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In-Space Repair and Refurbishment of Thermal Protection System Structures of Reusable Launch Vehicles

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Advanced repair and refurbishment technologies are critically needed for the thermal protection system of current space transportation systems as well as for future launch and crew return vehicles. There is a history of damage to these systems from impact during ground handling or ice during launch. In addition, there exists the potential for in-orbit damage from micrometeoroid and orbital debris impact as well as different factors (weather, launch acoustics, shearing, etc.) during launch and re-entry. The GRC developed GRABER (Glenn Refractory Adhesive for Bonding and Exterior Repair) material has shown multiuse capability for repair of small cracks and damage in reinforced carbon-carbon (RCC) material. The concept consists of preparing an adhesive paste of desired ceramic with appropriate additives and then applying the paste to the damaged/cracked area of the RCC composites with an adhesive delivery system. The adhesive paste cures at 100-120°C and transforms into a high temperature ceramic during reentry conditions. A number of plasma torch and ArcJet tests were carried out to evaluate the crack repair capability of GRABER materials for Reinforced Carbon-Carbon (RCC) composites. For the large area repair applications, Integrated Systems for Tile and Leading Edge Repair (InSTALER) have been developed and evaluated under various ArcJet testing conditions. In this presentation, performance of the repair materials as applied to RCC is discussed. Additionally, critical in-space repair needs and technical challenges are reviewed.

In-Space Repair and Refurbishment of Thermal Protection System Structures for Reusable Launch Vehicles

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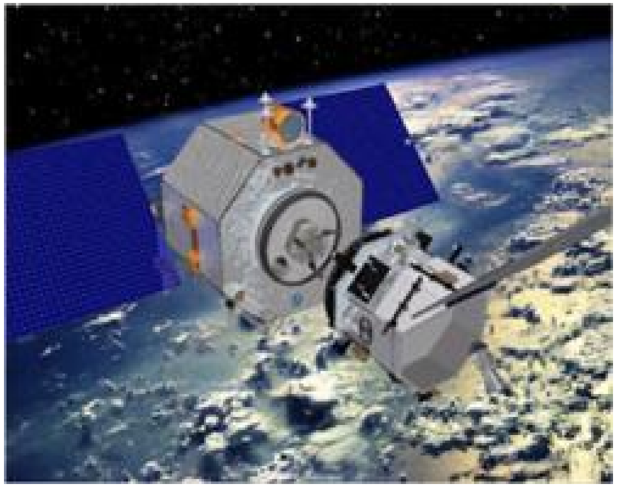
Outline

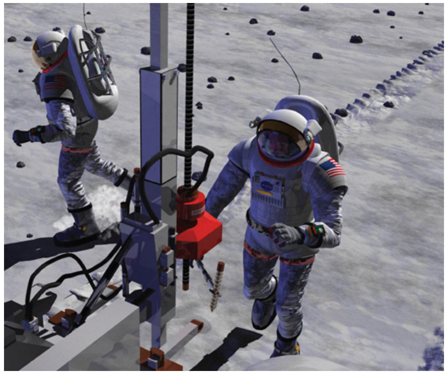
- **Introduction and Background**
- **Need for In-Space Repair and Inspection**
- **Technical Challenges**
  - ***Space Environment, EVA, Tools, Materials Issues***
  - ***Inspection, Verification, and Validation***
- **Repair Technologies**
  - ***Crack Repair Material: GRABER***
  - ***Integrated System for Large Area TPS Repair: InSTALER***
- **Testing and Characterization**
  - ***Physicochemical Characterization***
  - ***Plasma Performance (ArcJet Testing, Torch Testing, etc)***
  - ***Microstructural Characterization***
- **Applications**
- **Summary and Conclusions**

Repair of Hubble Space Telescope, Satellites, and Future Space Exploration Systems



ASTRO:
Autonomous Space Transfer and Robotic Orbiter

First Robotic Satellite Repair Man (DARPA)- ***Launched March 12, 2007***



Hubble Space Telescope Repair Missions

Lunar and Mars Exploration Missions

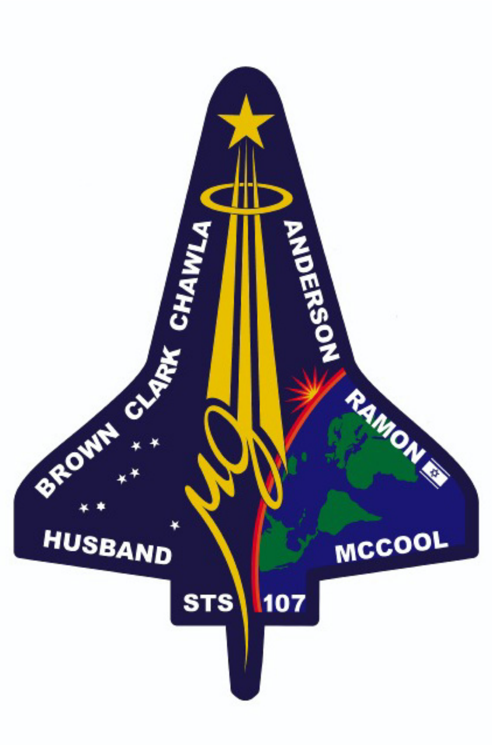
Damage Possibilities to Thermal Protection System (TPS)

- Impact damage during ground handling
- Damage due to falling of ice or other objects during launch
- Micrometeoroid and orbital debris impact
- Damage caused by different factors during launch and reentry (weather, launch acoustics, shearing, etc.)

Launch Pad Debris

Accent EFT Foam Damage

On-Orbit MMOD Damage



STS-107 Columbia

February 1, 2003

External Tank Bipod Area

Debris Strike Enhanced.mov

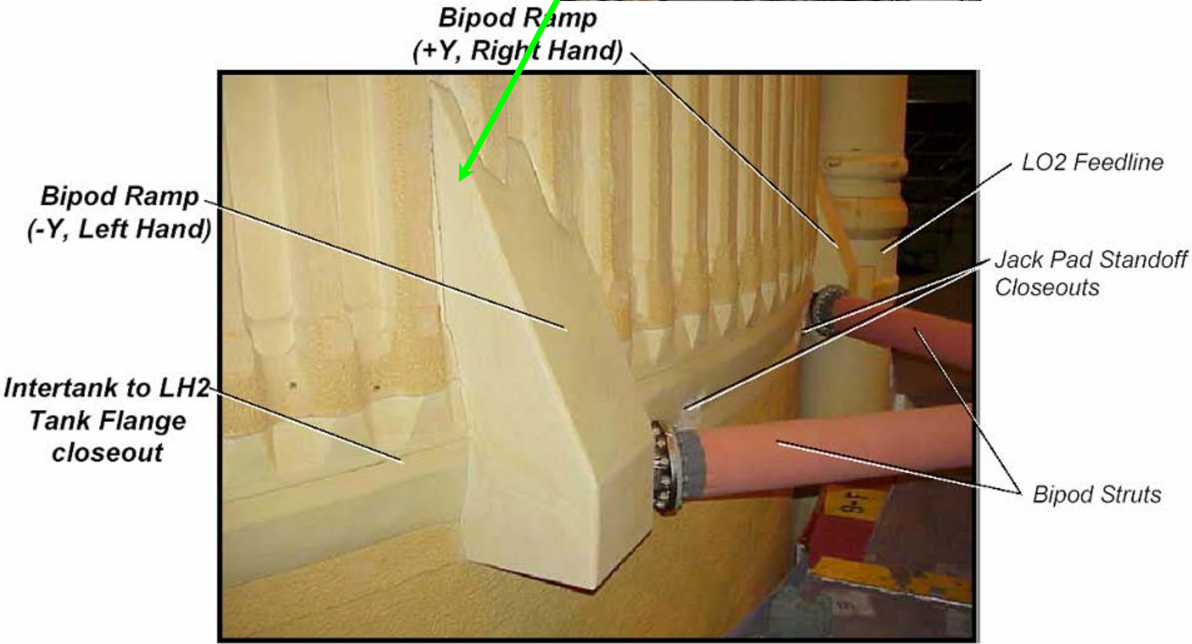
Foam separated from bipod ramp impacted on lower half of RCC panel #8

81.9 sec

21-27” long, 12-18” wide

625-840 ft/sec (416-573 miles/hr)

Bipod Fitting redesign



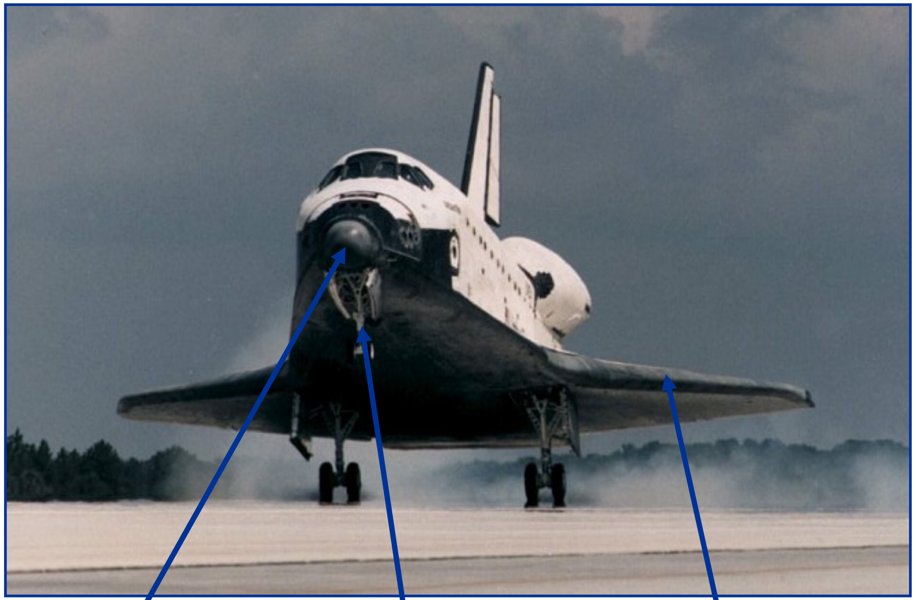
CAIB Recommendation R6.4-1

- For missions to the ISS, develop a practicable capability to inspect and effect emergency repairs to the widest possible range of damage to the **Thermal Protection System**, including both tile and RCC, taking advantage of the additional capabilities available when near to or docked at the ISS.
- For non-station missions, develop a comprehensive autonomous (independent of Station) **inspection and repair capability** to cover the widest possible range of damage scenarios.
- Accomplish an on-orbit Thermal Protection System inspection, using appropriate assets and capabilities, early in all missions.
- The **ultimate objective** should be a fully autonomous capability that an ISS mission fails to achieve the correct orbit, fails to dock successfully, or is damaged during or after undocking.

http://www.nasa.gov/columbia/home/CAIB_Vol1.html

Leading Edge Structural Subsystem (LESS)

