Development of Additive Manufacturing Technologies for 3D Printing of Spacecraft Heat Shields

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CME
NASA STEM
Symposium

ACS Fall 2023:Poly
8/14/2023

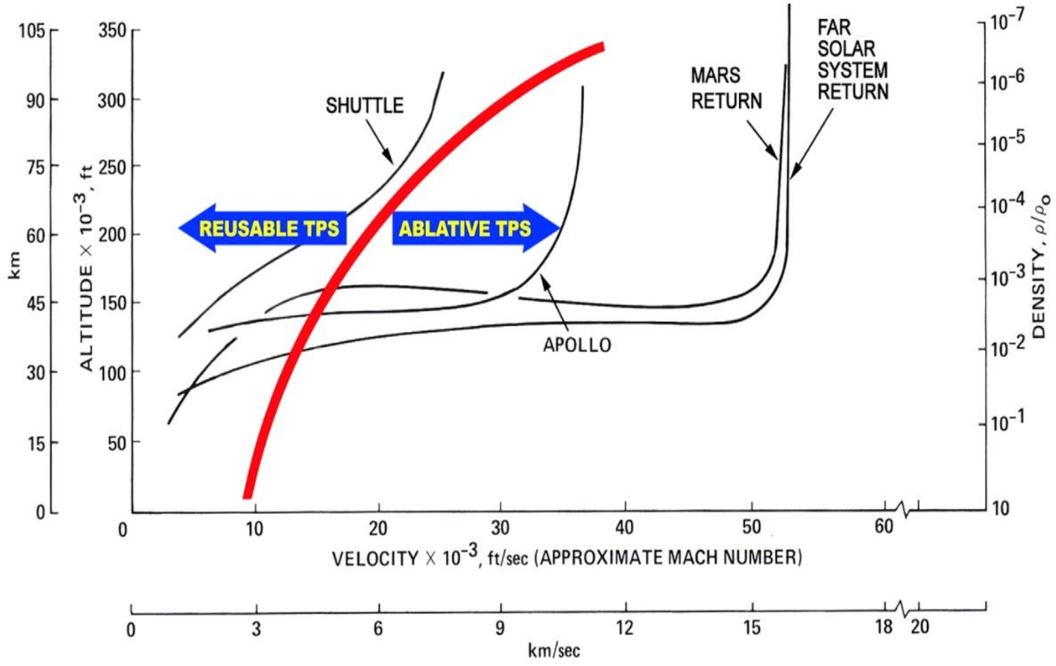
Overview of today's talk

We will give an overview of the exploratory efforts undertaken by NASA in evaluating the potential in Additive Manufacturing of Thermal Protection Systems (AMTPS)

Background & Motivation → NASA's R&D Approach → Early Efforts in AMTPS → ECI AMTPS Project Overview → Project Highlights & Future Work

Why pursue AMTPS development?

- Thermal protection systems (TPS) are essential for human and robotic space missions
- Cost of access to space has significantly reduced in the last decade and this is expected to continue
  - TPS has become relatively higher cost item and continues to be mission limiting and mission critical
- Emerging commercial space is looking to NASA for TPS
  - Need for cost effective and rapid manufacturing and integration without performance comprises

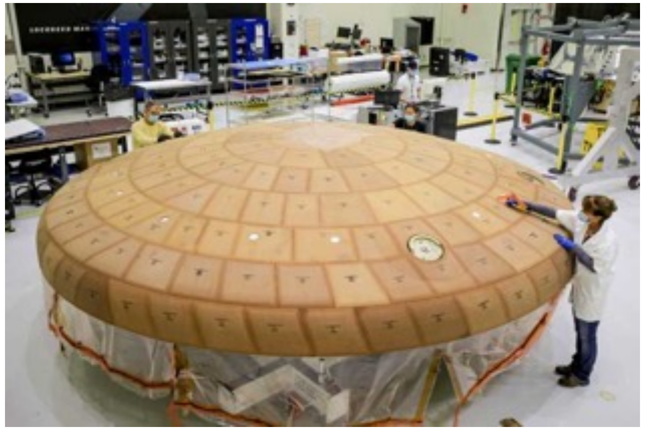


Why additive manufacturing for TPS?

