In-Space Repair of Reinforced Carbon-Carbon (RCC) Thermal Protection System Structures

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Advanced repair and refurbishment technologies are critically needed for the RCC-based 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, PLASTER (Patch Laminates and Sealant Technology for Exterior Repair) based systems 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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James I. Mueller Memorial Award Lecture

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Cocoa Beach, Florida
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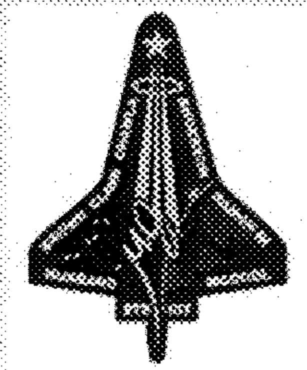
Outline

- **Introduction and Background**
- **Need for In-Space Repair and Inspection**
- **Technical Challenges**
  - *Space Environment*
  - *EVA, Tools, Materials Issues*
  - *Inspection, Verification, and Validation*
- **RCC Repair Technologies**
- **GRABER- Key Material Properties**
- **Testing and Characterization**
  - *Plasma Performance (ArcJet Testing, Torch Testing, etc)*
  - *Microstructural Characterization*
- **Summary and Conclusions**



STS-107 Columbia

Feb. 1, 2003

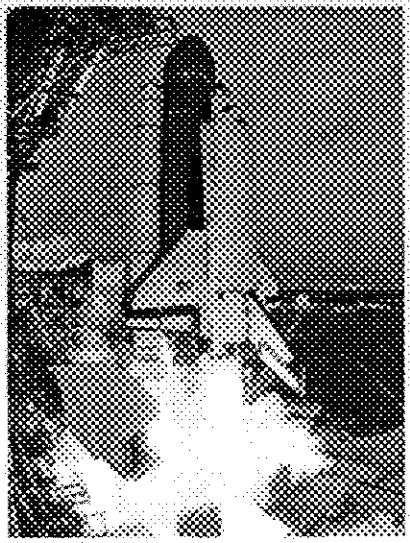
CAIB Recommendation R6.4-1

- 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.

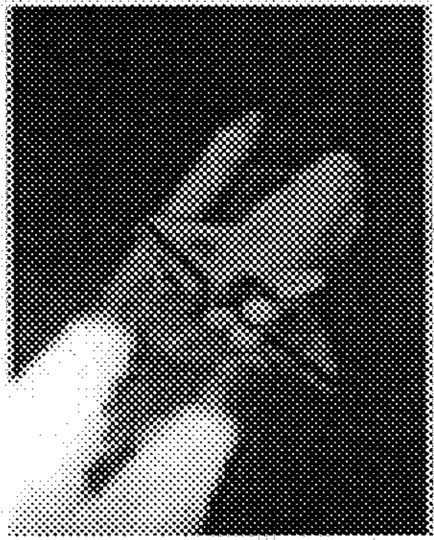
http://www.nasa.gov/columbia/home/CAIB_Vol1.html

Damage Possibilities to Thermal Protection System (TPS)

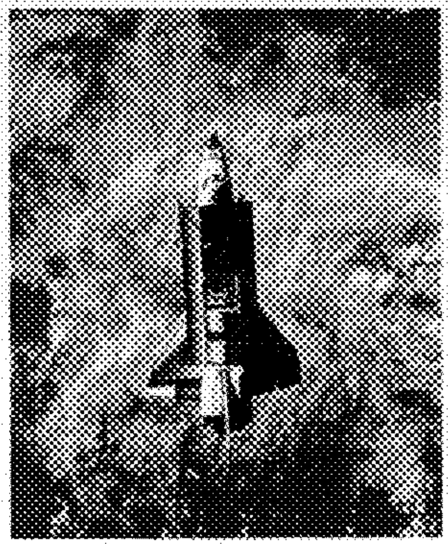
- Impact damage during ground handling
- Damage due to falling of ice or other objects during launch
- Micrometeoroid and orbital debris impact
- Damage caused by different factors during launch and reentry (weather, launch acoustics, shearing, etc.)



Launch Pad Debris



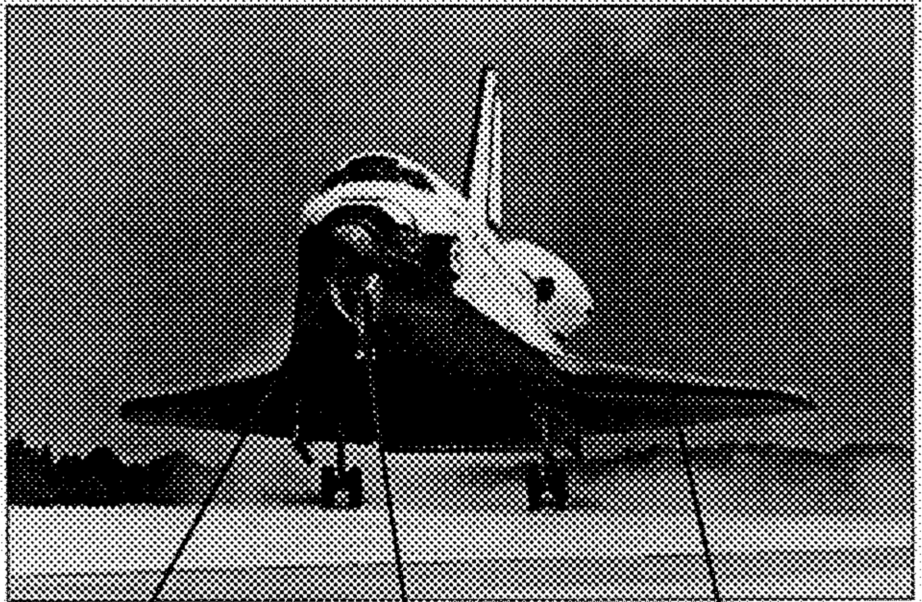
Accent EFT Foam Damage



On-Orbit MMOD Damage

Leading Edge Structural Subsystem (LESS)

RCC Components

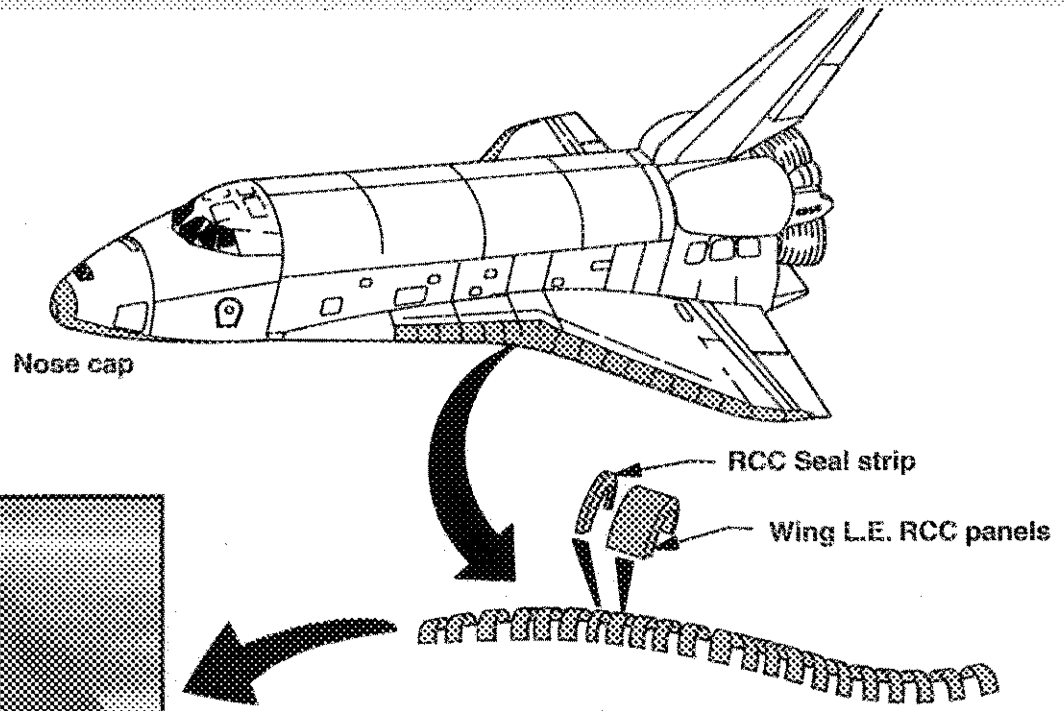


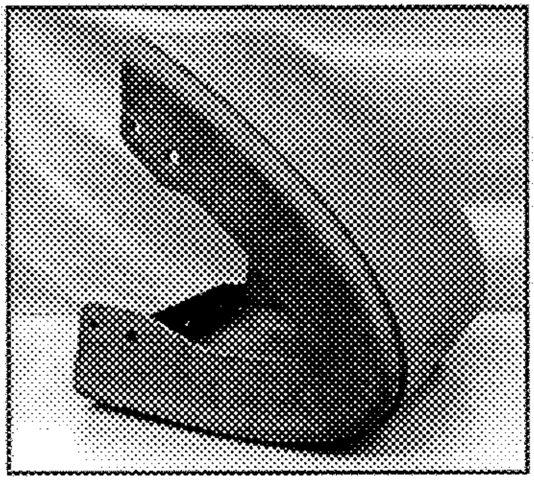
Nose Cap, Chin Panel, and Seals

Forward External Tank Attachment "Arrowhead" Plate

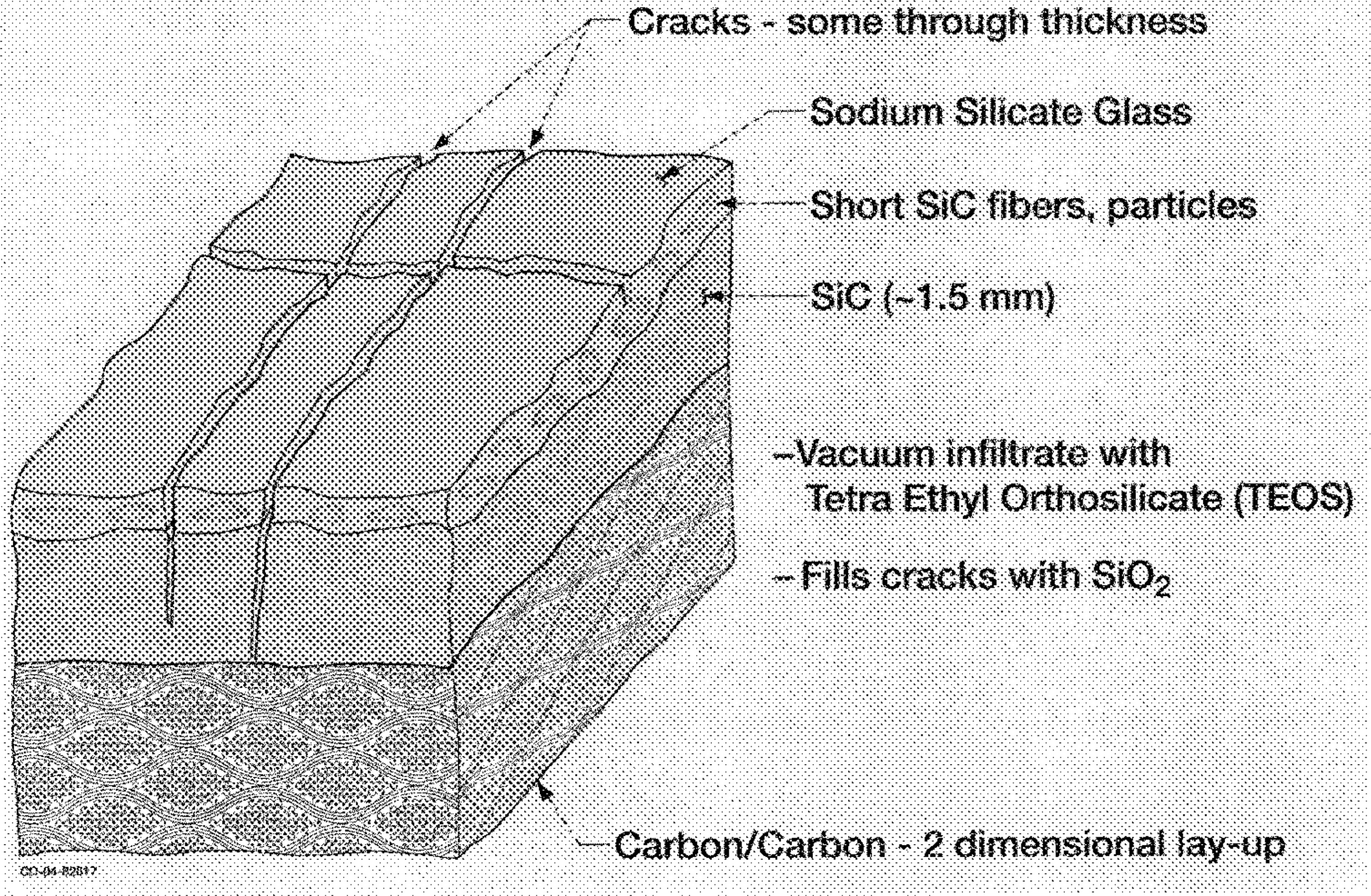
Wing Leading Edge Panels and Seals

Leading Edge RCC Panels and T-Seals





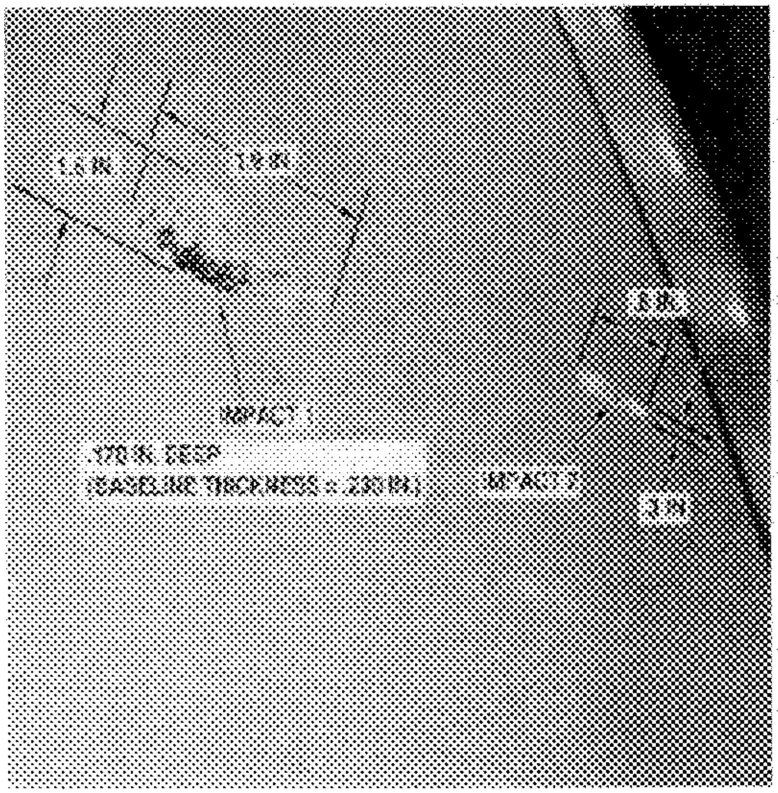
Reinforced Carbon-Carbon (RCC) Composite