RCC Components

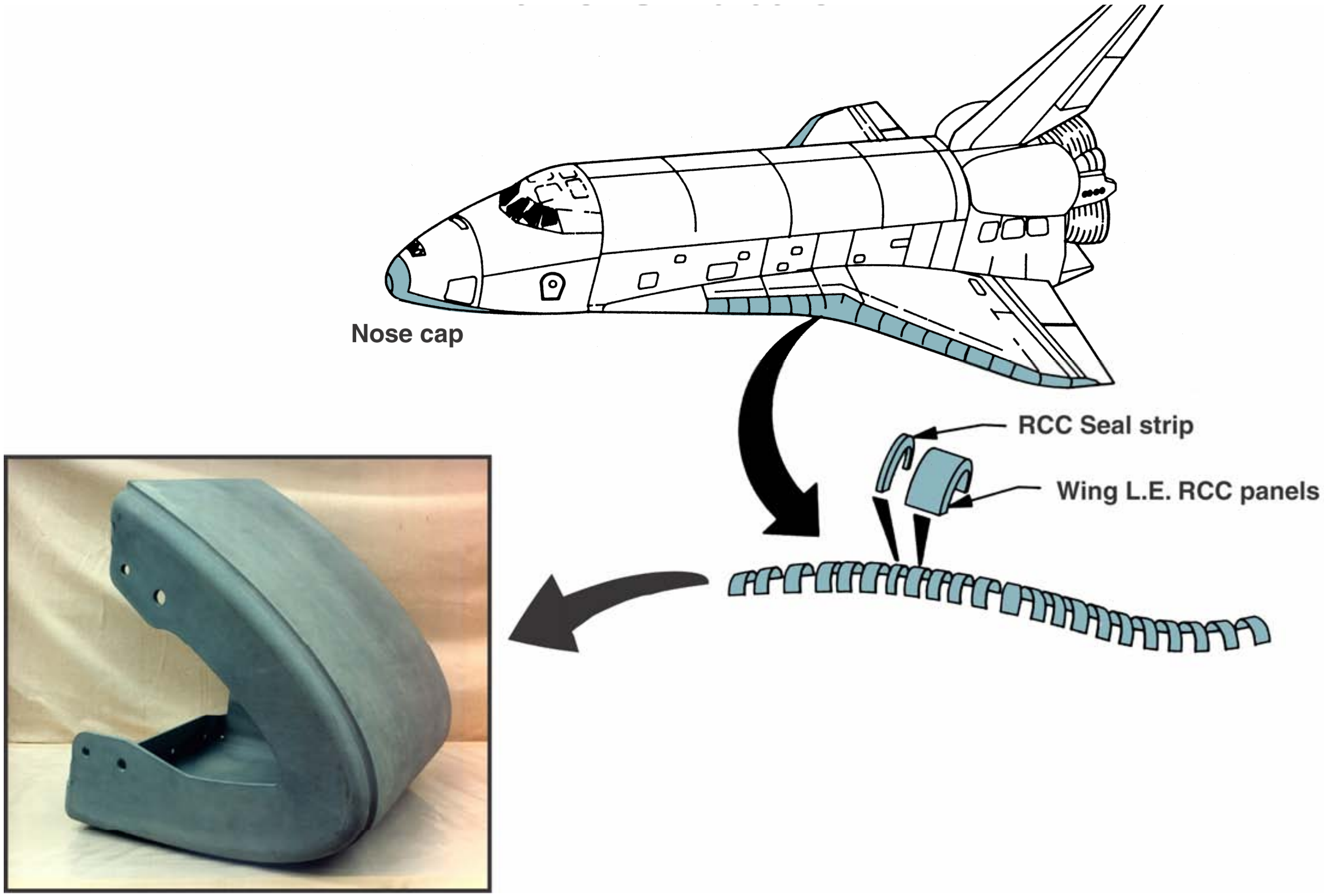


Nose Cap, Chin Panel, and Seals

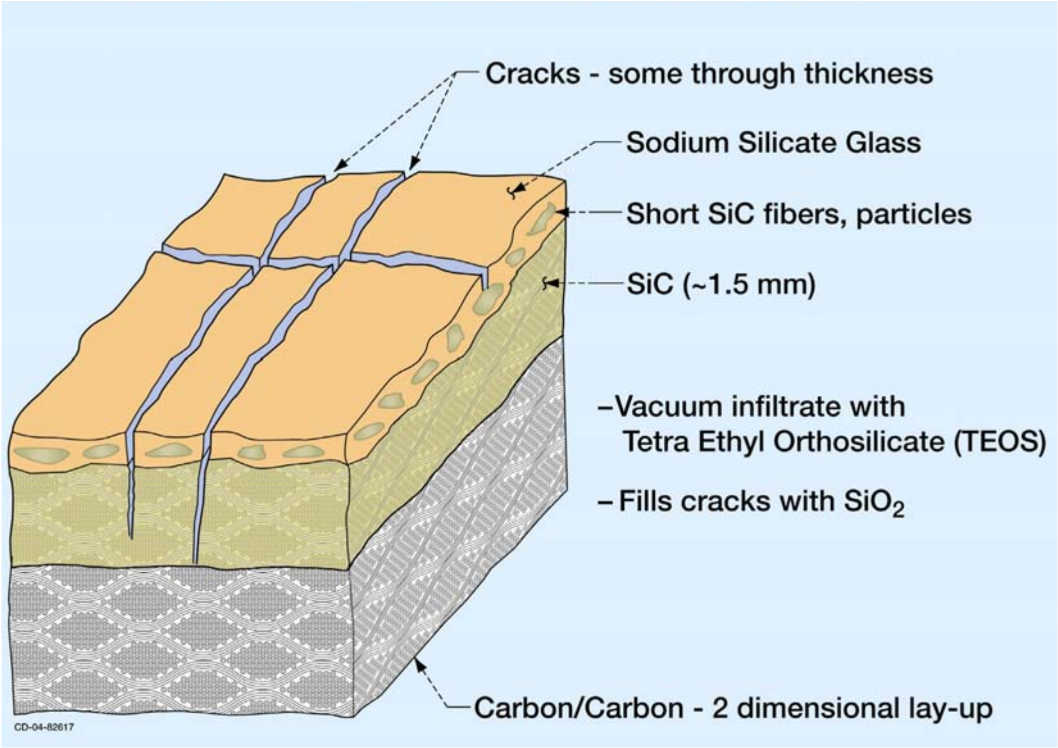
Forward External Tank Attachment "Arrowhead" Plate

Wing Leading Edge Panels and Seals

Leading Edge RCC Panels and T-Seals



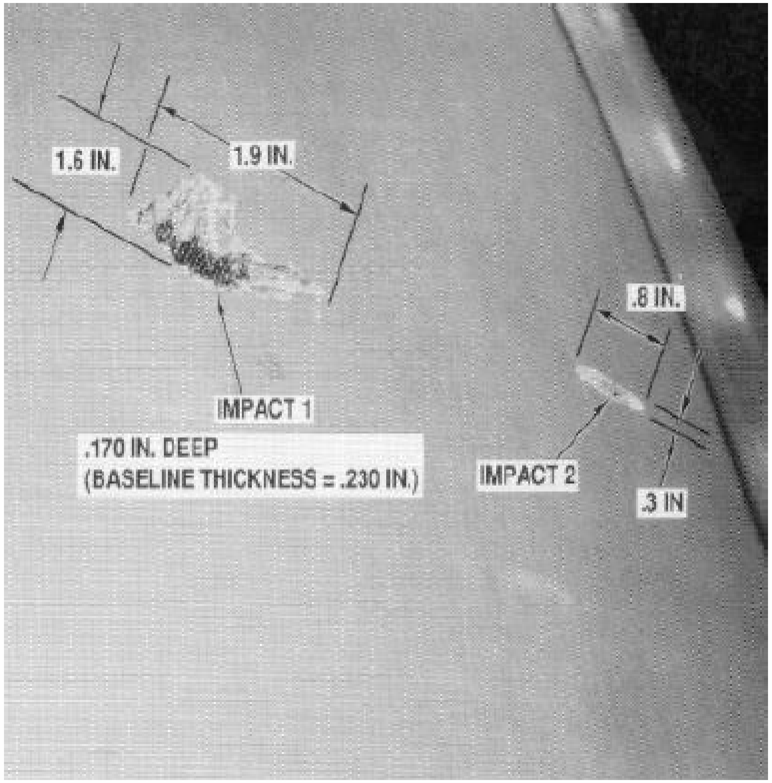
Details of Reinforced Carbon-Carbon (RCC) Composite TPS Structures



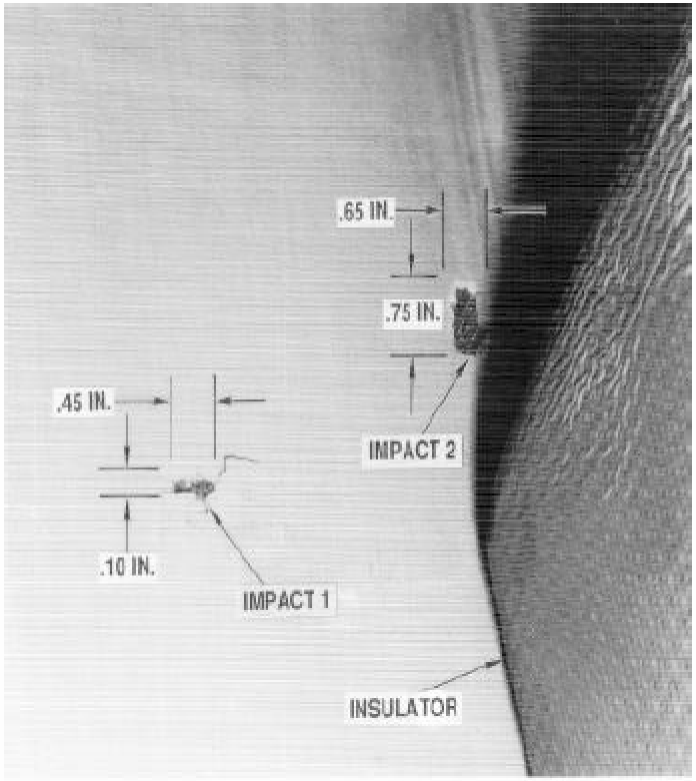
Cross Sectional View Showing Carbon/Carbon, SiC, and Type A Sealant

