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Produced by the NASA Center for Aerospace Information (CASI)
Nondestructive Testing As a Tool in the Space Shuttle Columbia Accident Investigation

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Abstract

Nondestructive testing (NDT) played a crucial role in determining the Columbia tragedy's cause. Over 84,000 pieces of debris were recovered; hundreds were subsequently subjected to NDT and materials analysis.

Visual NDT of the debris revealed localized areas of damage such as erosion, excessive heating, knife edging and mechanical damage.

Three-dimensional reconstructions were made of the left wing leading edge, utilizing a tripod-mounted laser scanning head and focused laser beam, and an advanced topometric optical scanner (ATOS) with digital white light to scan complex-shaped debris, producing monochrome 3-D models. Texture mapping provided a means to capture true colors of the debris and superimpose them on the scanned images.

Uniform deposits were found over large portions of debris, obscuring underlying materials. To determine what was beneath, inverse radiography was enlisted. The radiographs guided investigators to where samples should be taken. To ascertain compositions, these samples were subjected to analytical testing, including energy dispersive X-ray spectroscopy and electron microprobe analysis.

This combination of visual evidence, radiography, virtual reconstruction, and materials analysis allowed the forensic scientists to verify that a breach occurred in the leading edge of the left wing, the path the plasma followed, and the sequence of events that led to the loss.

1. Introduction

The role of nondestructive testing (NDT) in helping to determine the cause of the Columbia tragedy was significant. The disintegration of the vehicle began while the orbiter was travelling in excess of Mach 18, with an altitude of 208,000 feet/63 km; the
combination of altitude and velocity resulted in a debris field over 645 miles/1,038 km long and 10 miles/16 km wide. Of the 84,000+ pieces of debris recovered, hundreds of remnants considered of particular interest were subjected to NDT, specifically radiography, visual and macroscopic examination, focused laser scanning and topometric optical scanning.

2. Analysis

2.1 Visual NDT

Visual NDT of the debris revealed localized areas of unique damage, such as erosion, excessive heating, and knife edging, as well as mechanical damage (Figure 1). The erosion, heating, and knife edging were results of the extreme re-entry of the Columbia; the mechanical fractures generally resulted from either impact with other pieces of debris on descent or impact with the ground.

![Figure 1](image.png)

Visual Examination of *Columbia* Left Wing Leading Edge Panel Piece Showing Evidence of Erosion, Excessive Heating, and Mechanical Damage (right) and Knife Edging (left).

2.2 3-Dimensional Reconstruction

The evaluation and examination of the debris was not limited to the Kennedy Space Center. Experts from across the United States, in addition to experts from across the world, contributed to the effort. In order for scientists and engineers at remote sites to examine the debris, a three-dimensional reconstruction was performed of the leading edge of the left wing. Two scanning methods were utilized during the 3-D reconstruction. First, a tripod-mounted laser scanning head that projected a focused laser beam to image the object was primarily used to scan skin panels and thermal protection system (TPS) carrier panels. Secondly, an Advanced Topometric Optical Scanner (ATOS) used digital white light to scan objects and was used for debris with complex shapes requiring higher definition (Figure 2). Although the combined processing
produced a 3-D model of a scanned object, the object’s surface was monochrome. Texture mapping provided a means to capture the true colors of an object and place them on the scanned image. Texture mapping was achieved by taking a series of digital photographs from various aspects around the perimeter of the object and electronically mapping the photographs onto the scanned image (Figure 3).

Figure 2
3D Virtual Reconstruction of the Left Wing of Columbia

Figure 3
3D Reconstruction of the Left Wing of Columbia with Texturing and Color.
2.3 Radiography and Materials Analysis

As the samples were analyzed, a rather uniform deposit was found over a large percentage of the debris, obscuring any underlying material. In order to determine what was beneath the obscuring layer, the nondestructive method of radiography was enlisted. For ease of comprehension and interpretation by those involved in the investigation who were not well versed in interpreting radiographs, the inverse radiographic response was employed. The inverse response is essentially a negative of typical radiography; while denser materials appear lighter and less dense materials appear darker in typical radiography, the opposite holds true in inverse radiography. Therefore, denser constituents appeared darker and less dense materials appeared lighter (Figure 4).

