Invited Talk at the World Ceramics Congress (CIMTEC 2006)

In-Space Repair of Reinforced Carbon-Carbon Thermal Protection System Structures

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Advanced repair and refurbishment technologies are critically needed for the thermal protection system of current space transportation system as well as for future Crew Exploration Vehicles (CEV). The damage to these components could be caused by impact during ground handling or due to falling of ice or other objects during launch. In addition, in-orbit damage includes 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 adhesive delivery system. The adhesive paste cures at 100-120°C and transforms into a high temperature ceramic during simulated entry 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 system for tile and leading edge repair (InSTALER) have been developed. In this presentation, critical in-space repair needs and technical challenges as well as various issues and complexities will be discussed along with the plasma performance and post test characterization of repaired RCC materials.

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Outline

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

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

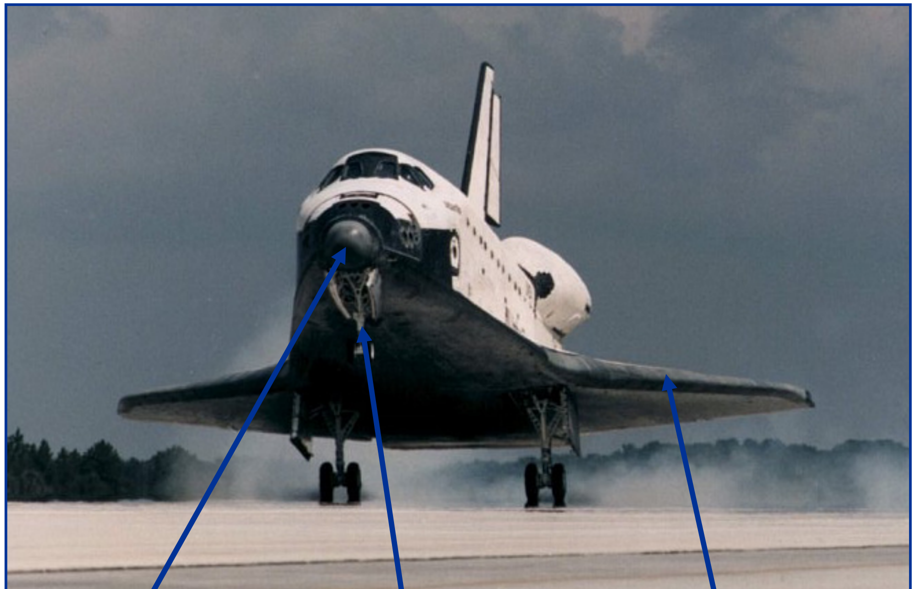
On-Orbit MMOD Damage

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

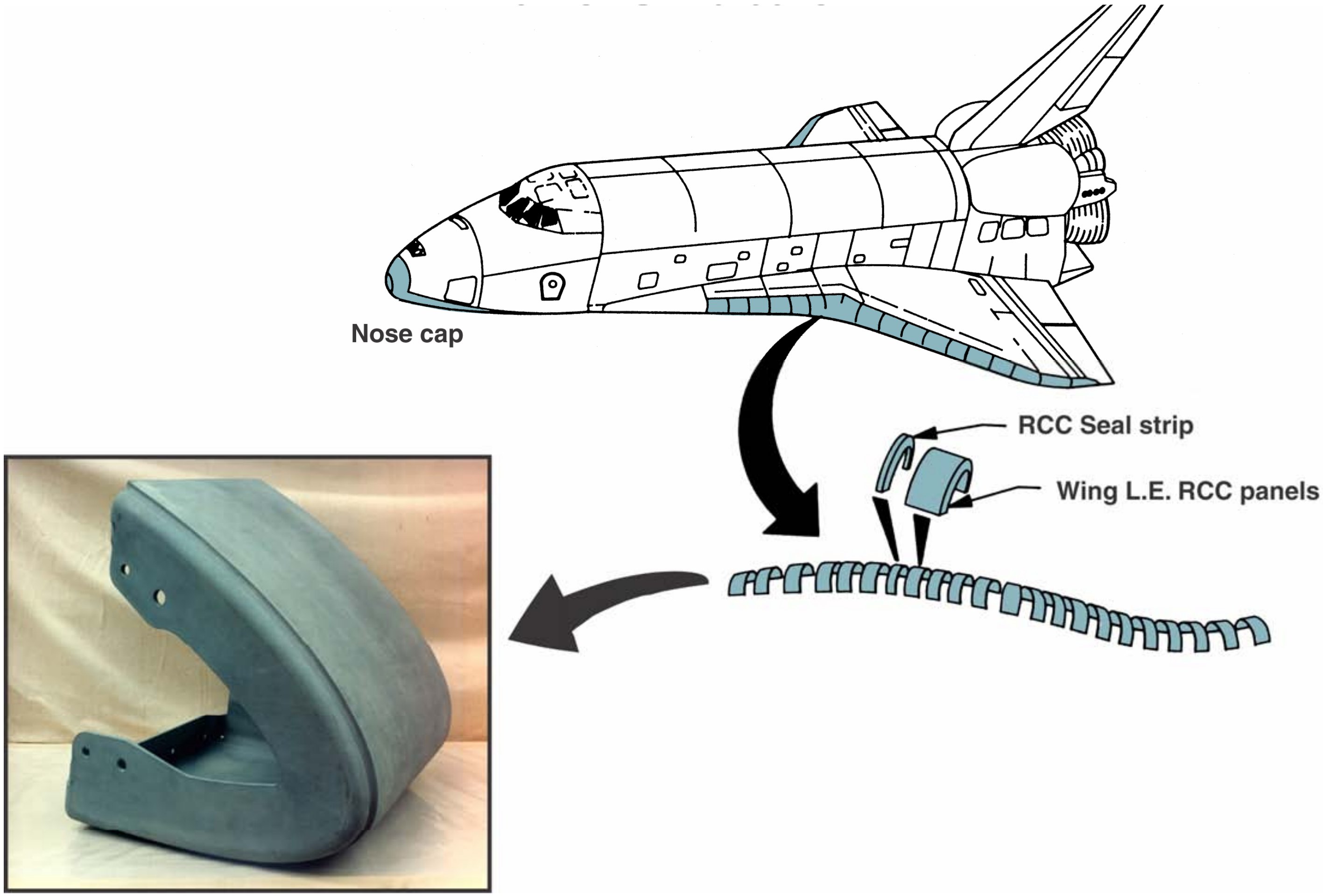


Nose Cap, Chin Panel, and Seals

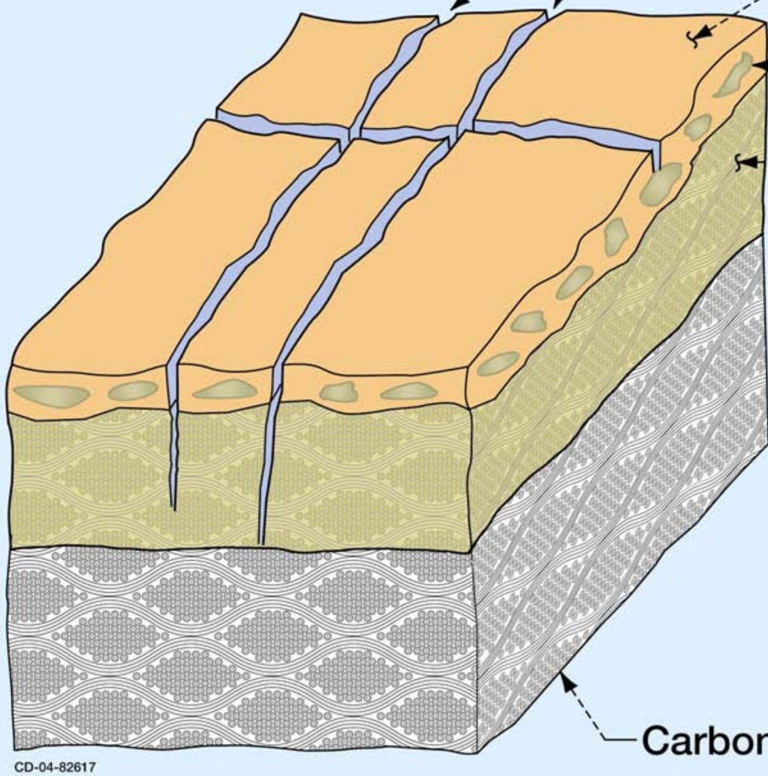
Forward External Tank Attachment "Arrowhead" Plate