Dr. Nathan Jacobson, NASA GRC

STS-45 Impact Damage on OV-104 WLE Panel 10R



Outer Surface Damage



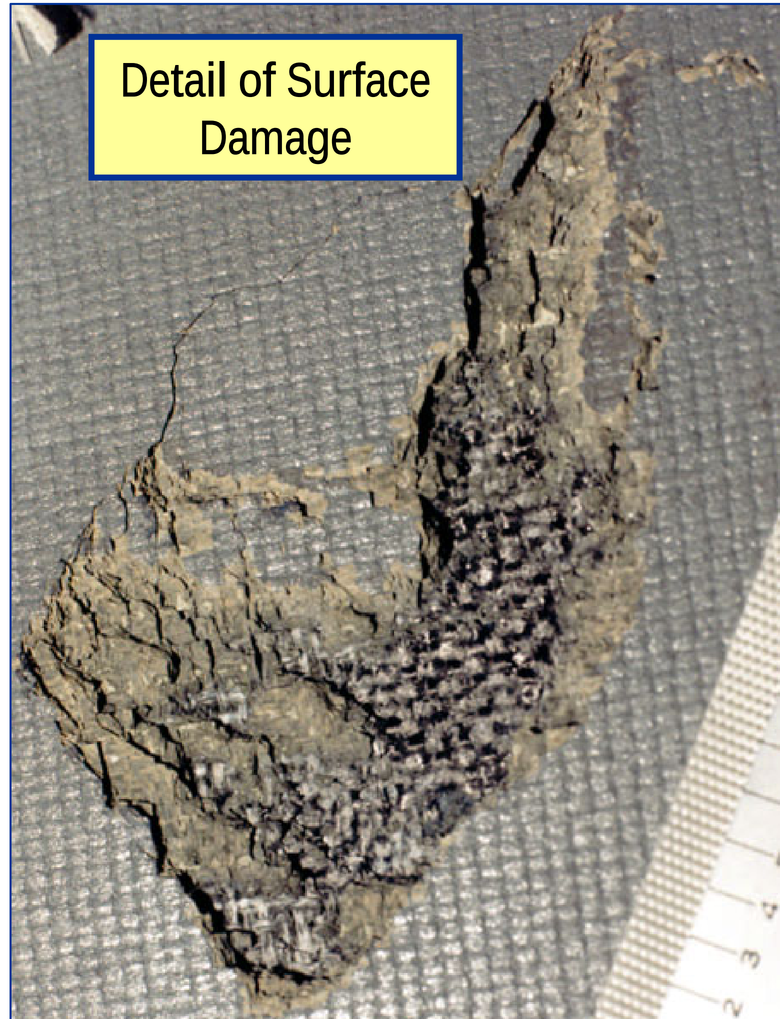
Inner Surface Damage

Don Curry, JSC

STS-45 Impact Damage on Atlantis WLE Panel 10R


Overall View of Impact Sites

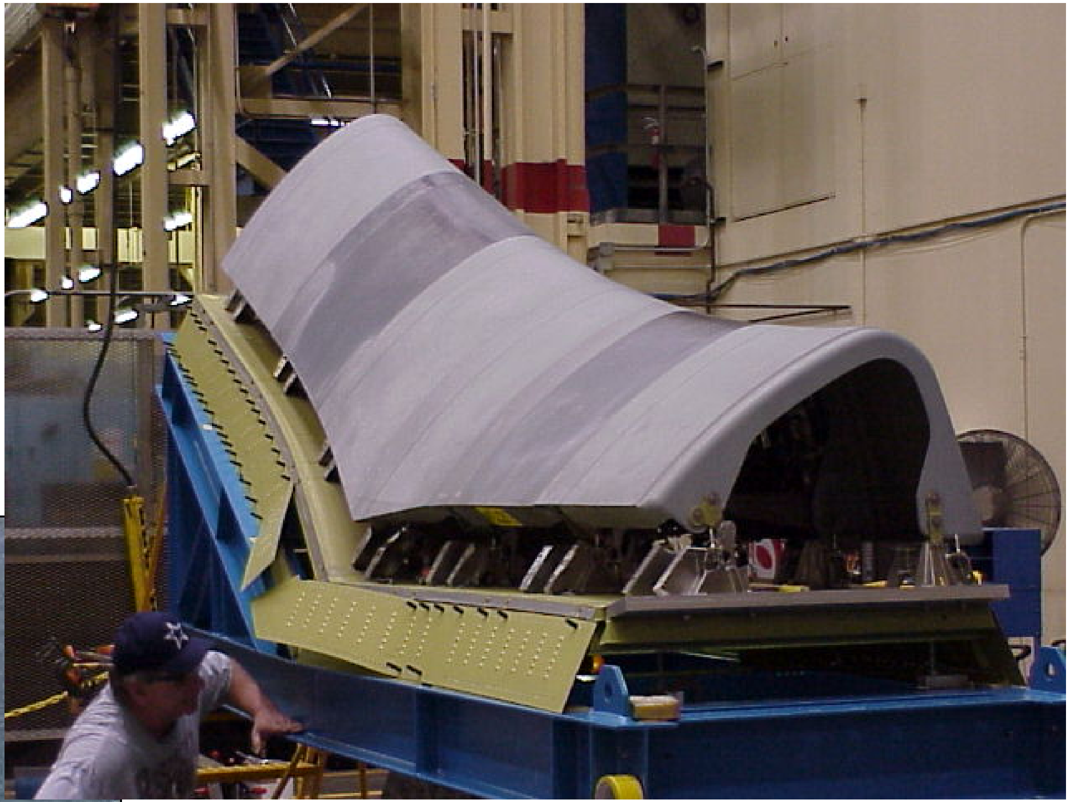

Detail of Backface Damage


Detail of Surface Damage

External Tank Foam Impact Test on Wing Leading Edge Reinforced Carbon-Carbon (RCC) Panel

Foam Impact External.mov

RCC Panel 8 Test Article



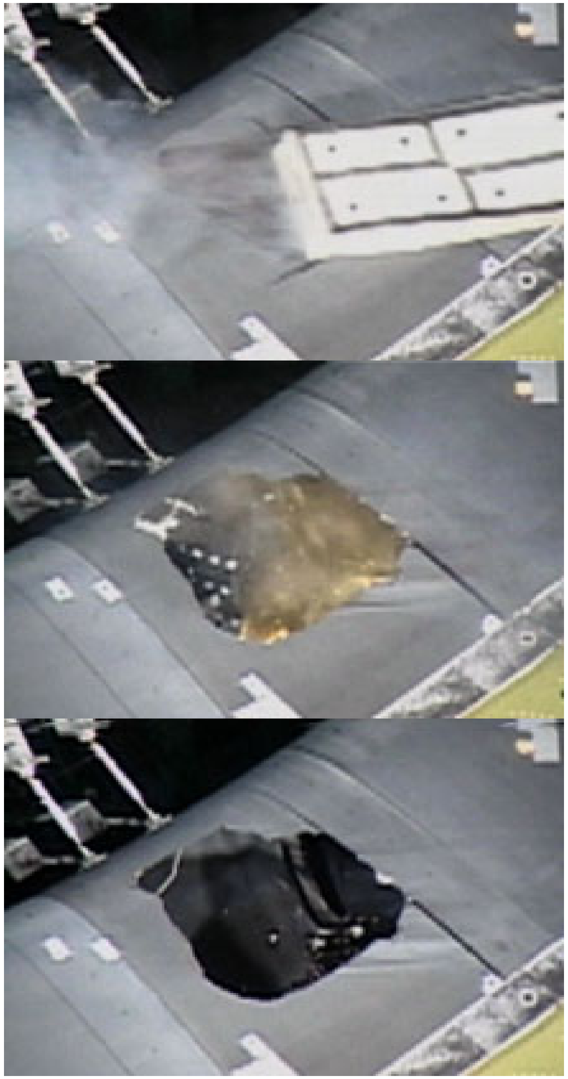
OV103 On-board Camera Image
(Port Wing Leading Edge Area)

Dr. Koichi Wakata, JAXA/JSC

Damage to Leading Edges During Impact Testing on Ground

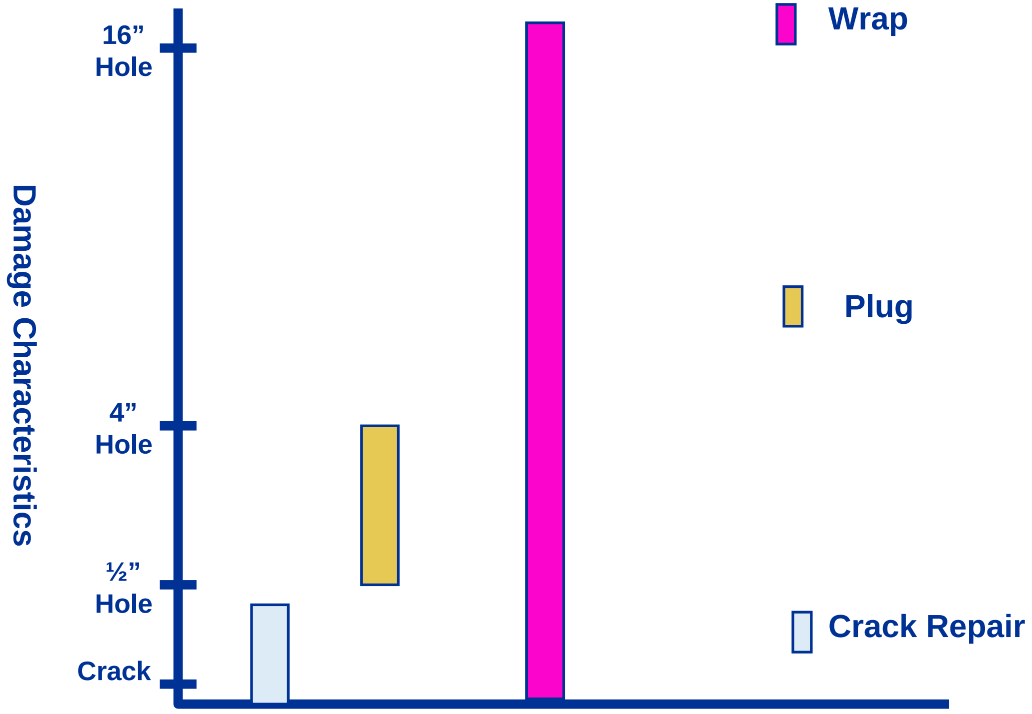
IML Damage Surface Panel 9L

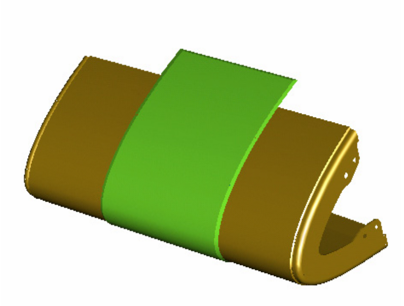
OML Damage Surface Panel 9L2



Foam Blasts 16-inch Hole in Final Shuttle Test @SWRI, TX, July 7, 2003

Different Repair Concepts for RCC Wing Leading Edge Damage





Performing Repair in Space Environment is Quite Complex and Challenging

- EVA is like floating in the large pool of water, in a pressurized and only partially form fitting balloon.
- Normal EMU pressure is 4.3 psi.
- Thermal environments of the repair poses a significant challenge (temperature changes from -175 F (-115°C) to +250 F (121°C) and the back again in the span of 90 minutes.
- In some areas, the temperature changes from extreme cold to extreme hot in about 20 minutes time.
- Space vacuum is quite high (10^{-7} or 10^{-8} Torr).