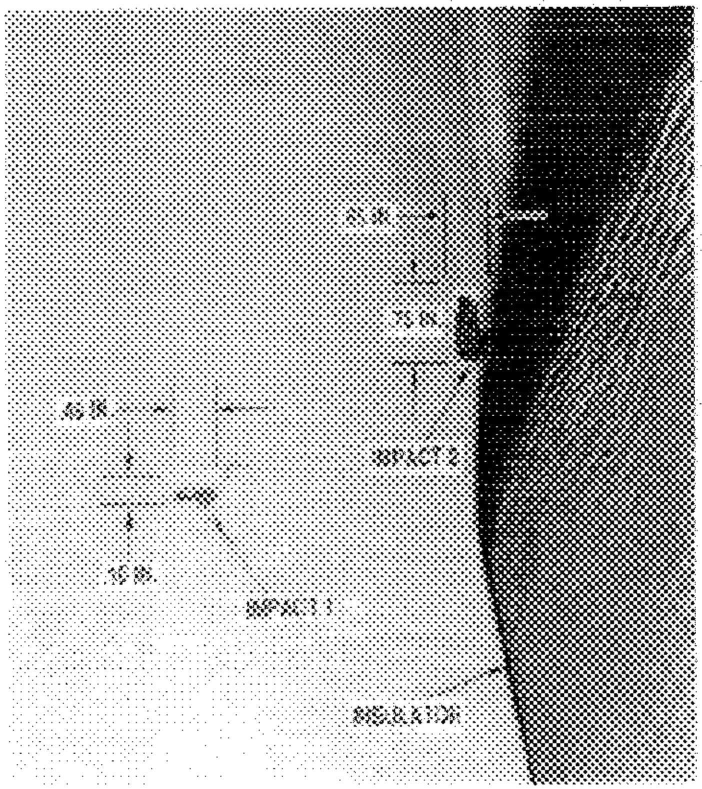
Dr. Nathan Jacobson, NASA GRC

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

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



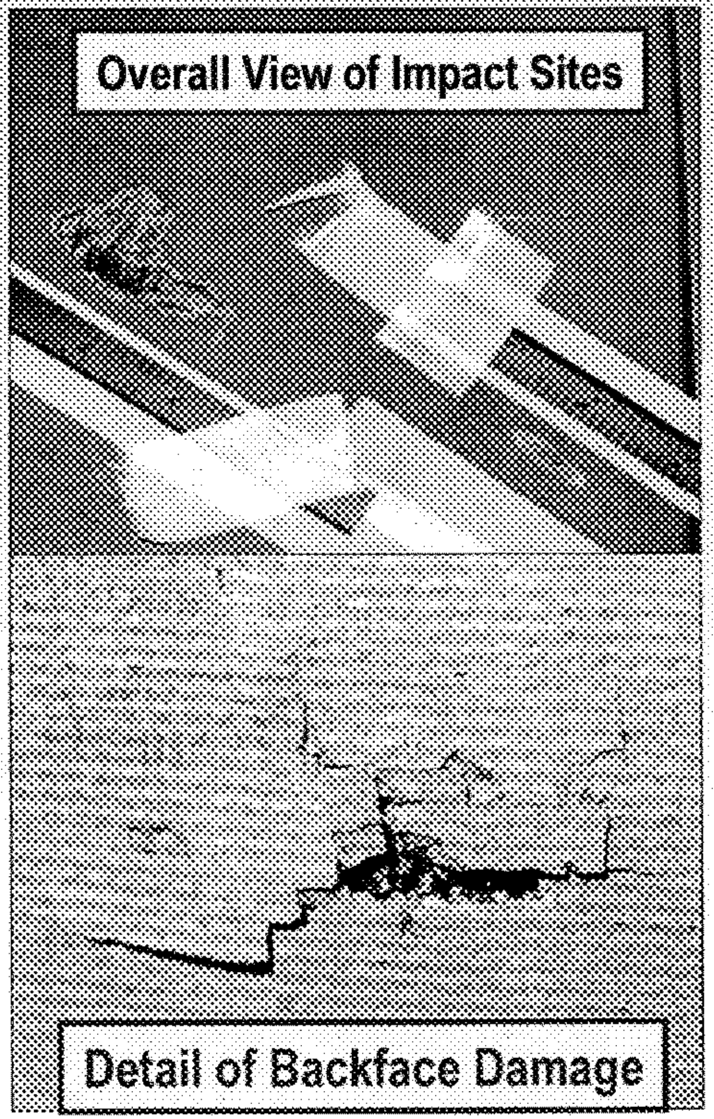
Outer Surface Damage

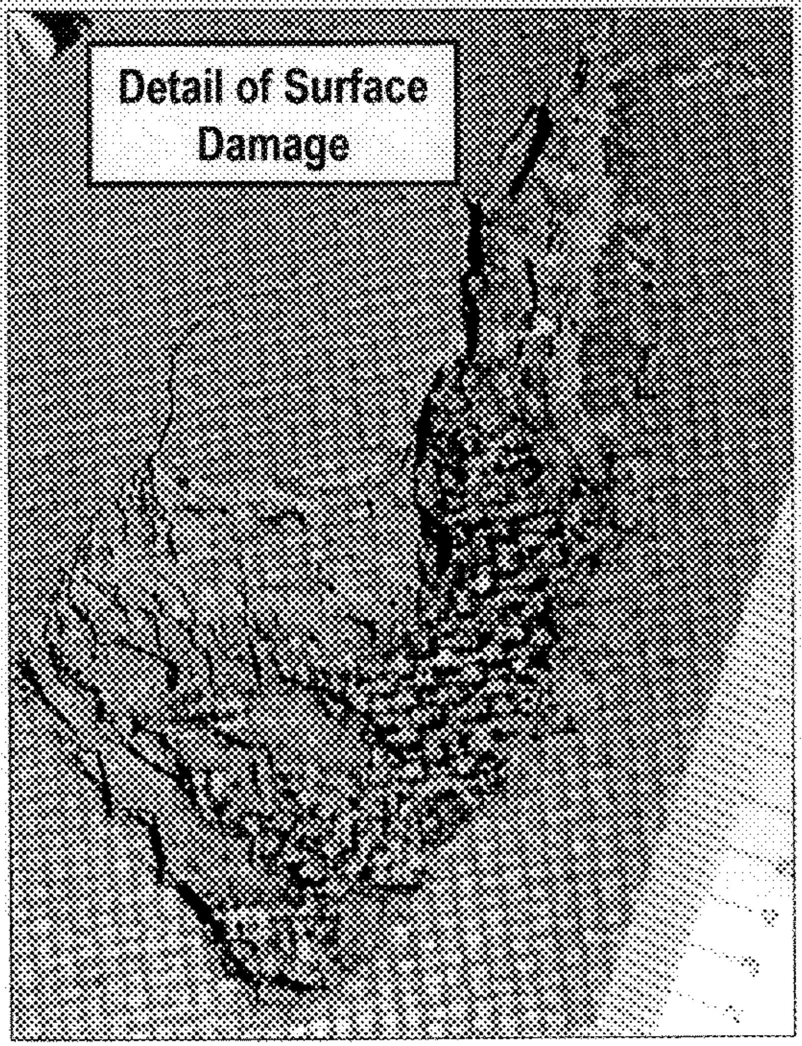


Inner Surface Damage

Don Curry, JSC

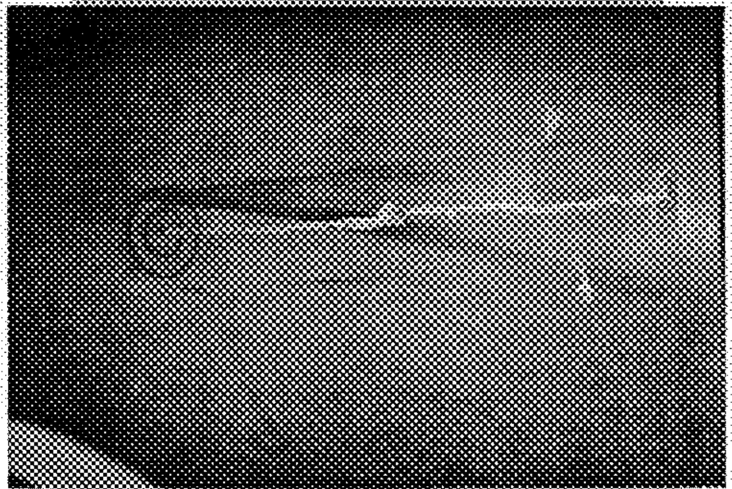
STS-45 Impact Damage on Atlantis WLE Panel 10R



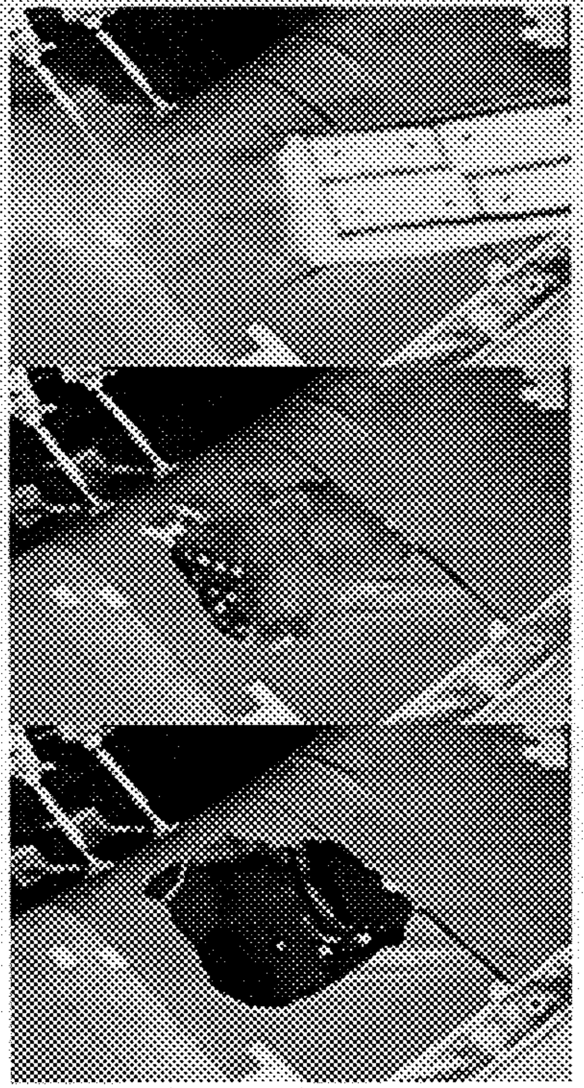


Damage to Leading Edges During Impact Testing on Ground

IML Damage Surface Panel 9L



OML Damage Surface Panel 9L2



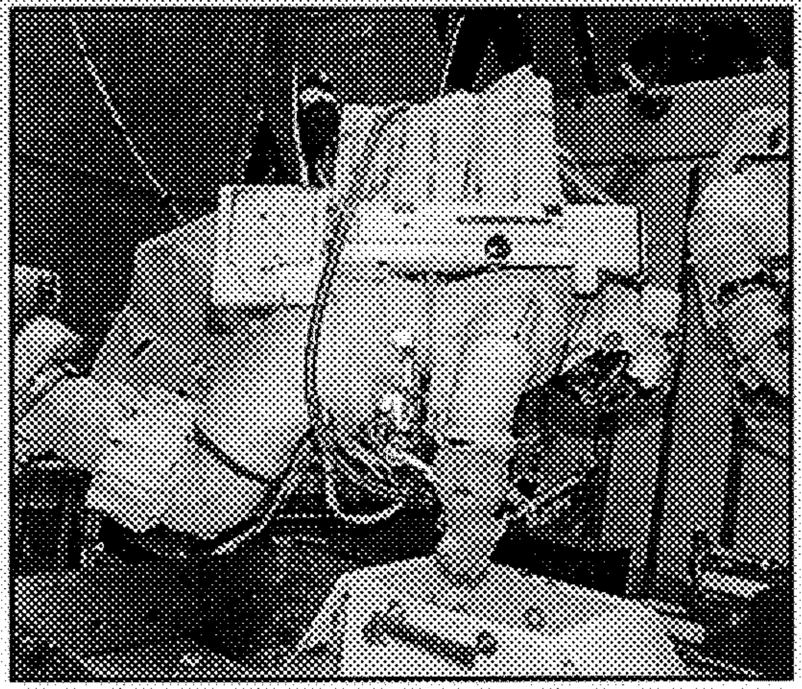
Foam Blasts 16-inch Hole in Final Shuttle Test @SWRI, TX, July 7, 2003

RCC Repair Evaluation on KC-135 Aircraft and at Neutral Buoyancy Laboratory

KC-135 Test Objectives:

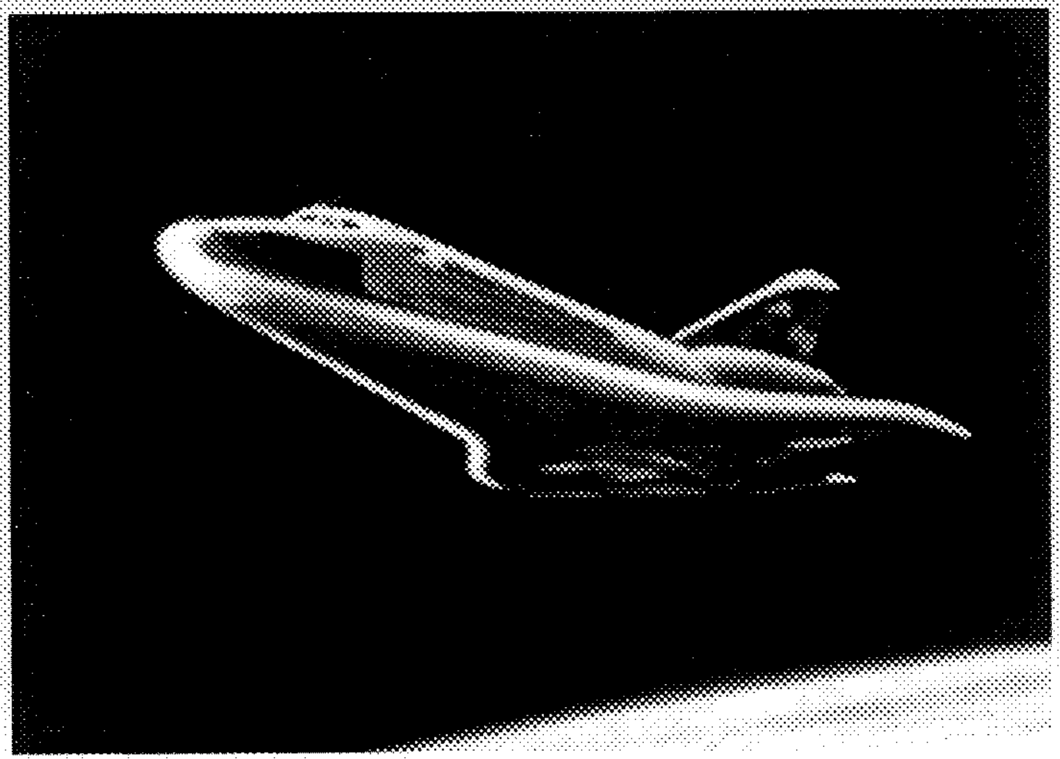
- Evaluation of the repair material wetting characteristics on RCC in micro-G
- Foaming and flow characteristics
- Evaluation of tool design such as crack repair gun/nozzle
- Evaluation of cleaning method, tool/material interaction, etc.