Wing Leading Edge Panels and Seals

Leading Edge RCC Panels and T-Seals



Reinforced Carbon-Carbon (RCC) Composite

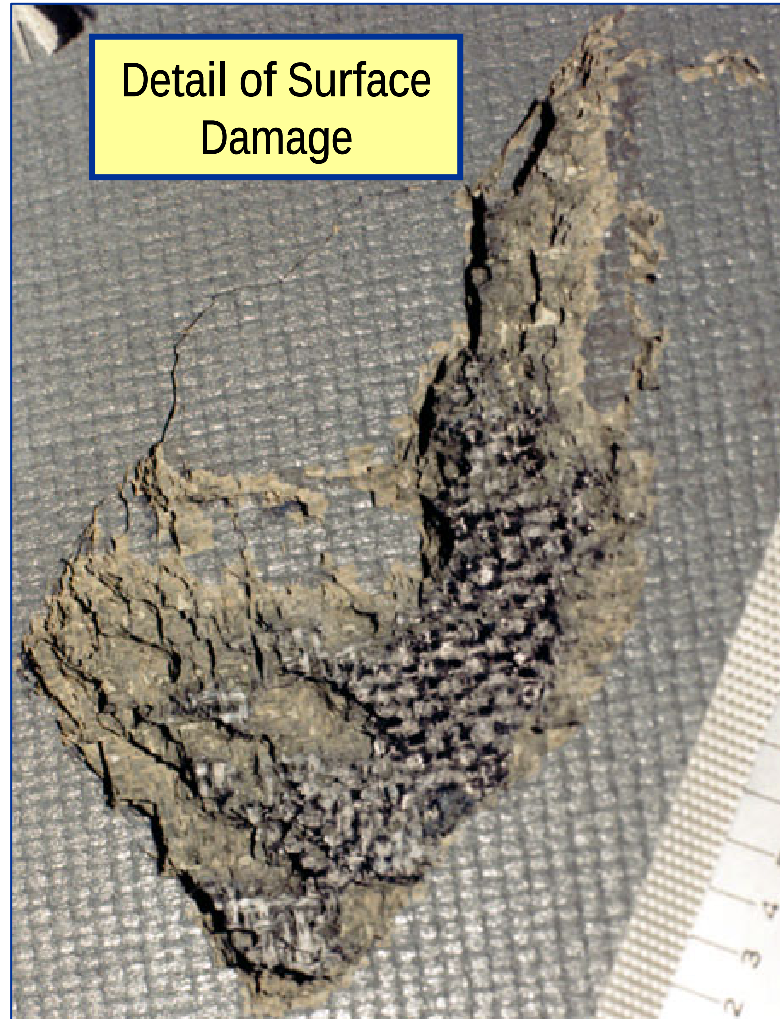


Dr. Nathan Jacobson, NASA GRC

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

Dr. Nathan Jacobson, NASA GRC

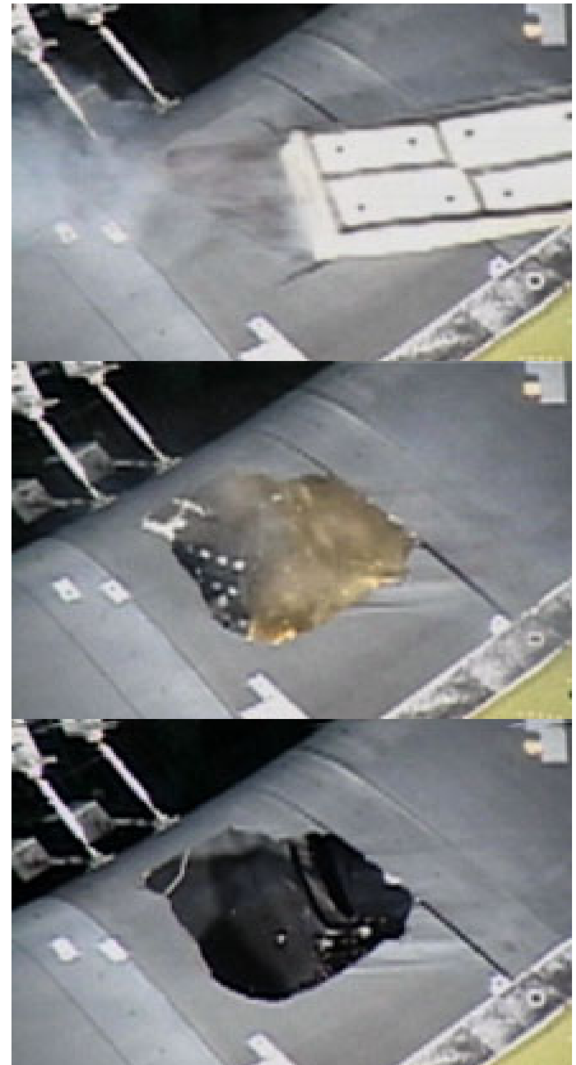
STS-45 Impact Damage on Atlantis WLE Panel 10R



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

Performing Repair in Space Environment

Technical and Operational Challenges

- **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

Nancy Patrick, JSC

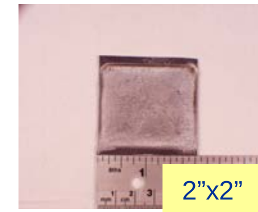
Space Shuttle Re-entry Conditions are Quite Harsh and Extreme

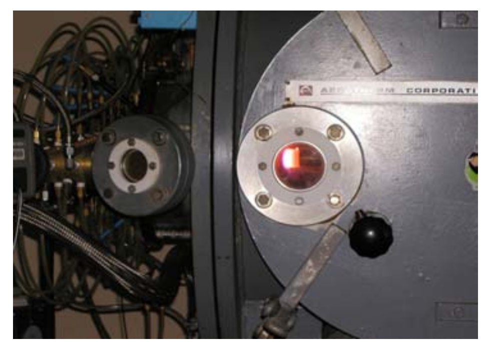
- Temperature to 2000 K
- Reduced pressure--0.005 to 0.010 atm
- Gases--O_2, N_2, CO_2
  - Shock leads to O, N and ions
- Short times ~15 minutes/re-entry
- Best simulated with arc-jet

Typical High Temperature Testing Steps for Evaluation of Repair Materials

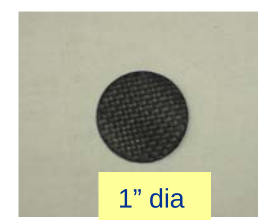
Simulated Testing in High Temperature Furnace (1650 C)