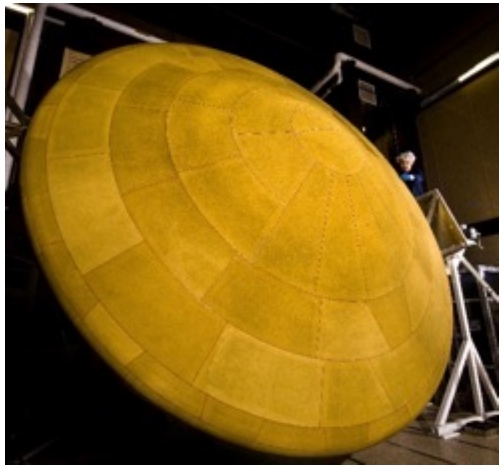
Traditional Approaches

Manual fabrication, bonding in segments, single formulation

Apollo



Orion



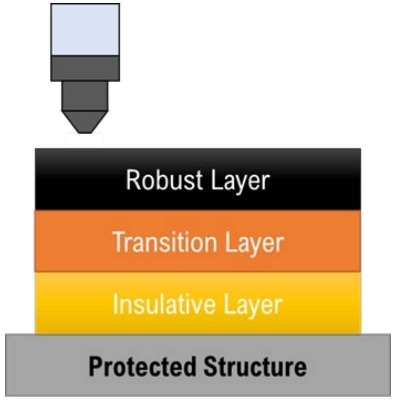
Mars Science Laboratory

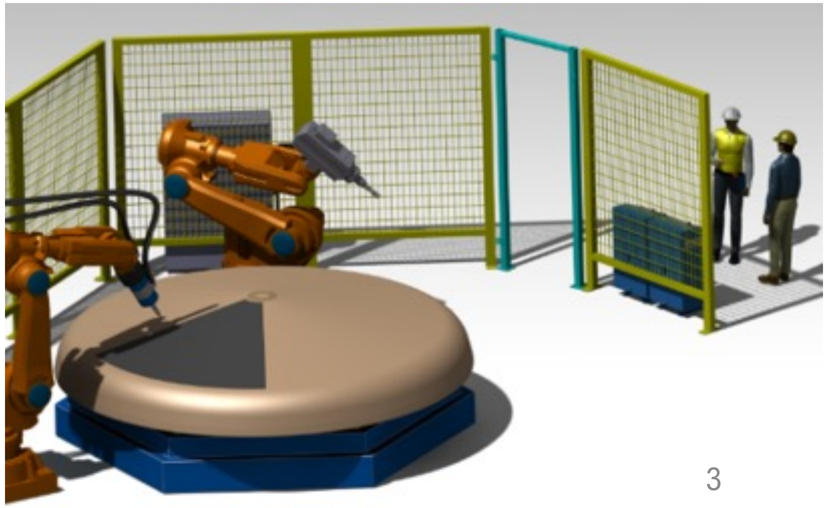
Photo Credits
Left: B. Anthony Stewart/National Geographic/Getty Images, The Amazing Handmade Tech That Powered Apollo 11's Moon Voyage – HISTORY
Top right: NASA/Isaac Watson, Heat Shield Milestone Complete for First Orion Mission with Crew | NASA
Bot right: NASA/JPL-Caltech/Lockheed Martin, Large Heat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