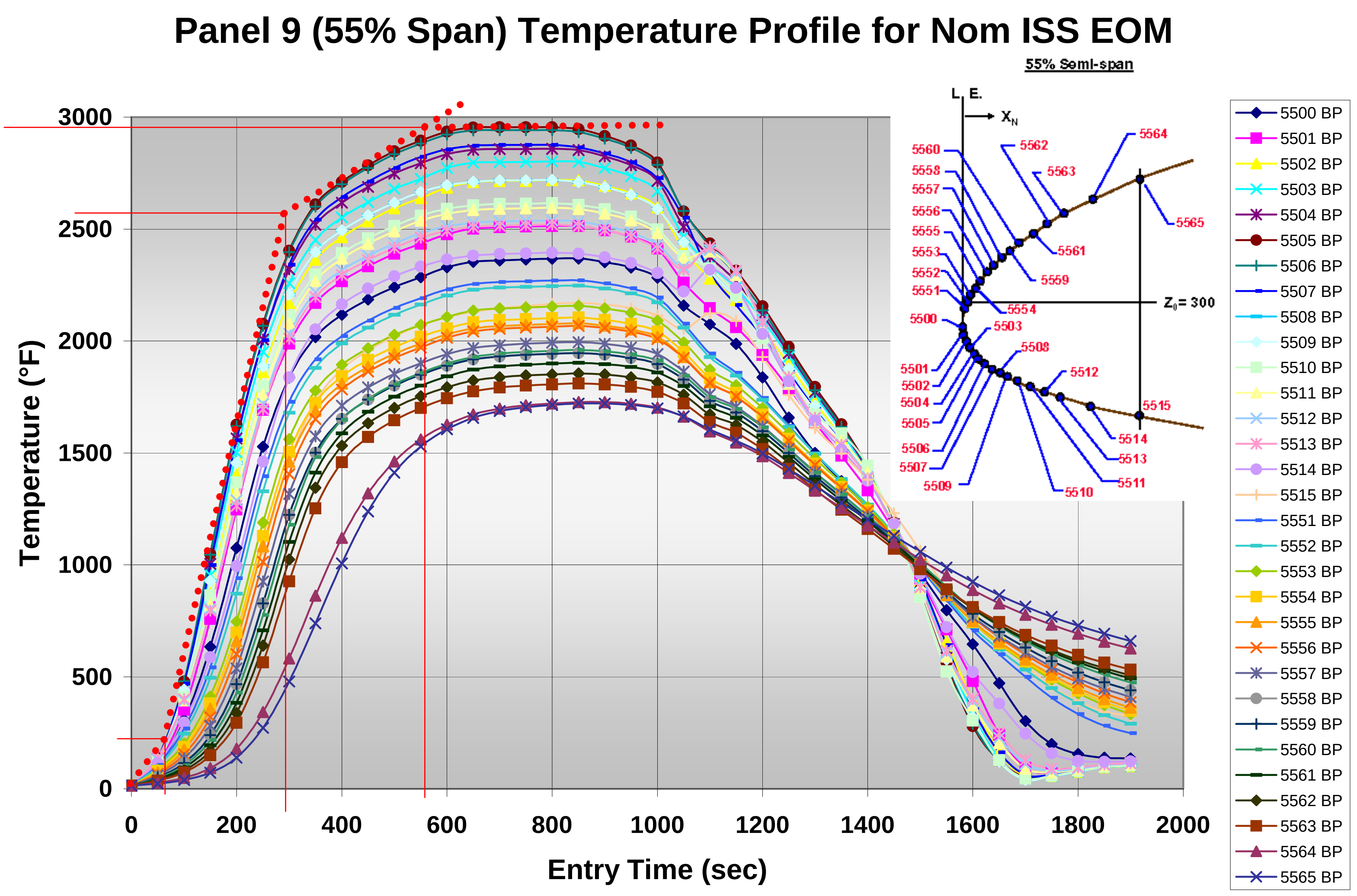
EVA Considerations and Concerns for In Space Repair

- **EVA Access to the damage site – getting the EVA crewmember there**
- **EVA Worksite Restraint – keeping the crewmember in place and in a stable orientation to effect the repair and react the loads associated with the repair**
- **EVA Tools Design and Development – designing, certifying and manufacturing the tools required for access, restraint, repair and cleanup**
- **EVA Repair Techniques Development – developing and validating the particular techniques required to accomplish access, restrain the crewmember and effect the repair**

Space Shuttle Re-entry Conditions are Quite Harsh and Extreme

- Temperature to 2000 K
- Reduced pressure--0.005 to 0.010 atm
- Gases--O_2, N_2, CO_2
  - Shock leads to O, N and ions
- Short times ~15 minutes/re-entry
- Best simulated with arc-jet

WLE Entry Temperature Profiles



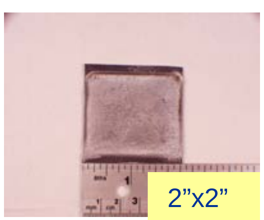
Glenn Refractory Adhesive for Bonding and Exterior Repair (GRABER) for Crack Repair

- High temperature adhesive based on organic based systems with a number of inorganic constituents.
- Viscosity and curing behavior (time, temperature) can be tailored to suit the needs.
- GRABER has been used to prepreg a wide variety of ceramic fiber weaves (C, SiO_2, SiC).
- It bonds very well with a wide variety of surfaces and cures up to 120°C with heat.
- It can be acid cured at lower temperatures as well.

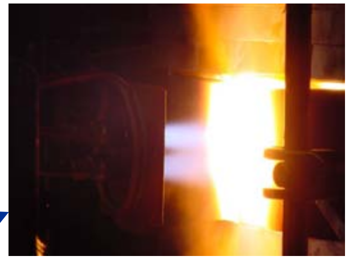
- **2005 R&D 100 Award**
- **Northern Ohio Live Magazine- Awards of Achievement, S&T Category- Runner Up**

Typical High Temperature Testing Steps for Various Repair Materials

Simulated Testing in High Temperature Furnace (1650 C)



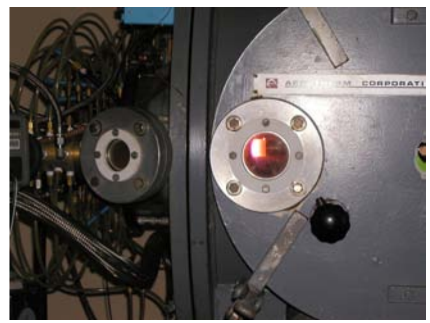
2”x2”



Plasma Torch (MSFC, ATK)

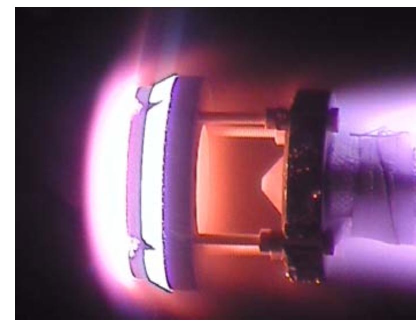
QARE Rig (GRC)

Specimen viewed during test



HYMETS (LaRC)

1” dia



ArcJet Testing (Stagnation and Wedge) at JSC, ARC, and Boeing LCAT)

2.8”

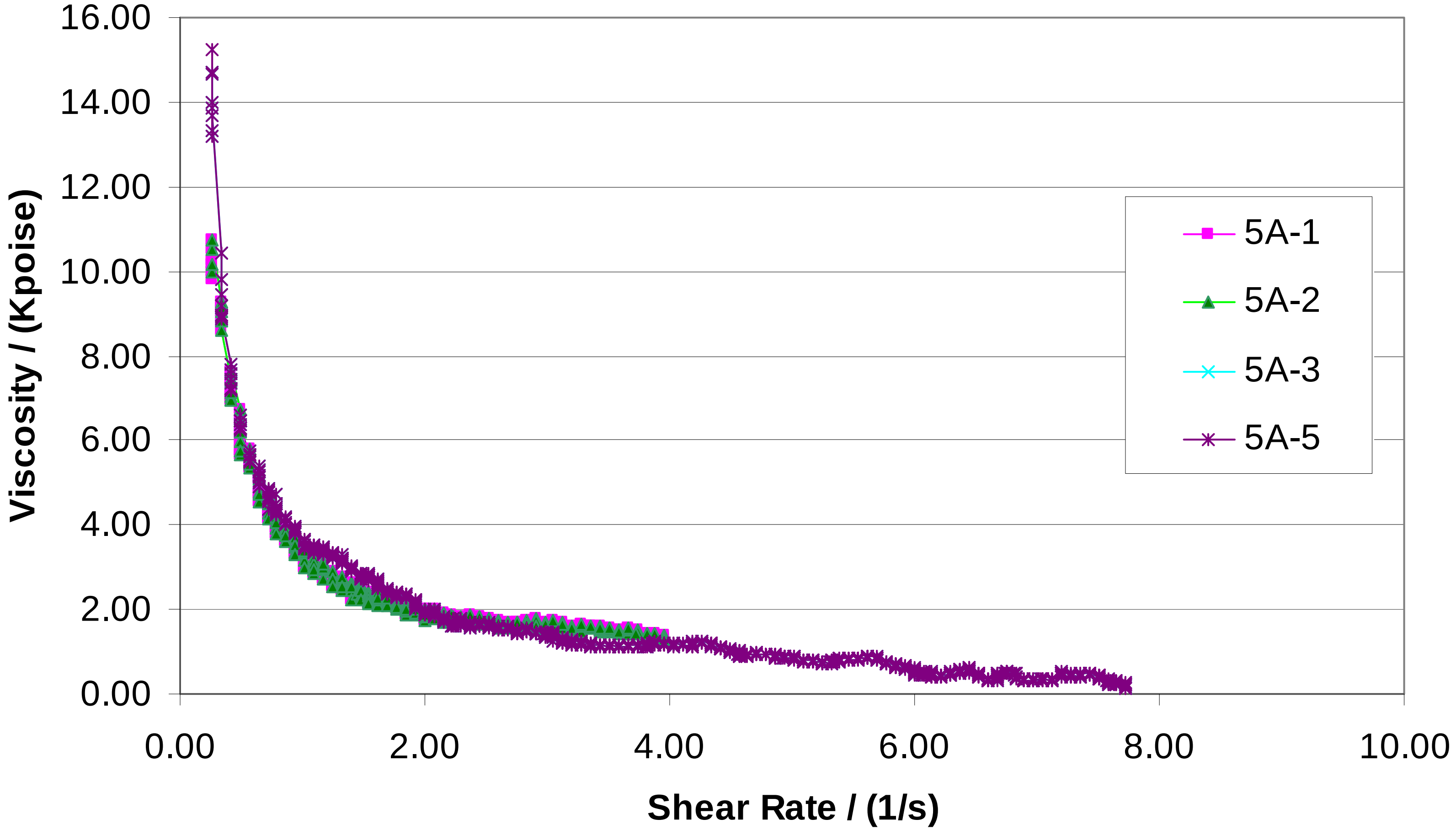
Reproducibility, Storage, and Shelf Life Characterization

