Recent Developments of Thermal Protection Materials to Enable Lower Cost Space Missions

Arnaud Borner[1], Ethiraj Venkatapathy[2], Matt Gasch[2], Keith Peterson[2], Josh Monk[2], and Mairead Stackpoole[2]
[1]AMA, Inc. at NASA Ames Research Center, Moffett Field, CA 94035
[2]NASA Ames Research Center, Moffett Field, CA 94035

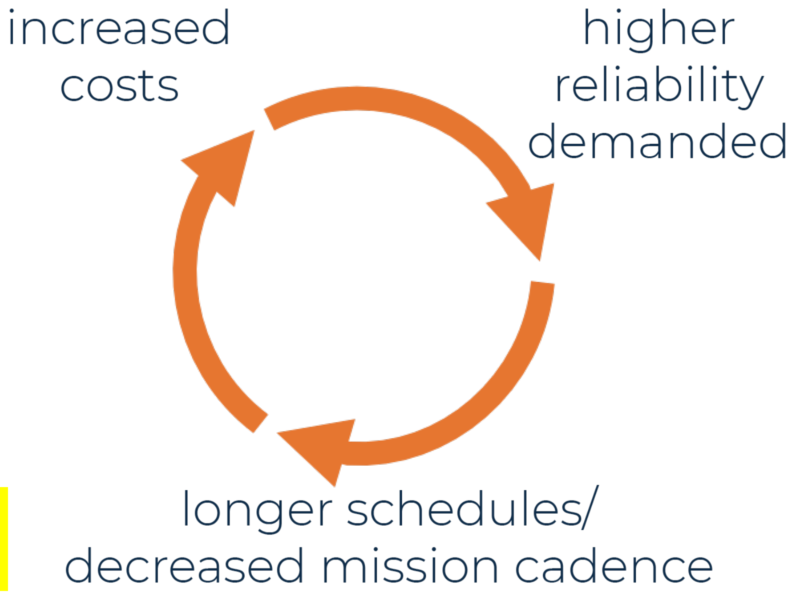
*Leveraging a lot of good ideas and content from the White Paper Submission for the 2023-2032 Planetary Science and Astrobiology Decadal Survey *"Why and How to Leverage the Commercial Space Sector for the Benefit of Planetary Science and Its Community"* by Elizabeth A. Frank, Casey Dreier, Benton Clark and Clive R. Neal.

Outline

- Introduction about Low-cost Missions
- Need for Advanced Ablative TPS
- Ablators Update
- Commercial Mission Infusion
- Examples of NASA SIMPLEx Mission Concepts
- Summary

The Relationship Between Cost and Risk

- Cost and risk inexorably linked.
- Spacecraft and component reliability can be improved by rigorous project management and additional testing.
- Risk mitigation strategies are expensive and lengthen schedules -> decreased mission cadence.
- Result = culture of risk aversion, higher cost, low mission rates.



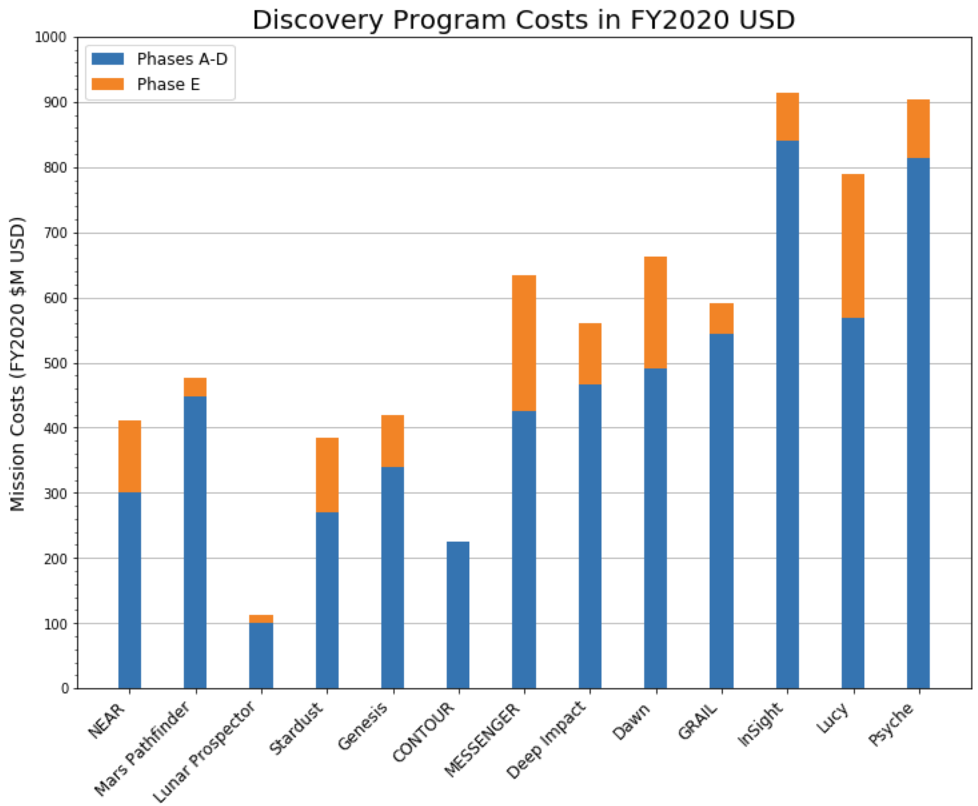
The “space spiral” (Wertz *et al.* 2011)

