Unlocking the Mystery of Columbia’s Tragic Accident Through Materials Characterization

Presented to Mississippi State University Materials Working Group

By Dr. Sandeep Shah
Gregory Jerman
James Coston

October 15th, 2003

Acknowledgement: This work is a result of a team effort involving KSC, JSC, MSFC, LaRC, GRC, Boeing, USA and Columbia Accident Investigation Board personnel.
IN MEMORY OF STS-107 ASTRONAUTS
Space Shuttle Columbia In Orbiter Processing Facility (OPF) and Rollout to Vehicle Assembly Building (VAB).
Shuttle Landing Facility Hangar Prior to Debris Recovery
STS107 Reconstruction - Wing and Underbelly Surfaces Only

Right Wing

Left Wing

Aft

Forward
Location of each part found tracked on map - Trend emerges.
Believed to be Left Wing Main Landing Gear Assembly
Part Adjacent to Left Main Landing Gear Door
Wing Leading Edge RCC panels 1-22

RCC staging area

Xo1040-Xo1191 MLG Wheel Well Area

Left Wing Leading Edge Recovered Parts – Panels 1-22
Parts Recovered and Location or Potential Location – Underbelly View

Every part numbered and tracked in database. Location of each part found tracked on a map.
M&P Organizational Structure

- Hardware Forensics Team – “Gray Beard” members from Boeing, NASA Langley, NASA Johnson.
  - Evaluate Debris
  - Interact, disseminate and apply findings with other working groups (reconstruction, scenario, fault tree, etc.)
  - Direct specific Failure Analysis. Participate in determining Cause of Failure.

- Materials & Processes Problem Resolution Team.
  - Establish procedures – sample extraction, cleaning…
  - Interface with Hardware Forensics Team.
  - Generate Failure Analysis Plans.
  - Execute Failure Analysis Plans. Provide “Concrete Data”
  - Members included Boeing, USA, NASA KSC, NASA JSC, NASA MSFC, NASA GRC
When and Where to Begin Failure Analysis?

- Complex and Challenging Analysis.
- New material added weekly.
- Parts originally located could move as more parts are received.
- Where to Begin? What Questions to ask?
- How many parts to analyze?
- Who to and how to prioritize Failure Analysis?
- How to distinguish between damage in flight vs free fall and impact.
- Initial Constraint – Perform all analysis locally at KSC. Parts could not be sent outside even to other NASA centers.
- CAIB owned the hardware. NASA only in support role.
- Every step/analysis/procedure required documentation through approval from CAIB and NAIT.
When and Where to Begin Failure Analysis?

- Breach suspected in Left Wing.
- Begin with Factual Observations (Fact Sheets)
- Let Factual Observations guide the initial analysis.
- Initial Failure analysis included Left Wing:
  - Midbody Panel
  - Main Landing Gear Strut
  - Uplock Rollers
  - Tires
  - Leading Edge Carrier Panel Fastners
  - Tiles
  - Leading edge RCC material deposit
- M&P Failure Analysis Leads were assigned for each
Highest Level Questions

• Where (location in vehicle) did breach(es) occur?
• What specific component(s) failed and how?
• What was the sequence of events?
Initial Failure Scenarios and Breach Locations – April 14\textsuperscript{th}, 2003
Scenarios Team
Key Finding

• MADS/OEX Data Recorder Found—“black box”.
• Key thermocouple inside and outside left wing leading edge panel 9.
• Temperature in this location starts increasing prior to early debris observations.

Spotlight/focus shifts to Left wing leading edge damage
Dynaflex insulation – In601 foil with cerachrome fibers inside

RCC panel

RCC rib

Spanner Beams

Closeout/Carrier Panels and Tiles

Legend:
- RCC
- Aluminum
- LI2200
- LI900
- Inconel-Dynaflex
- Inconel 718
- A-286 steel
Left Wing Leading Edge Heat Damage Observations

- Heavy "Slag" deposits on select RCC panels.
- Eroded and knife-edged RCC rib sections.
- Excessive overheating and slumping of carrier panel tiles.
- Missing or molten attachment bolts but intact bushings.
- Deposit mainly on "inside" RCC panel.
- Deposit on some fractured RCC surface.
Qualitative Deposition Assessment:
“Very Light” to “Very Heavy”

Distribution of “slag” deposition volume was centered around panels 8 & 9 on Left Wing Leading Edge RCC.
Example Debris, LH RCC 8

SLAG Deposit on “INSIDE” RCC
High Level Questions

Sample the slag deposits on RCC & Tiles to:

- Identify the location of breach in the wing leading edge.
- Identify the sequence of deposition/events
- Understand plasma flow direction and related thermal damage.
Analysis Plan Challenges

- Understand Pros and Cons of Analysis Techniques (destructive and non-destructive)
  - Objective is to downselect analysis techniques fast.
- What are the leading edge materials?
- Understand Chemistry of reactions with atmospheric elements.
- Understand effects of melting and mixing of different materials.
- All analysis to be complete by end of May, 2003. Wrap-up in June.
## Analysis Techniques