GRABER was successfully tested on a number of KC-135 flights and in DGV experiments



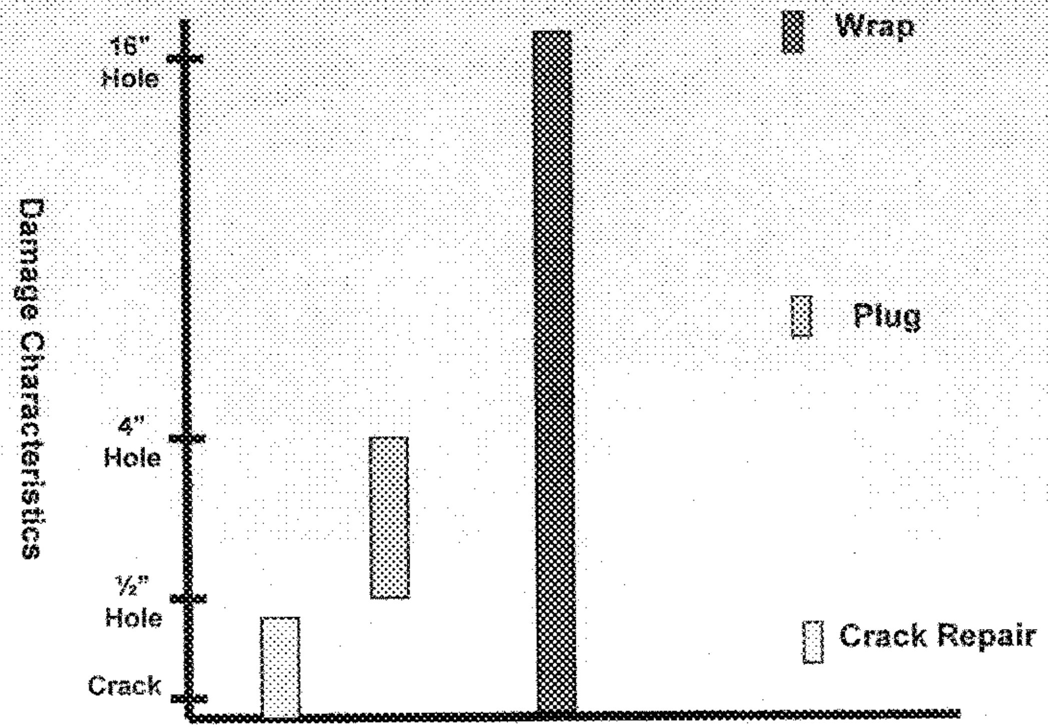
JAXA Astronaut Soichi Noguchi in JSC Neutral Buoyancy Laboratory (NBL) pool.

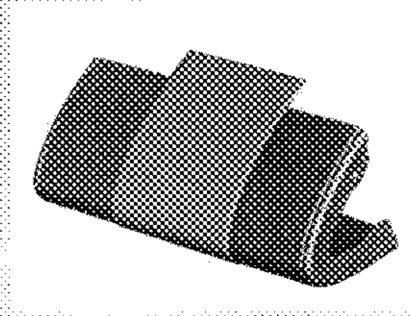
Space Shuttle Re-entry Conditions are Quite Harsh and Extreme

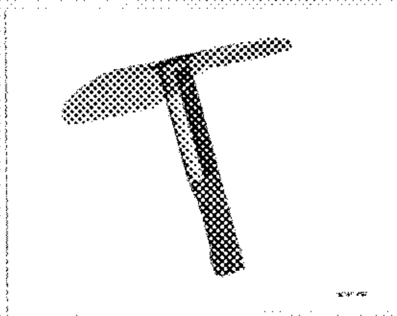


- Temperature to 2000 K
- Reduced pressure--0.005 to 0.010 atm
- Gases--O_2, N_2, CO_2
  - Shock leads to O, N and ions
- Short times ~15 minutes/re-entry
- Best simulated with arc-jet

Repair Concepts for WLE Damage







Glenn Refractory Adhesive for Bonding and Exterior Repair (GRABER)

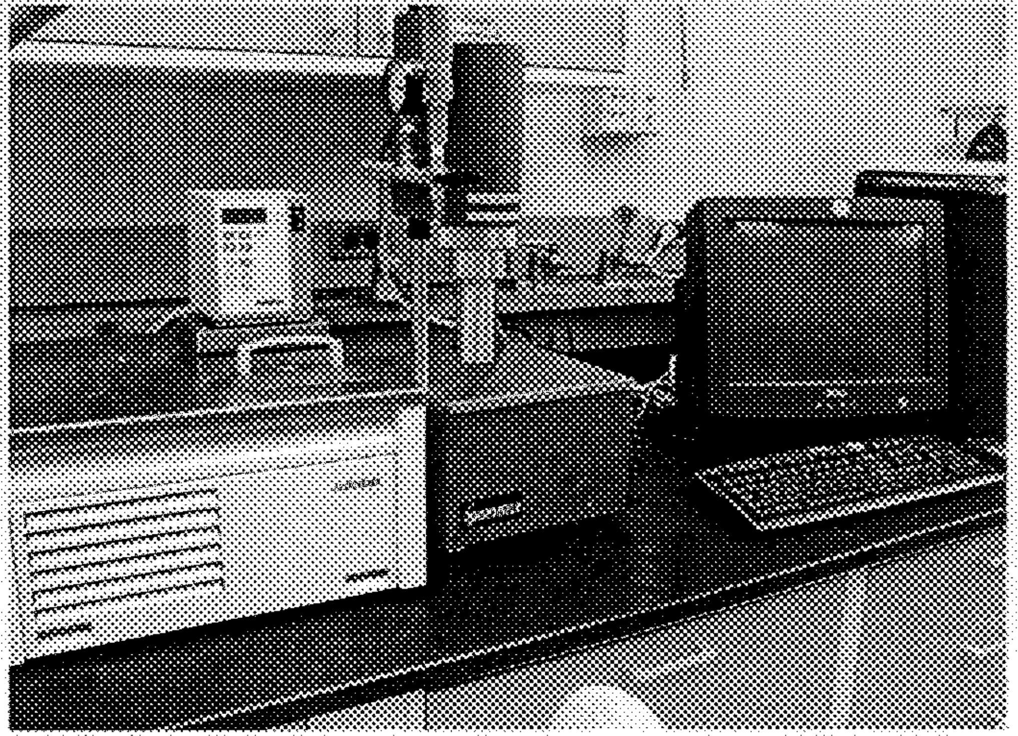
- High Temperature adhesive based on organic based systems with a number of inorganic constituents.
- Viscosity and curing behavior (time, temperature) can be tailored to suit the needs.
- GRABER has been used to prepreg a wide variety of ceramic fiber weaves (C, SiO_2, SiC).
- It bonds very well with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

Multifunctionality of GRABER Based Materials

- **Crack Repair Materials**
  - Repair of cracks and damaged coatings
- **Adhesive and Sealants**
  - Bond and seal the edges in plug concept
- **Inner to Outer Mold Line (ITOM) Materials**
  - Filled Wing Concept
- **Flexible Prepregs**
  - Repair of large size damage
- ***Manufacturing of Bulk Composites***
- ***Joining and Assembly of C/C Composites***
- ***Repair of C/C Based Composites***
- ***Functionally Graded Coatings for C/C Composites***

Reproducibility, Storage, and Shelf Life Characterization

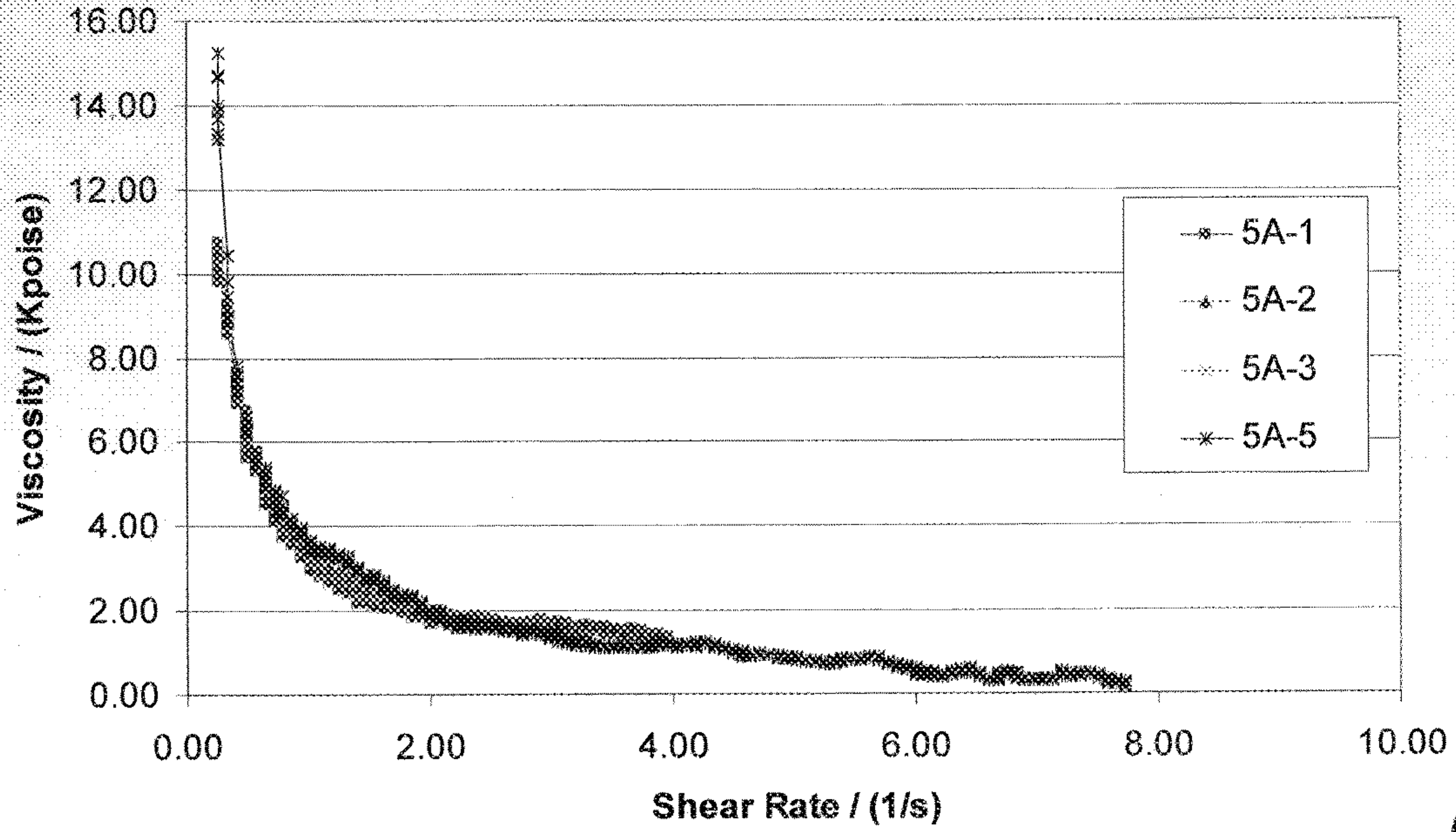
Brookfield PVS Rheometer Used for the Viscosity Measurements



