Development of Low Density Flexible Carbon Phenolic Ablators

Mairead Stackpoole, Jeremy Thornton, Wendy Fan and Parul Agrawal
ERC Inc., NASA Ames Research Center, Moffett Field, CA 94035

Evan Doxtad, NASA Education Associates Program, NASA Ames Research Center, Moffett Field, CA 94035

Matt Gasch, NASA Ames Research Center, Moffett Field, CA 94035

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Outline

- **Background**
  SoA Low Density Carbon Phenolic Ablators
  Challenges with SoA Configurations
  What are flexible ablators?

- **Motivation**
  Why flexibles - what are the advantages?

- **Applications**
  Potential Applications

- **Testing**
  Preliminary Thermal and Mechanical Tests

- **Summary**

Background

State of the Art (SoA) Low Density Carbon Phenolic Ablators

- Phenolic Impregnated Carbon Ablator (PICA) was an enabling TPS material for the Stardust mission where it was used ***as a single piece heatshield***
- PICA has the advantages of low density (~0.27g/cm^3) coupled with efficient ablative capability at high heat fluxes
- More recently, PICA was chosen as the primary heatshield for Mars Science Lab (MSL) and Space-X's Dragon as ***a tiled configuration***

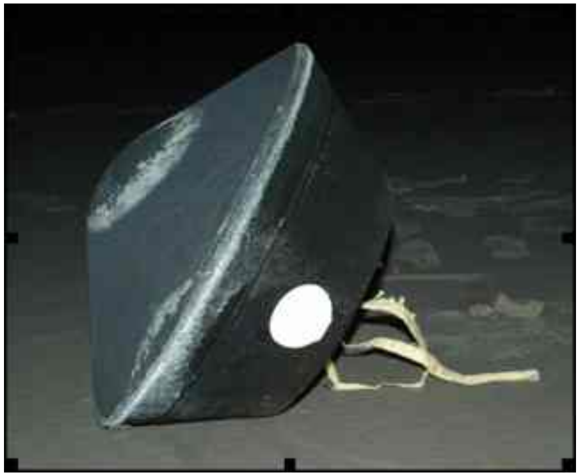


Image of the sample return capsule post flight with PICA as the forebody TPS.

MSL Heat Shield
(4.5m diameter)

Background

Challenges with SoA Configurations

- Under the Orion program PICA was shown to be capable of both ISS and lunar return missions
- Some unresolved issues remain for its application in a tiled configuration for the Orion-specific design including a brittle char and developing a suitable gap filler
- The problem of developing an appropriate gap filler resulted in the Orion program selecting AVCOAT as the primary heatshield material over PICA.

Background

Char Cracking in System Level Tile Array Tests

- Solar Tower testing on an array of PICA tiles with various gap filler materials induced high in-plane compressive stresses (caused by the high temperature gradients) in the samples.

- Articles survived the heating, however additional loads caused char cracking and failure in the char. For the image shown the additional loading caused some of char to fall off adjacent tiles. This highlights the challenges when designing with gap filler materials not compatible with PICA


Pre test PICA tile Array


Post test PICA tile Array

Background

Developing Suitable Gap Filler Solutions for PICA

- Developing a suitable gap filler material that meets the thermal and structural requirements is not trivial

- Images to the right highlight the challenges with compatible gap filler materials. In the lower heat flux condition, fencing of the gap filler material is observed as it recedes slower than the PICA material, however in the higher test condition the gap filler material recedes faster leaving a gap

156 W/cm^{2,} 100 sec

643 W/cm^{2}, 70 sec

Making PICA Flexible

- PICA is a low density carbon phenolic
- Composition works very well up to 1000 W/cm^2
- Retain the composition but change the architecture