<table>
<thead>
<tr>
<th>Analysis Technique</th>
<th>Purpose</th>
<th>Why/Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photography</td>
<td>Photo documentation</td>
<td>Documentation to maintain traceability</td>
</tr>
<tr>
<td>Scanning Electron Microscopy – SEM/EDS</td>
<td>Semi-quantitative elemental composition</td>
<td>Elements present, identify difference between top and bottom of sample</td>
</tr>
<tr>
<td>X-ray Diffraction - XRD</td>
<td>Identify compounds</td>
<td>Identify compounds of crystalline structure</td>
</tr>
<tr>
<td>Electron Microprobe</td>
<td>Identify elements</td>
<td>Determine exact composition</td>
</tr>
<tr>
<td>Fourier Transform Infra-Red - FTIR</td>
<td>Qualitative organic composition</td>
<td>If organic, aid in identification</td>
</tr>
<tr>
<td>ESCA/XPS</td>
<td>Identify inorganic &amp; organic compounds</td>
<td>Aid in tracking of oxidation states, such as oxide; compound identification</td>
</tr>
<tr>
<td>Metallography + SEM</td>
<td>Layering of material</td>
<td>Composition through deposit layers</td>
</tr>
<tr>
<td>Inductively coupled plasma - ICAP</td>
<td>Quantitative elemental composition</td>
<td>Elements present, Quantify bulk composition of sample</td>
</tr>
<tr>
<td>NDE Inspections-Radiography, CT, Ultrasonics</td>
<td>Non-destructive Inspection and identification</td>
<td>See through the material, identify differences in materials, identify defects</td>
</tr>
</tbody>
</table>

Repeatability and Reproducibility of results emphasized
Approach and Downselection of Analysis Techniques

• Radiograph RCC panels & Tiles
• Strategically locate samples - minimize the sample count. Two samples of each feature.
• Use diagnostic techniques (X-section, SEM, Microprobe, XRD) to identify:
  – Content of slag
  – Layering of slag
• Use “Interpretation Criteria” to correlate deposit analysis $\Longleftrightarrow$ WLE source material

Apply results to ALL radiographs and visual features to answer the high level questions.
X-ray Image

Hardware

Left Wing RCC panel 8. Inside View.
2200, LH RCC #8 Upper Apex, Part I, Matches 18477
Interpretation Criteria - Examples

• **How to identify specific alloys in the deposit?**
  - A286 or IN601, IN718, IN625 can be distinguished based on (Ni/Fe) ratio and evidence and amounts of Mo, Nb, Co and Ti.
  - 2024 can be identified by presence of metallic Al + Cu, Al$_2$O$_3$ + Cu.

• **How to identify Cerachrome in deposit?**
  - Cerachrome is approximately 43%Al$_2$O$_3$ 53%SiO$_2$ 3%Cr$_2$O$_3$.
  - It can be identified from a combination of back-scattered imaging, color, x-ray diffraction and presence and quantification of Al, Si, O, & Cr.

• **How to identify SiO2 from Tile?**
  - SiO2 from tile will not have with other elements as in cerachrome. It could still pick up a coating of alumina then morphological features will be used to distinguish.
MSFC Contribution

- Help Organize, Plan, and Co-ordinate all sampling activity.
- Metallography, Microprobe, & SEM.
- Generated 1000 pages of data & reports in 6 weeks.
LH WLE Analysis

*Sample Locations

- RH 37770
- RH 37770
- RH T
- RH 6
- RH 7
- RH 8
- RH 43709
- RH 18477
- RH 61143 Side Rib

55083 not shown
Mates 37770

31985

2200
LH RCC #8 - Slag Feature 1
Thick Tear Shaped

Slag Item 43709, Sample 2A1

Radiograph of Item 43709
LH RCC #8 - Slag Feature 2
Thick Globules

Slag Item 2200, Sample 6A1

Radiograph of Item 2200
LH RCC #8 - Slag Feature 3 Spheroids

Slag Item 2200, Sample 6C1

Radiograph of Slag Item 2200
RH RCC #8 - Slag Feature 4
Uniform Deposit

Slag Item 16523, Sample 4A1

Cerachrome+Aluminum+Inconel+Alumina
Aluminum+Inconel+Cerachrome+Type A Coating
SiC
Carbon-Carbon

Radiograph of Item 16523
RCC Slag Significant Findings
LH RCC #8

- Large amounts of melted ceramic cerachrome insulator
  ➢ High temperature >3200°F
- No indication of stainless steel spar fittings (A286) in slag
  ➢ Breach location away from spar fittings
- Cerachrome + Inconel in first deposited layers
  ➢ Melting of spanner/foil/fittings + Insulator
- Aluminum deposition secondary event

Slag layering suggests plasma impingement location

Slag distribution & shape suggests plasma flow direction and deposition duration
RCC Slag Significant Findings
- All RCC other than LH RCC #8
  - Including RH RCC panels

- All analyzed slag layers contain aluminum
  - CONCURRENT Spar/Inconel/Insulator melting

- Slag is generally uniform and relatively thin
  - No region where melting was concentrated i.e. plasma heating for short periods
Reconstructed View
LH CPanel 9 Tiles, lower

Horse Collar Fabric Deposit
Insert
Tile Slumping

# 57754  # 22571  # 50338  # 16692

Molten Slag on Tile

Realtime X-ray, Sidewall View

Carrier Panel
High-Z material
Reconstructed View
LH Carrier Panel 9  Tiles, Lower Slag Analysis Results

These findings suggest flow of material from inside the RCC out through the upper and lower CP locations.
Proposed Breach Location & Plasma Flow Based On Slag Results

Flow Exiting through RCC 8 on to lower Carrier Panel 9 tiles