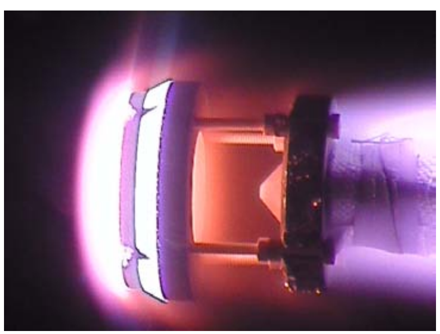
QARE Rig Testing (GRC)





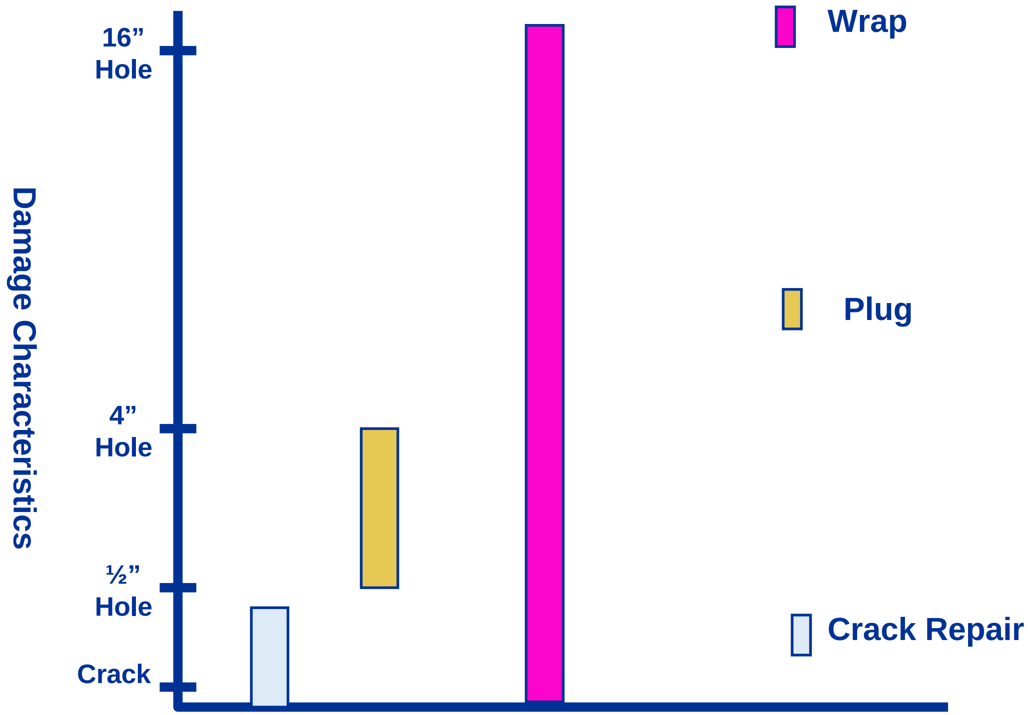
HYMETS (LaRC)

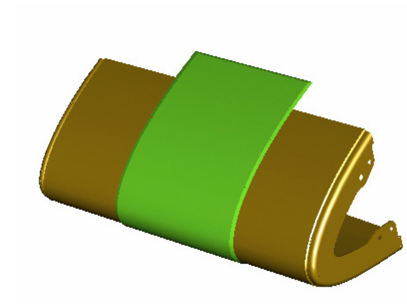




ArcJet Testing at ARC and LCAT

Repair Concepts for Wing Leading Edge Damage





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.

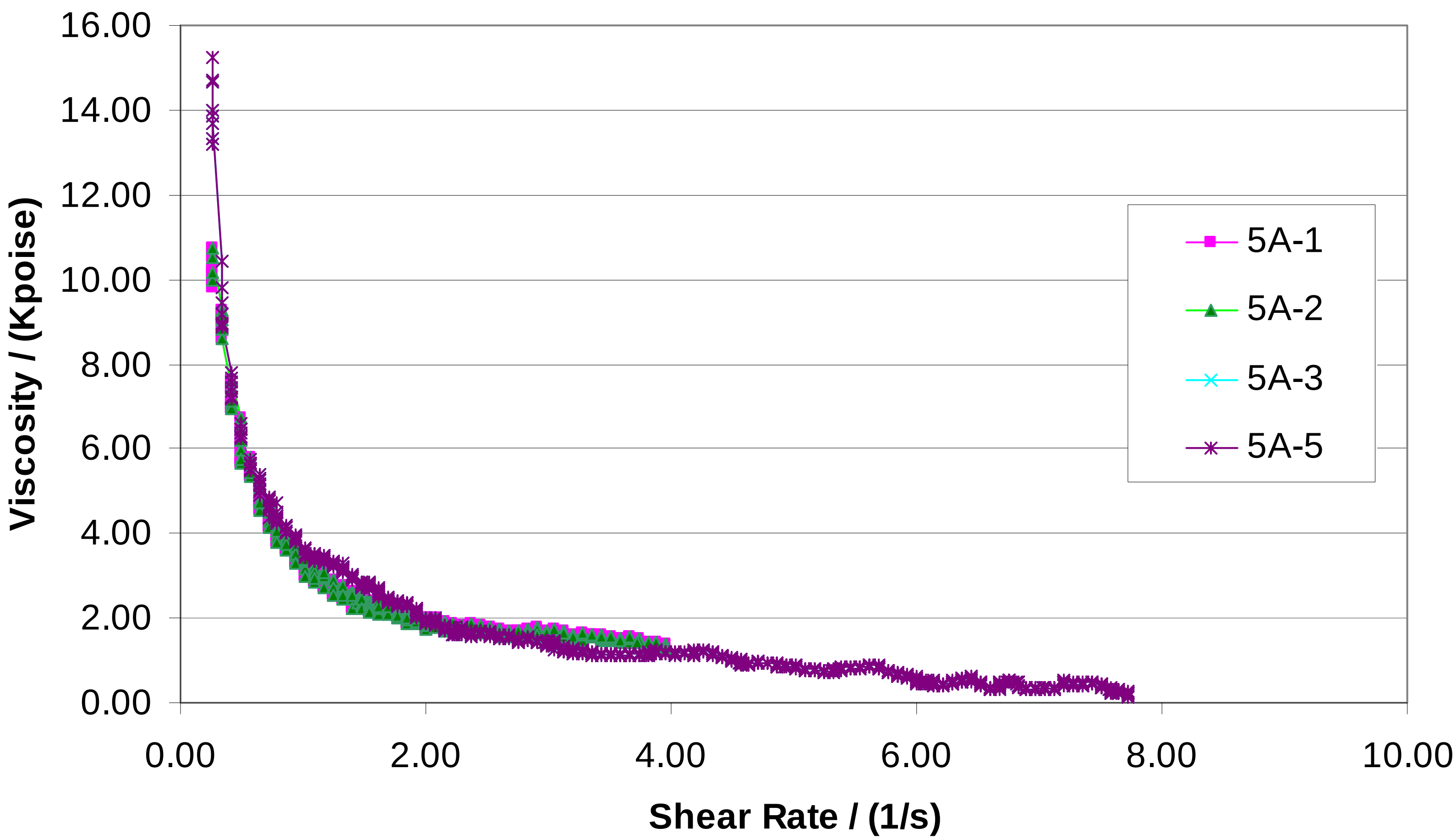
Reproducibility, Storage, and Shelf Life Characterization