The Original Low-Cost Program

- Can you guess it?

The Original Low-Cost Program

- Discovery!
- Created as low-cost mission program in the 1980s.
- Starting from the 3rd Discovery mission, all competed and PI-led.
- Initial Discovery cost cap: $150M in FY92 ($310M in FY20).
  - Launch vehicle limited to low-cost, medium sized Delta II.
  - Mission development time: 36 months max.
  - Expectation of a launch every 18 to 24 months.
  - NASA had “to be prepared to cancel any non-performing missions, in any Phase, from A to C/D” (Neufield, 2018).
- Today’s Discovery cost cap: $500M in theory (often exceeds).
- Discovery missions are no longer low-cost!
- Discovery program no longer structured to incentivize teams to take technical risks and keep costs down.



The New Low-cost Program(s)

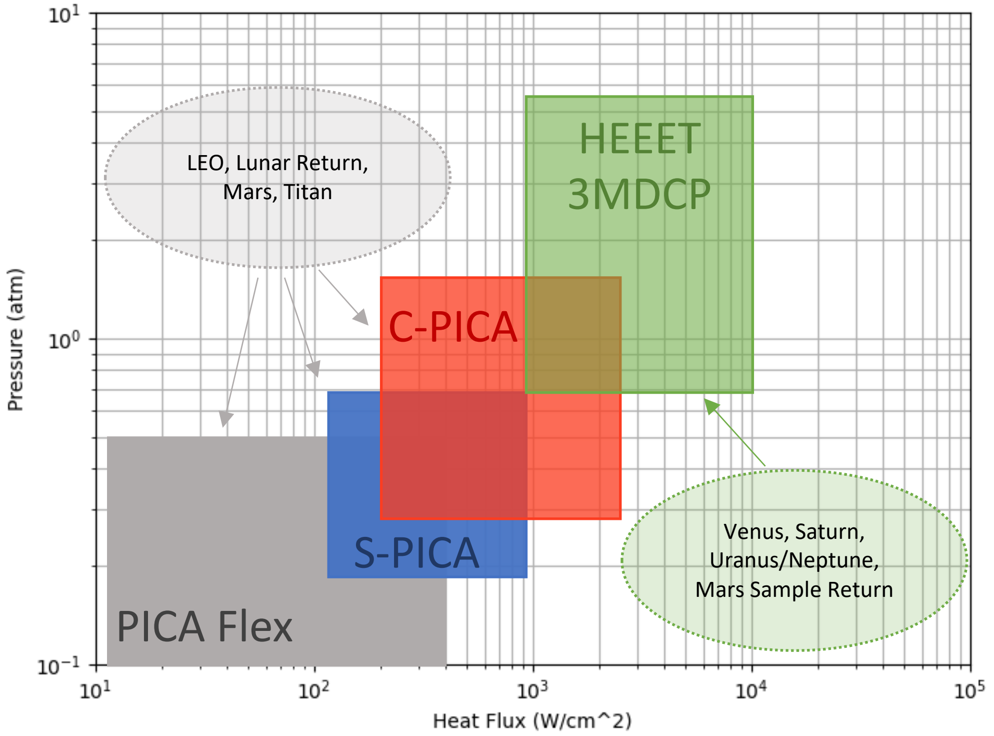
- SIMPLEx (and CLPS)!
- SIMPLEx cost cap: $55M (excluding launch vehicle).
- At a technical crossroads: increasing capable technology in smaller packages.
- SIMPLEx: Cat. 3 with class D payloads:
  - Accept “medium” amount of technical risk.
  - Non-traditional spacecraft providers (universities, small businesses, etc…)
- In parallel, NASA supporting growth of commercial space:
  - Commercial cargo
  - Commercial crew
  - CLPS
    - Compared to traditional contracts, these are fixed-price with payment upon meeting milestones.
    - Programmatic risk mitigated through selection of multiple companies at earliest project phases.