Substrate

Carbon fiberform
Carbon Felt
Other conformal substrates

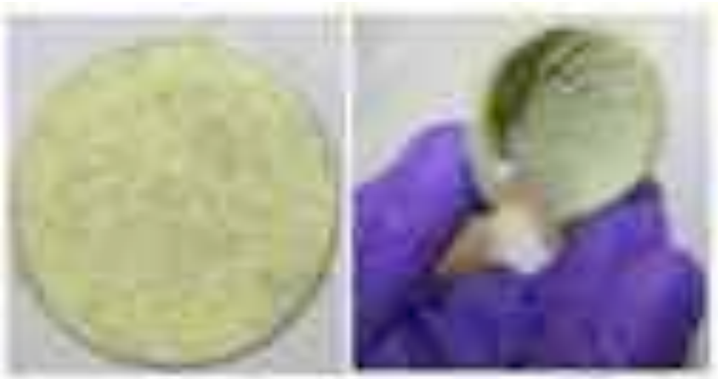
Phenolic

Resin
Modified Resins
Other

Making PICA Flexible

Flexible PICA from a Felt Substrate

- Material is comparable in composition to PICA
- Material remains flexible after charring
- Material can be processed as large pieces
- Parameters such as thickness, density etc are tailorable



as processed demonstrating the flexibility of the material in the virgin state

as processed demonstrating the flexibility of the material in the charred state

Advantages of Flexible Ablators

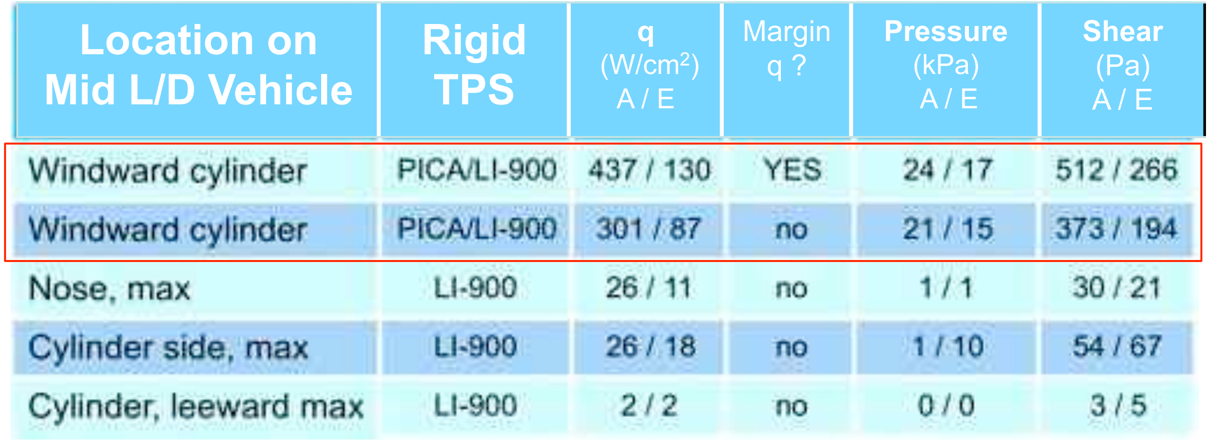
- **Flexible ablators have significant design, system integration, and performance advantages as compared to rigids**
  - Manufacturability
  - Reduction in piece-parts
  - Ease of assembly
  - Enables larger diameter aeroshells
  - Eliminates gap and seam issues (thermo-mechanical, aero-physics phenomena)
- **Orion and MSL aeroshell designs are at the upper limit with respect to mass and size for rigid ablators**

Orion Heat Shield
(5 m diameter)

MSL Heat Shield
(4.5 m diameter)

Potential Conformal Applications for Flexible TPS

Potential applications for Heavy Mars Down-mass Concepts



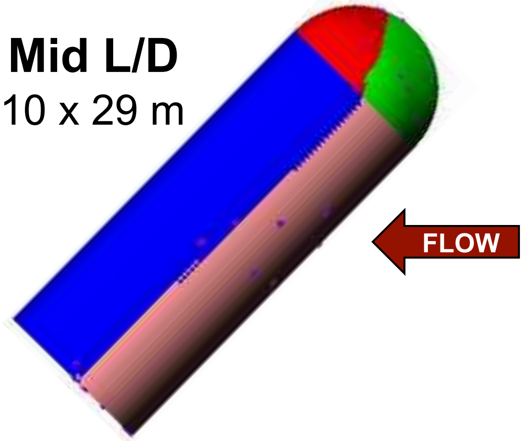
Location on Mid L/D Vehicle	Rigid TPS	q (W/cm^2) A / E	Margin q ?	Pressure (kPa) A / E	Shear (Pa) A / E
Windward cylinder	PICA/LI-900	437 / 130	YES	24 / 17	512 / 266
Windward cylinder	PICA/LI-900	301 / 87	no	21 / 15	373 / 194
Nose, max	LI-900	26 / 11	no	1 / 1	30 / 21
Cylinder side, max	LI-900	26 / 18	no	1 / 10	54 / 67
Cylinder, leeward max	LI-900	2 / 2	no	0 / 0	3 / 5

