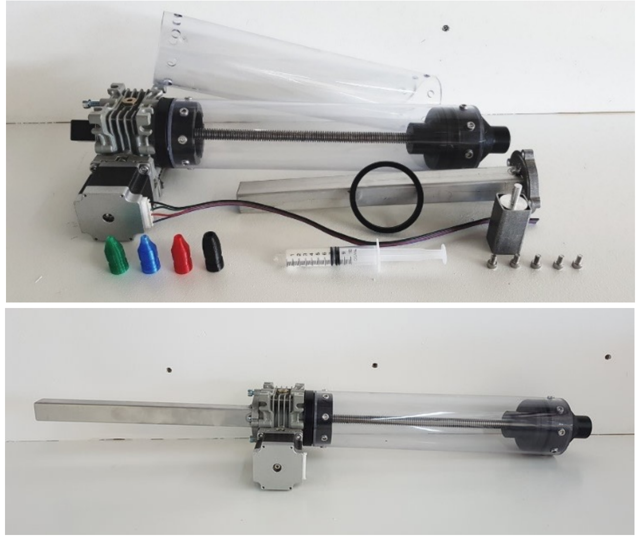
- **P**rintable, mid-density **A**blator for **F**orebody
- Phenolic-based resin / dual layer
  - *Robust*: higher density; higher temp capability ablative layer
  - *Insulative*: lower density, more insulating internal layer

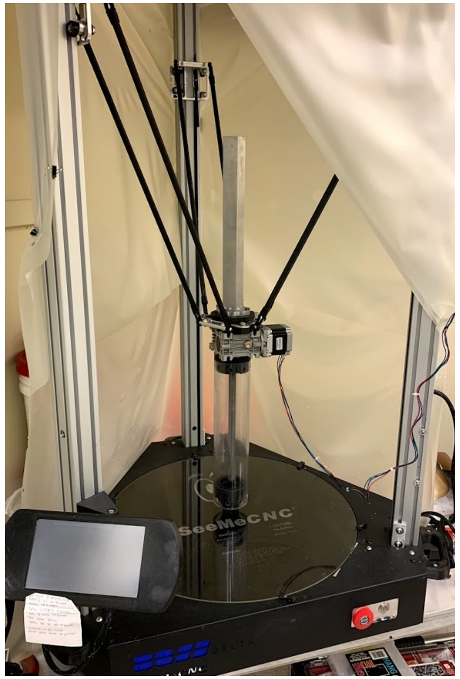


Dual layer TPS layer configuration

Building material characterization database

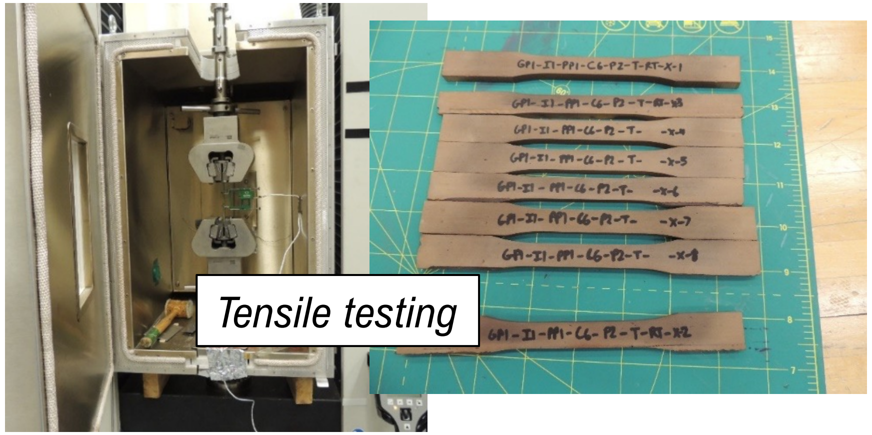
Lab scale printer



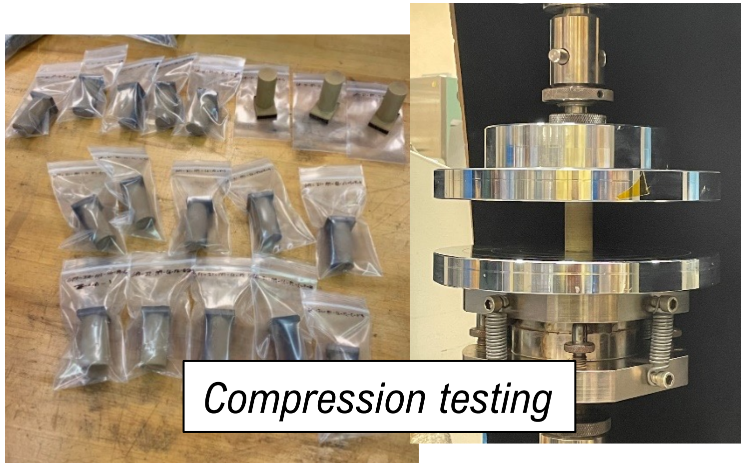


PotterBot 1000mL Extruder
(Direct drive, 1L capacity)