Brookfield PVS Rheometer Used for the Viscosity Measurements

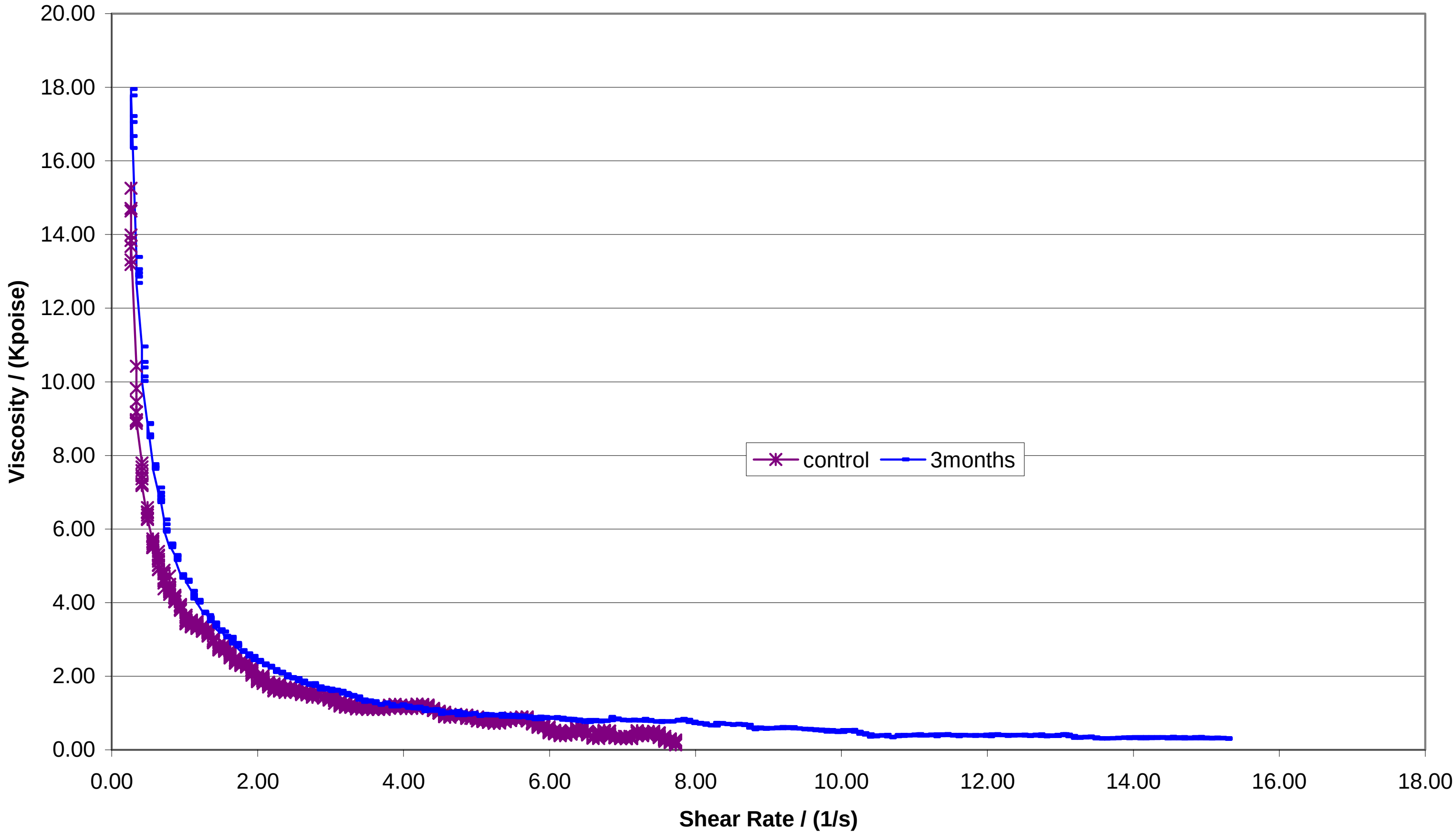
The temperature control bath has capability from – 20 C (- 4 F) to 180 C (356 F)

Reproducibility of GRABER 5A

Materials made at different times and in varying amounts show consistent viscosity



Viscosity of GRABER Stored at Room Temperatures



Materials stored for different times at room temperature show consistent viscosity

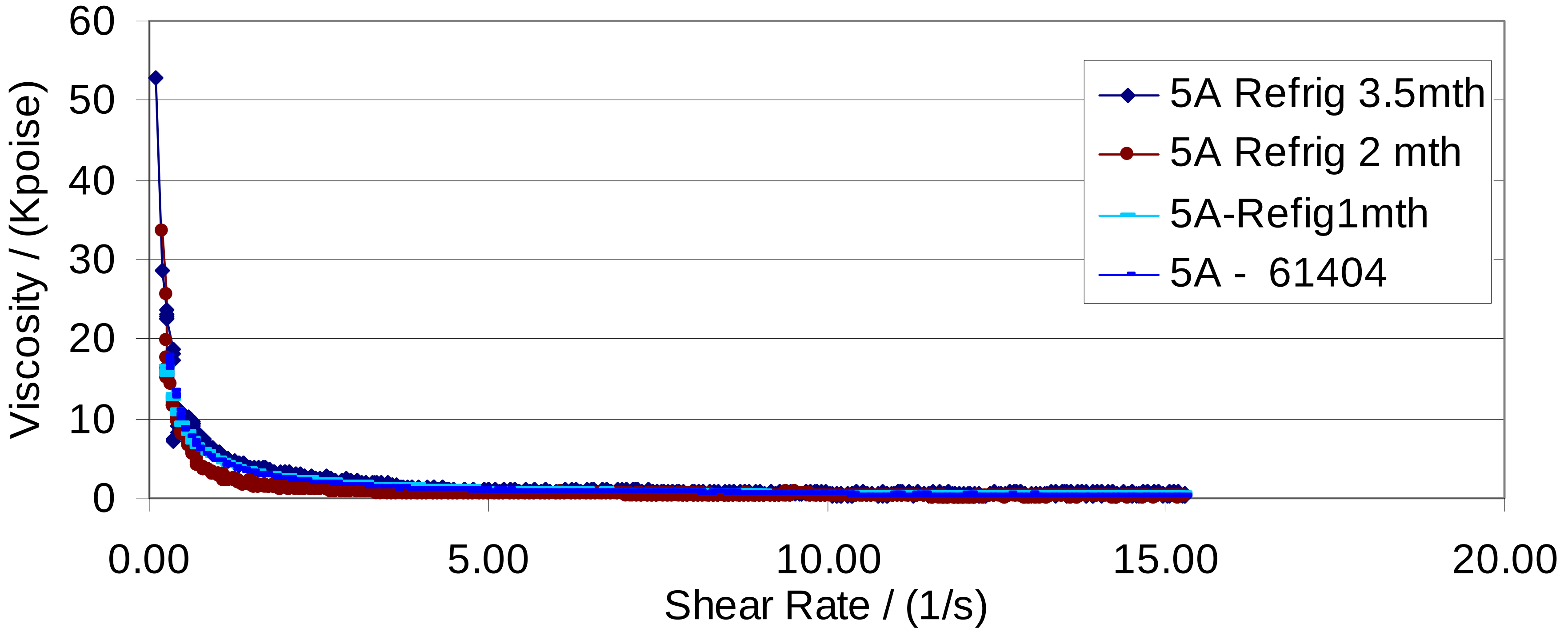
Effects of Storage Times & Temperatures

Materials	One Month		Two Months		>Three Months	
	0°C	-15°C	0°C	-15°C	0°C	-15°C
Graber-5	X	X	X	X	X	X
Graber-5A	X	X	X	X	X	X
Graber-12A	X	X	X	X	X	X

Storage Temperature Effects on GRABER 5A

Material Stored in a Refrigerator at 0 C

Materials stored for different times (1-3 months) had similar type of viscosity behavior as freshly prepared materials

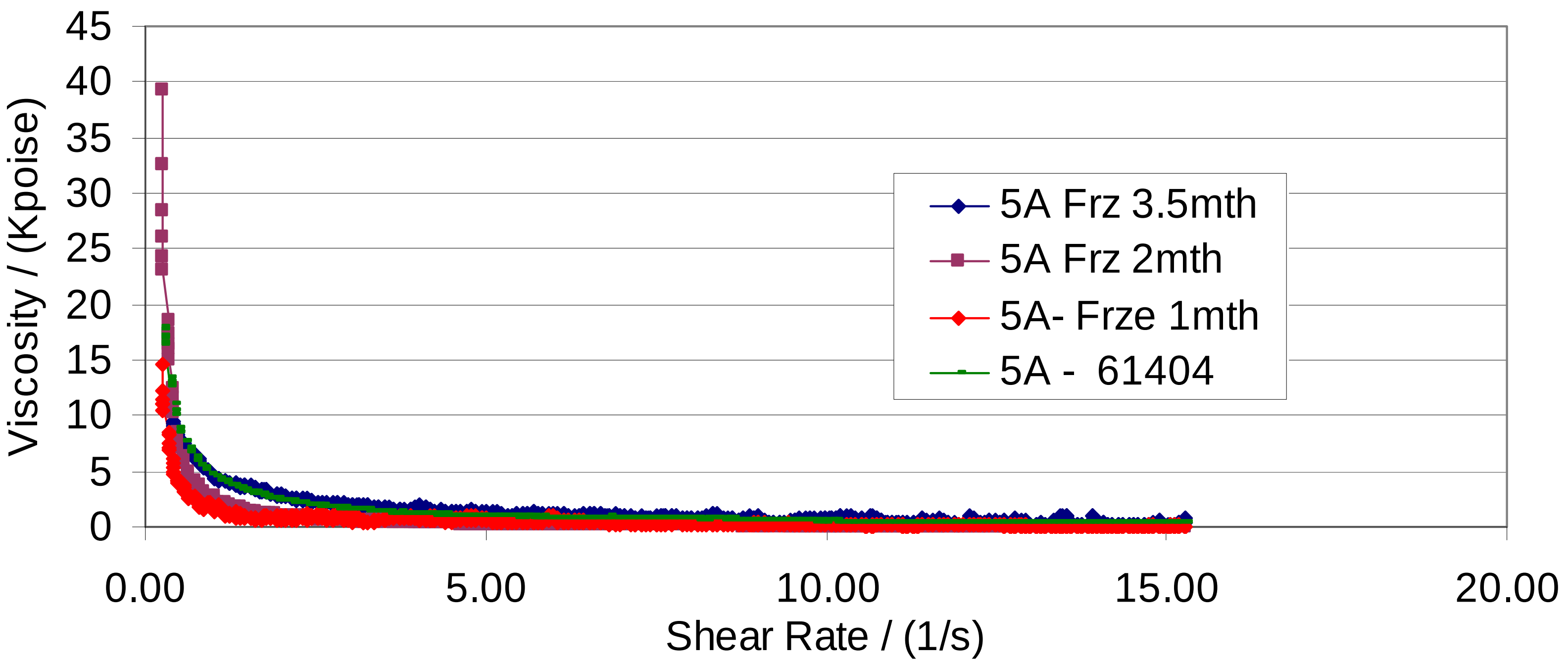


Material was Tested under Vacuum

Storage Effects on GRABER 5A

Material Stored in a Freezer at -15 C

Materials stored for different times (1-3 months) had similar type of viscosity behavior as freshly prepared materials