![Image](image)

Figure 4
Inverse Radiograph of a Left Hand RCC Upper Apex Displaying Three Distinct Deposition Types and Locations

The radiographs guided investigators to locations that had underlying materials deposited. Samples were located, removed, and subjected to analytical testing to ascertain the chemical composition of the deposits. Analytical techniques included energy dispersive X-ray spectroscopy (EDS) and electron microprobe analysis (EMPA). The EDS analysis provided semi-quantitative X-ray dot maps of the samples. The dot maps gave an overall idea of the layering sequence and rough composition; EMPA yielded truly quantitative compositions of the depositional layers.

3. Conclusions

The combination of visual evidence, inverse radiography, virtual reconstruction, and chemical analysis allowed the forensic scientists to verify not only that a breach had occurred in the leading edge of the orbiter's left wing, but also the path the plasma followed (Figure 5), and the sequence of failure events that ultimately led to the loss of the Columbia.
Since the shuttle fleet returned to flight in 2005, several condition monitoring upgrades have been implemented. Sixty-six accelerometers, recording over 20,000 measurements per second, were placed in each wing to detect impacts during launch and to evaluate the magnitude of any strike. Additionally, twenty-two temperature sensors were placed in each wing leading edge to help measure the heat of the wings’ interiors and to determine heat flow. An Orbiter Boom Sensor System laser-scanner allows on-orbit observations and evaluations of previously unreachable locations on the orbiter. Since shuttle flights must now be able to dock with the International Space Station (ISS) *Alpha*, as the orbiter approaches the ISS, the station crew uses digital cameras and high-powered lenses to photodocument the visiting orbiter’s thermal protective tiles, as well as several additional vital regions, such as its main and nose landing gear doors. These images are then sent back to Earth, where a team of two hundred digital imagery experts analyze the data. One final monitoring improvement is the implementation of the Rendezvous Pitch Maneuver, wherein just prior to docking with the ISS, the shuttle rotates end over end at a rate of 3/4 degree per second; this way the ISS crew members can photograph the underside of the visiting orbiter in detail. All these measures, taken both individually as well as in concert, help ensure that the remaining flights of the shuttle fleet are as safe as possible. Ultimately, the information learned during the course of the shuttle program will be transferred to NASA’s next generation of space vehicles, helping to minimize the likelihood of future *Columbia*-type mishaps.
Emphasis Placed on Left Hand Wing Leading Edge

- Evidence of extreme overheating and heavy deposits on specific WLE hardware appeared to correlate with the instrumentation and sensor data.

- To validate proposed break-up scenarios under consideration the investigation was concentrated on three areas of interest associated with the Wing leading Edge Subsystem (LESS):
  - Carrier Panel Tiles
  - RCC Panels
  - Wing substructure attach hardware
Wing Leading Edge
LESS Observations

- Unique indications of heat damage:
  - Excessive overheating and slumping of carrier panel tiles
  - Eroded and knife-edged RCC rib sections
  - Heavy deposits on select pieces of RCC panels
# Left Hand Wing Debris Points to RCC 8/9

(\#) = Number of attach fitting bolts on the piece  
T = Tile piece, no structure  
F = Fitting with some RCC in it  
S = Spar only (metal, no RCC)

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**USA**  
United Space Alliance  
**Boeing**
Relative Metallic Deposition on L/H Wing Materials

Qualitative deposition assessment:
from "Very Light" to "Very Heavy"

Distribution of metallic deposition volume
was centered around panels 8 & 9
Slag Deposit Example, 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