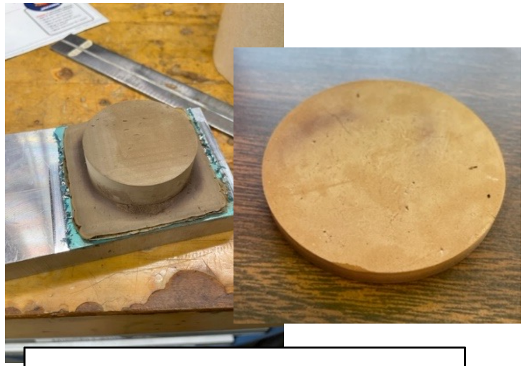
Mechanical and Thermal Testing



Tensile testing



Compression testing



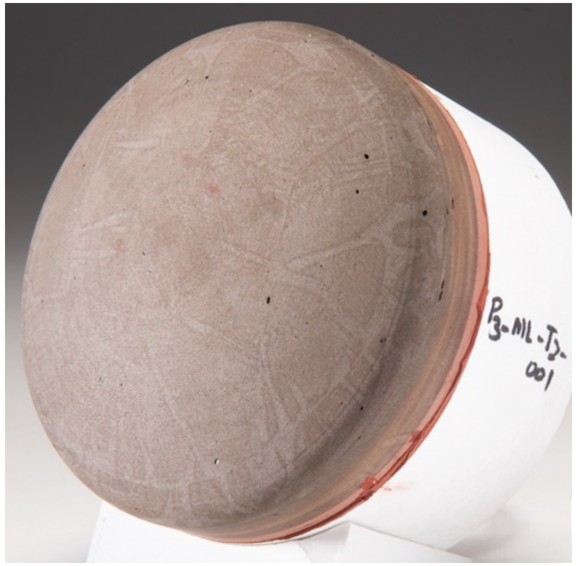
Thermal conductivity test articles

Good performance in arcjet testing

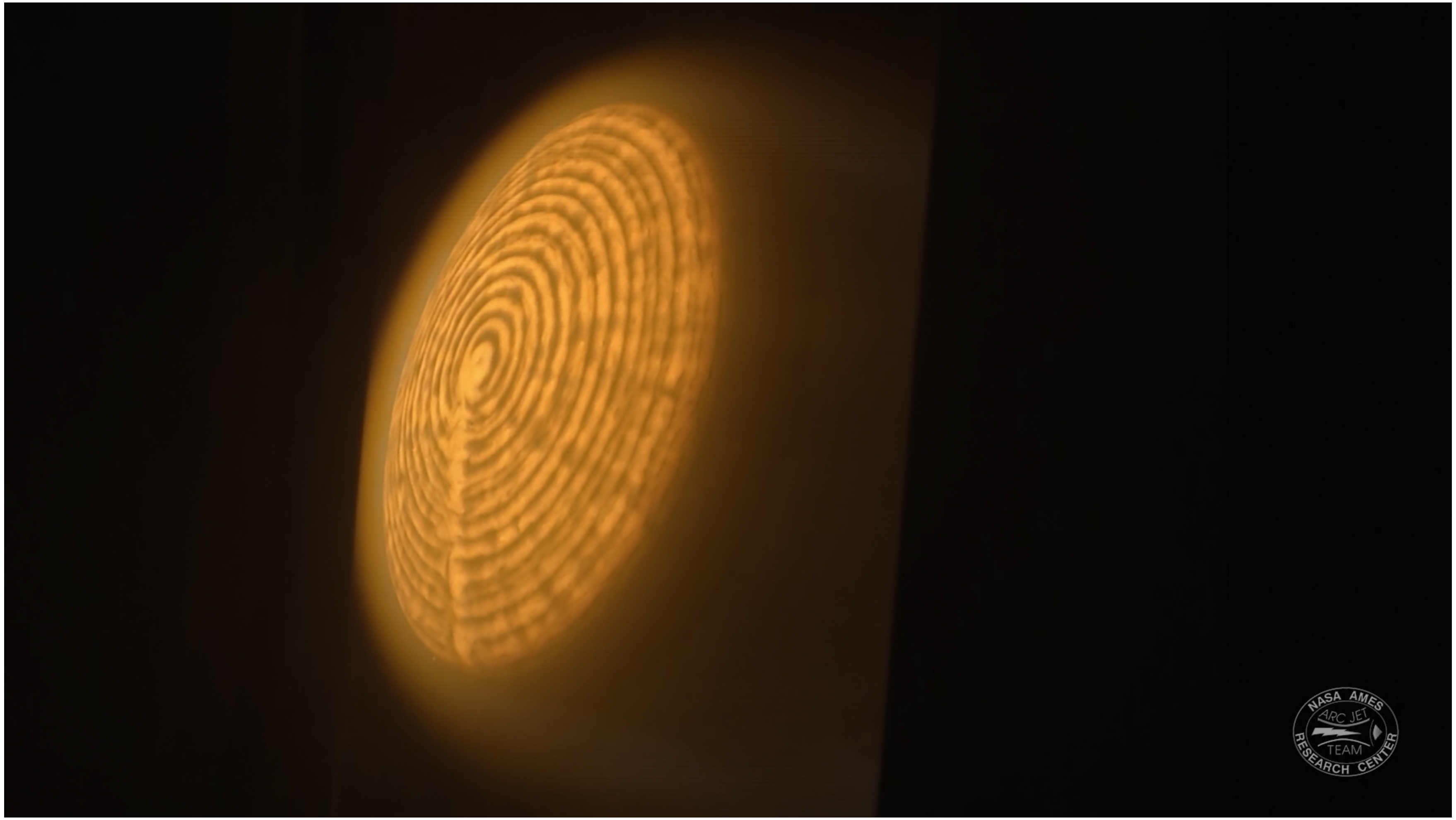
- Two rounds of arcjet testing at NASA Ames AHF facility in 2021 and 2022
- 4” diameter iso-q models
- 30 second exposures

Pre-test

4” diameter AMTPS iso-q
Multi-layer (insulative → robust)