AMTPS

Automated, monolithic fabrication, graded formulation

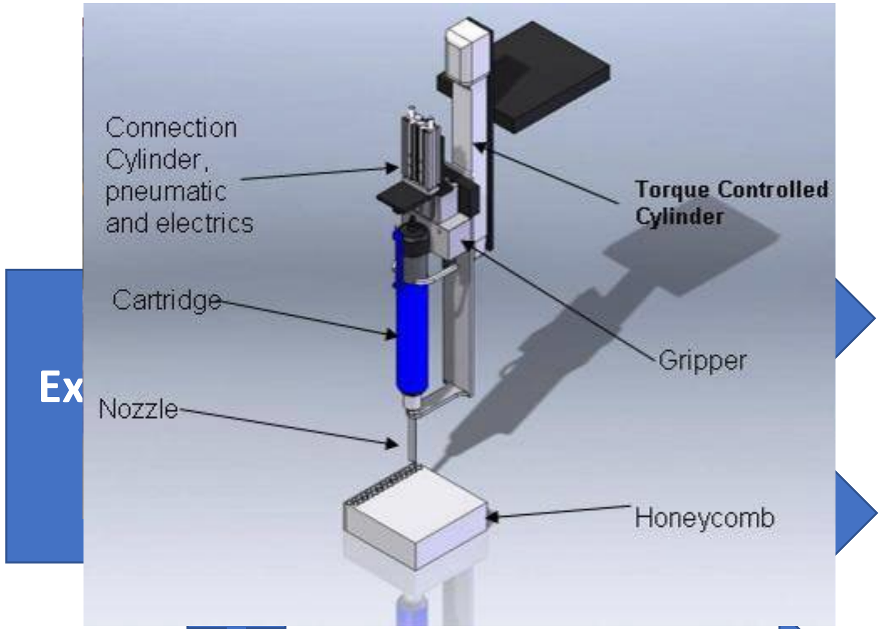
Video: G. Larsen/ORNL

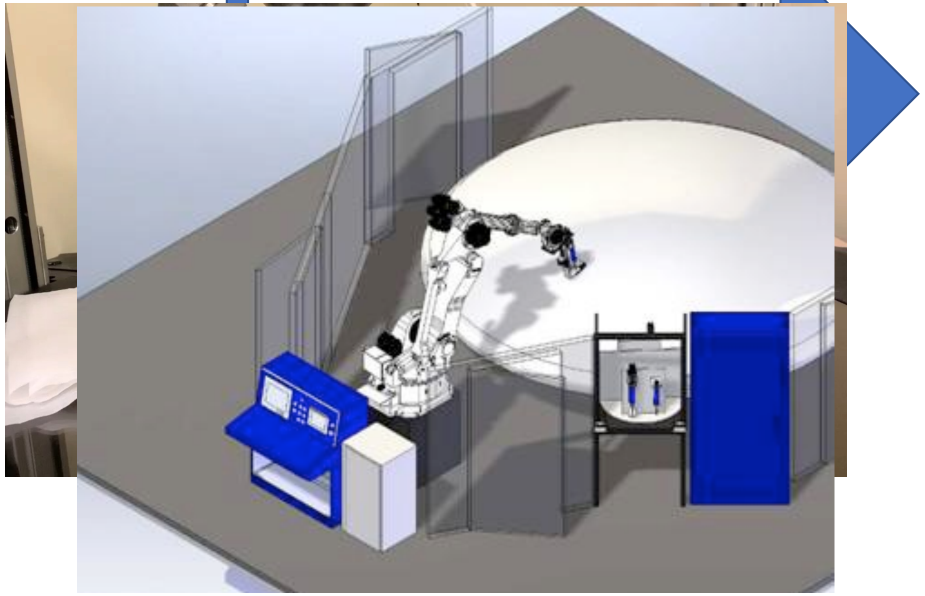




NASA approach for AMTPS development

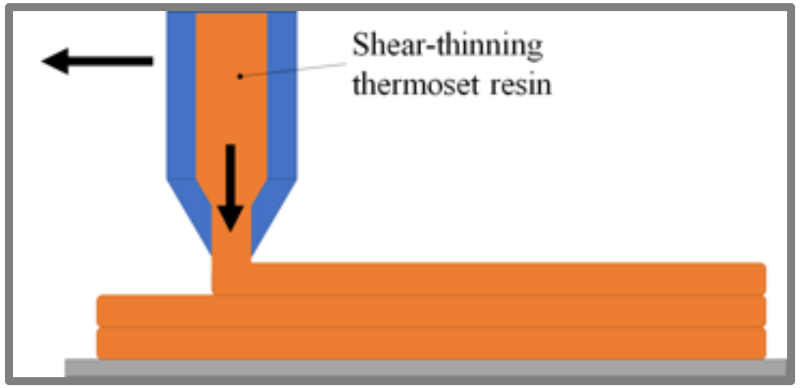
- **2007 – 2009:** Explored automation for TPS
  - Crew Exploration Vehicle (CEV, a precursor to Orion) TPS Advanced Development Project
- **2018:** AM manufacturing successes, especially in composite structures, led to exploratory efforts in AMTPS with internal funds at JSC with the following goals:
  - Rapidly evaluate and perform design of experiments
  - Design integrated structures and TPS with multi-functionality
  - Reduce timeline for design-to-mission infusion
- **2019 – Present:** NASA has continued exploratory efforts both internally & externally
  - Early Career Initiative (ECI) Project
  - SBIR/STTR Program
  - AMTPS Workshop (March 2022)