Location on COBRA 14297 Vehicle	Rigid TPS	q (W/cm^2) A / E	Margin q ?	Pressure (kPa) A / E	Shear (Pa) A / E
Windward cylinder	PICA	174 / 63	no	13 / 13	175 / 114
Nose, max	LI-900	26 / 10	no	1 / 1	29 / 21
Cylinder side, max	LI-900	26 / 11	no	1 / 1	28 / 21
Leeward cylinder	LI-900	1 / 1	no	0 / 1	2 / 4

Analysis of heat rates suggest flexible ablators should be considered for windward cylinder and nose locations

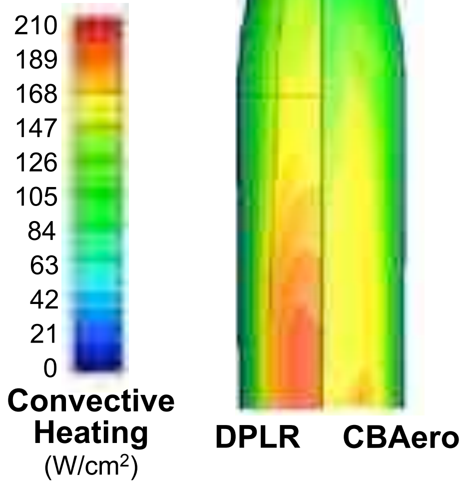
Mid L/D

10 x 29 m



COBRA

14297

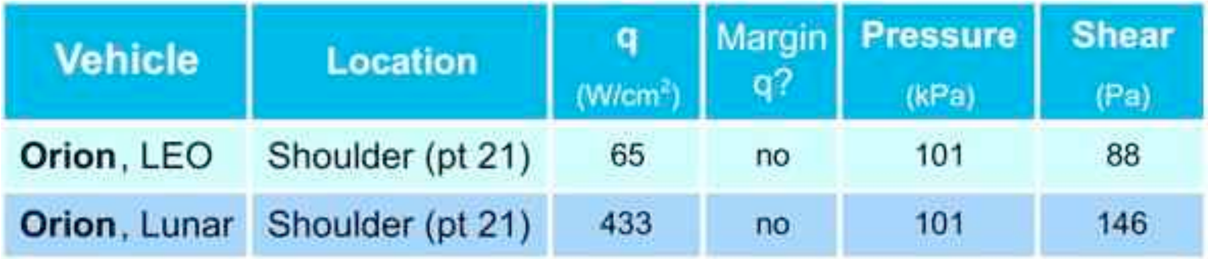


Courtesy: J. Arnold ARC

Data in charts are representative for max heat load locations

Potential Conformal Applications for Flexible TPS

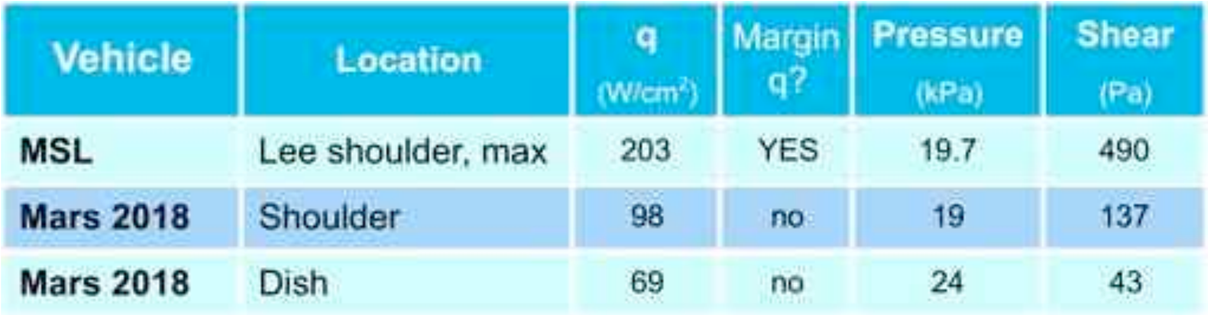
Potential applications for Lunar Return and Robotic Mars missions