During test

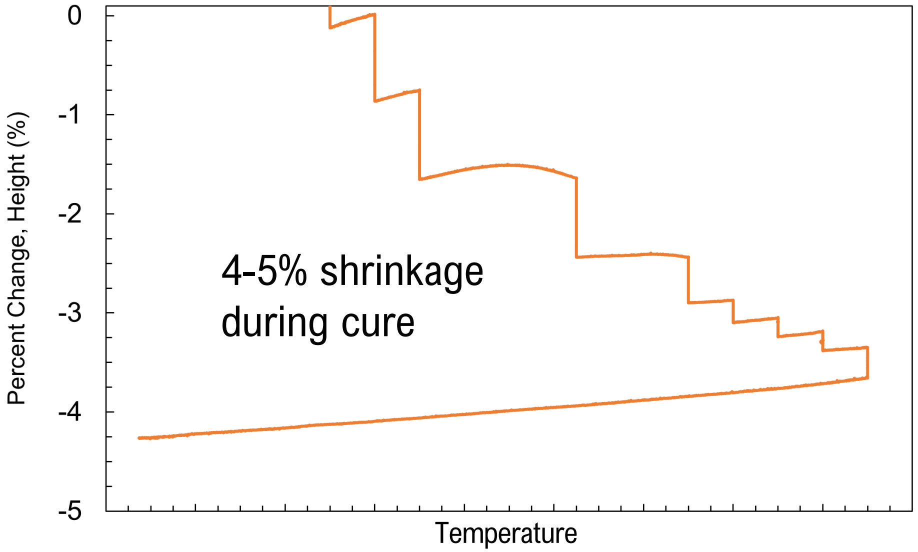


Thermoset resin shrinkage leads to disbond during cure

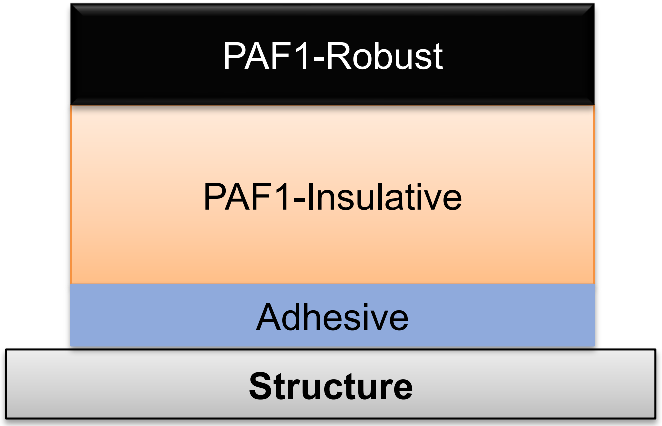
AMTPS

3D printed ablative material does not stick to aluminum or titanium

Goal: Print TPS directly onto capsule. Cure and bond in a single step.

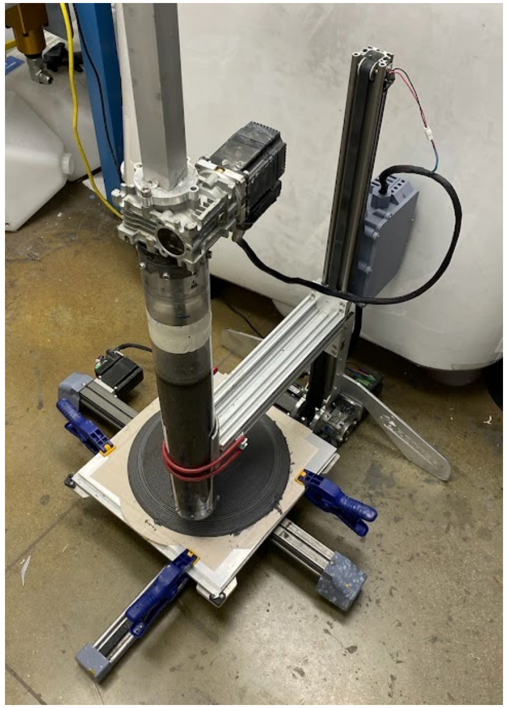


To cure ablative TPS material directly onto a structure, an adhesive or mechanical solution must be implemented.



Flight testing

- Flight testing a key component of ECI project (and future AMTPS development)
  - **Nothing like testing/demonstrating in the actual flight environment**
- Partnered with Univ. of Kentucky for KREPE orbital reentry missions
  - Small capsules fly to ISS onboard Cygnus; released upon reentry and breakup
  - **KREPE1**: 3 capsules flew on NG-16 (re-entry in Dec 2021)
  - **KREPE2**: 5 capsules currently manifested on NG-20 (late 2023 launch)



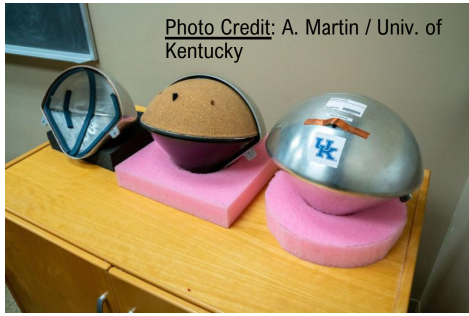


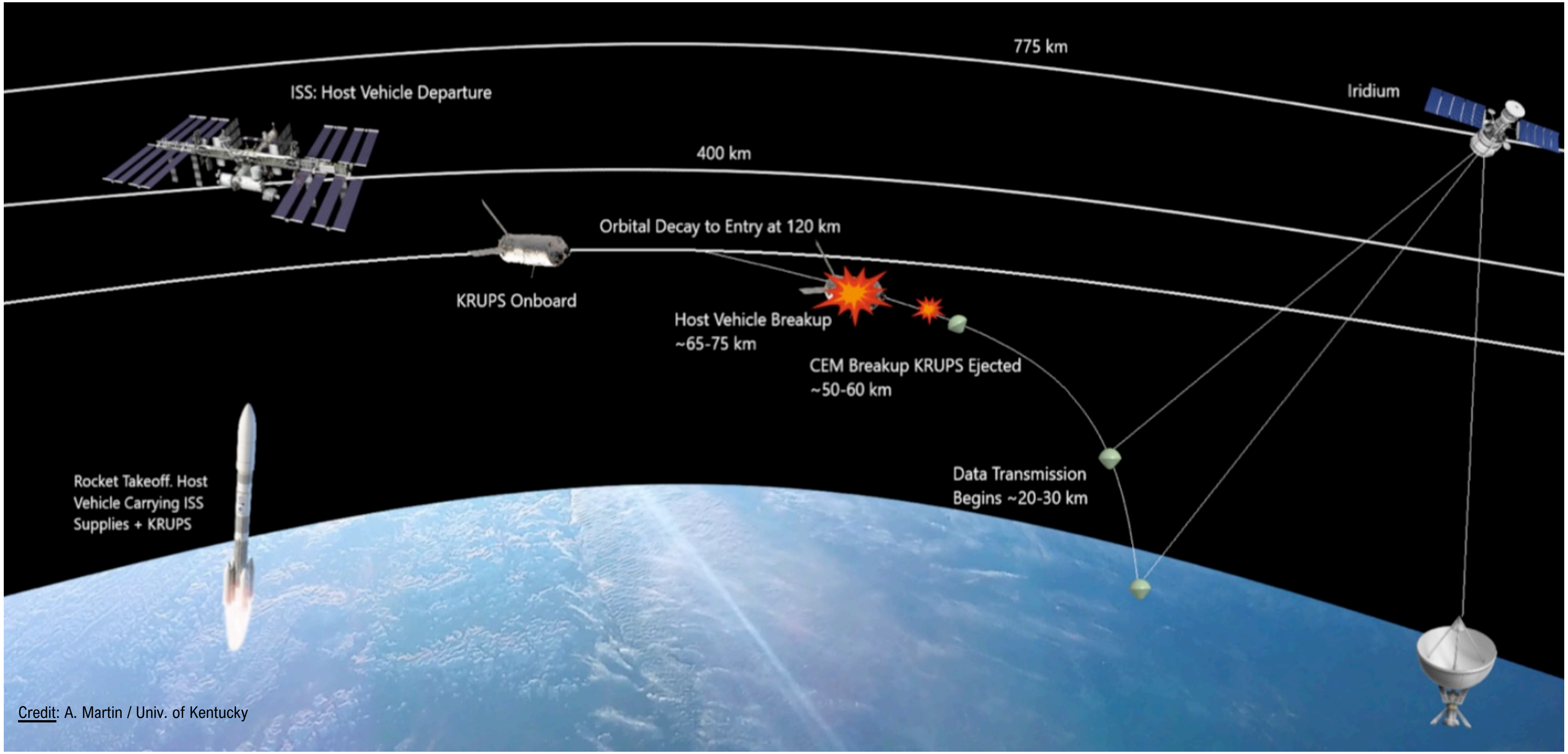
Photo Credit: A. Martin / Univ. of Kentucky