Material was Tested under Vacuum

Crack Repair, ArcJet Testing, and Post Test Characterization

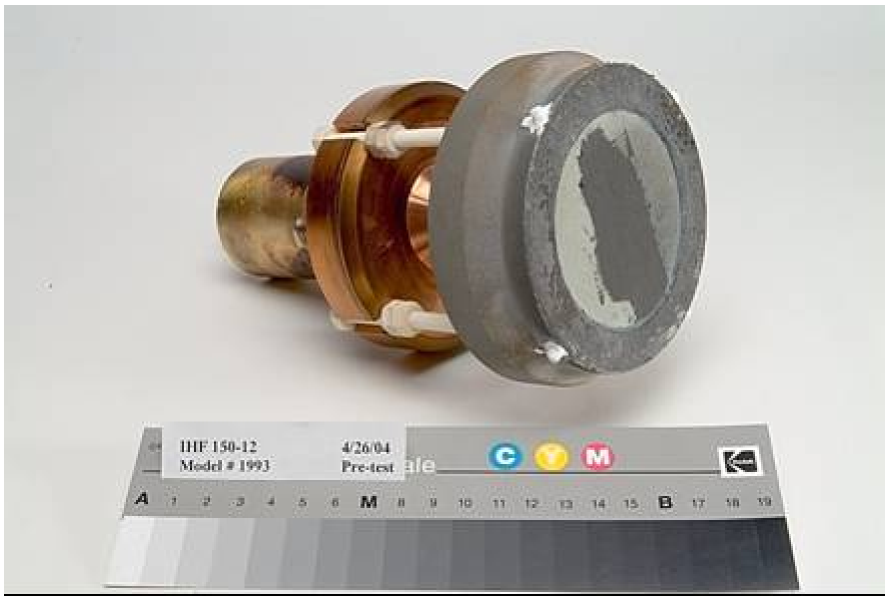
- **GRABER 5 (0.035” and 0.062” wide cracks-ARC)**
- **GRABER 5A (0.035” and 0.062”-ARC)**
- **GRABER 12A (0.035”-JSC and 0.035” and 0.062”-ARC)**

No failure through repaired cracks was observed during the ArcJet Tests

Pre-Test Photographs of Repaired Specimens

Run 12 – Model 1993

(0.035”or ~0.89 mm wide crack, GRABER-5A)

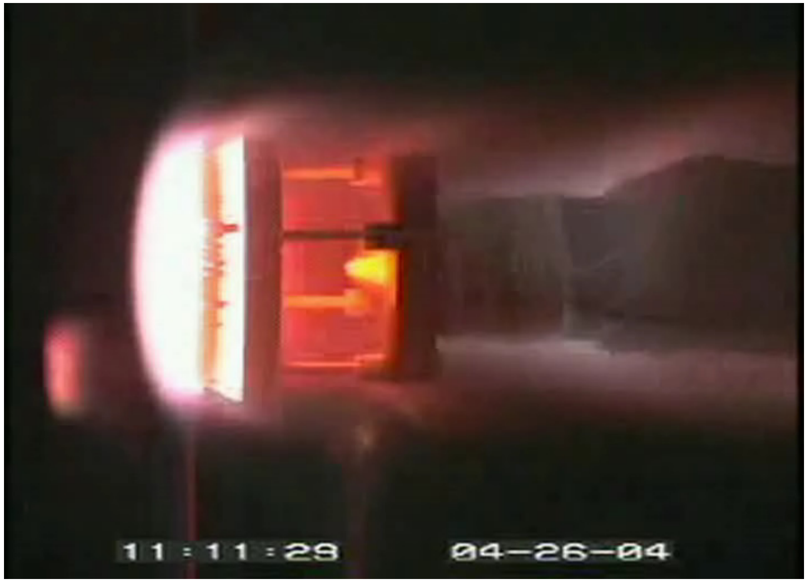


Percent Argon = 6% @ 2960F condition
Add air = 11.6% @ 2960F condition
Anomaly: water leak from electrode, which allowed water vapor in the stream

ArcJet Testing of Repaired Specimens

Run 12 – Model 1993
(0.035”or ~0.89 mm wide crack, GRABER-5A)

Front View



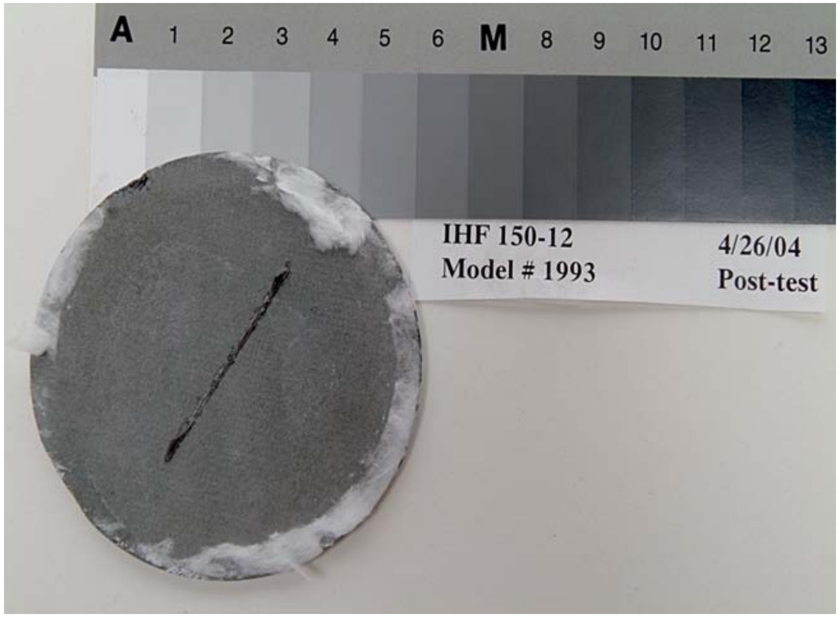
Side View

Percent Argon = 6% @ 2960F condition
Add air = 11.6% @ 2960F condition
Anomaly: water leak from electrode, which allowed water vapor in the stream

ArcJet Testing of Repaired Specimens

Run 12 – Model 1993

(0.035”or ~0.89 mm wide crack, GRABER-5A)



Post Test- Front Side

Post Test- Back Side

ArcJet Testing of Repaired Specimens

Run 17 – Model RCC 1

(0.062”or ~1.6 mm wide crack, GRABER-5A)

Percent Argon = 6% @ 2960F condition
Add air = 11.6% @ 2960F condition
Anamoly: Edge failure, sample removed after ~130 seconds @ 2960F condition

ArcJet Testing of Repaired Specimen

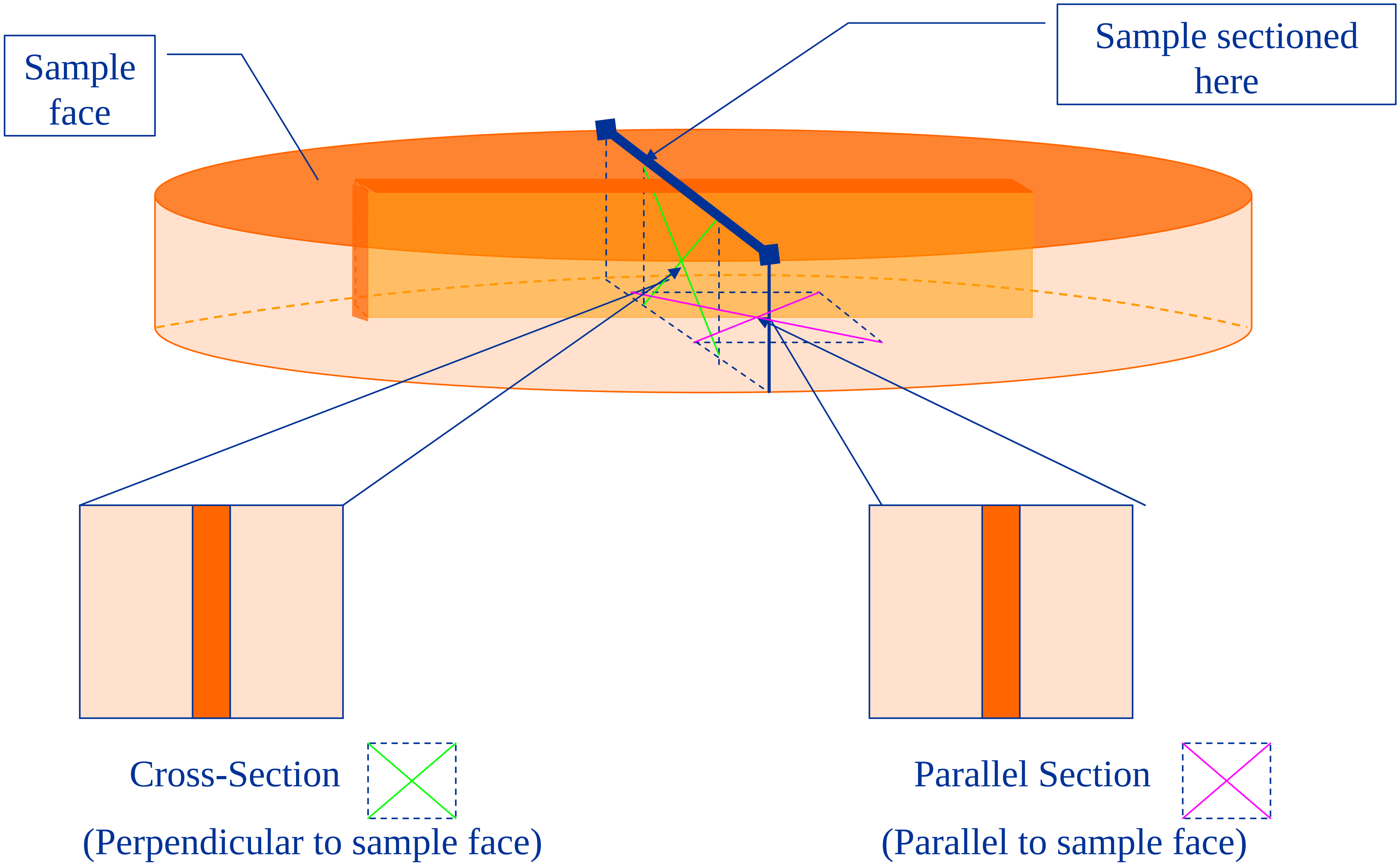
Run 17 – Model RCC 1
(0.062”or ~1.6 mm wide crack, GRABER-5A)