Vehicle	Location	q (W/cm²)	Margin q?	Pressure (kPa)	Shear (Pa)
Orion, LEO	Shoulder (pt 21)	65	no	101	88
Orion, Lunar	Shoulder (pt 21)	433	no	101	146

Flexible ablators can mitigate PICA integration issues

Orion Heat Shield
(5 m diameter)



Vehicle	Location	q (W/cm²)	Margin q?	Pressure (kPa)	Shear (Pa)
MSL	Lee shoulder, max	203	YES	19.7	490
Mars 2018	Shoulder	98	no	19	137
Mars 2018	Dish	69	no	24	43

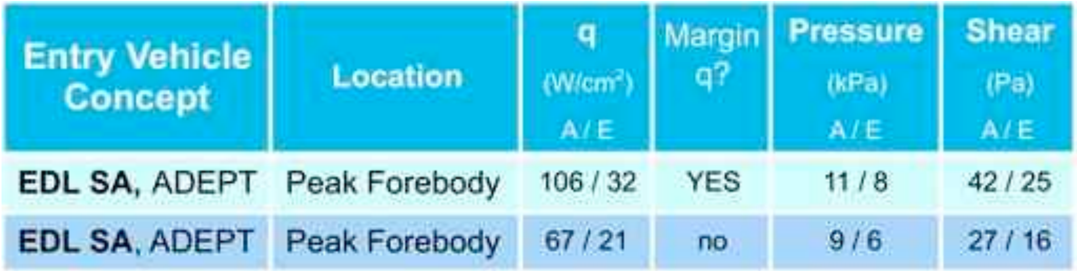
Flexible ablators are an attractive alternative to rigid PICA for future MSL class rigid aeroshells

MSL Heat Shield
(4.5 m diameter)

Courtesy: J. Arnold ARC

Potential Applications for Flexible TPS

Flexible ablators are enabling for many other future entry missions



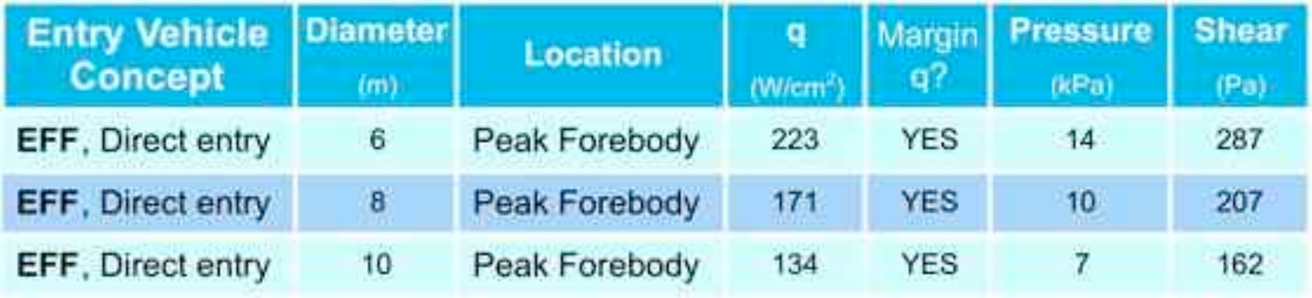
Entry Vehicle Concept	Location	q (W/cm^2) A / E	Margin q?	Pressure (kPa) A / E	Shear (Pa) A / E
EDL SA, ADEPT	Peak Forebody	106 / 32	YES	11 / 8	42 / 25
EDL SA, ADEPT	Peak Forebody	67 / 21	no	9 / 6	27 / 16

[1] Hypersonic Inflatable Aerodynamic Decelerator

[2] Adaptive Deployable Entry-system Project

HIAD[1] Concept
(23 m diameter)