1st AMTPS Entry Flight Heat Shield flown in 2021

KREPE Mission ConOps

AMTPS

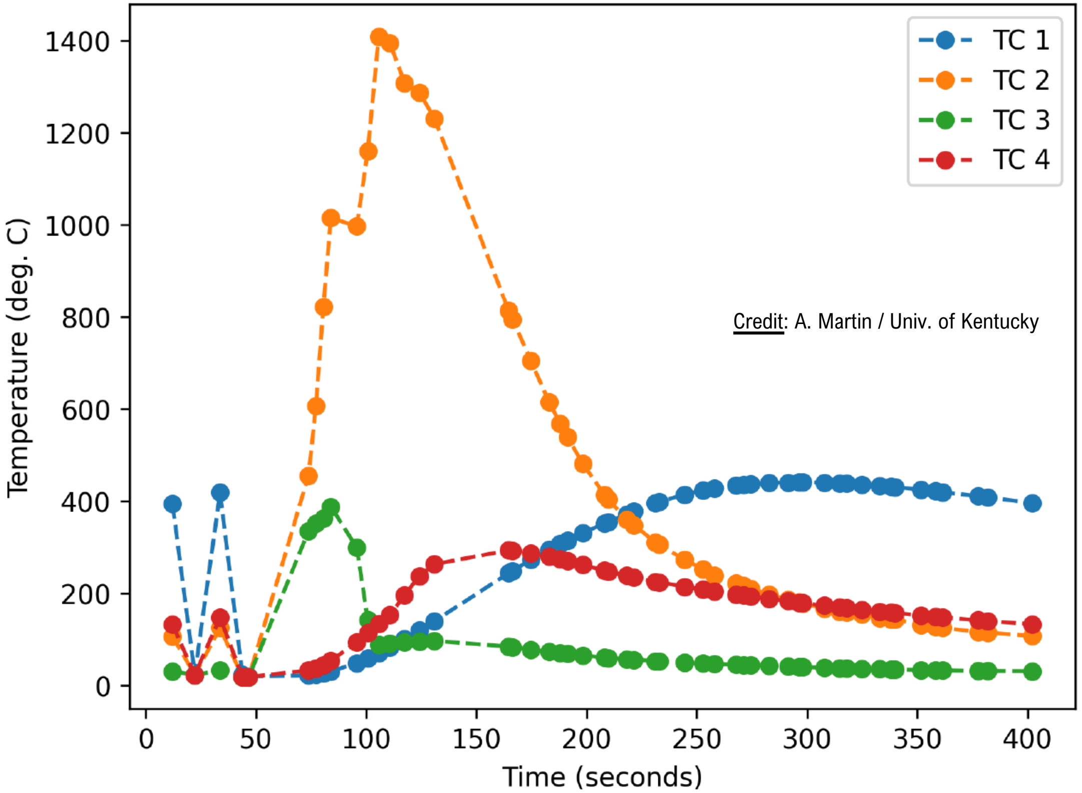
- KREPE capsules launched to ISS onboard Cygnus re-supply vehicle
- Capsules depart ISS onboard Cygnus
- Re-entry and breakup of Cygnus; capsule fly free to ground and telemeter data