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



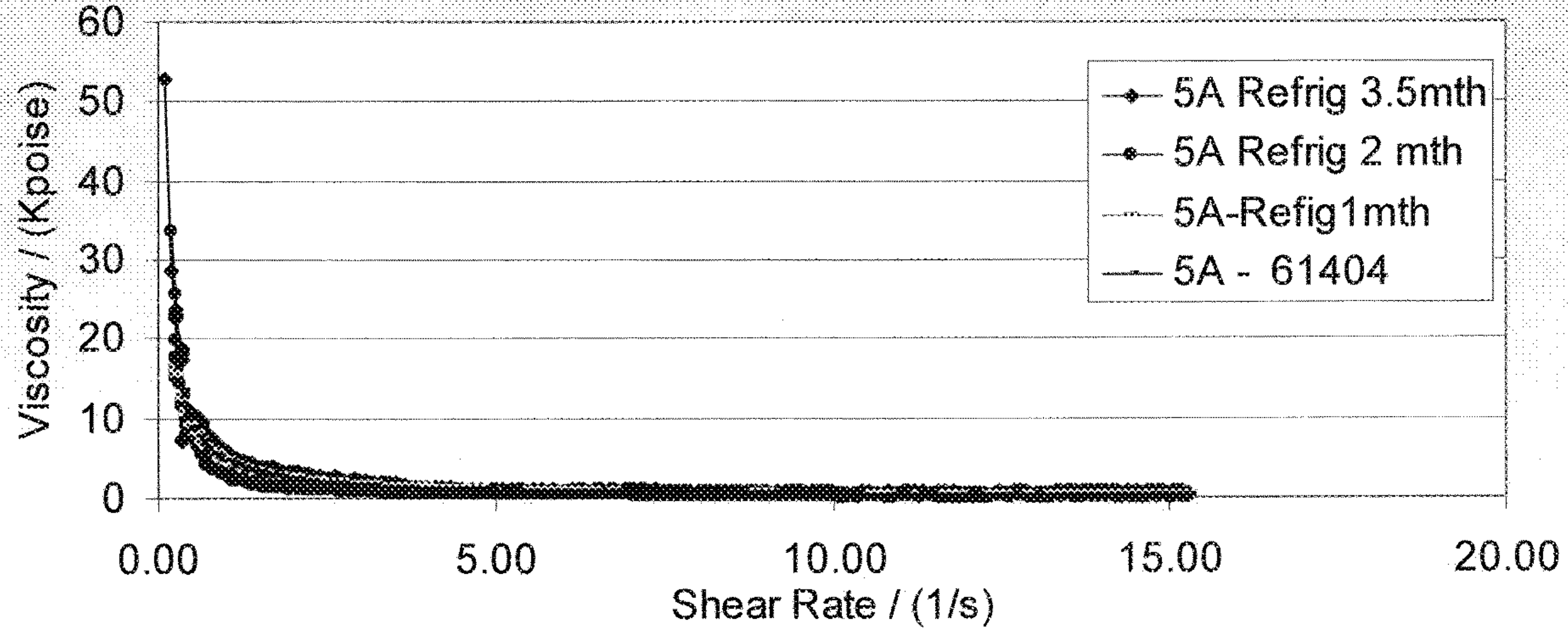
Effects of Storage Times & Temperatures

	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

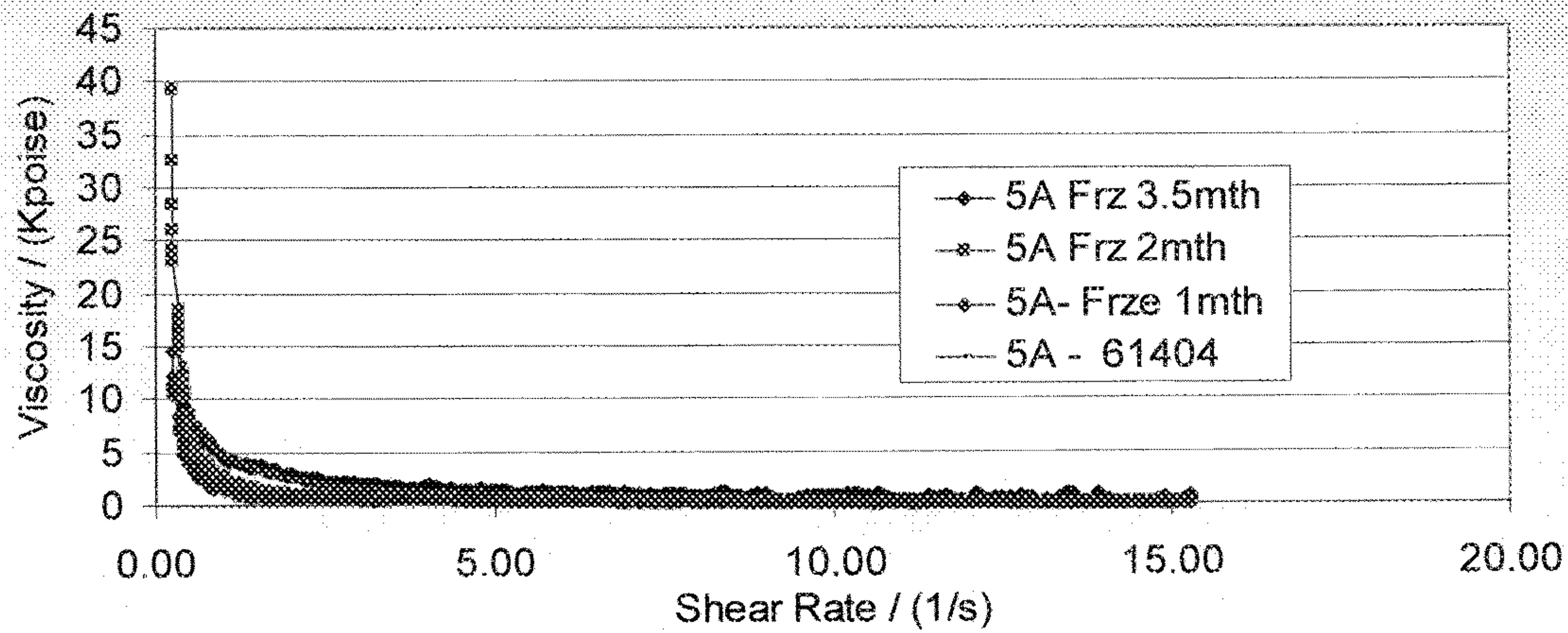


Material was Tested under Vacuum

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

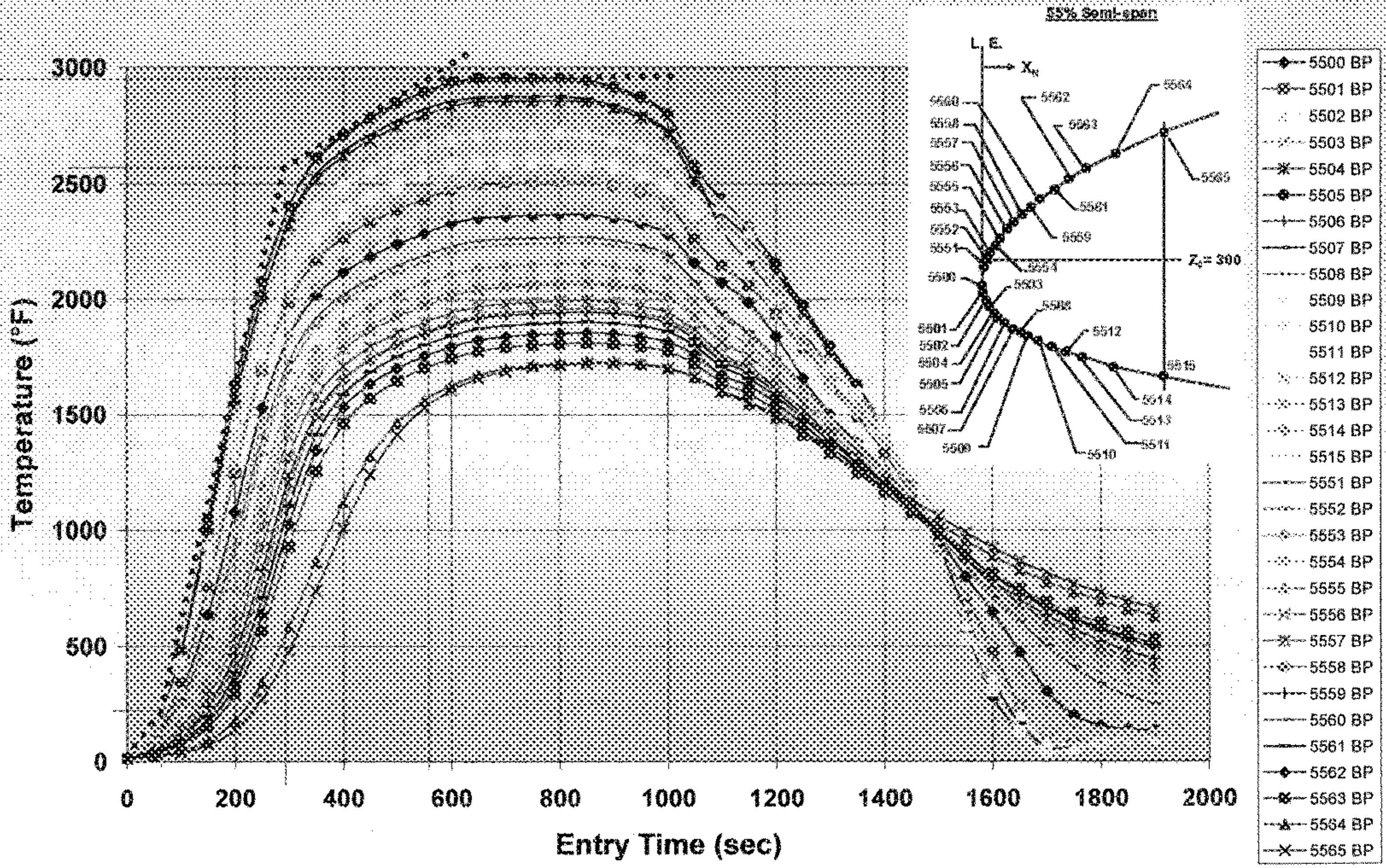
Crack Repair, ArcJet Testing, and Post Test Characterization

- 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

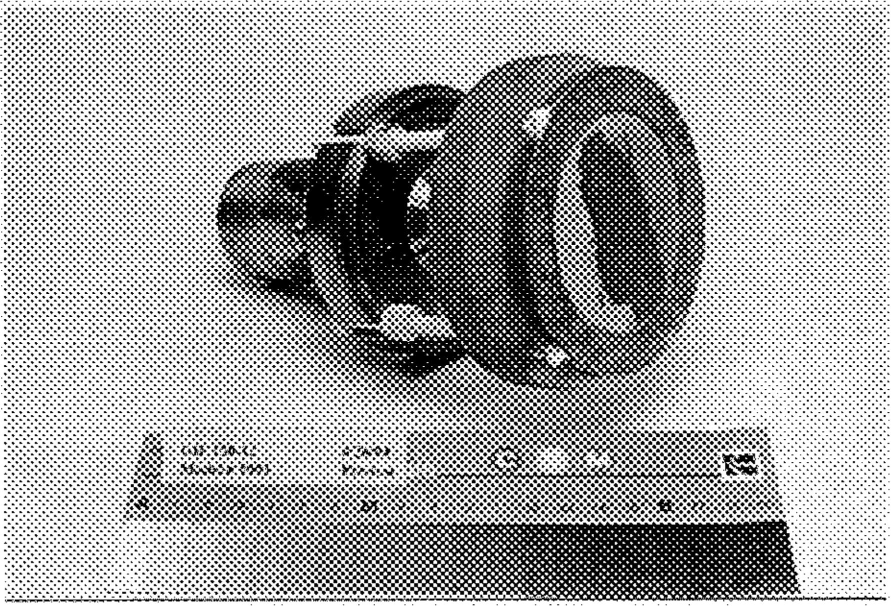
Panel 9 (55% Span) Temperature Profile for Nom ISS EOM