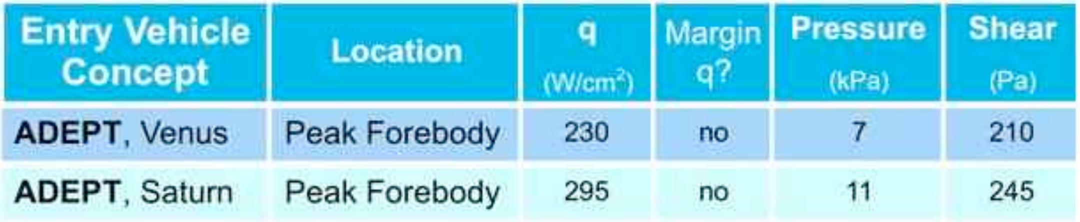
ADEPT[2] Concept
(23 m diameter)



Entry Vehicle Concept	Diameter (m)	Location	q (W/cm^2)	Margin q?	Pressure (kPa)	Shear (Pa)
EFF, Direct entry	6	Peak Forebody	223	YES	14	287
EFF, Direct entry	8	Peak Forebody	171	YES	10	207
EFF, Direct entry	10	Peak Forebody	134	YES	7	162

7.2 km/s entry, capable[1] of delivering 3.4 mt to Mars surface[2] (7.2 mt arrival mass)

Exploration FeedForward
(EFF) **Concepts**
(6, 8, 10 m diameters)



Entry Vehicle Concept	Location	q (W/cm^2)	Margin q?	Pressure (kPa)	Shear (Pa)
ADEPT, Venus	Peak Forebody	230	no	7	210
ADEPT, Saturn	Peak Forebody	295	no	11	245

ADEPT Concept
(2.13 m diameter)