The Need for Advanced Ablative TPS

- TPS materials take significant money and time to develop and to bring to TRL 6.
  - Commercial Space as well as future NASA Planetary Missions relying on call for proposals do not have the time to develop their own TPS.
- NASA has a few mid/high TRL TPS materials (PICA-D, C-PICA, HEEET, 3MDCP) which are ready today to adopt for LEO entry, lunar return, and other planetary missions.
  - Also, Ames in innovating new TPS with S-PICA and PICA-Flex to address cost, cadence and broader needs. *Please see Matt Gasch's NSMMS 2024 presentation for more details (ITAR, please contact us for relevant charts/slides).*
- Commercial companies look to NASA as a starting point for their TPS needs, and often rely on technology transfer. Bringing manufacturing in house allows them to control the cost.
- A shift in paradigm is emerging:
  - Previously: Develop TPS up to TRL 6, then had to fly it to bring it to 9.
  - Now: Increasing TRL in parallel: Commercial companies willing to fly a TPS before TRL 6, then NASA uses the flight data to increase the TRL. Cost of flight testing is eliminated by leveraging commercial companies.

Low-density Ablators Update

- NASA faced 2 significant challenges with PICA in the late 2010s:
  - Sustainability issues with heritage rayon source for PICA preform
  - FMI decided to stop the commercial production of FiberForm
- Today, FMI is making Lyocell based PICA-D for Dragonfly and MSR SRL.
- Ames is developing several different flavors of low-density Carbon and Phenolic systems:
  - C-PICA (Conformal PICA, using a flexible carbon felt as substrate)
  - S-PICA
  - PICA Flex
- Also, mid-density 3D woven TPS materials (HEEET and 3MDCP).
- C-PICA – beneficial to future aerocapture missions and as a backup for PICA-D.



Commercial Missions Infusion: Varda

- Varda's Winnebago-1 vehicle successfully returned to Earth from LEO on Feb. 21st, 2024.
- NASA Ames manufactured and provided a C-PICA heatshield to Varda.
- Currently in the process of tech transferring C-PICA to Varda through an STMD Tipping Point.
- 2 more Varda flight mission demonstrations planned for 2025 and 2026 under NASA/AFRL/Varda public-private partnership.
- Opportunity to test, instrument, and collect data on C-PICA, S-PICA and PICA Flex.

Varda's LEO capsule is capable of a Mars entry; the commercial payload must simply be replaced by a science payload (same with Inversion's).

VARDA SPACE INDUSTRIES

Credit: Varda Space Industries / John Kraus

Commercial Missions Infusion (cont'd)

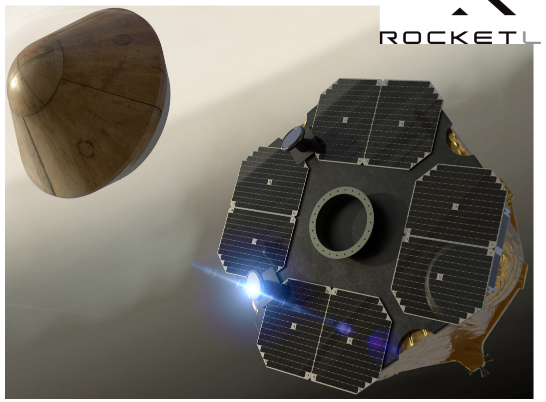
- Inversion Space's Ray spacecraft planned for test flight and return from LEO in late 2024.
- Inversion's end goal is to use space to transport cargo.
- NASA Ames provided C-PICA heatshield and SIRCA backshell.