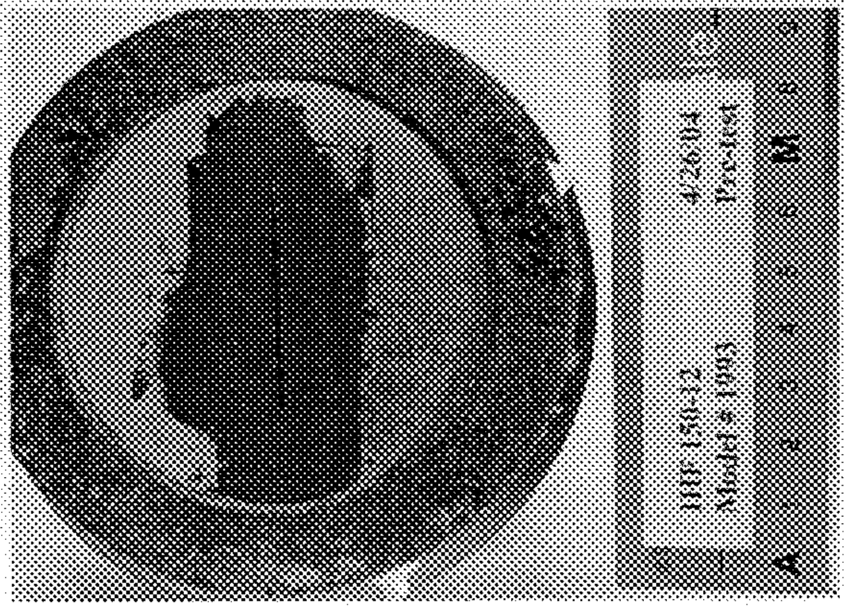


Pre-Test Photographs of Repaired Specimens

Run 12 – Model 1993

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





Percent Argon = 6% @ 2960F condition

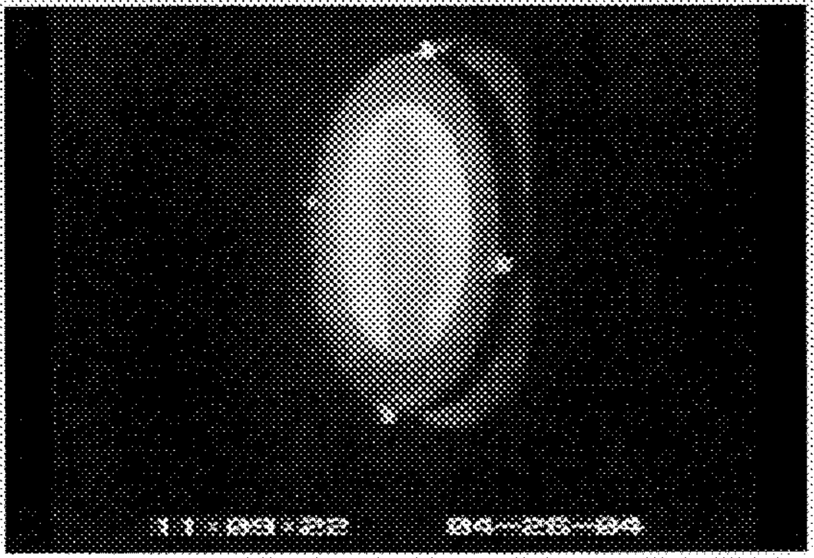
Add air = 11.6% @ 2960F condition

Anomaly: water leak from electrode, which allowed water vapor in the stream

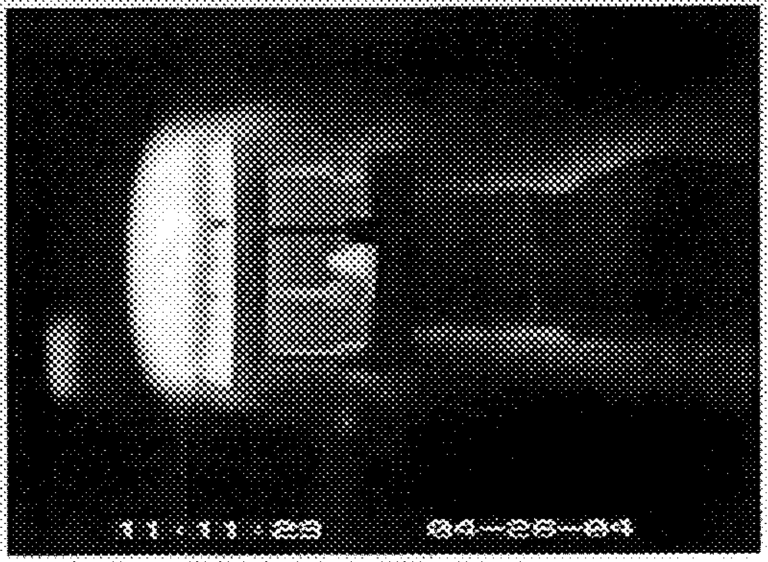
ArcJet Testing of Repaired Specimens

Run 12 – Model 1993

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



Front View



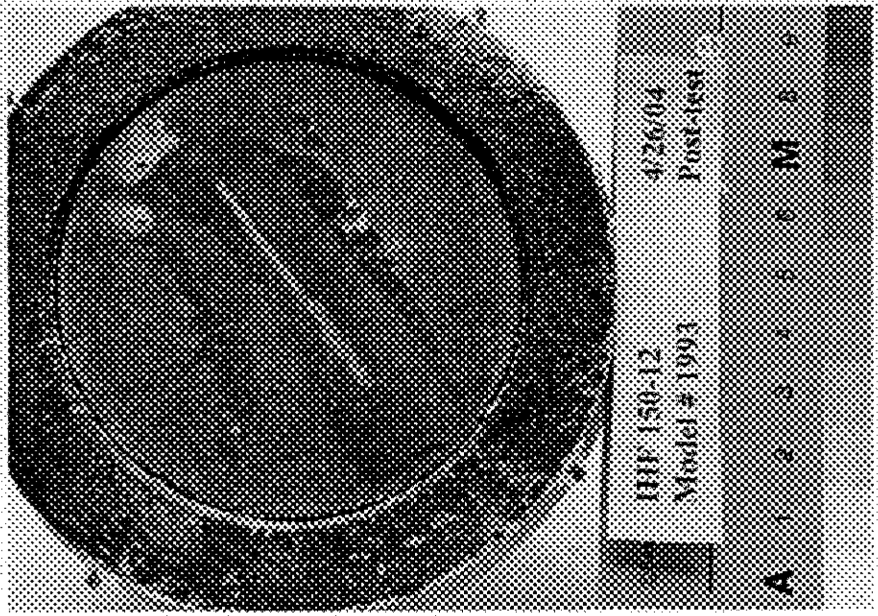
Side View

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

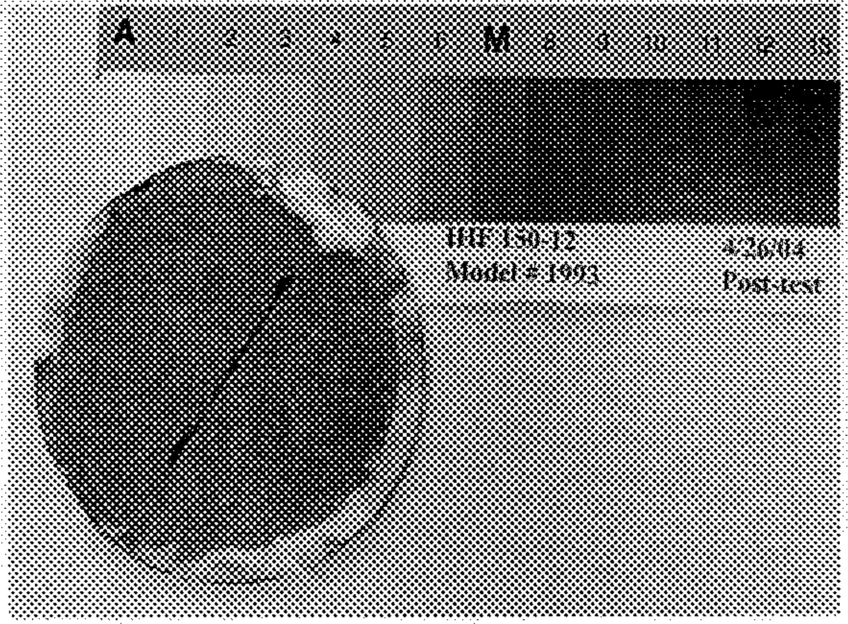
ArcJet Testing of Repaired Specimens

Run 12 – Model 1993

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



Post Test- Front Side

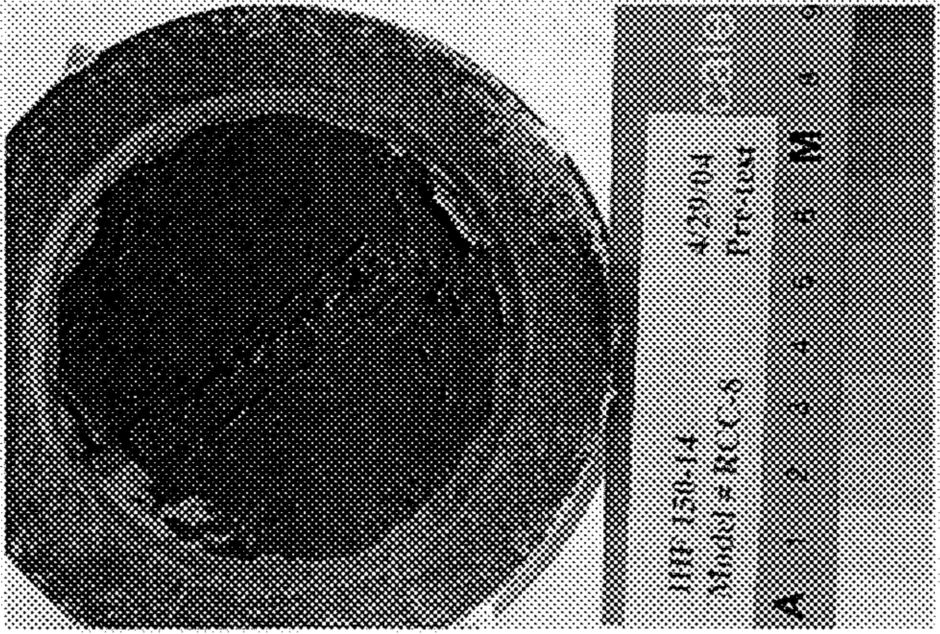


Post Test- Back Side

ArcJet Testing of Repaired Specimens

Run 14 – Model RCC 8

(0.062”or ~1.58 mm wide crack, GRABER-12A)



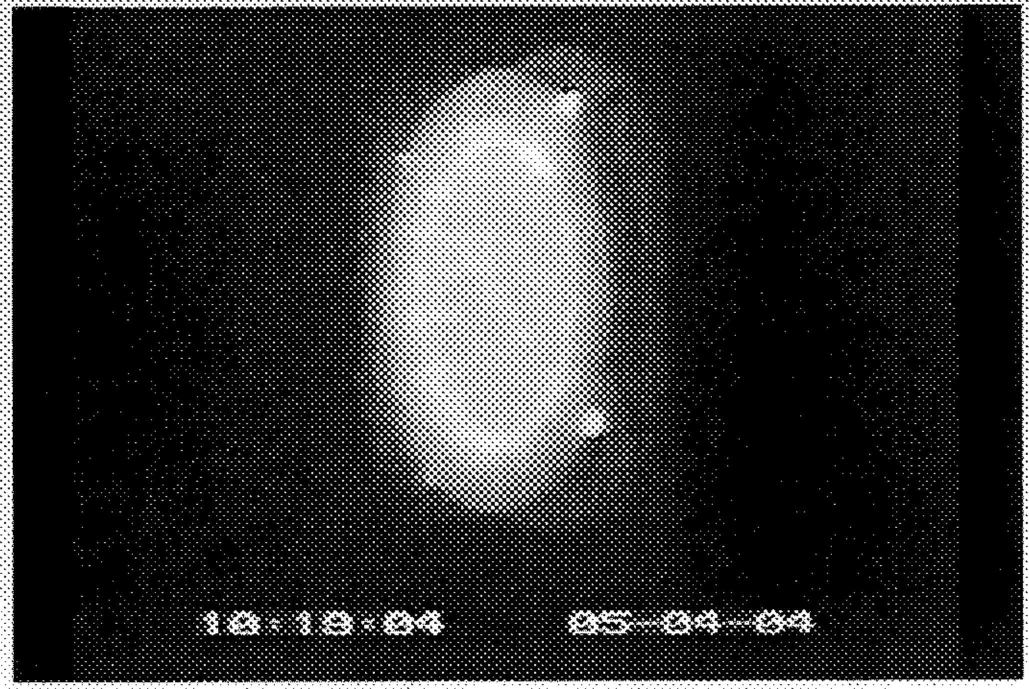
Percent Argon = 6% @ 2960F condition

Add air = 11.6% @ 2960F condition

Temperatures on model face were higher than previous runs (~3100F)

ArcJet Testing of Repaired Specimen

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



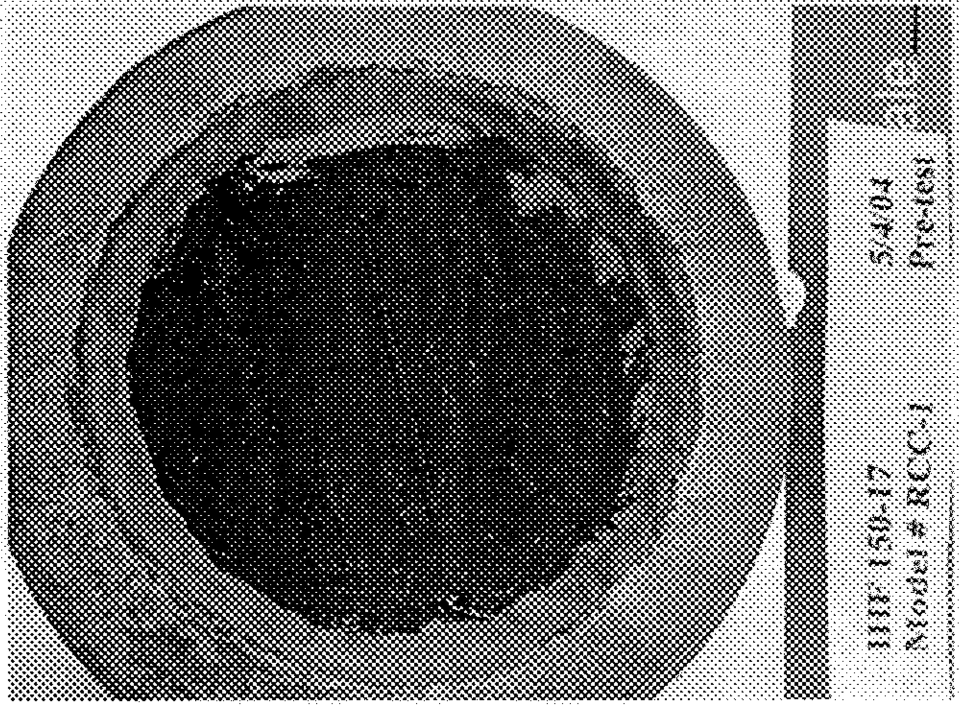
Front View

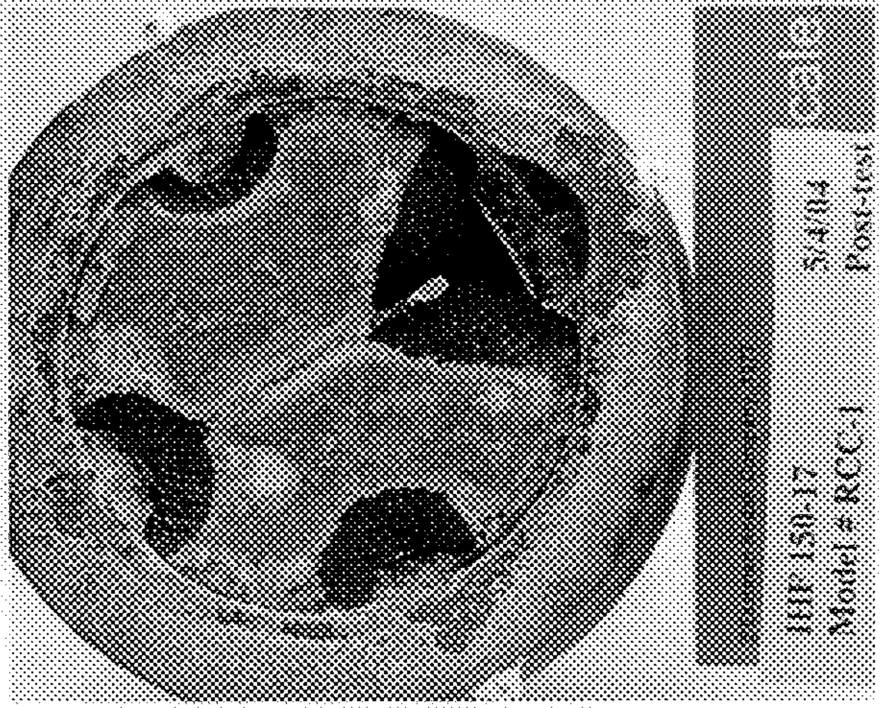
Percent Argon = 6% @ 2960F condition
Add air = 11.6% @ 2960F condition
Anamoly: Edge failure, sample removed after ~130 seconds @ 2960F condition