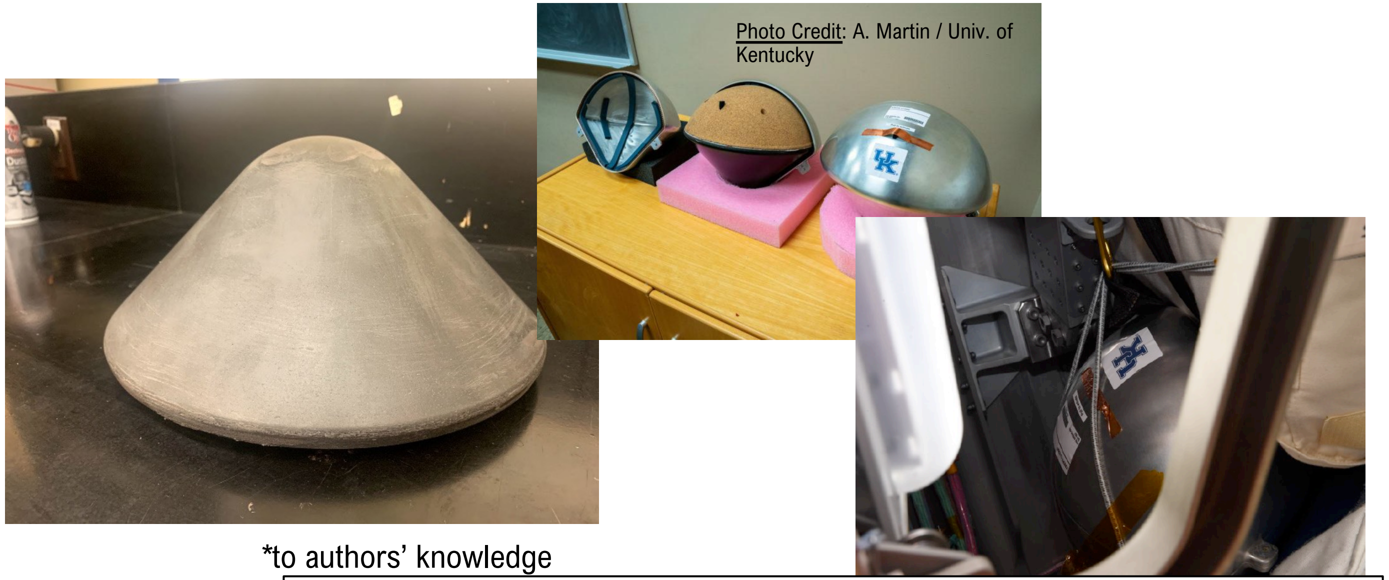


KREPE1 Mission: 1st AMTPS Heat Shield

AMTPS

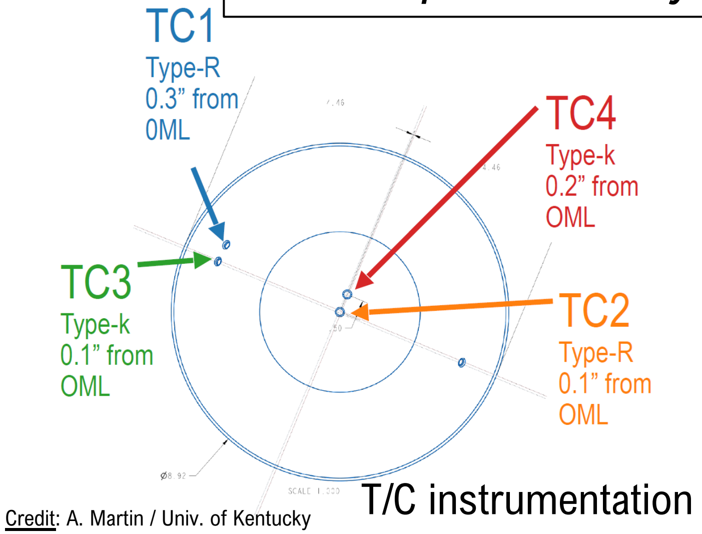
- 1 of 3 KREPE capsules protected by AMTPS heat shield
  - 11" diameter, 45 degree sphere-cone
  - Built in ~2 weeks, single piece, multi-layer construction
- Cyanate ester-based printable ablator
- **Successfully returned in Dec 2021**



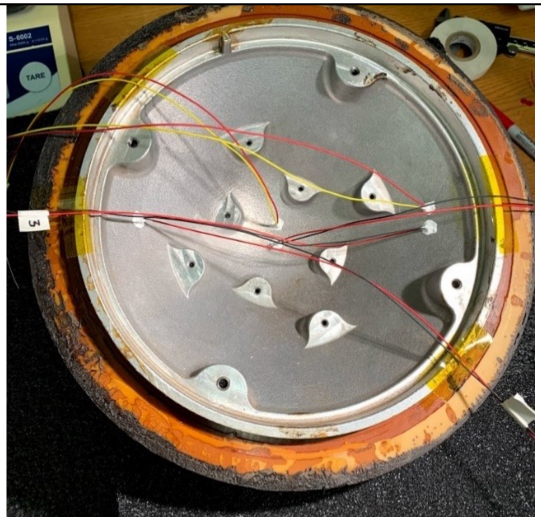


*to authors' knowledge

*First 3D printed entry flight heat shield in history**



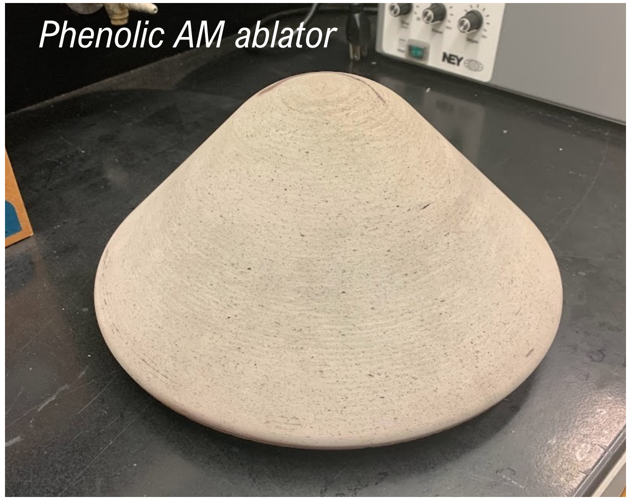
T/C instrumentation

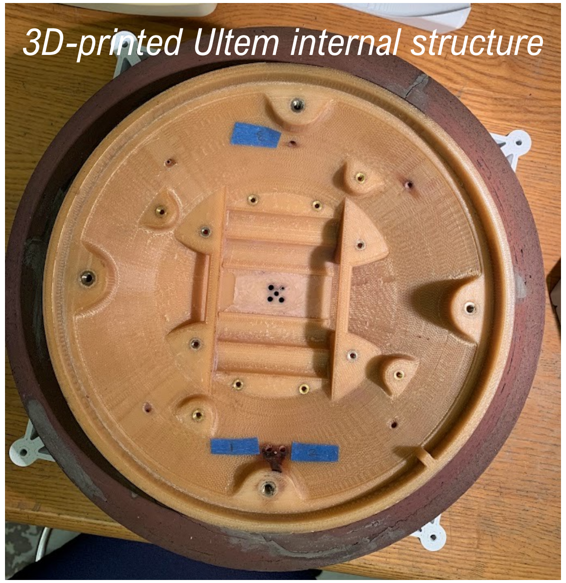


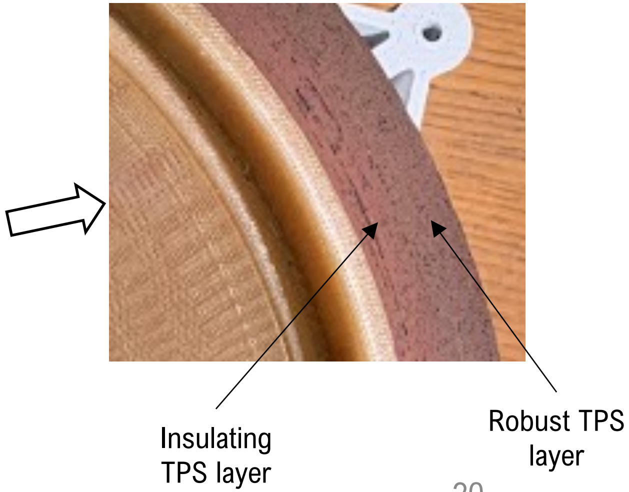
KREPE2 Mission: Same mission, new material *AMTPS*