Credit: Inversion Space

- Kentucky Re-Entry Probe Experiment (KREPE): low-cost flight experiment. Next re-entry from ISS: late 2024.
- 3 instrumented Kentucky Re-entry and Universal Payload System (KRUPS) capsules.
- NASA Ames provided C-PICA, S-PICA, and a dry 3D woven material.

- Rocket Lab low-cost mission to Venus, scheduled for launch in early 2025.
- First planned private exploration of Venus.
- NASA Ames provided single layer HEEET TPS, and SIRCA backshell.

Credit:
Rocket Lab USA



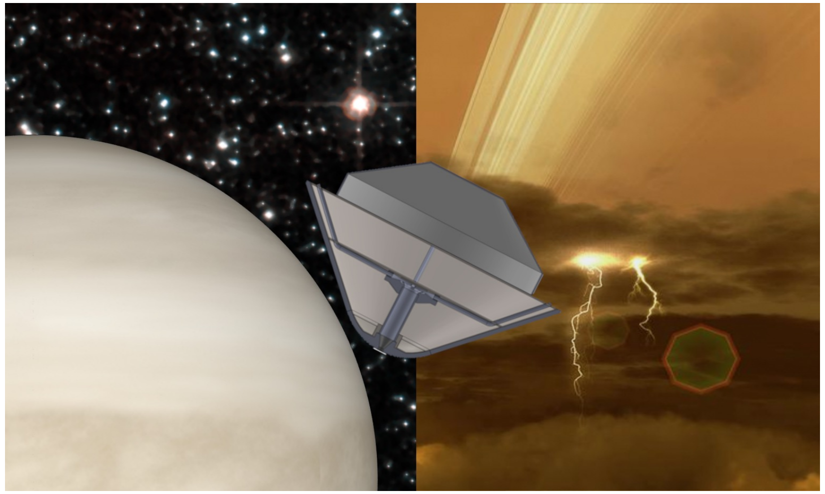
Commercial companies willing to take the risk and fly mid-TRL TPS. Also, will provide NASA with post-flight data.

Bringing 3D woven HEEET TPS to high TRL by flying it to Venus!

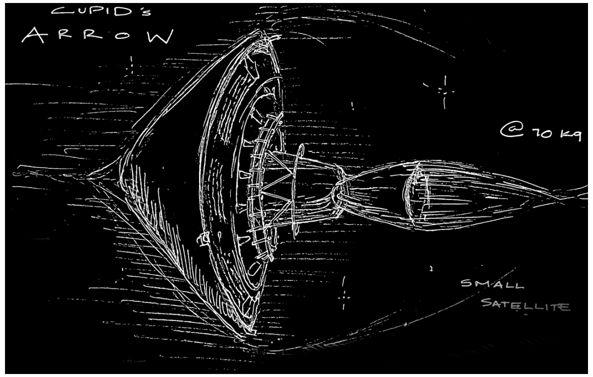
A Couple Examples of SIMPLEx Mission Concepts

- **Nephele**: NASA ARC small probe mission concept to collect and analyze the clouds of Venus, in particular aerosols.
- Baselined for future SIMPLEx call, as class D mission.
- Heat shield: Single layer HEEET with a 3D Carbon/Carbon nose for sampling inlet.

Credit:
Nephele team / NASA



- **VATMOS-SR**: Venus upper atmosphere small probe sample return mission. Will skim the Venusian atmosphere at 110 km altitude.
- Baselined for future SIMPLEx call, as class D mission, or ESA F-class mission call.
- Heat shield: Single layer HEEET or C-PICA with a 3D Carbon/Carbon nose for sampling inlet.



Credit: JPL/NASA/CalTech

Hoping to leverage a higher TRL single layer HEEET TPS from Rocket Lab Venus flight.