[1] EDL SA 2010 study [2] Viking (MSL) technology can deliver ~ 1.2 mt

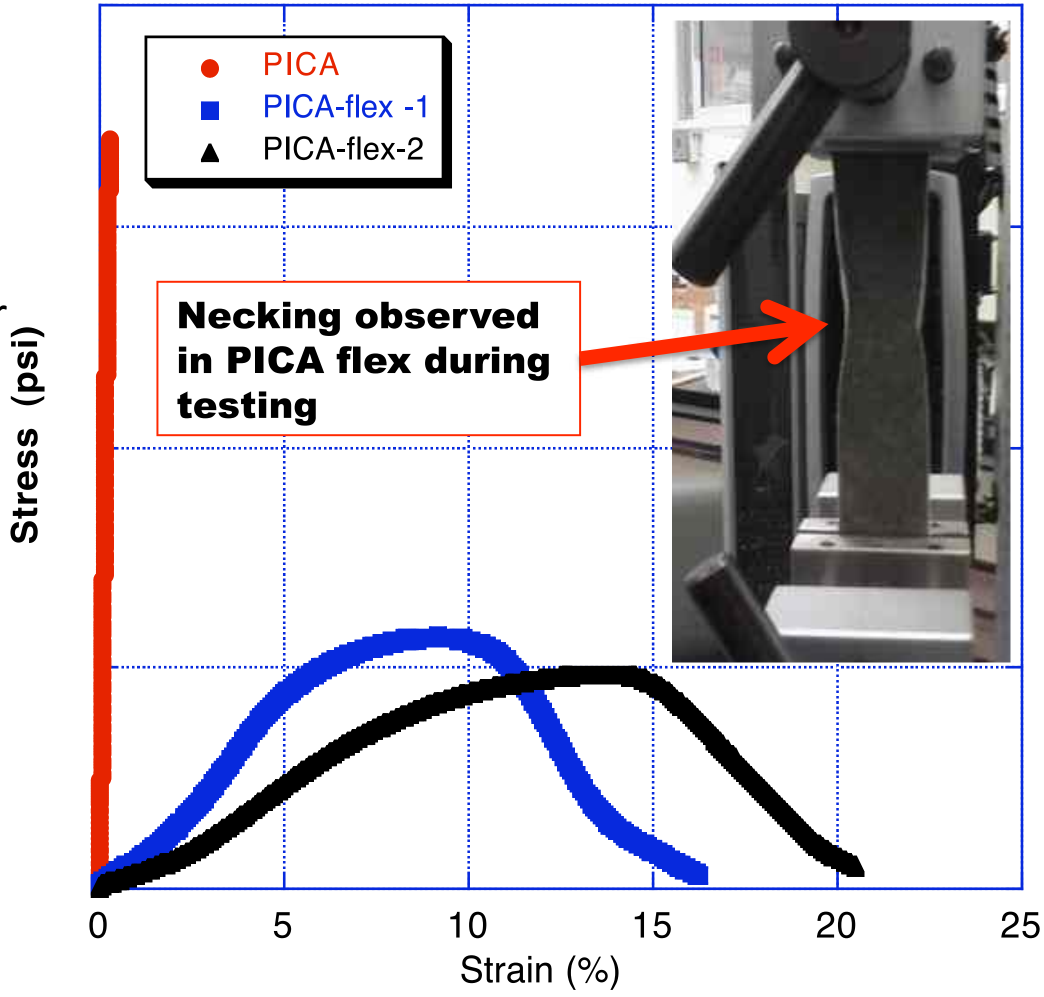
Courtesy: J. Arnold ARC

Results from Preliminary Screening Tests

- Candidate systems have been processed and are currently going through a series of screening tests that include mechanical, thermal and relevant environment screening (arc jet, LHMEL, HyMETs)
- Preliminary Results:
  - Mechanical
  - Thermal Conductivity
  - Microstructure
  - Arc Jet testing
  - LHMEL Testing

Mechanical Testing

- Samples were tested in tension in the IP direction to evaluate strength and strain to failure. (8" x 1")
- PICA flex failed very gracefully during the test and showed necking behavior – a phenomenon that is traditionally present in very ductile materials.
- PICA flex was able to withstand about 8%-12% strain before onset of necking
- For comparison, a PICA stress strain curve is also provided - strain to failure of PICA is < 1% which leads to difficulties in designing with PICA
- While PICA has higher strength, in applications that are strain to failure driven, PICA flex has advantages



Necking observed in PICA flex during testing

Stress strain data comparing PICA flex to PICA

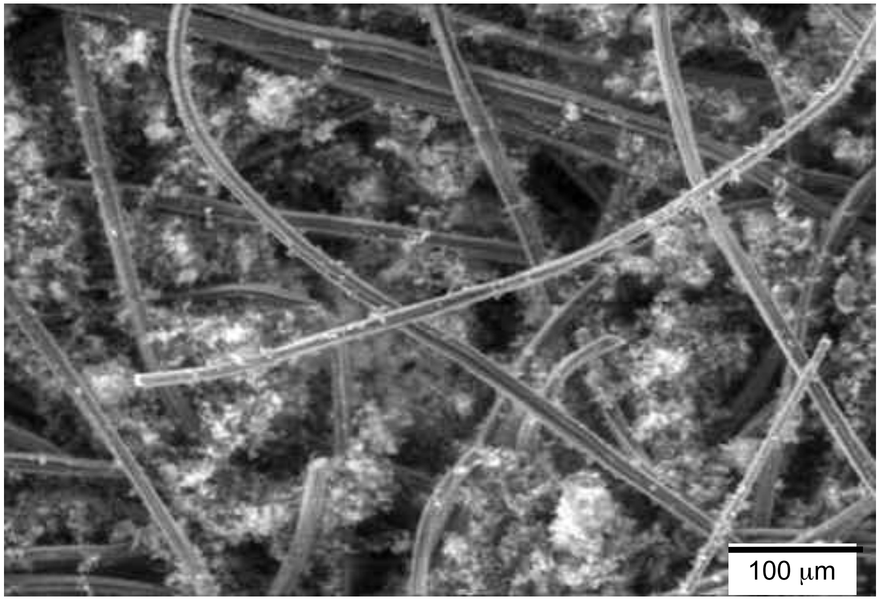
Room Temperature Thermal Conductivity

- The laser flash method was used to evaluate thermal conductivity in PICA flex
- Data presented is an average of 3 samples
- For comparison, the thermal conductivity of PICA are also provided
- For this test series the PICA and PICA flex samples have comparable densities, however, the thermal conductivity of PICA flex is approximately a third of that of rigid PICA