ArcJet Testing of Repaired Specimens

Run 17 – Model RCC 1

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





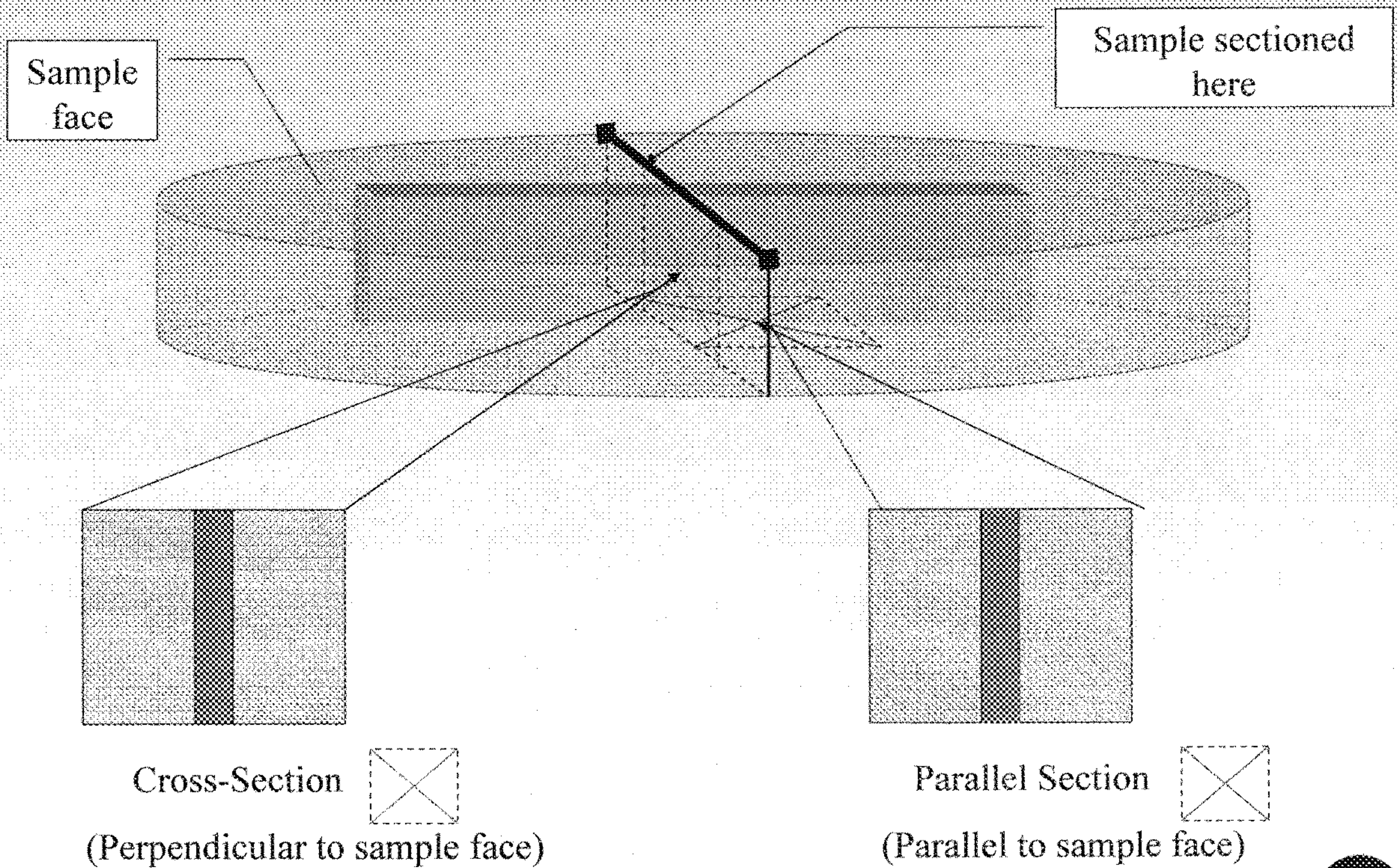
Percent Argon = 6% @ 2960F condition

Add air = 11.6% @ 2960F condition

Anamoly: Edge failure, sample removed after ~130 seconds @ 2960F condition

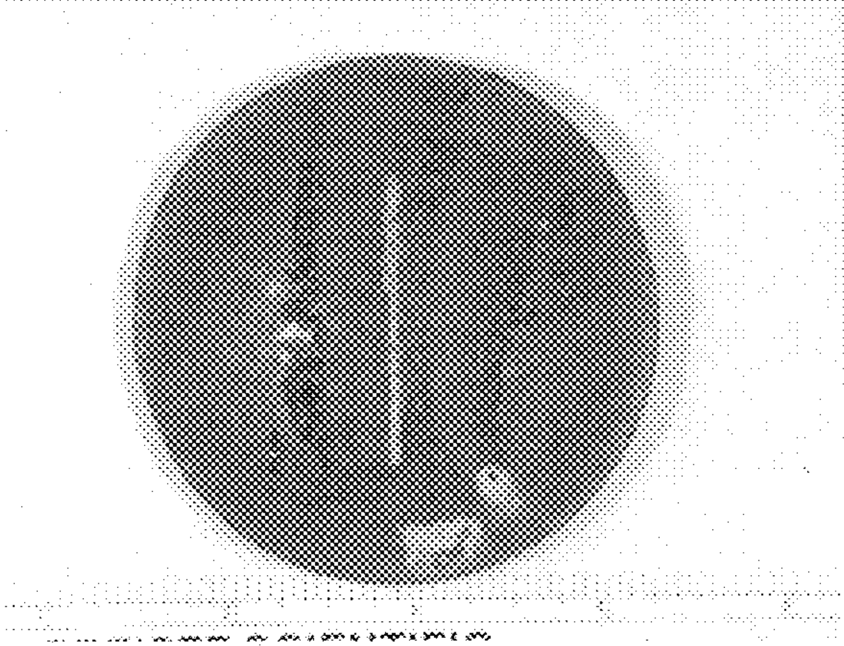
Microstructural Characterization of ArcJet Tested Specimens