Summary

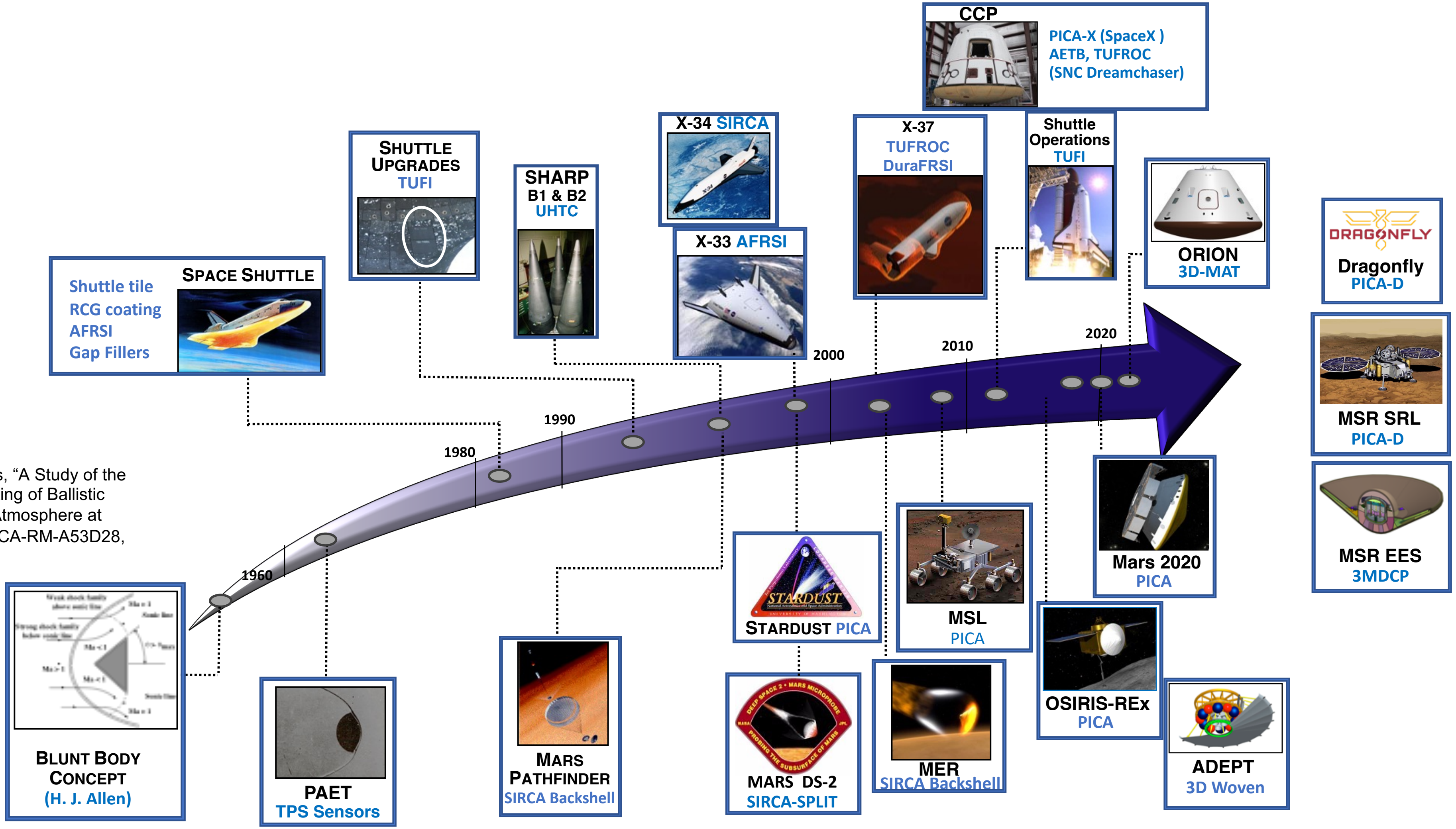
- Cost and risk are inexorably linked.
- SIMPLEx is NASA's low-cost program today, but NASA is also supporting commercial space.
- NASA Ames developed and matured several low and mid-density TPS options.
- NASA is providing TPS to commercial companies, who in turn are flying their probes and providing flight data at a much faster pace than NASA can.
- A shift in testing/flying paradigm is emerging.
- Commercial partnerships allow for the sustainable development of technologies, especially ablative TPS and, in turn, will enable future NASA missions.

Questions?