Brookfield PVS Rheometer Used for the Viscosity Measurements

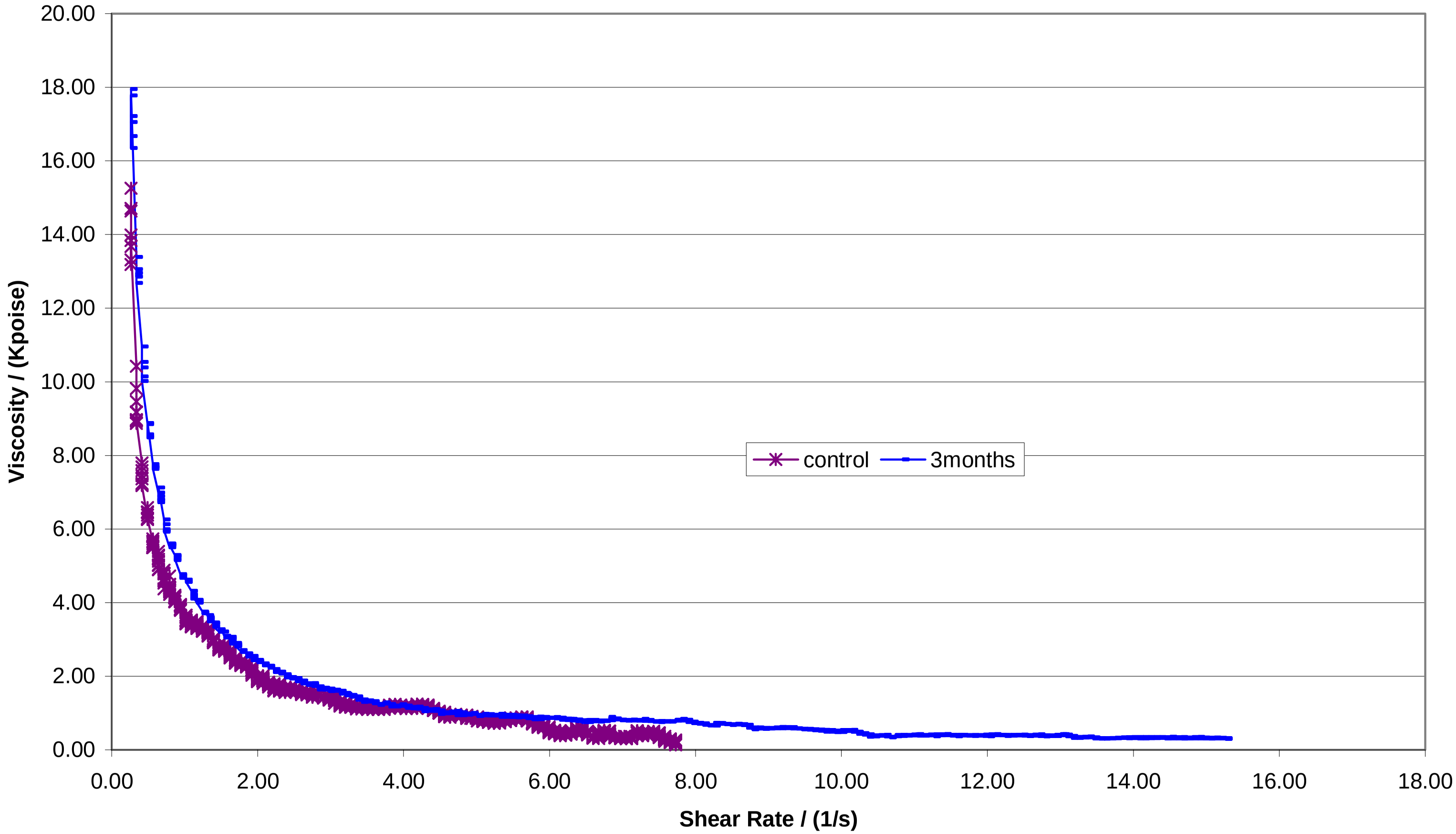
The temperature control bath has capability from – 20 C (- 4 F) to 180 C (356 F)

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

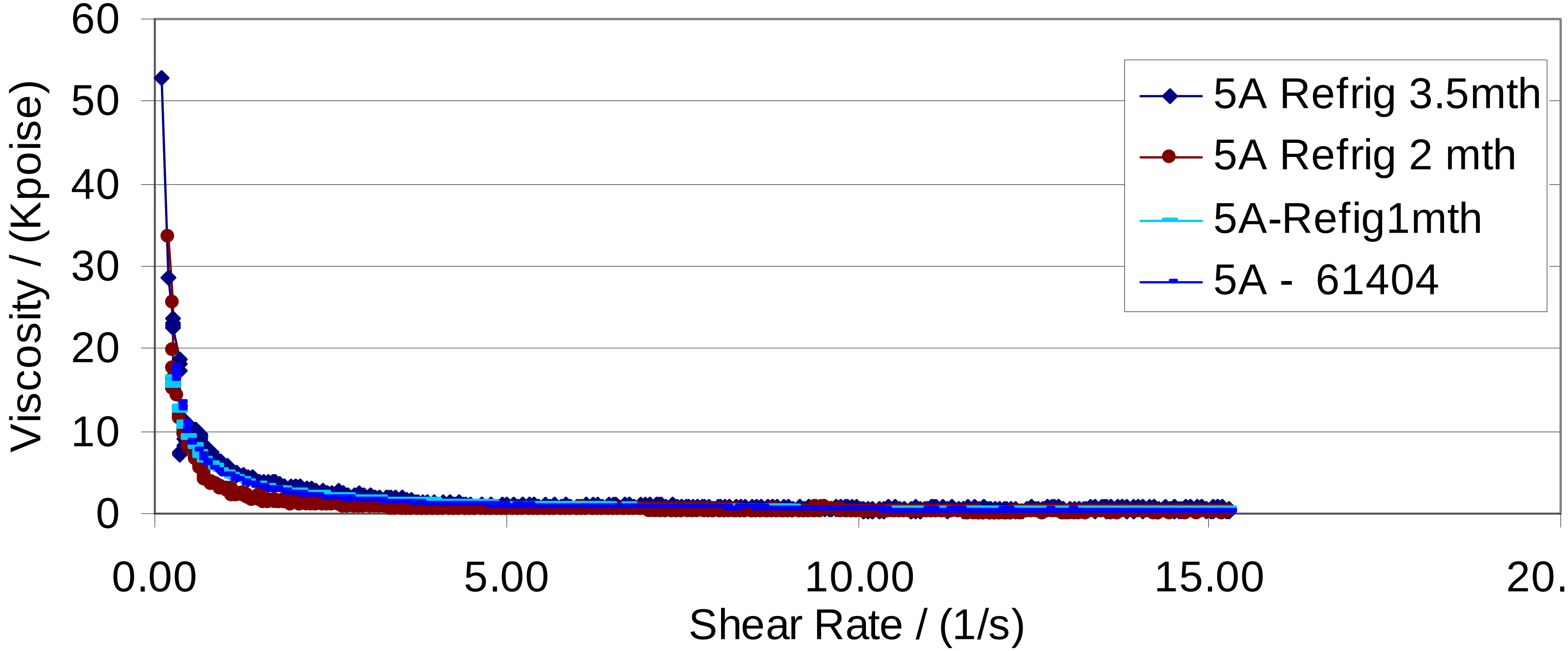
Effects of Storage Times & Temperatures

	One Month		Two Months		>Three Months	
Materials	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