- 1 of 5 KREPE capsules protected by AMTPS heat shield
  - Same geometry: 11” diameter, 45 degree sphere-cone
  - Printed in ***2 days***
- Phenolic-based printable ablator
  - Dual layer system (robust + insulative)
  - Adhesive layer for bond
- Instrumentation
  - 6 thermocouples
  - 5 forebody pressure sensors
  - 1 spectrometer
  - GPS / IMU for reconstruction
- **Scheduled to launch on NG-20 in late 2023**

Second 3D printed entry flight heat shield to fly in 2023



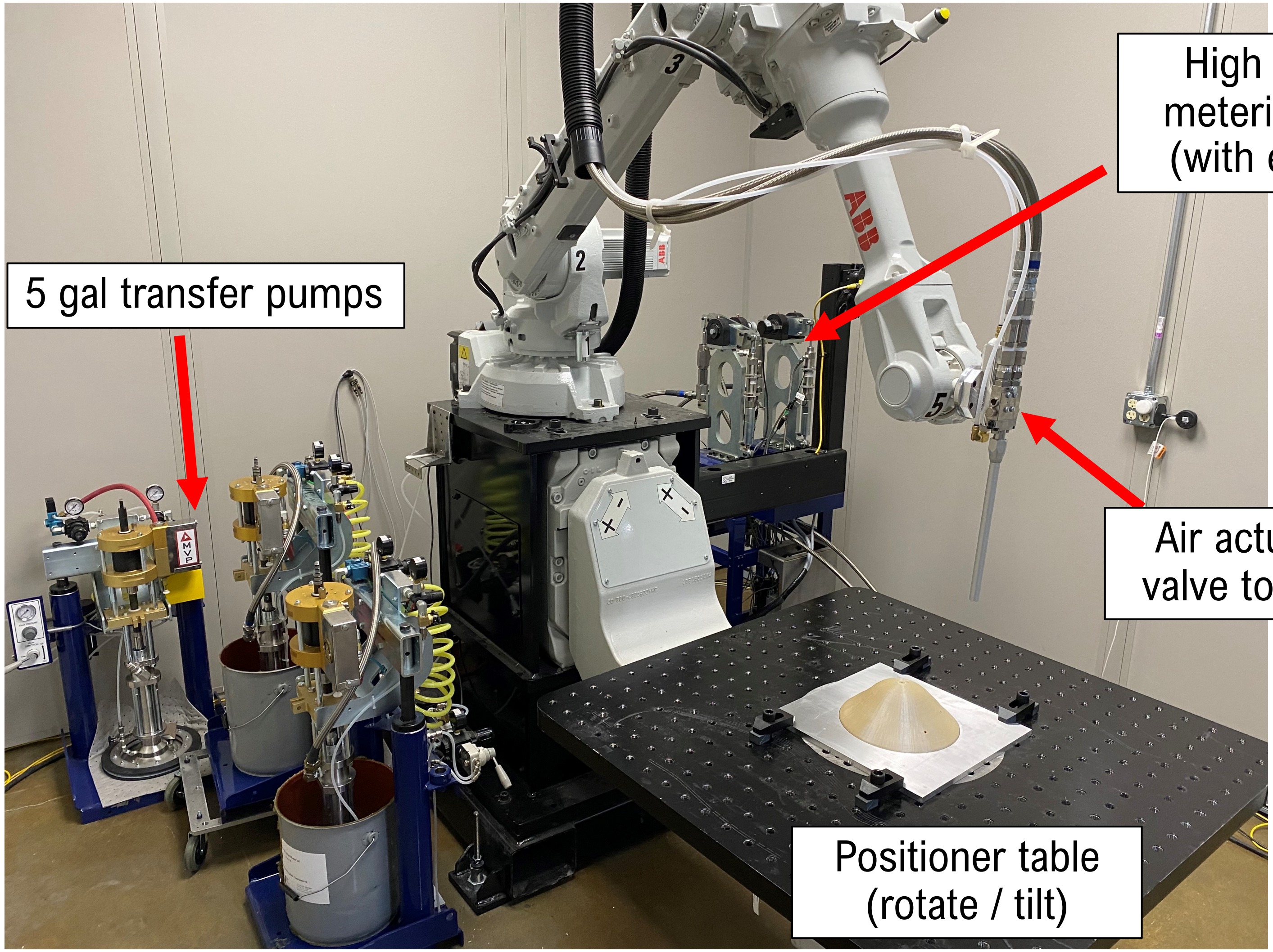




Manufacturing an AMTPS heat shield

- *Positioner table* affords toolpath flexibility (**6+2 axis printer**)
  - Concentric/spiral
  - Rectilinear/crosshatch (e.g. 0/90 or 0/45/90/45/0)
  - Combo of concentric/rectilinear
- Software tools translate to manufacturing cell
  - Hypermill
    - Machining focus with AM capabilities) will output position and orientation vector, post process for robot motion planning
  - ROS rviz and Gazebo
    - Robot motion planning and simulation

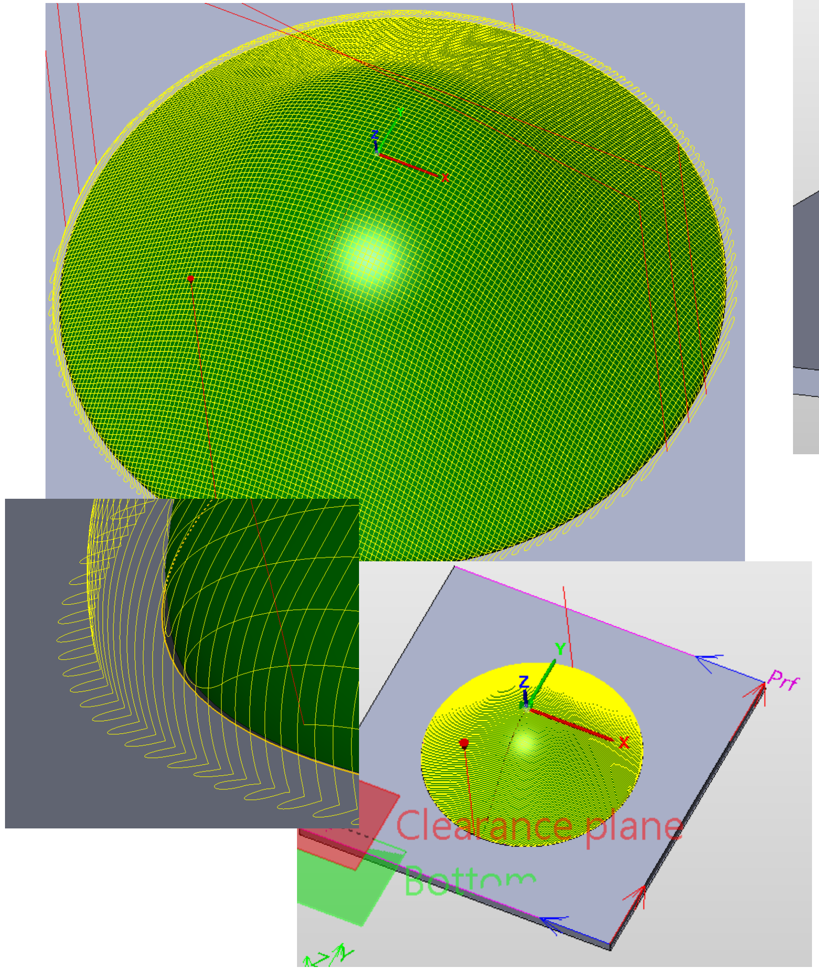
1 or 2K system; expandable to multi material systems