Arcjet Sample Description and Preparation

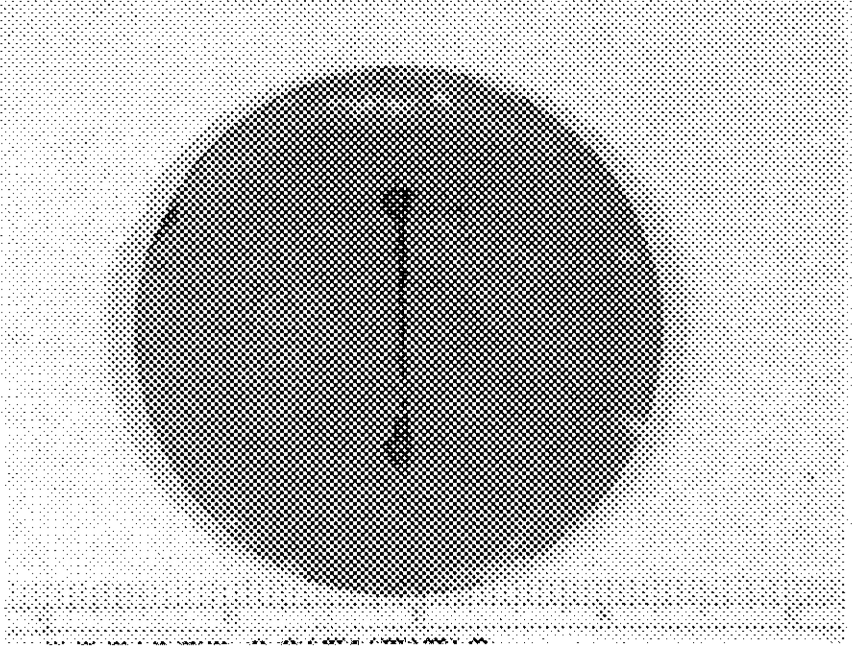


ArcJet Sample 1993, Graber 5A, 0.035" Crack Width

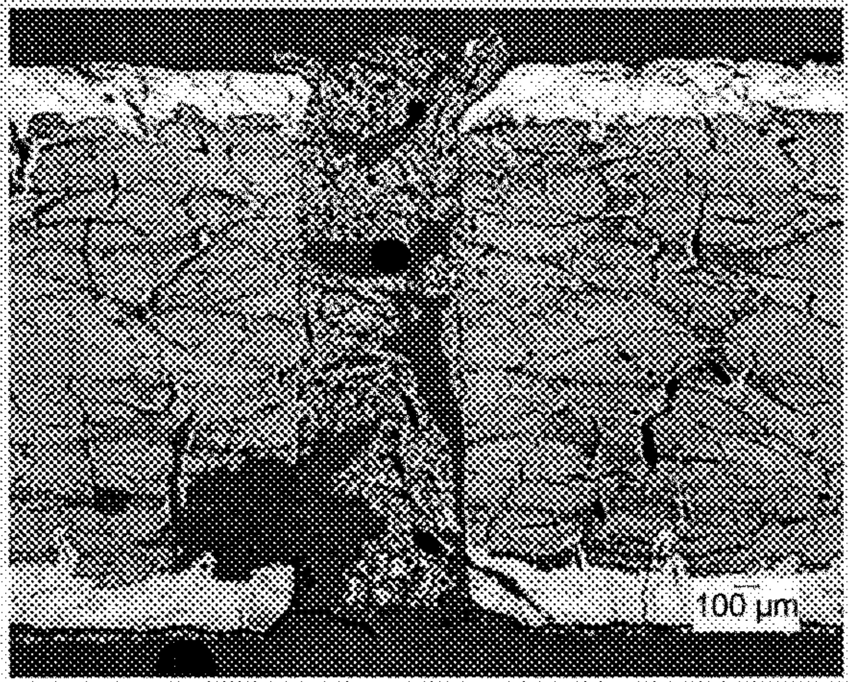
Front side

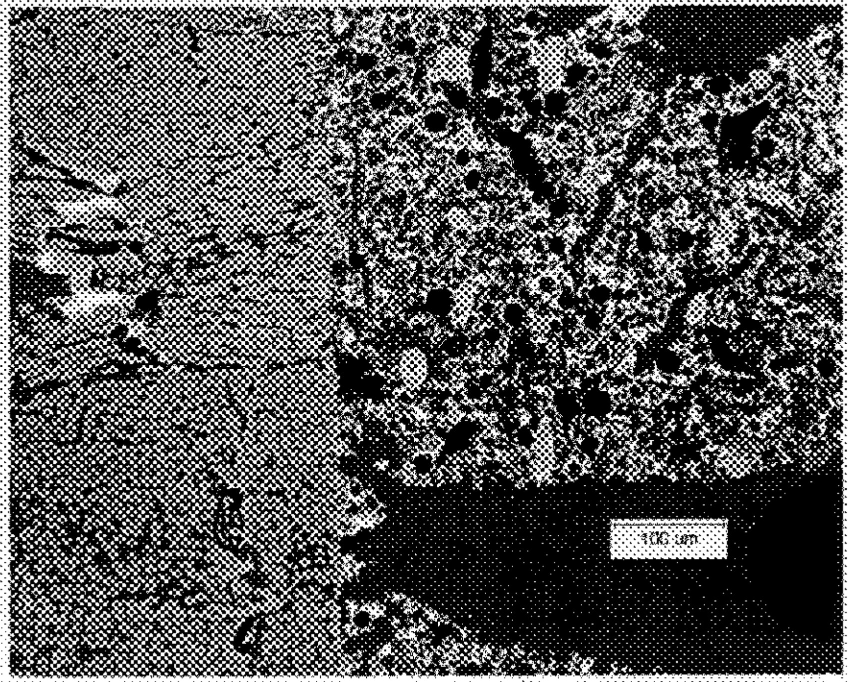


Back side



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

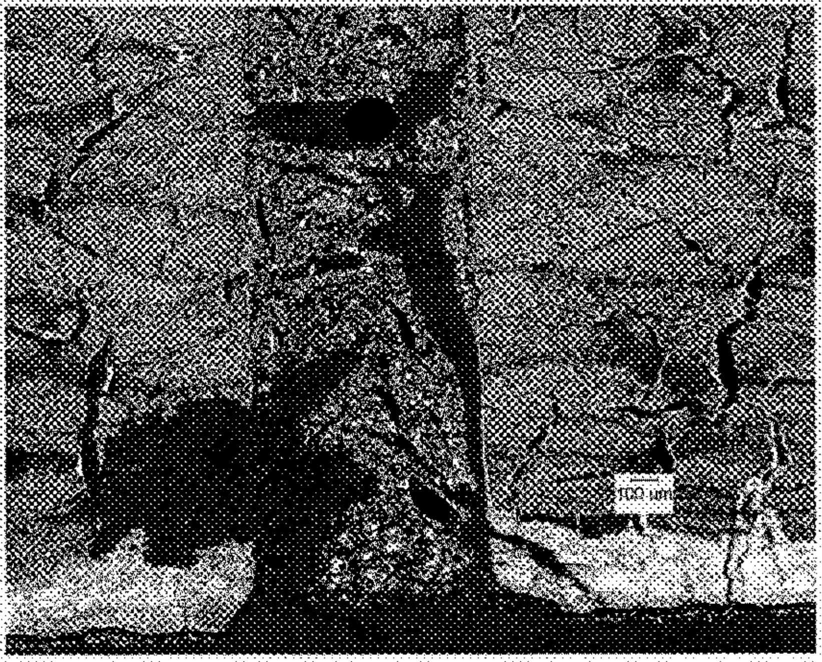


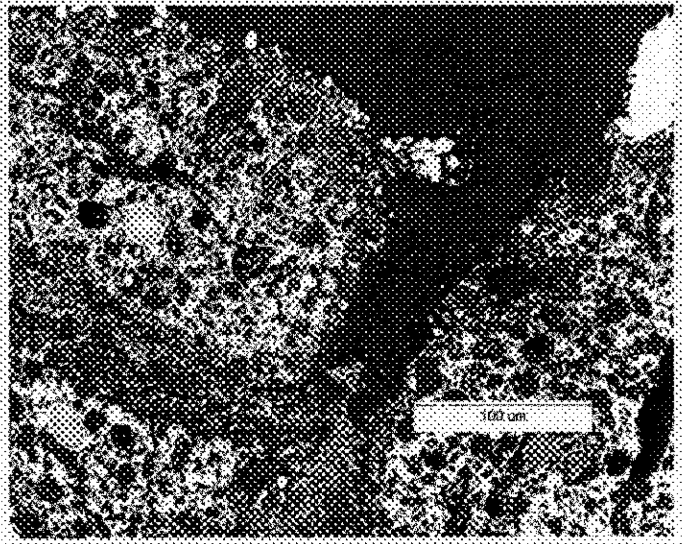


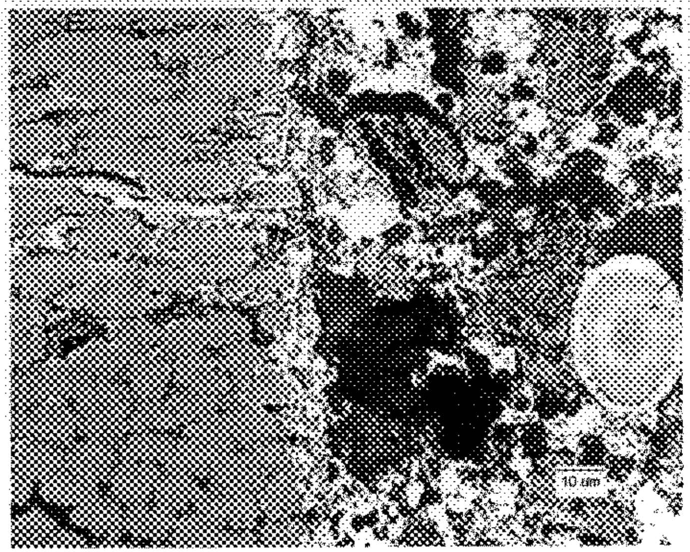
Front Side

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

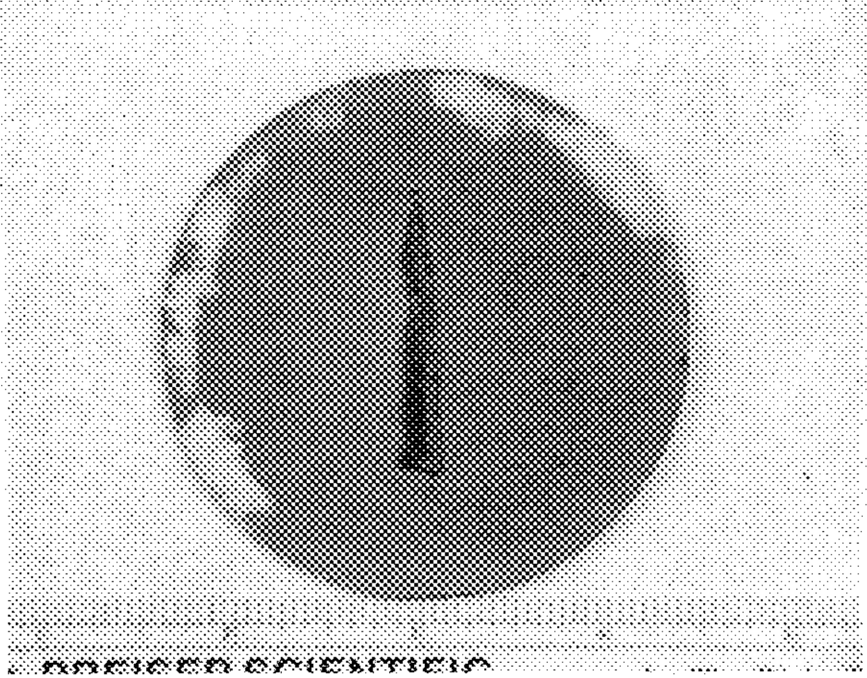




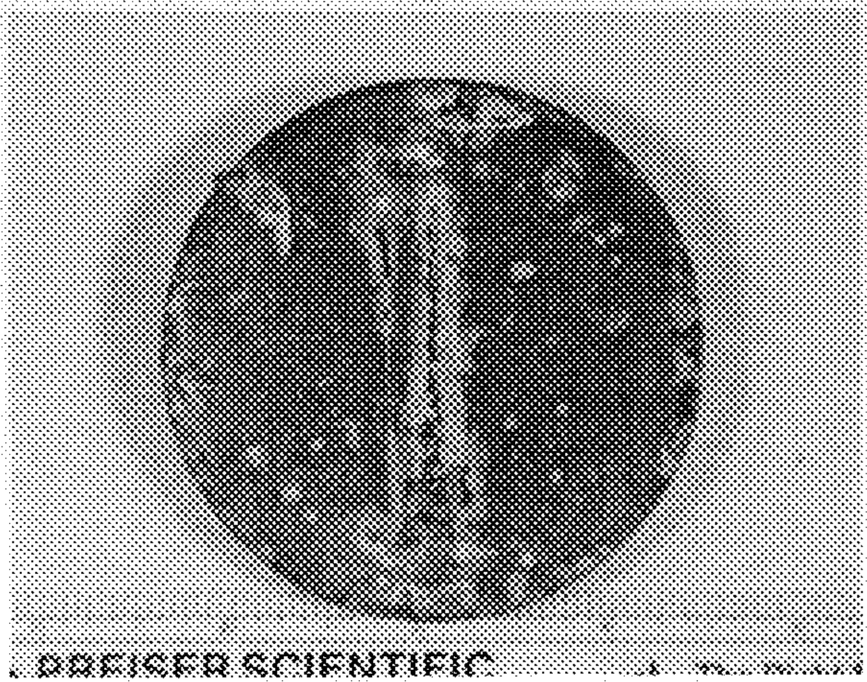


ArcJet Sample 150-14, RCC-8, GRABER 12A, 0.062" Crack Width

Back side

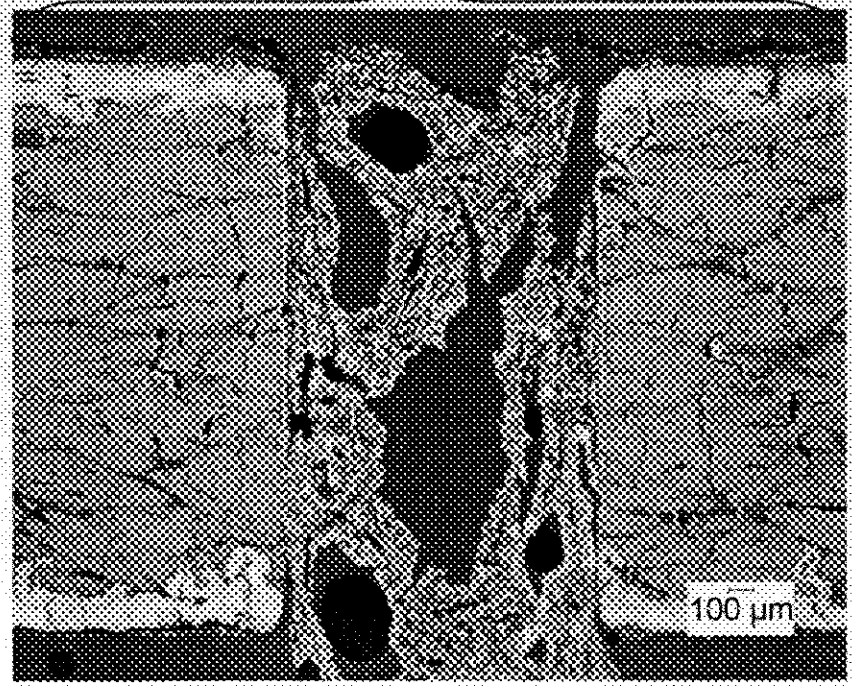


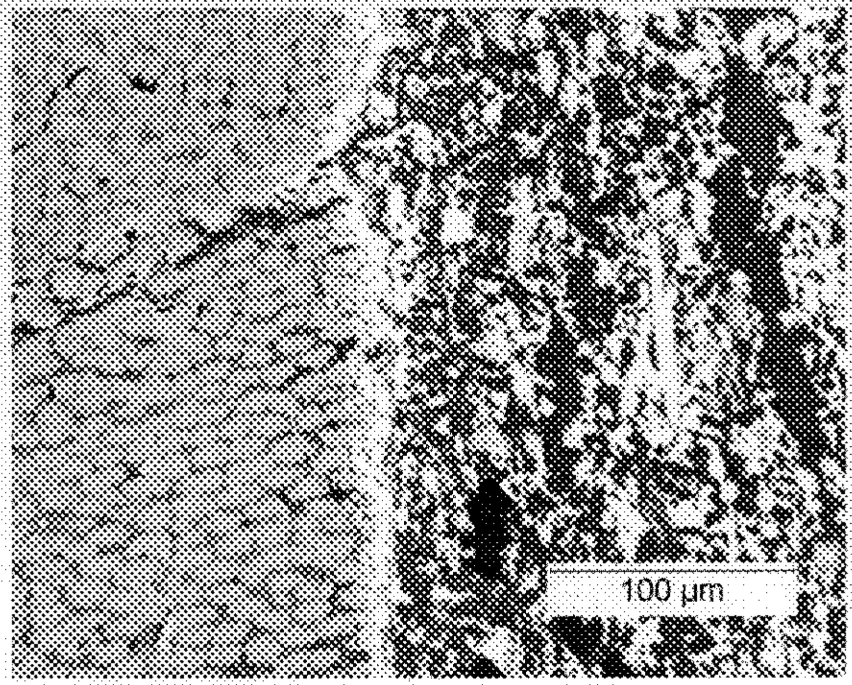
Front side



ArcJet Sample 150-14, RCC-8, GRABER 12A, 0.062" Crack Width

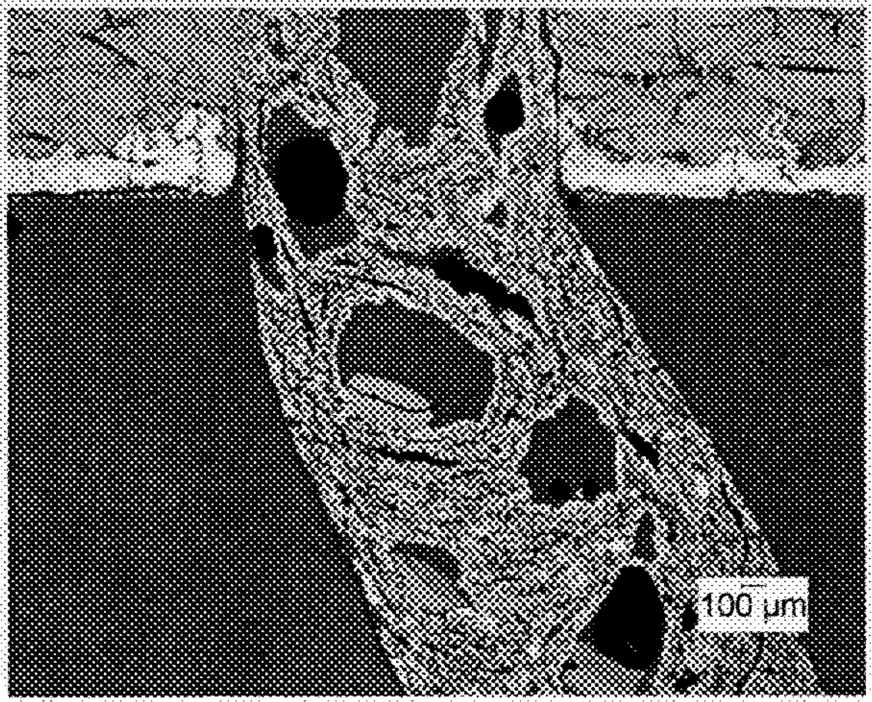
Front Side

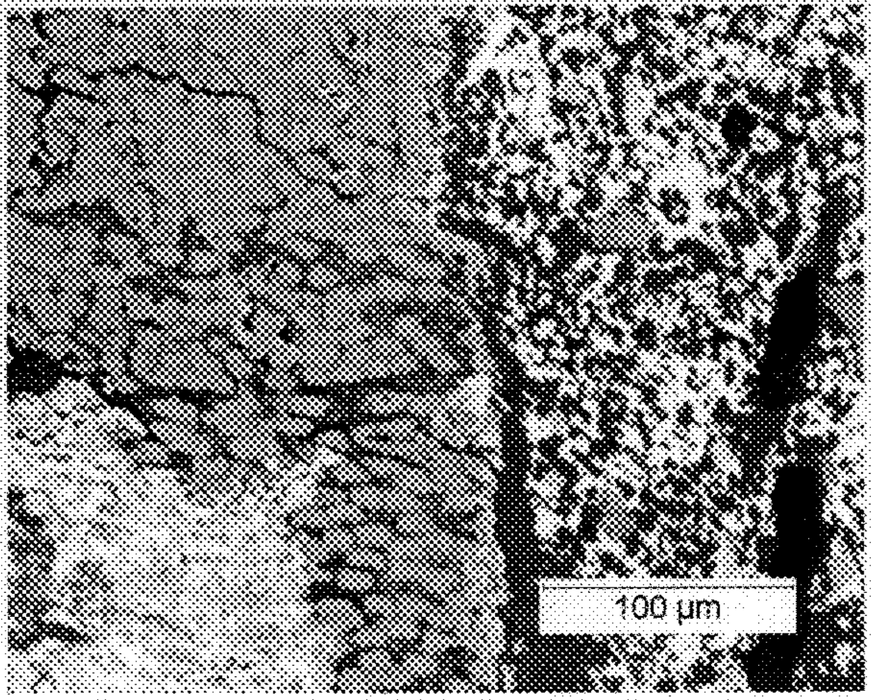




There are large voids within the Graber material. The bonding between the Graber material and the C/C substrate looks good as seen on the right.

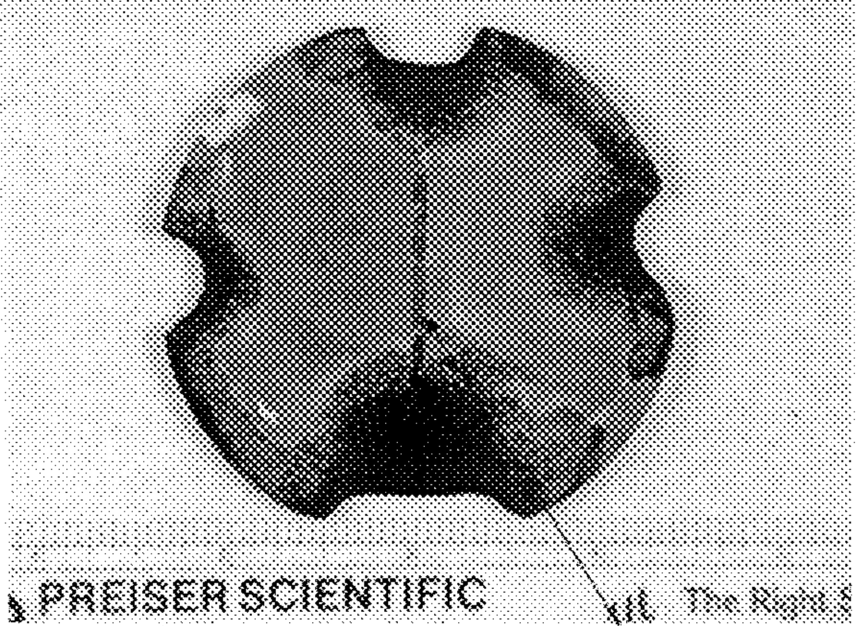
ArcJet Sample 150-14, RCC-8, GRABER 12A, 0.062" Crack