Front View

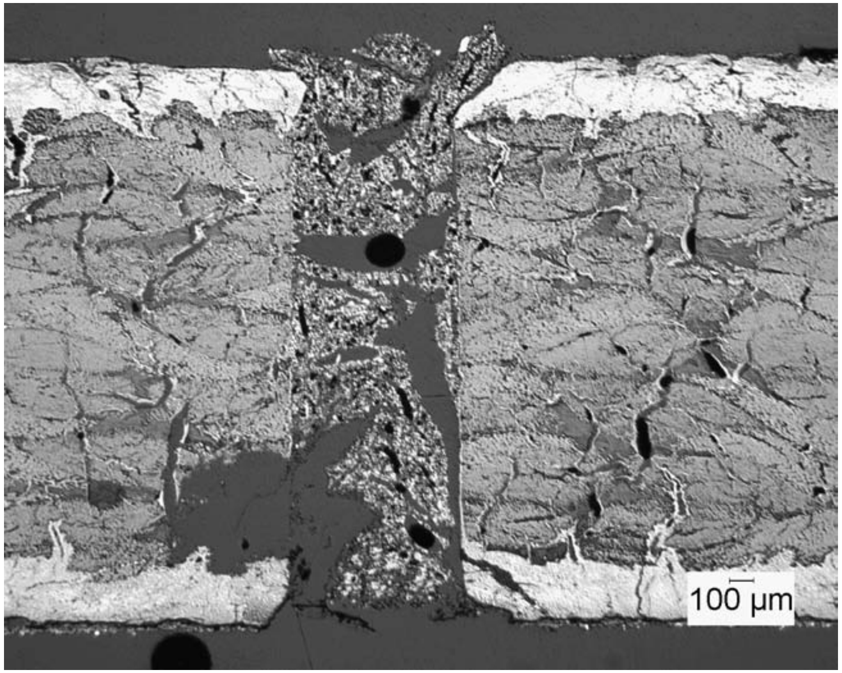
Percent Argon = 6% @ 2960F condition
Add air = 11.6% @ 2960F condition
Anamoly: Edge failure, sample removed after ~130 seconds @ 2960F condition

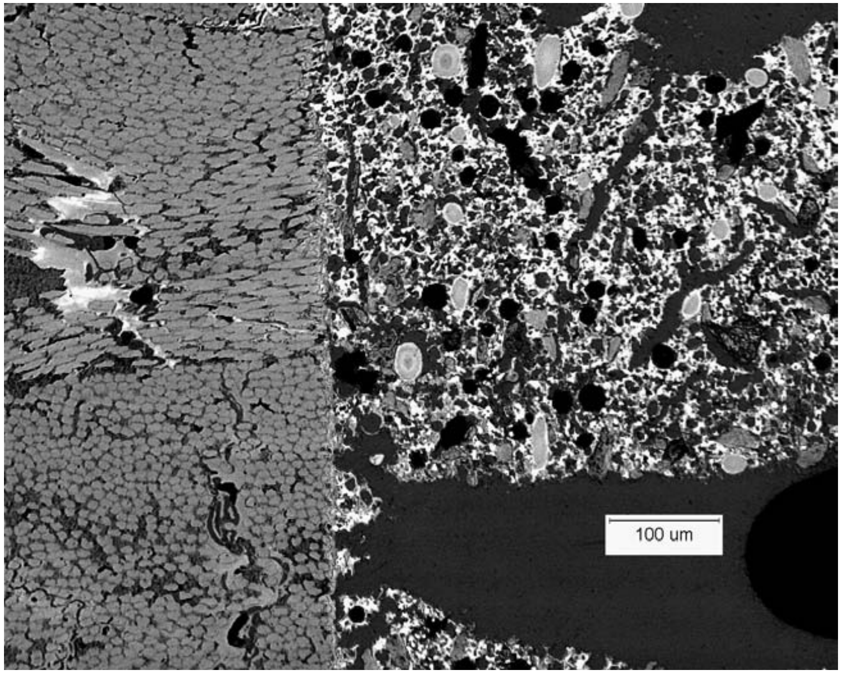
Microstructural Characterization of ArcJet Tested Specimens

Arcjet Sample Description and Preparation



ArcJet Sample 1993 (150-12), Graber 5A, 0.035" Crack Width

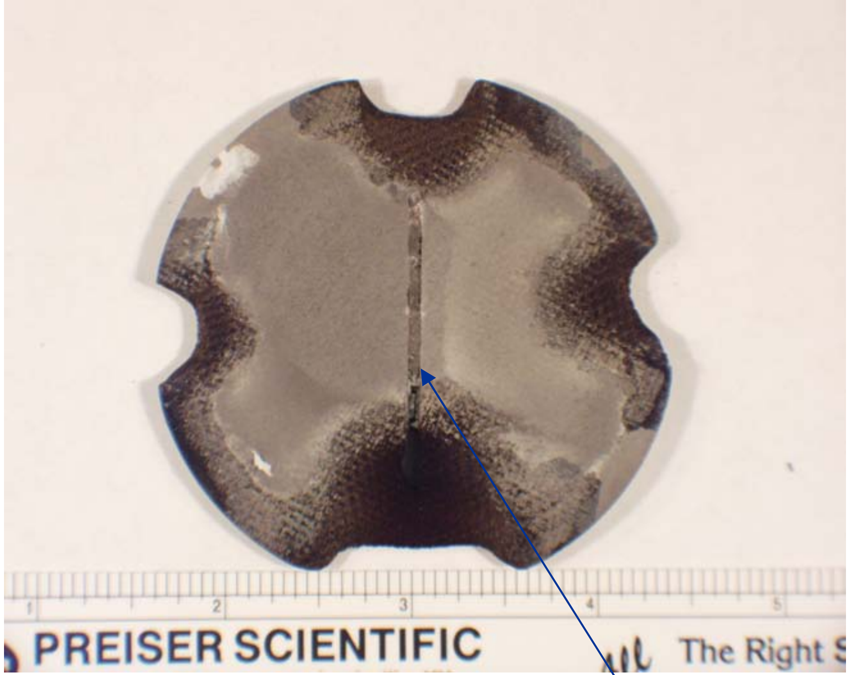




Front Side

There are a few large voids where oxidation has taken place. The Graber material appears fairly well adhered to the C/C material even after testing.

ArcJet Sample 150-11, RCC-1,GRABER 5A, 0.062" Crack Width

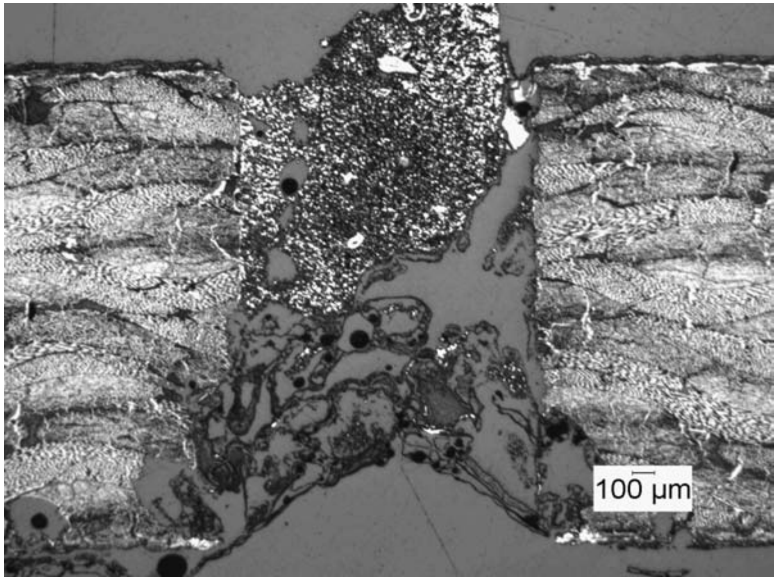


Back side

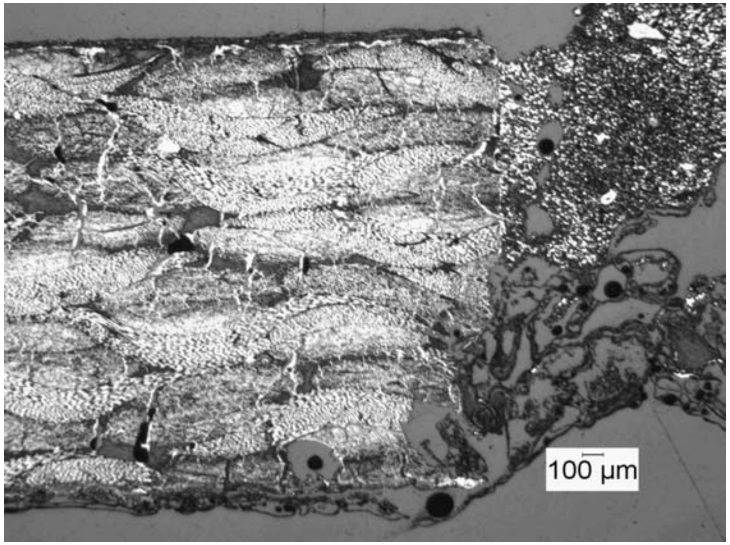
Front side

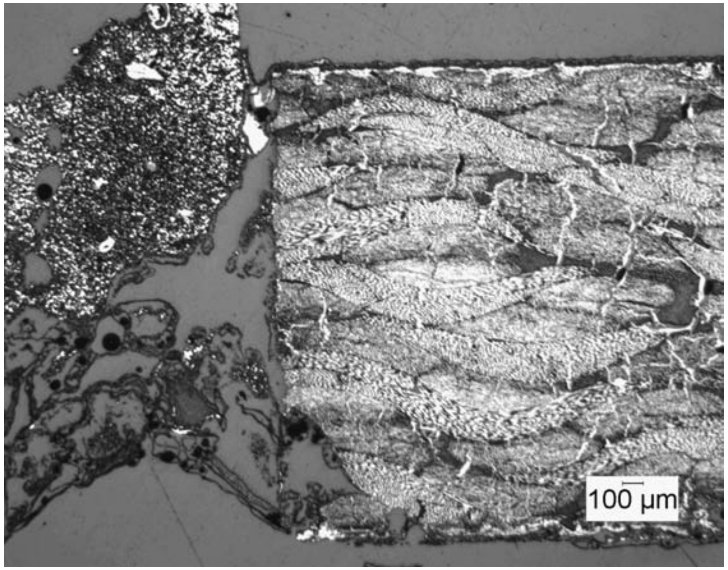
Crack filled with Graber material

ArcJet Sample 150-11, RCC-1,GRABER 5A, 0.062” Crack Width



Front Side





It appears in this sample that oxidation has reached an advanced stage. There is only a skeleton left of the Graber material which appears to be a glassy phase.