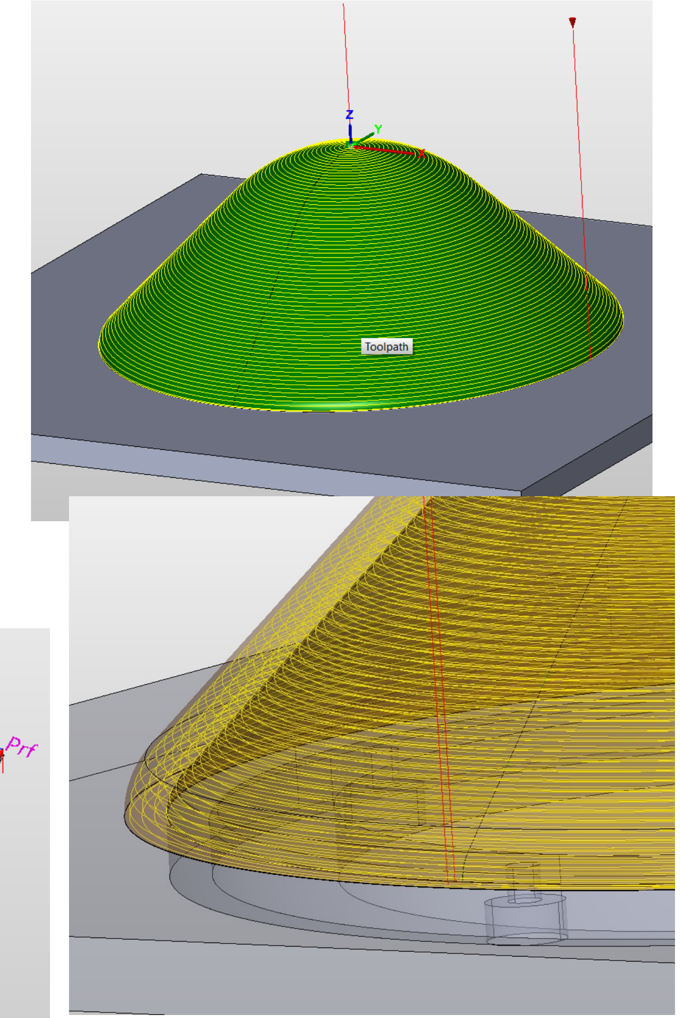
Flexibility in toolpath design

AMTPS

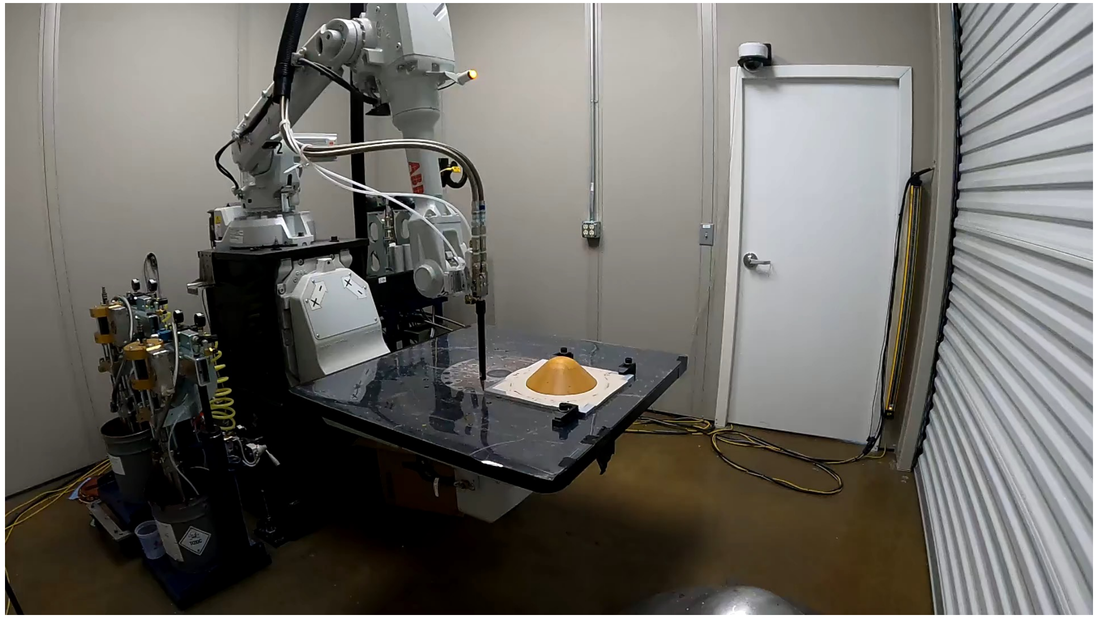
Rectilinear/Crosshatch



Concentric

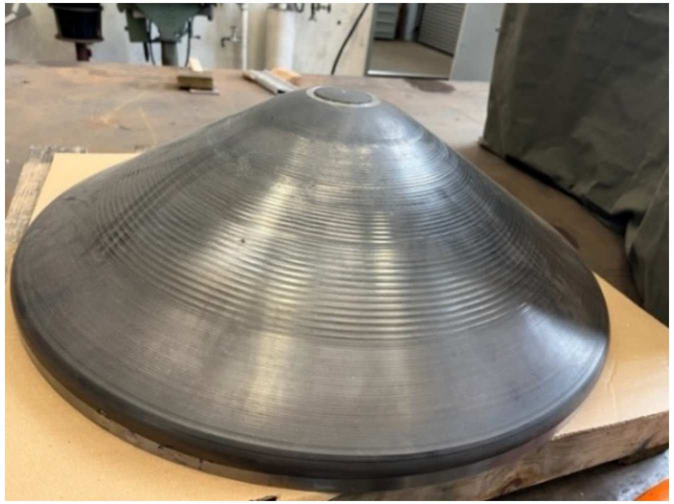


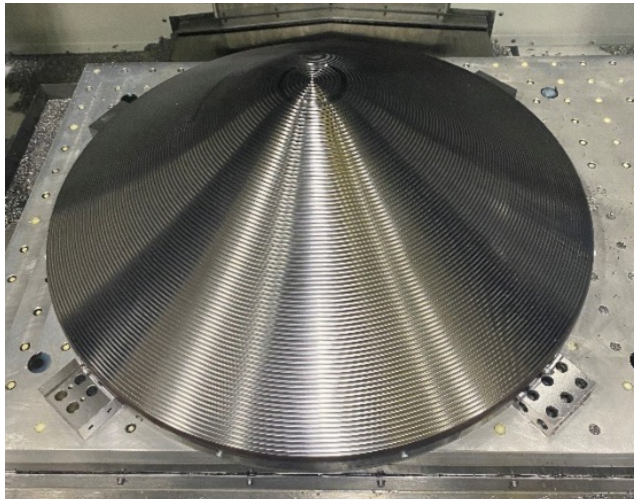
In operation



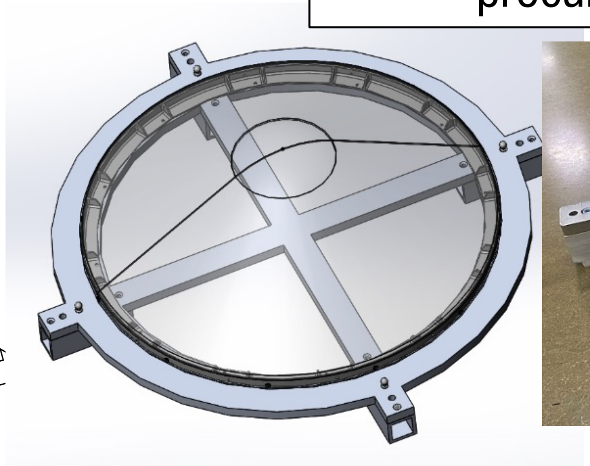
Plan to demonstrate scale up

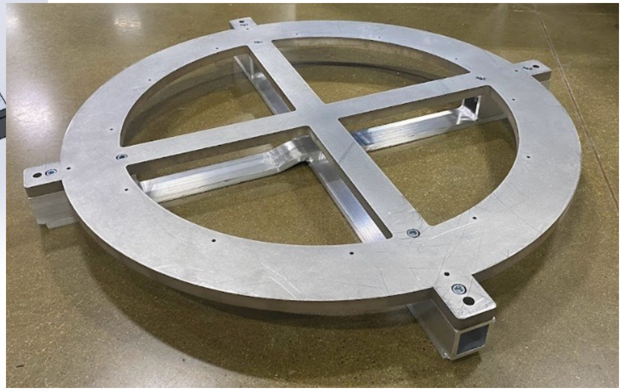
REV-TD forebody structure
0.7-meter diameter / titanium



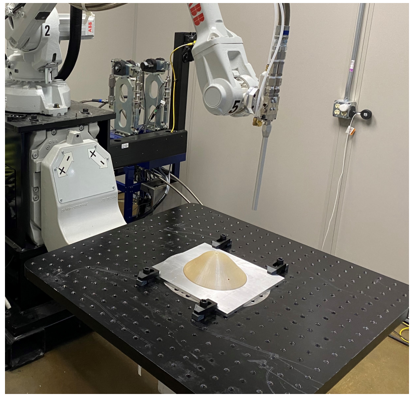


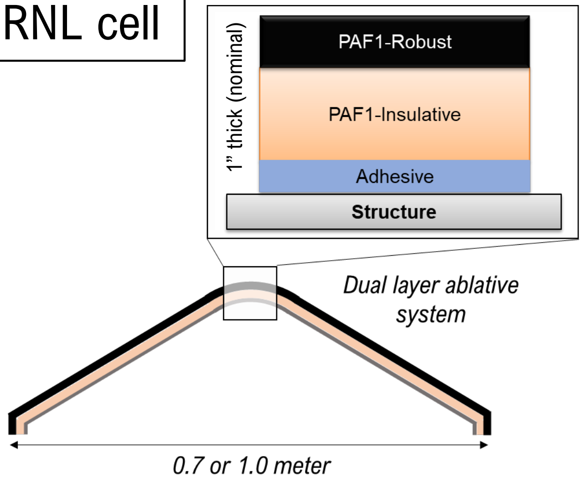
Support structure designed and procured by ORNL





Fixturing and printing in ORNL cell





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Recap and where are we going next?

- **FY20-FY23**: ECI project will wrap up in current FY
  - Developed, tested, and characterized dual-layer, printable TPS material system
    - Excellent ablative performance in arc jet testing; mechanical properties on par with heritage TPS
  - Conducted flight testing of AM heat shields with Univ. of Kentucky
    - 1st 3D printed entry heat shield in history returned from LEO in 2021
    - 2nd 3D printed entry heat shield to fly ~end of 2023
  - Process scale up to ~0.7 meter size vehicle with ORNL (*by end of FY*)
- **FY24+**: Follow on project sought to continue maturing the technology
  - Pursuing additional funding to continue advancing **AM ablators**
    - Advance the technology
      - Mature phenolic-based AM ablator; reduce shrinkage and improve bonding
      - Explore alternative AM ablative materials
    - Conduct larger scale **orbital re-entry flight demonstration**
      - Flight demonstration of ~0.7-meter size or larger AMTPS heat shield → **interested in partnership/collaboration with others (NASA, DoD, industry)**
    - Establish future viability
      - Mission infusion into a current or future entry vehicle
  - Generating proposals for kick-starting **AM reusable TPS materials**

Thank you!