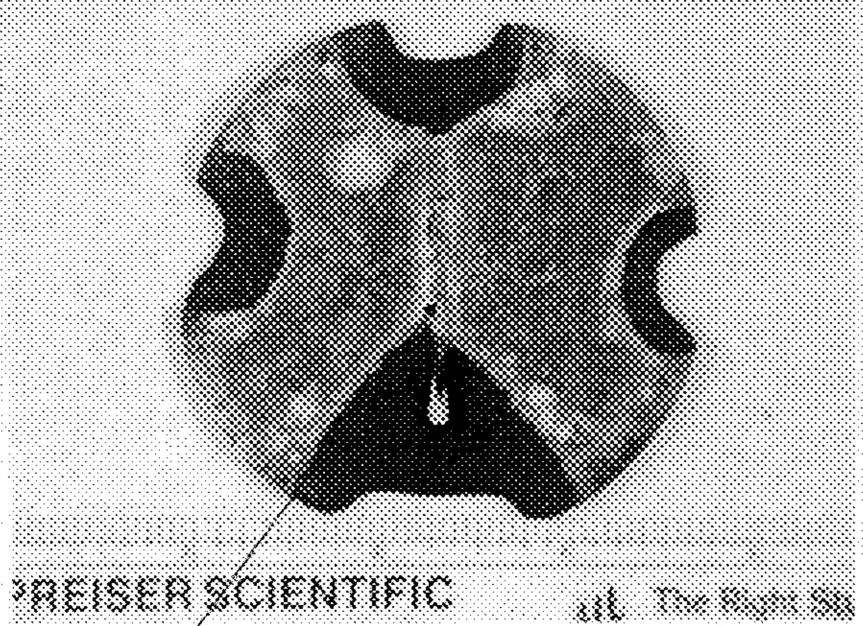


Backside

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



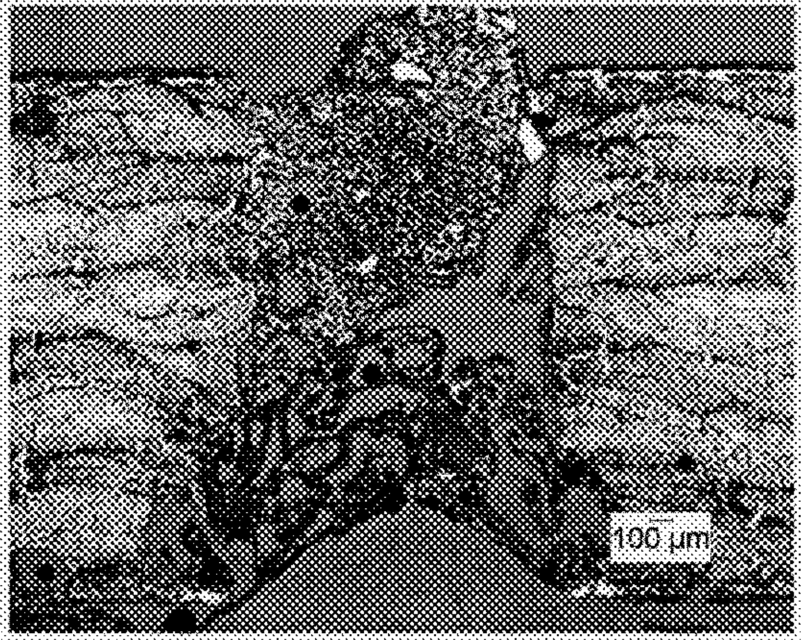
Back side



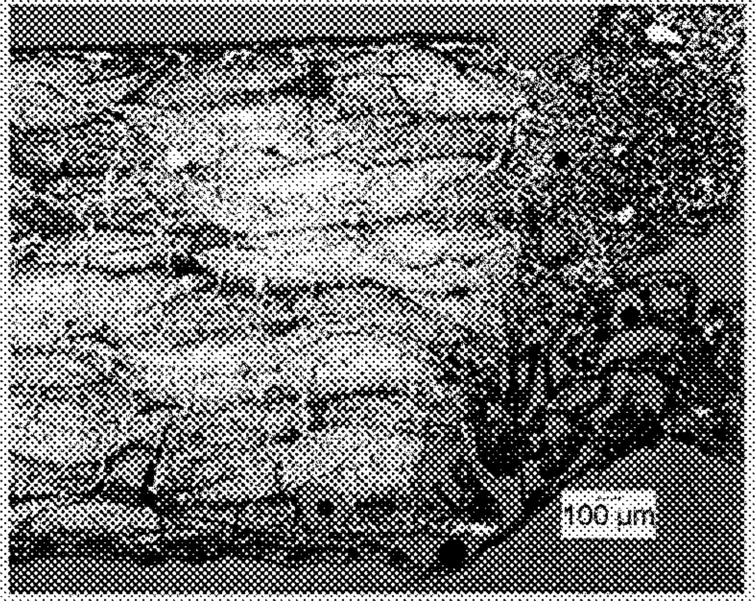
Front side

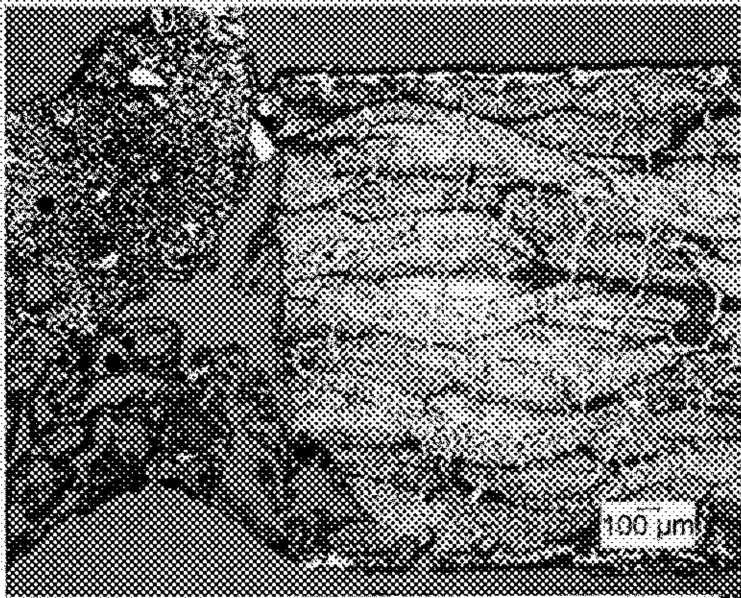
Crack filled with Graber material

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



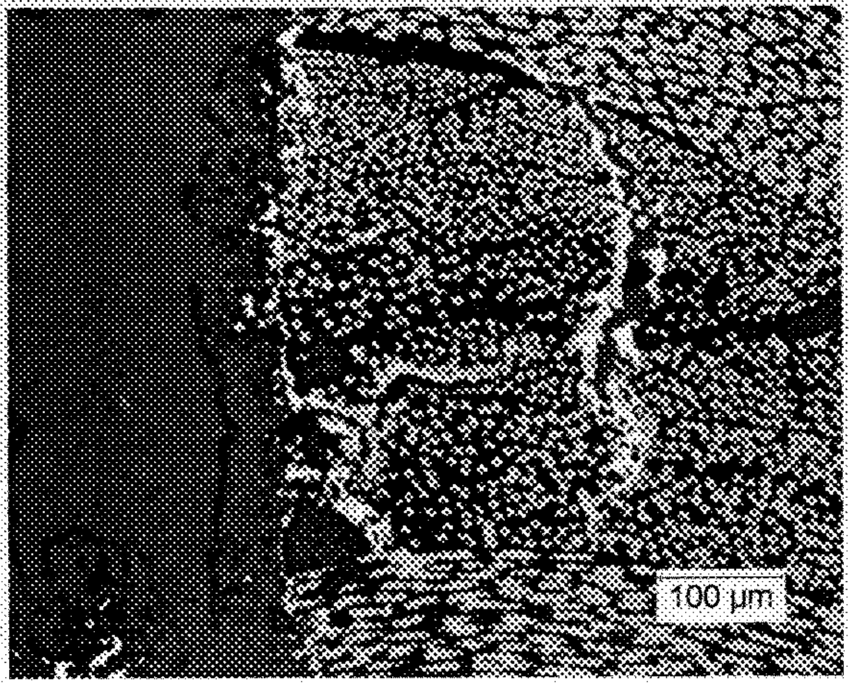
Front Side

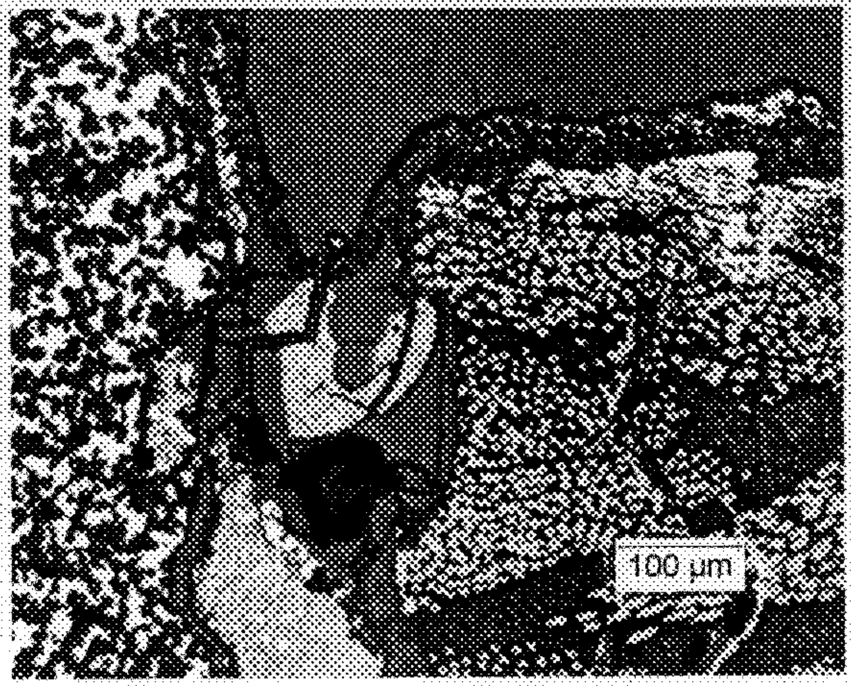




It appears in this sample that oxidation has reached an advanced stage. There is only a skeleton left of the Graber material which appears to be a glassy phase.

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

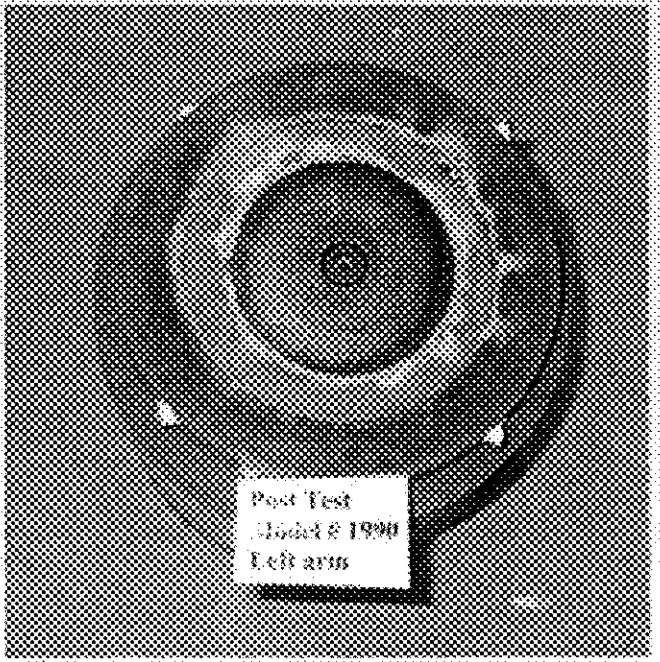




These higher magnification images show more clearly the glassy phase left of the Graber material. You can also see the degradation of the C/C material.

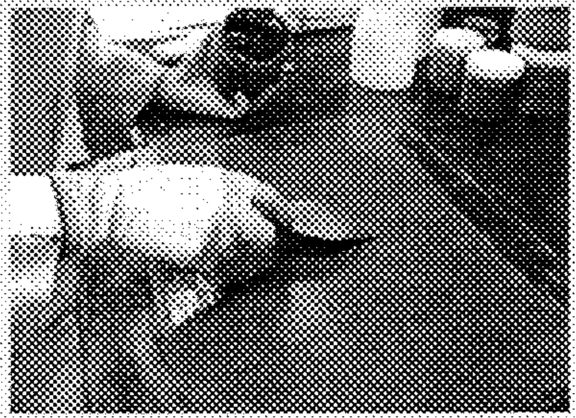
Patch Laminates and Sealant Technology for Exterior Repair (PLASTER)

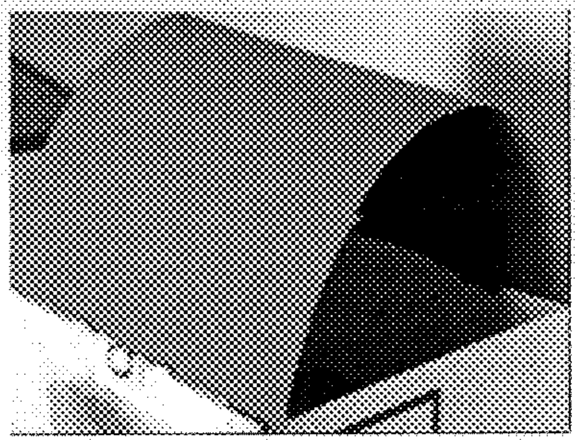
Sealant Technology Development



- Analogue RCC Plug Sealed with GRABER 5A Crack Sealant
- Survived the ArcJet Testing at JSC

Flexible Ceramic Overwrap Technology





Laminates for Patches and Overwraps

Summary and Conclusions

- **GRABER-based materials have multiuse capability and multifunctionality for a wide variety of repair applications.**
- **This system can be easily modified to obtain adhesive materials with desired properties (viscosity, composition, curing behavior, etc.).**
- **The material has long shelf life. Normal storage and handling techniques can be used.**
- **These materials are affordable since the cost of raw constituents is very low (few dollars a pound)**
- **Excellent plasma performance in ArcJet testing conditions at various facilities.**

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  - Mike Effinger, Mike Terry
- **Ames Research Center, CA**
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- **ATK Thiokol**
  - Dean Lester and Plasma Torch Testing Staff

Additional Information about GRABER

- ON-ORBIT SHUTTLE REPAIR TAKES SHAPE, www.aiaa.org/aerospace/images/articleimages/pdf/Iannottaaugust04.pdf
- NASA One Step Closer to Shuttle Repair in Orbit, New Scientist, May 22, 2004, 24, www.newscientist.com
- Nepszabadsag Online, www.nol.hu
- NASA Glenn Working to get shuttle flying, The Plain Dealer, www.cleveland.com, October 21, 2004.
- www.grc.nasa.gov/WWW/MDWeb/hilights/HCY2004.html
- NASA - Making the Space Shuttles Safer: Return To Flight Efforts, www.nasa.gov/centers/glenn/projects/RTF_summary.html