Potential Applications of GRABER Based Materials

- Joining and Assembly of C/C Composites
- Repair of C/C Based Composites
- Functionally Graded Coatings for C/C Composites
- Crack Repair System for CMCs
    - Repair of cracks and damaged coatings
    - Bonding and sealing of the edges
    - Repair of large size damage
- Joining of CMCs
- Manufacturing of Bulk CMCs

Integrated System for Large Area Tile and RCC Repair

Flexible Ceramic Wraps, *Gaskets/sealants*

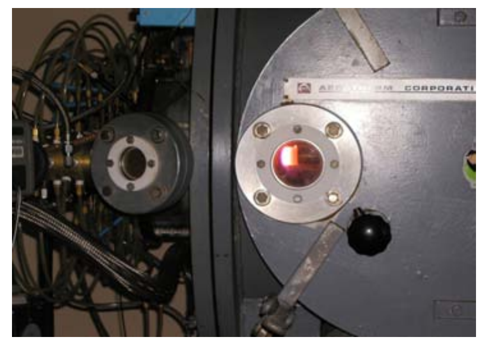
Integrated System for Leading Edge and Tile Repair (InSTALER)

Flexible Ceramic Overwrap

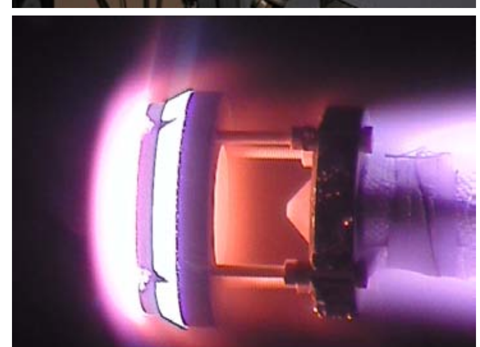
DEVELOPMENT

TESTING

QARE Rig Testing (GRC)

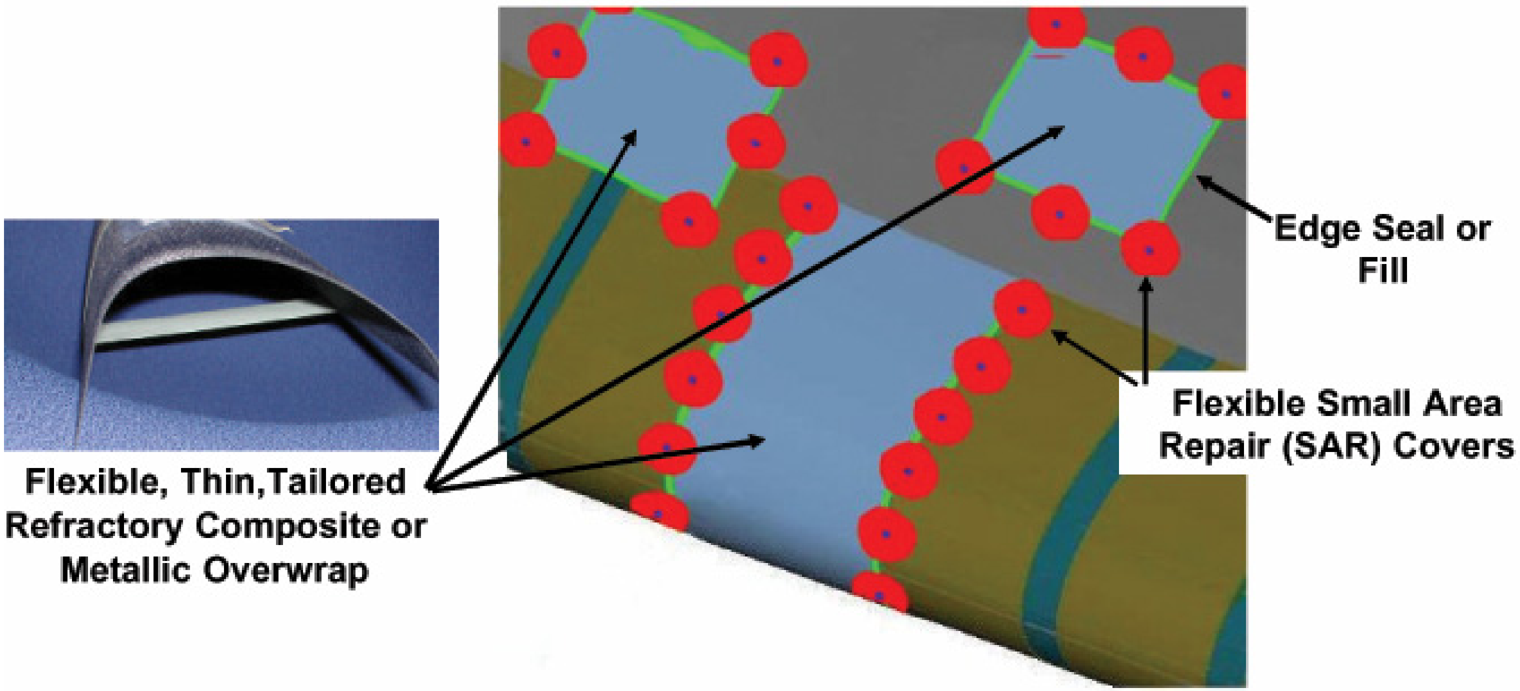


HYMETS (LaRC)



ArcJet Testing at JSC, ARC, and LCAT

Large Area RCC Leading Edge and Tile Repair



Drill/Tap Tools

Fasteners

Gaskets

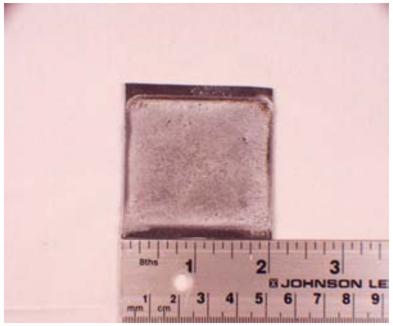
SAR Patch

Post Test Observation of Tile Area Repair (TAR) Flexible Cover Materials

Typical Quick Access Rocket Exposure (QARE) Post Test Specimens

Material survived without any signs of burn through. But sample had large pores and bubbles.

TRS4G7 with Silica Fiber



Sample has smooth surface (no pores or signs of off gassing). No signs of burn through.

GRC-2 with SiC Fiber

HYMETS Post Test Specimens

Tile Test Profile
900 Sec.
Mass loss ~ 19%

GRC-2 (SiC Fiber)

Tile Test Profile
900 Sec.
Mass loss ~ 17%

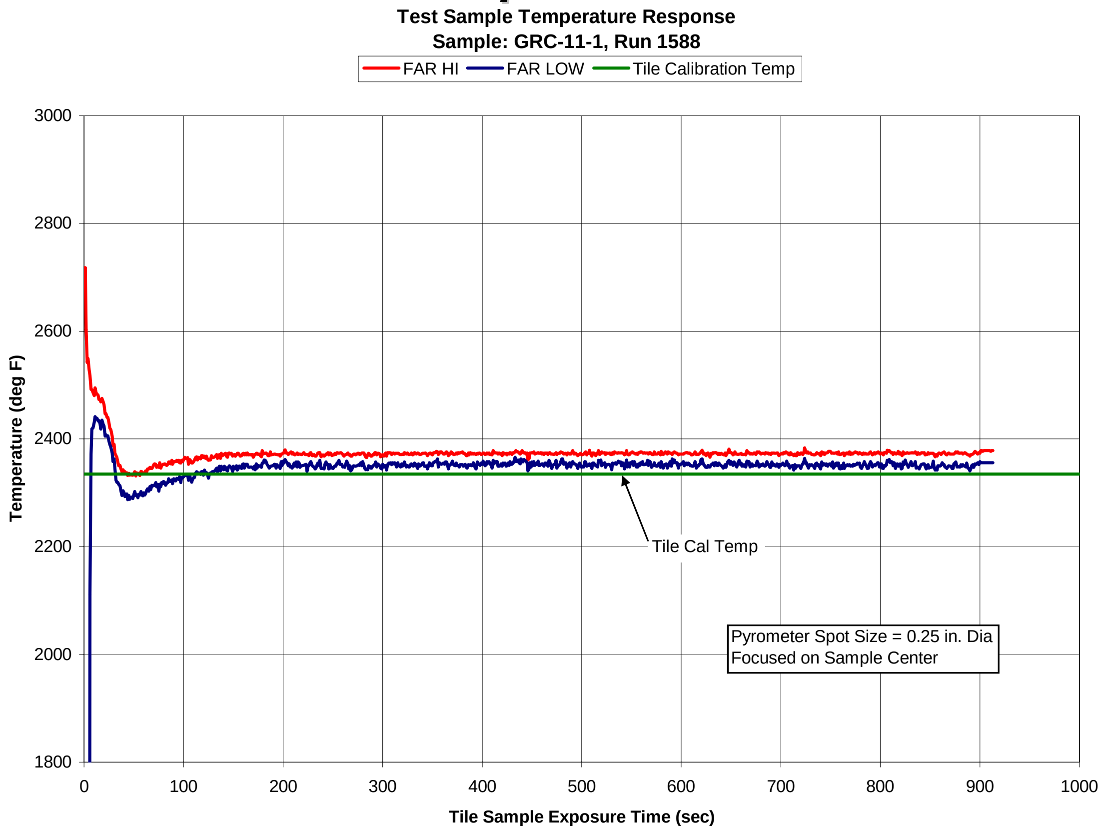
GRC-9 (SiC Fiber)

Integrated System for Leading Edge and Tile Repair (InSTALER)

Flexible Ceramic Overwrap

Pre-Test

Post Test



Excellent Plasma Performance in ArcJet Tests

Summary and Conclusions

- **GRABER-based materials have multiuse capability and multifunctionality for a wide variety of repair applications. These systems have shown excellent plasma performance.**
- **This system can be easily modified to obtain adhesive materials with desired properties (viscosity, composition, curing behavior, etc.).**
- **These materials have long shelf life and normal handling and storage techniques can be used. In addition, these materials are affordable since the cost of raw constituents is very low (few dollars a pound)**
- **Flexible ceramic overwraps have shown excellent plasma performance in ArcJet testing conditions.**

Acknowledgments

- **Glenn Research Center, Cleveland, OH**
  - Tarah Shpargel, Ron Phillips, Ray Babuder, Craig Robinson
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- **Marshall Space Flight Center, Huntsville, AL**
  - Mike Effinger, Mike Terry
- **Langley Research Center, Hampton, VA**
  - Steve Scotti, Wally Vaughn
- **Ames Research Center, CA**
  - Frank Hui, George Raiche, and ArcJet Test Facility Staff
- **Boeing LCAT Staff**