National Aeronautics and Space Administration

Ames Research Center
Entry Systems and Technology Division

NASA Entry Vehicles and Missions Supported by Ames-developed TPS



* H. Julian Allen and Al Eggers, "A Study of the Motion and Aerodynamic Heating of Ballistic Missiles Entering the Earth's Atmosphere at High Supersonic Speeds," NACA-RM-A53D28, 1953 / NACA-TR-1381, 1958.

Starting with Mercury, Ames has supported every NASA mission with an entry, particularly the development of TPS.

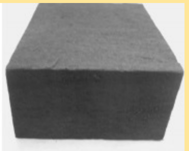
Advanced Felted TPS Manufacturing Overview

State of the Art (Rigid PICA)

Rayon Fiber

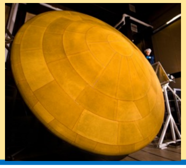
Carbonized Fiber

Net Cast FF Billet or single piece heatshield
Rigid Preform – low strain to failure



Infused PICA-D Billet or single piece heatshield – long process cycle

Complex integration of tiled architectures – high tolerances, wide seams, small tiles



State of the Art PICA-D

- Low density efficient ablator up to 2000W/cm2
- NASA unique process that is not leveraging commercial line processes for preform
- Low strain to failure
- Integration complexity

Manufacturing flow C-PICA

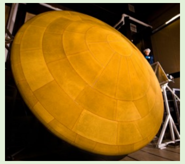
Rayon Fiber

Felting

Felt Billet
Compliant Preform – high strain to failure

Infused C-PICA Billet – long process cycle

Complex integration of tiled architectures – high tolerances, wide seams, small tiles

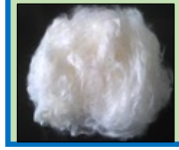


C-PICA Comparison to SoA PICA-D

- Low density efficient ablator up to 2000W/cm2
- Leverages commercial line felting processes for preform
- High strain to failure preform
- Integration complexity

Manufacturing flow S-PICA

Rayon Fiber

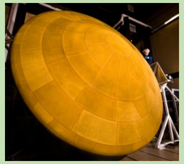


Felting

Felt Billet
Compliant Preform – high strain to failure

Infused S-PICA Billet – long process cycle

Less complex integration of tiled architectures – low tolerances, narrow seams, large tiles



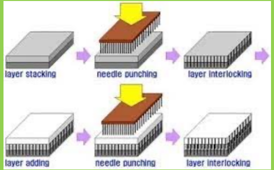
S-PICA Comparison to SoA PICA-D

- Low density efficient ablator up to 1000W/cm2
- Leverages commercial line felting processes for preform
- High strain to failure preform and material compliant after infusion
- Integration complexity reduced

Manufacturing flow PICA-FLEX

Phenolic Fiber and carbon fiber

Felting



Carbon phenolic felt
Compliant Preform – high strain to failure

No infusion process required.

Lowest integration complexity

PICA Flex Comparison to SoA PICA-D

- ***Utilize and advance the non-conventional commercial supply of felted substrates: easy tech transfer. Looking to reduce fabrication costs >50%***
- ***Further reduce touch labor and integration costs beyond that of CPICA or SPICA systems. Looking to reduce machining/integration >75%***

Patent Pending
ARC-19046-1

Highest Fabrication and Integration Cost

Most Integration Complexity

Least Fabrication and Integration Cost

Least Integration Complexity

Woven TPS Update

- Addressing a critical gap between low and high density TPS.
- HEEET:
  - TRL 6 (per Independent Review Board)
  - Mid-density, 3D woven, dual layer carbon phenolic
  - Capable of withstanding extreme entry environments (~4000 W/cm^2, 6 atm)
    - Venus, Saturn, Uranus/Neptune, and higher speed sample return missions
  - Single layer version (insulative layer only) also exists
  - Dry weave woven by BRM

- 3MDCP:
  - Allows for single piece 3D woven heat shield
    - Elimination of seams improves reliability and reduces risk
  - Baselined for MSR EES heat shield
  - Dry weave woven by SPIRIT Textiles

How Will More Commercial Opportunities Benefit NASA?

- Sharing of risk (development, cost, consequences) between NASA and Commercial partners
- Rapid technology iteration
- Opportunities to visit unexplored or underexplored targets
- Availability of new mission architectures