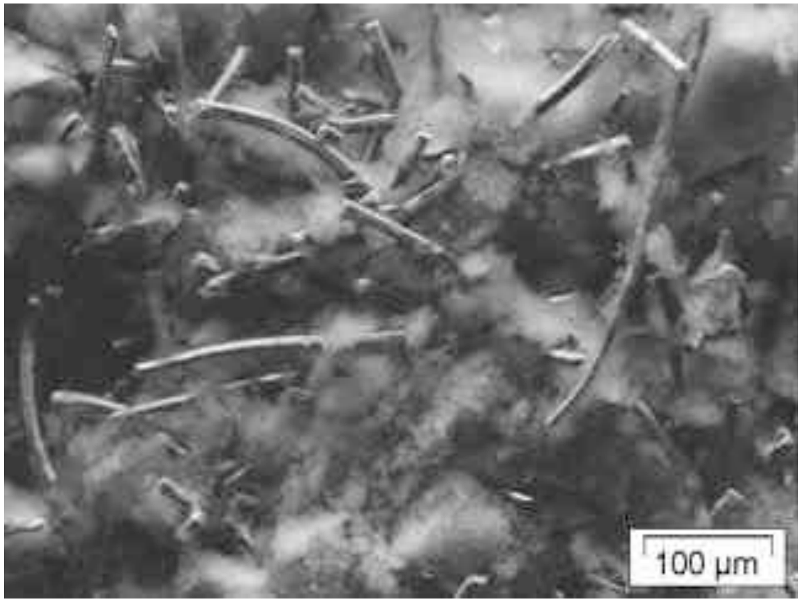
Normalized thermal conductivity comparing PICA flex to PICA

Microstructure

- Characterizing the microstructure of a TPS material is important as the constituent distribution at the microstructural level will influence properties
- PICA flex has a microstructure that resembles PICA in many aspects; distributed phenolic phase in a carbon matrix



Representative PICA flex microstructure



Representative PICA microstructure

LHMEL Screening Tests

- Exposure 115 W/cm^2 for 30 seconds
- Comparable areal mass for all materials

Material	**Max. Backface Temperature (°C)**	**Time to Reach Max. Backface Temperature (sec)**
SIRCA	198	120
PICA Flex Variant 1	72	310
PICA Flex Variant 2	64	152
PICA Flex Variant 3	80	186

Pre test

Post test

LHMEL Screening Tests

1st Exposure

- 450 W/cm^2 for 25 seconds

Material	Max. Backface Temperature (°C)	Time to Reach Max. Backface Temperature (sec)
PICA	240	93
PICA Flex Variant 1	118	213
PICA Flex Variant 2	75.5	246
PICA Flex Variant 3	133	143

- Comparable areal mass for all materials

2nd Exposure

- 115 W/cm^2 for 50 seconds

Material	Max. Backface Temperature (°C)	Time to Reach Max. Backface Temperature (sec)
PICA	276	108
PICA Flex Variant 1	128	223
PICA Flex Variant 2	84	232
PICA Flex Variant 3	173	144

Arc Jet Exposure

- Initial arc jet screening has been completed at the Johnson Space Center arc jet facility
- Samples were 3” diameter by ~ 1” thick and bonded to an LI 2200 tile holder and were instrumented with a backface thermocouple
- Initial arc-jet tests show PICA flex performing well at 520 W/cm^2, 35 kPA
- Performance limits for flexible ablators have yet to be determined


Pre test


Post test

Summary

- We are currently looking at alternative architectures to yield flexible and more conformal carbon phenolic materials with comparable performance to PICA
- Flexible TPS concepts address some of the design issues faced in the application of a tiled PICA heat shield
- Initial testing of flexible PICA concepts has been encouraging:
  - Substantially higher strain to failure than PICA
  - Lower thermal conductivity than PICA
  - Survived a 520 W/cm^2, 35 kPa arc jet exposure
- Flexible ablator technology is enabling for upcoming NASA missions :
  - rigid and deployable TPS applications
  - for the 23 m HIAD and ADEPT deployable

    decelerators and for revolutionary ADEPT missions to Venus and Saturn.
- Testing will begin under Office of the Chief Technologist funding in Fiscal Year 2012.

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Families of Ablators Under Development at Ames

Advanced PICA-like ablators

Graded Ablators

Conformable PICA

Flexible PICA

Flexible SIRCA