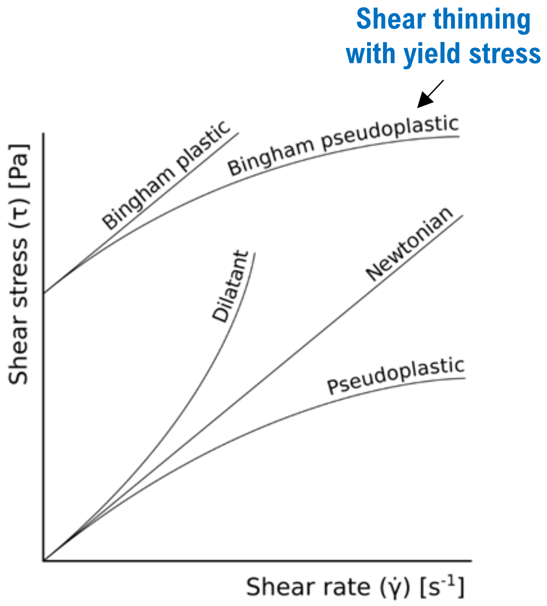


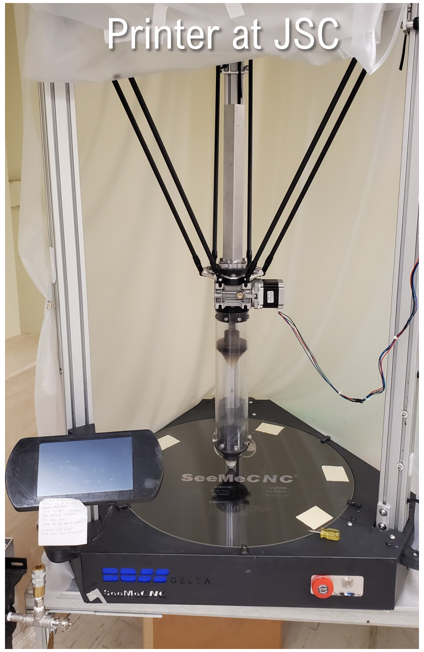
AM technologies under development

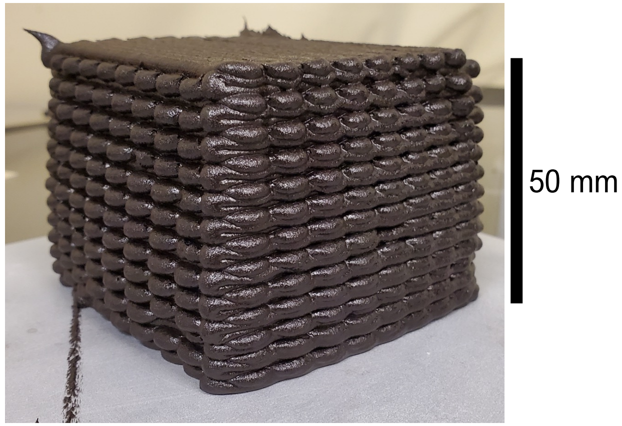
- **NASA:** Evaluation of additive manufacturing techniques at JSC led to Direct Ink Write (DIW) for ablative TPS.
  - Allows for usage of mostly traditional TPS material constituents with modest modification
  - Use a commercial 3D printer modified to utilize a custom-designed paste extruder
  - Rheology improvement eventually allowed parts to be built up to approximately 50 mm in height by the end of 2021



A direct ink write (DIW) approach allows the shear-thinning material to be extruded out of a nozzle and built up in layers







- **External:** NASA competitively selected and funded small businesses under the SBIR/STTR Program to explore AMTPS → expand number of technologies under consideration
  - 11 companies were funded under Phase 1 (13-month effort)
  - 3 companies further received funding for Phase 2 (2-year effort)

AMTPS efforts under Early Career Initiative

- **Space Technology Mission Directorate's Early Career Initiative (ECI)**
  - Competitively selected proposals on advanced technology maturation topics are funded
  - Goal is to allow primarily early career employees to lead projects
    - Encourages inter-center and external collaborations
- **AMTPS project proposed by Adam Sidor as PI (2020) was selected and funded as a two-year effort**
- **Three primary development goals:**
  - To create and characterize a printable, graded AMTPS material system
  - To demonstrate scale up of the AMTPS process through fabrication and testing of a manufacturing demonstration unit (MDU)
  - To design and build a small capsule with AMTPS heat shield for flight demonstration
- **Partnerships:**
  - Oak Ridge National Laboratory (ORNL)
    - To lead manufacturing scale up of the AMTPS process at the Manufacturing Demonstration Facility
  - University of Kentucky
    - To design and build the flight demonstration vehicle