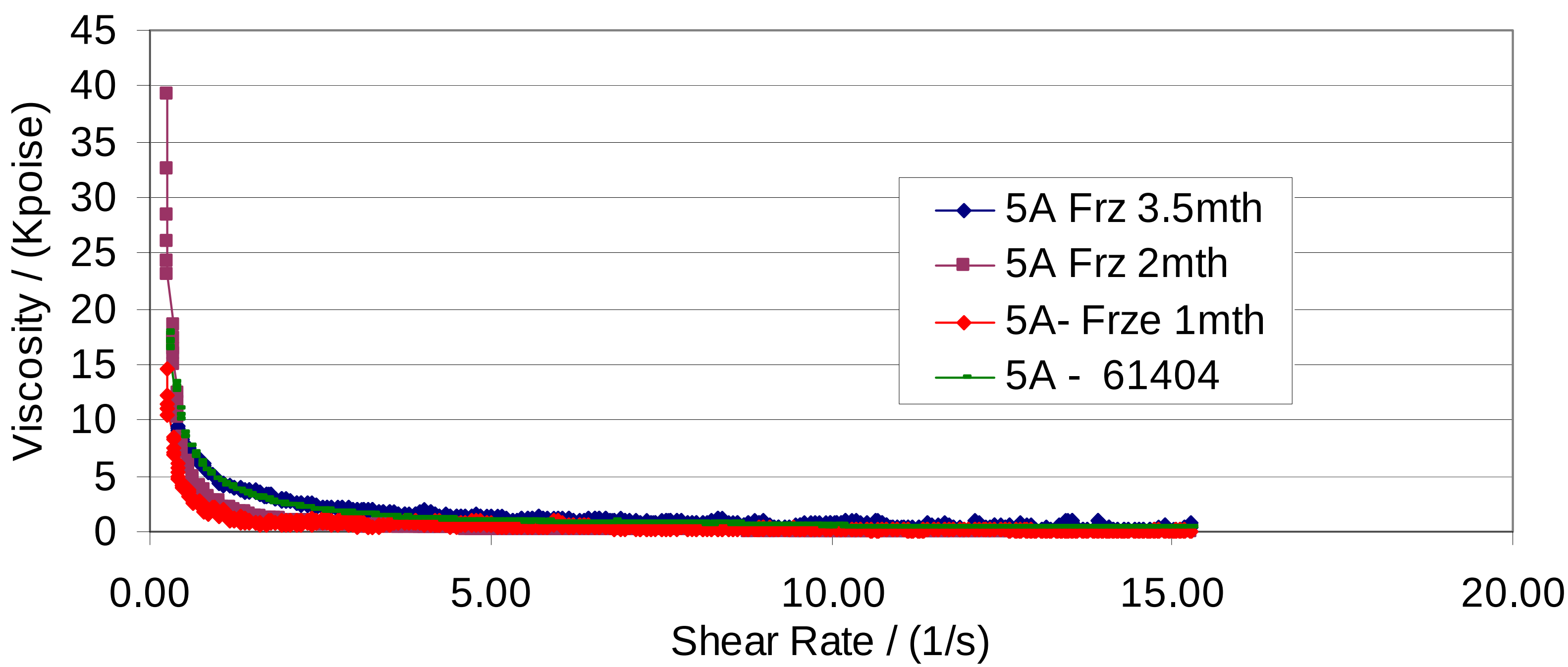


Material was Tested under Vacuum

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

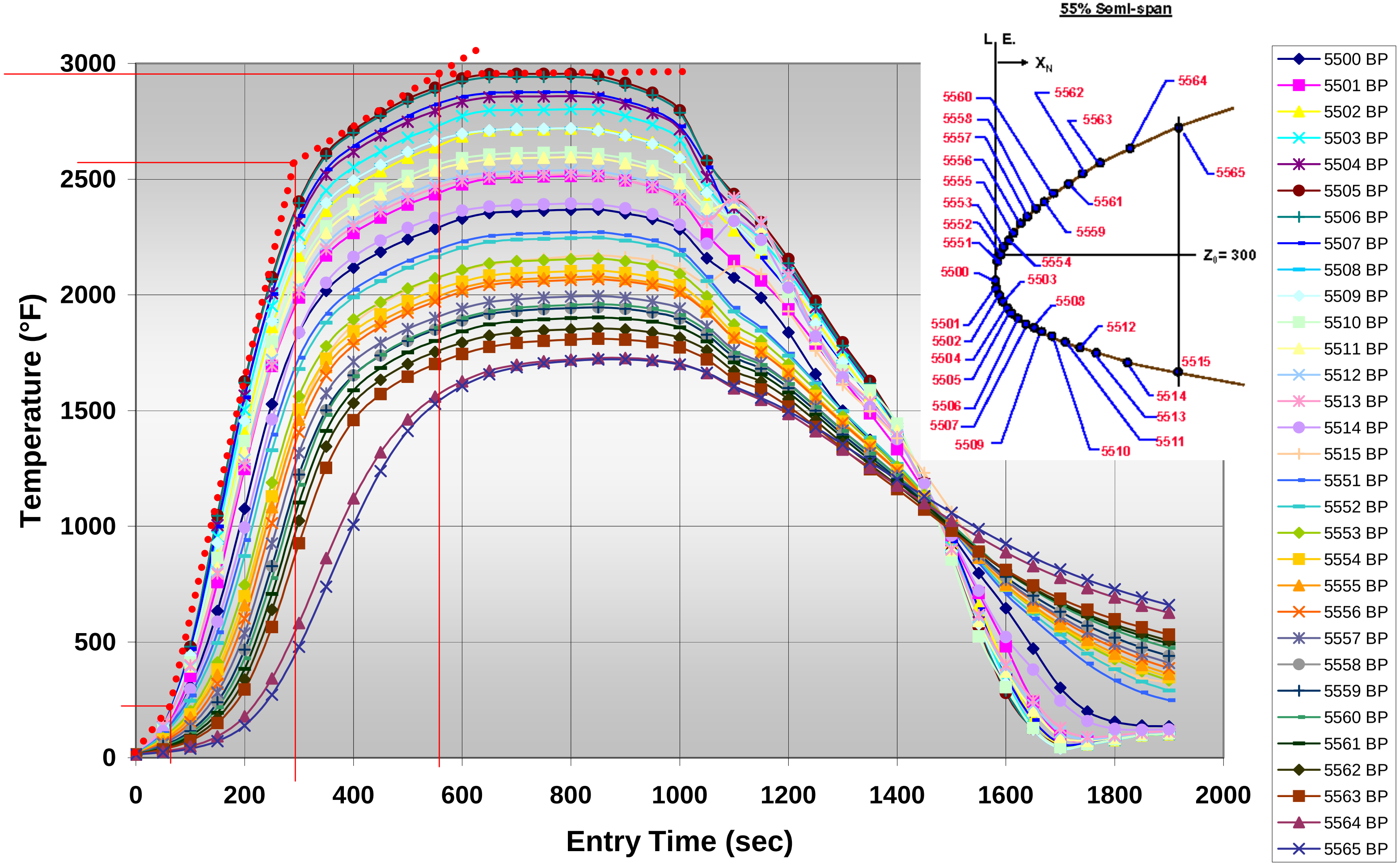
Crack Repair, ArcJet Testing, and Post Test Characterization

- 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)