Oak Ridge National Laboratory

Johnson Space Center
Ames Research Center
Langley Research Center

University of Kentucky

Considering the two principles below to create and characterize a printable, graded AMTPS material

1) Material selection principle

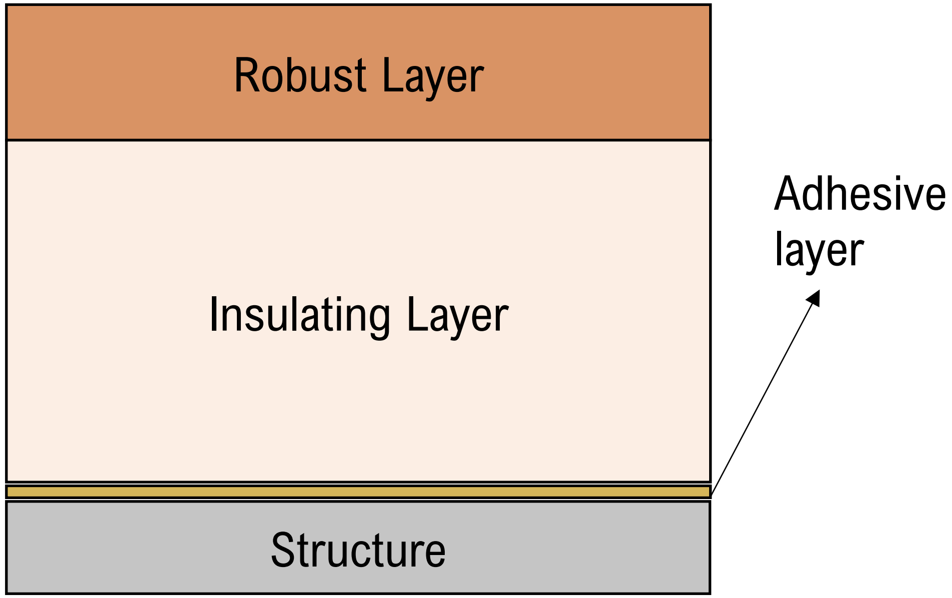
Aerothermal performance	Printability	Curing Condition	Integration	Logistics	Safety
Minimum swelling and shrinkage	Able to extrude; maintain the structure	Able to cure at low temperature	Able to bond to underlying vehicle structure	Low cost, long shelf life, availability	Easy to handle with limited environmental and human impact

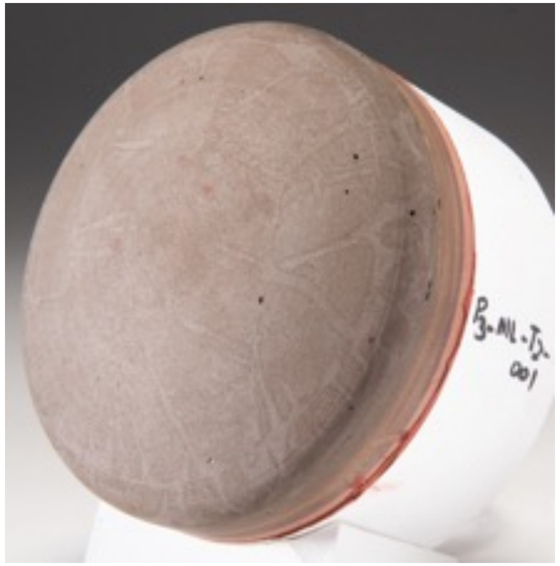
2) Desired material properties

Density	CTE	Thermal Conductivity TTT	Tensile strength IP	Char yield
0.6g/cc	<5x10^{-6}/deg F	<0.2 W/m-K	>3 MPa	>50%

AMTPS Baseline & Test Results

- Downselected resin system is loaded with fibers, and other fillers to achieve desired properties.
- The components were mixed to obtain printable paste
- Arc jet models were printed with the same resin system but loaded with different amount and type of fillers to alter material properties:
  - High density robust layer
  - Low density insulative layer
- All the models exhibited excellent ablative performance such as low spallation, and low recession