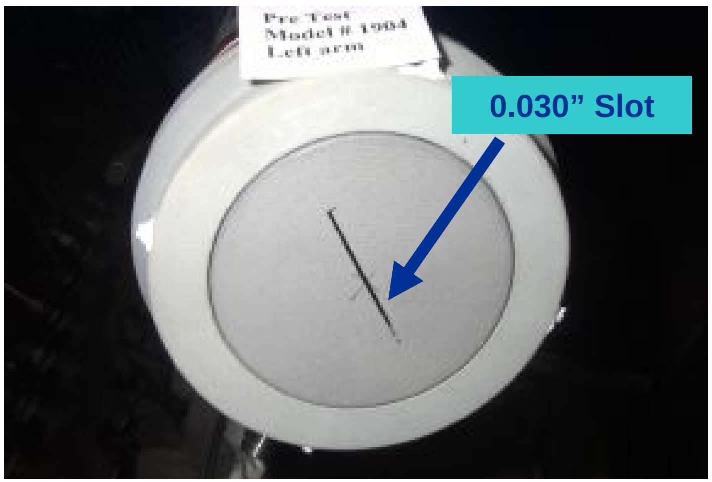
No failure through repaired cracks was observed during the ArcJet Tests

WLE Entry Temperature Profiles

Panel 9 (55% Span) Temperature Profile for Nom ISS EOM



Arcjet Tests of Damaged RCC Without Any Repair Material



Front-side Pre-Test View of 0.030” Dia. Slot

Front-side Post-Test View of 0.030” Dia. Slot

Pre-Test Photographs of Repaired Specimens

Run 12 – Model 1993

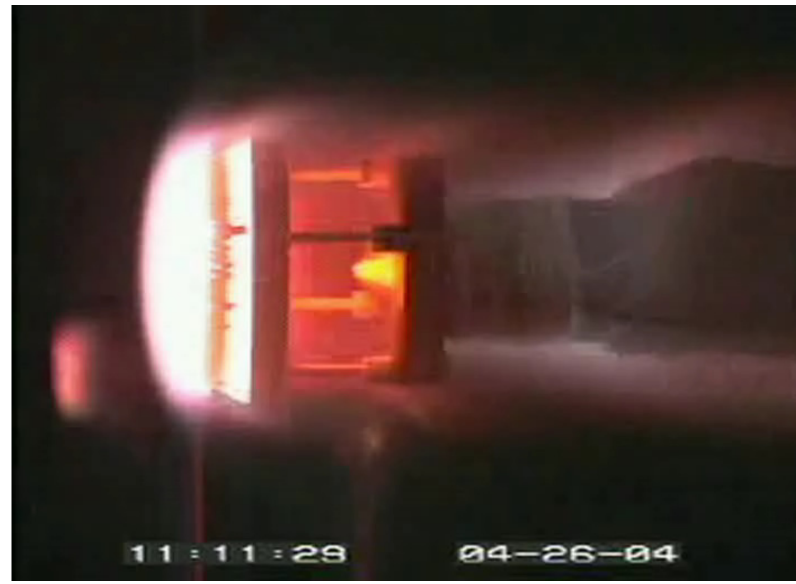
(0.035”or ~0.89 mm wide crack, GRABER-5A)

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

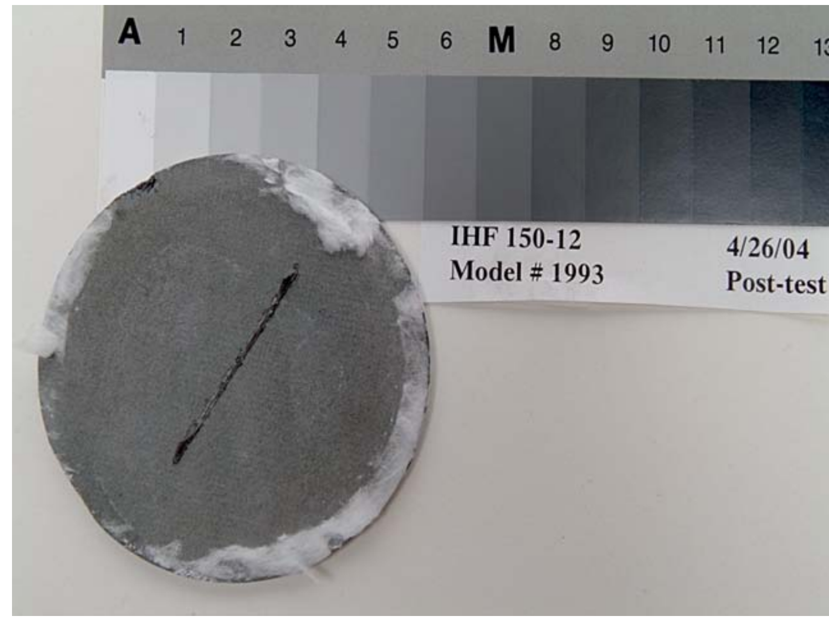
Percent Argon = 6% @ 2960F condition
Add air = 11.6% @ 2960F condition
Anomaly: water leak from electrode, which allowed water vapor in the stream

ArcJet Testing of Repaired Specimens

Run 12 – Model 1993

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

Post Test- Front Side



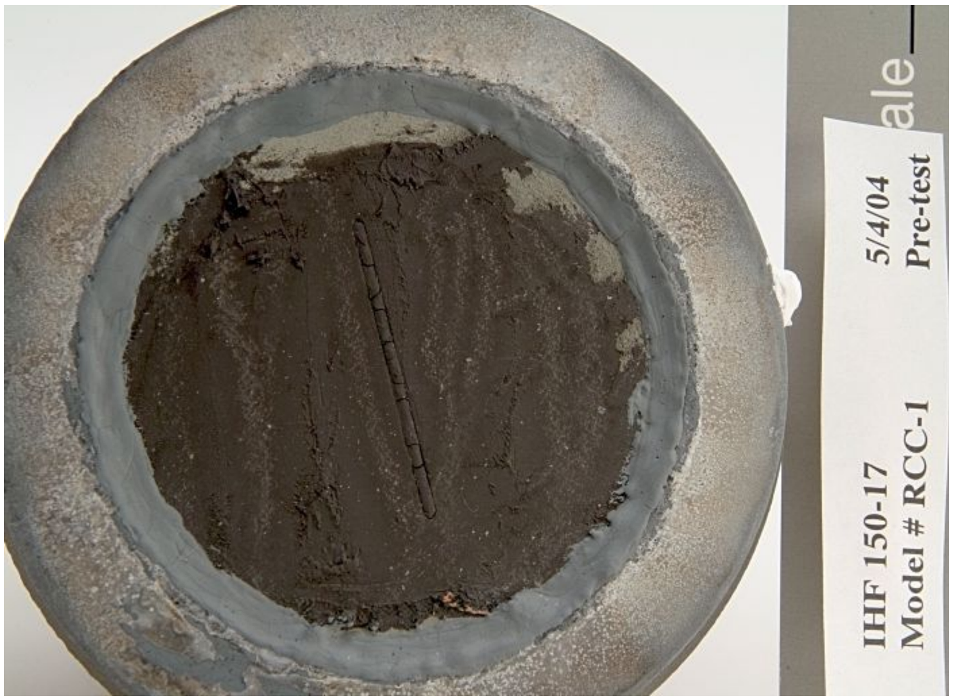
Post Test- Back Side

ArcJet Testing of Repaired Specimens

Run 14 – Model RCC 8
(0.062”or ~1.58 mm wide crack, GRABER-12A)

Percent Argon = 6% @ 2960F condition
Add air = 11.6% @ 2960F condition
Temperatures on model face were higher than previous runs (~3100F)

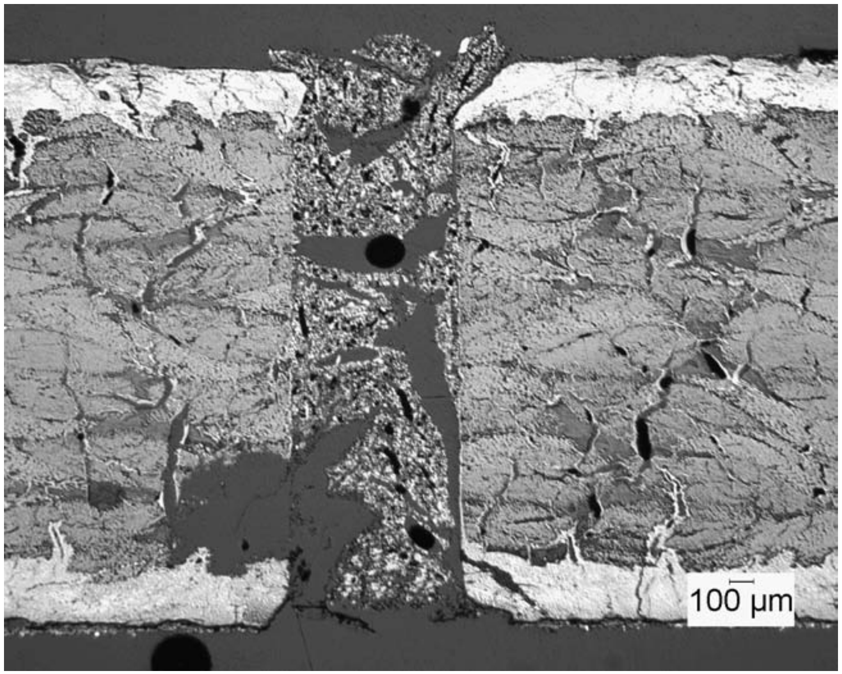
ArcJet Testing of Repaired Specimens
Run 17 – Model RCC 1
(0.062”or ~1.6 mm wide crack, GRABER-5A)

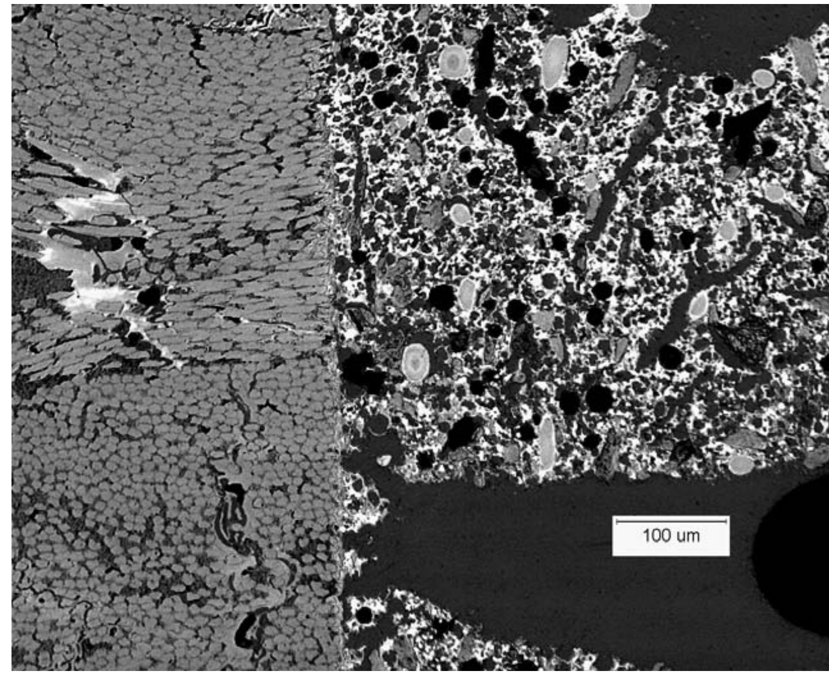


Percent Argon = 6% @ 2960F condition
Add air = 11.6% @ 2960F condition
Anamoly: Edge failure, sample removed after ~130 seconds @ 2960F condition