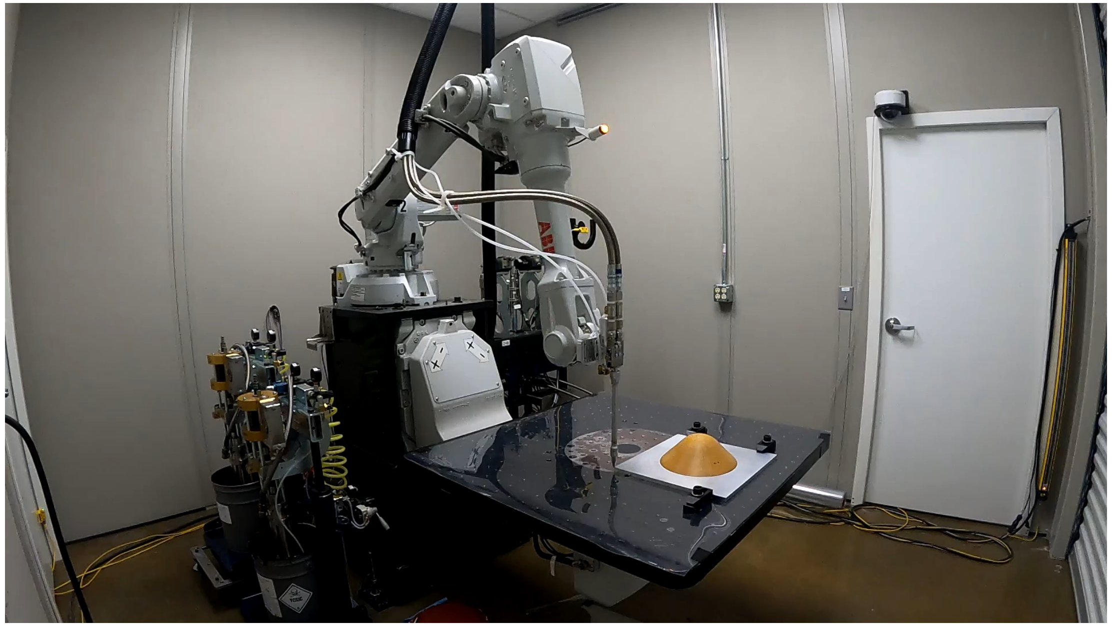
Before the test

After the test

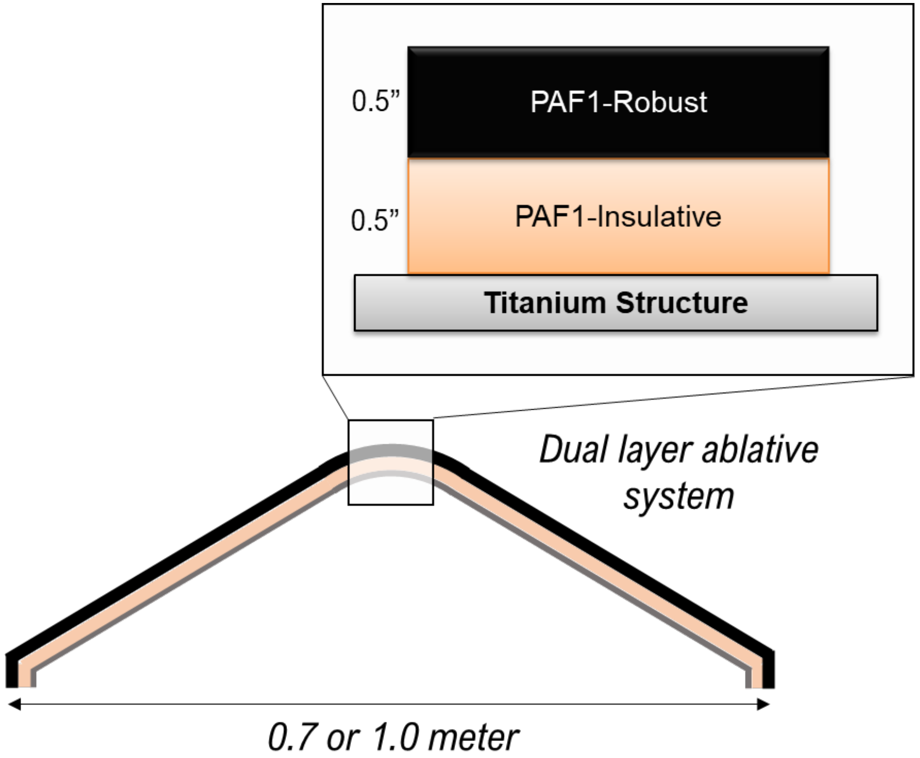
One of the 3D printed arc jet model

Manufacture a ~ 1m scale MDU in partnership with ORNL.