Microstructural Characterization of ArcJet Tested Specimens

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

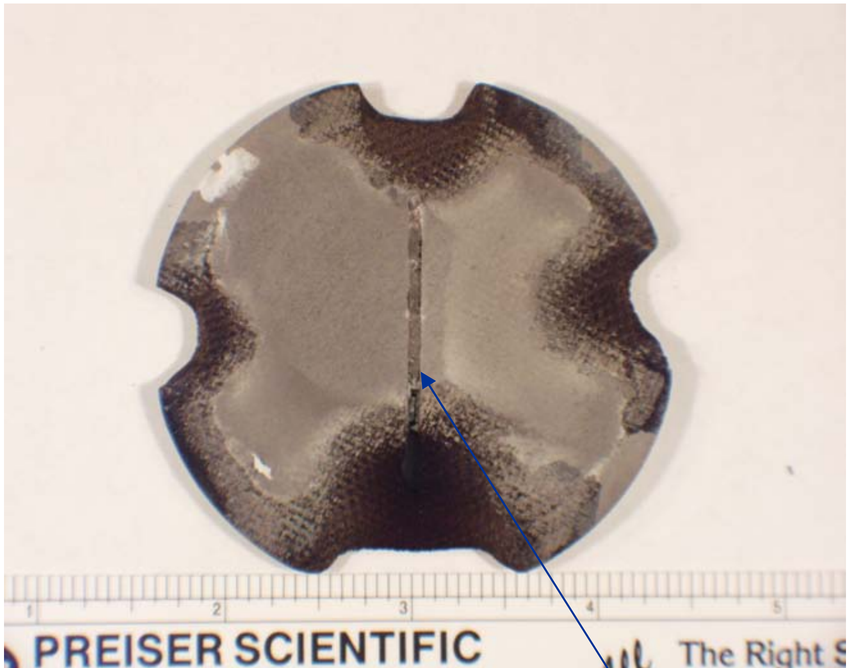




Front Side

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 5, 0.062" Crack Width

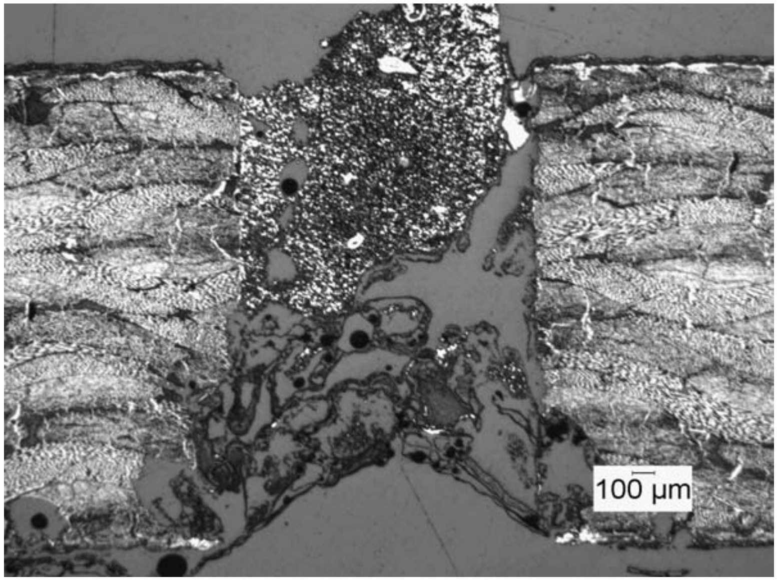


Back side

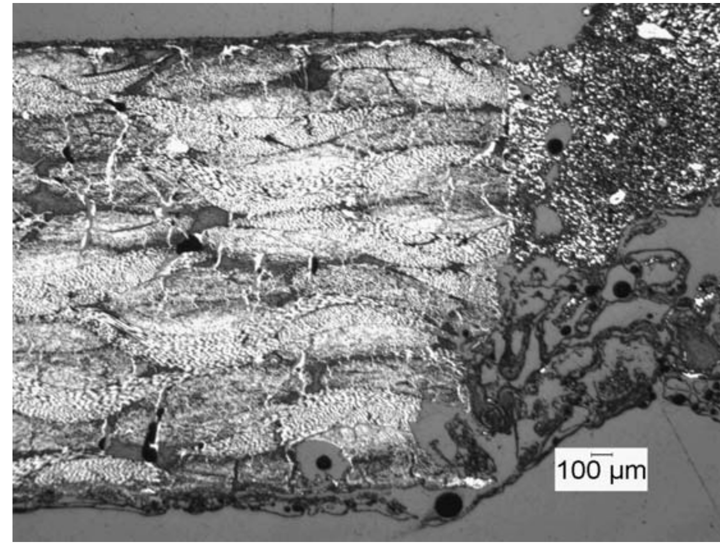
Front side

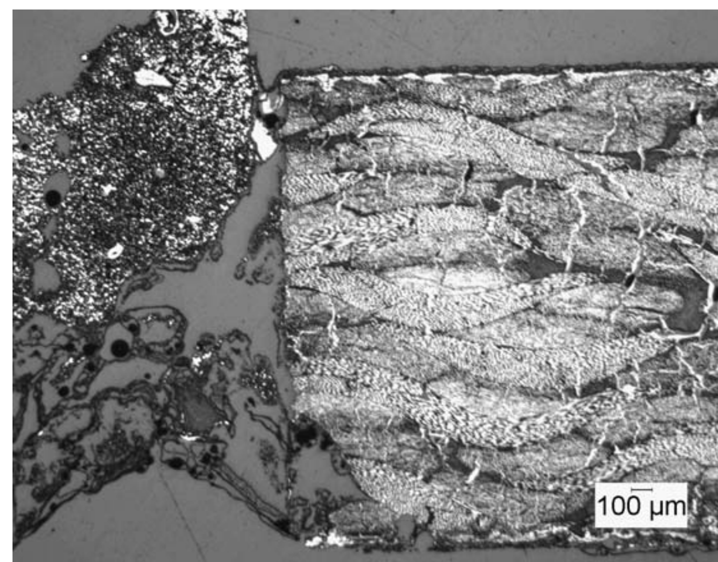
Crack filled with Graber material

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



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.

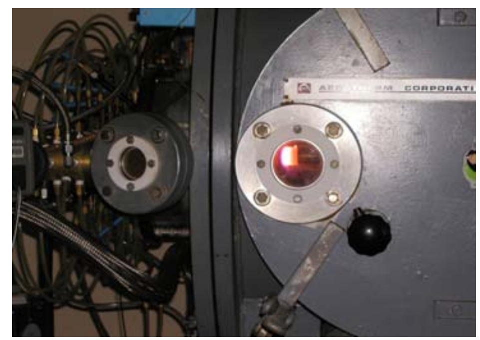
Integrated System for Leading Edge and Tile Repair (InSTALER)

Flexible Ceramic Overwrap

DEVELOPMENT

TESTING

QARE Rig Testing (GRC)



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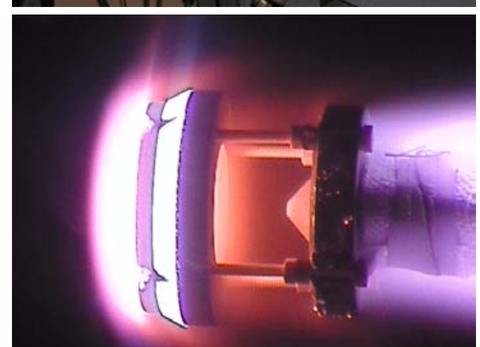
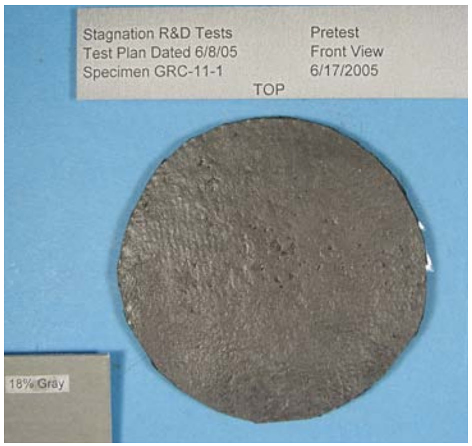


ArcJet Testing at JSC, ARC, and LCAT

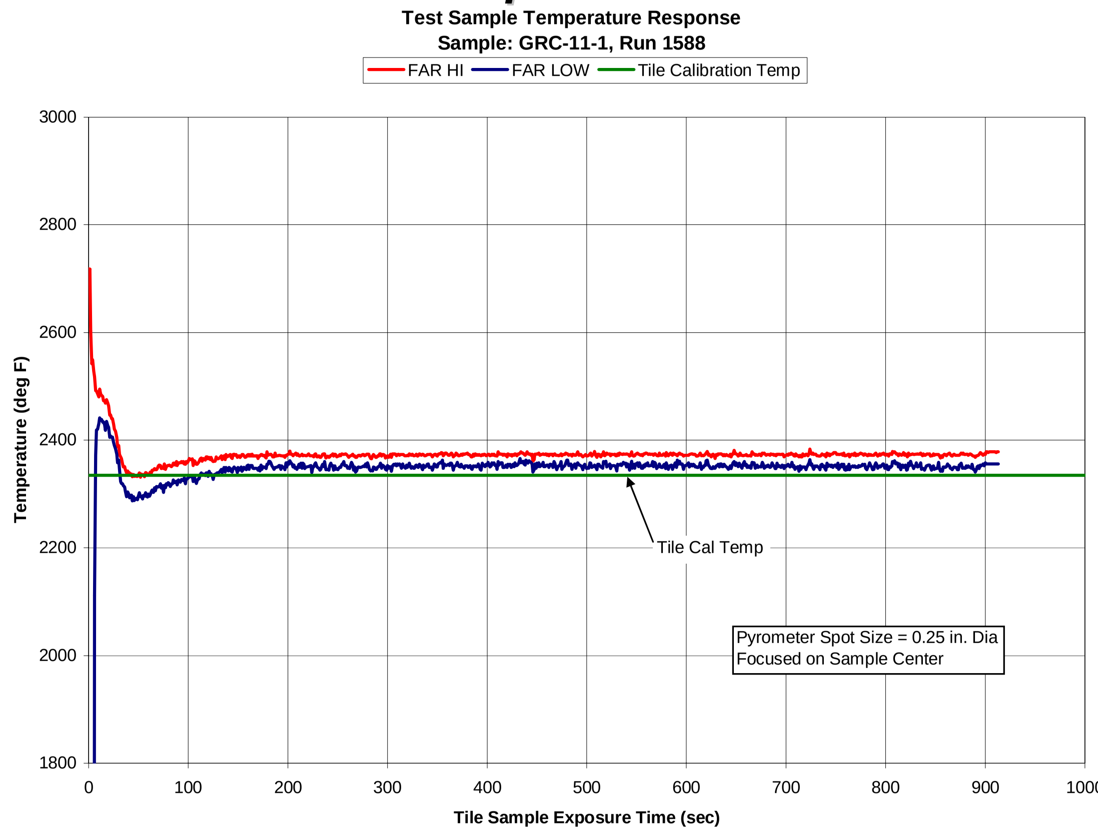
Integrated System for Leading Edge and Tile Repair (InSTALER)

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.**