- ORNL is currently building a fully robotic system that combines a high-pressure pumping system for transporting and metering the flow of material with a multi-axis mechanical deposition system. Builds are planned for the 2nd half of 2022.
- MDU will be demonstrated on a titanium, 0.7-meter, 60-degree sphere-cone and an aluminum, 1.0-meter, 45-degree sphere-cone.



AMTPS Robotic Manufacturing Cell at ORNL Manufacturing Demonstration Facility (MDF)



Notional MDU design planned with two-layer, 1” AMTPS heat shield

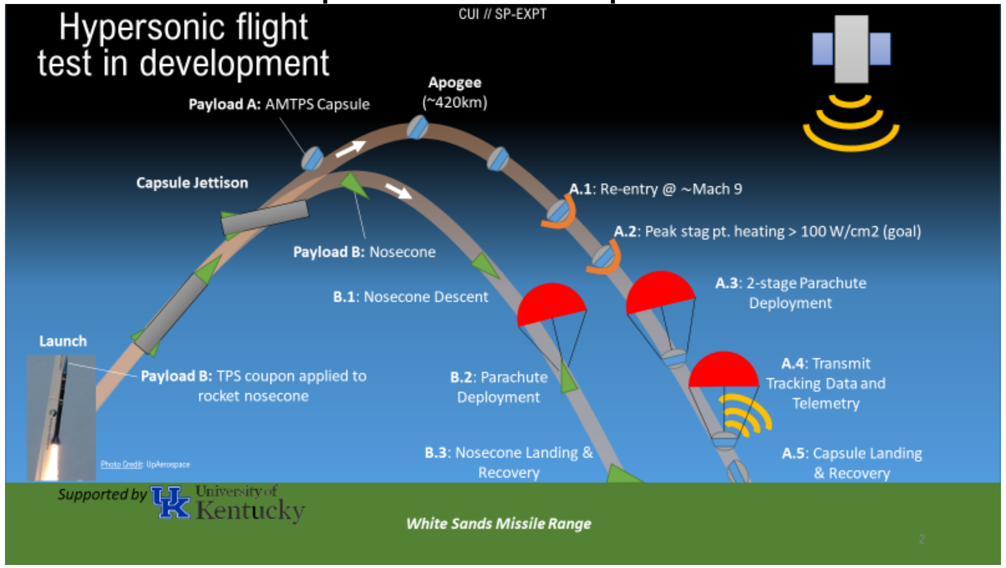
AMTPS Project Goal #3: Flight Testing

Flight test a subscale vehicle with an AMTPS heat shield to demonstrate the capability in flight

- A collaborative effort allowed AMTPS Capsule to be flight tested by University of Kentucky (Dec 2021)
  - NASA provided cyanate ester-based AMTPS heat shield (11” reentry capsule)
  - Successfully returned from International Space Station onboard NG-16 Cygnus vehicle and released on breakup
- Suborbital test flight in development for current phenolic-based AMTPS material
  - Flight capsule configuration is a 14” diameter, 45-degree sphere-cone
  - Entry at Mach 9 - peak stagnation heating in excess of 100 W/cm2 (cold wall).
  - The vehicle has a parachute system for soft landing and subsequent recovery will allow for post-flight analysis of the heat shield.

11” capsule with AMTPS heat shield flown by Univ. of Kentucky on NG-16

Suborbital flight test with 14” AMTPS capsule in development



Conclusion & Remarks

- AMTPS has many advantages over traditional TPS manufacturing process such as:
  - Through-thickness grading of formulation
  - Monolithic fabrication
  - Fully automated
  - Low cost
  - Shorter downtime
- Since 2018 NASA has continued explore the efforts in AMTPS with internal and external funding
- AMTPS was further studied through JSC Early Career Initiative project in partner with Oak Ridge National Lab and University of Kentucky
- ECI AMTPS project focused on three important goals:
  - Developing a printable, ablative TPS material system
  - Scaling up processing (through build of ~1-meter sized Manufacturing Demonstration Unit)
  - Flight testing (both orbital and suborbital)
- 3D printed models were tested in arc jet and performed flight test with promising results
- Lessons learned from the ECI AMTPS project as well as externally funded SBIR will allow us to plan for future technology maturation