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<tr>
<th>Analysis Technique</th>
<th>Purpose</th>
<th>Why/Advantages</th>
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<tbody>
<tr>
<td>Photography</td>
<td>Photo documentation</td>
<td>Documentation to maintain traceability</td>
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<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>
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<tr>
<td>X-ray Diffraction - XRD</td>
<td>Identify compounds</td>
<td>Identify compounds of crystalline structure</td>
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<tr>
<td>Electron Microprobe</td>
<td>Identify elements</td>
<td>Determine exact composition</td>
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<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>
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<tr>
<td>Metallography + SEM</td>
<td>Layering of material</td>
<td>Composition through deposit layers</td>
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<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>
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Repeatability and Reproducibility of results emphasized
Analysis Approach

- 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 \(\leftrightarrow\) WLE source material

Apply results to ALL radiographs and visual features to answer the high level questions.
Radiographic Features

- Four types of deposit patterns were identified from LH RCC Panel 8:
  - Uniformly thick; Spheroidal; Tear-shaped; Globular
Radiography WLE LH Panel 8

X-ray Image

Hardware
LH RCC 8 Upper Apex
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, Al₂O₃ + Cu.

• How to identify Cerachrome in deposit?
  - Cerachrome is approximately 43%Al₂O₃, 53%SiO₂, 3%Cr₂O₃.
  - 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.
LH RCC 8 – Slag Feature: Thick Tear Shaped

Slag Item 43709, Sample 2A1

Radiograph of Item 43709

USA
United Space Alliance

Boeing

SiC
Carbon-Carbon

+ Alumina + Inconel

Cerachrome
Inconel
LH RCC 8 – Slag Feature: Thick Globules

Slag Item 2200, Sample 6A1

Radiograph of Item 2200

USA
United Space Alliance
LH RCC 8 – Slag Feature: Spheroids

Slag Item 2200, Sample 6C1

Radiograph of Slag Item 2200

Alumina

Aluminum + Alumina + Inconel

SiC

Carbon-Carbon
LH RCC 8 – Slag Feature: Uniform Deposit

Slag Item 16523, Sample 4A1

Cerachrome + Aluminum + Inconel + Alumina

Aluminum + Inconel + Cerachrome + Type A Coating

SiC

Carbon-Carbon

Radiograph of Item 16523
Significant Findings - Sampling LH RCC Panel 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**
Significant Findings – Sampling All Other Panels

• Significant findings includes all LH RCC Panels except panel 8 and all RH RCC panels sampled

• 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
LH RCC Panel 9 Lower CP Tiles

Realtime X-ray, Sidewall View

Horse Collar Fabric Deposit

Insert

Tile Slumping

Molten Slag on Tile

Spar

RCC

Carrier Panel

High-Z material

# 57754

# 22571

# 50338

# 16692

NASA

USA

Boeing

(IML)
These findings suggest flow of material from inside the RCC out through the upper and lower CP locations.
Proposed Breach Location and Plasma Flow

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

Cerachrome Globules

Inconel Spheroids

Inconel Tears

>3200°F

Plasma

RCC
Aluminum
LJ2200
LJ900
Inconel-Dynaflex
Inconel 718
A-286 steel
Overall Forensic Conclusions

- Overall forensic assessment is consistent with M&P Team conclusions
- All forensic evidence suggests a breach occurred on the lower surface of the LH RCC panel 8, close to the T-seal with panel 9
- The breach was present early during reentry allowing the ingestion of hot gasses into the wing leading edge cavity, which continued for several minutes prior to vehicle breakup
- Sequence of events:
  - Melting and vaporizing the Inconel 601 foil-covered cerachrome insulation blankets
  - Slumping the wing carrier panel tile immediately aft of the breach
  - Eroding the RCC adjacent to, and downstream of, the breach
  - Melting and/or weakening the Inconel 718 and A286 leading edge attach hardware
  - Destroying the nearby instrumentation and wire bundles
  - Penetrating the aluminum wing leading edge spar
Conclusions

- The hot gasses, having flooded the wing interior, quickly heated the upper and lower wing surfaces allowing the aluminum honeycomb facesheets and the wing tiles to debond. The thin-wall aluminum truss tubes would soon collapse and the aerodynamic and structural integrity of the left wing would be effectively destroyed.

- The forensic evidence is consistent with the observed External Tank foam impact 81 seconds into launch. This is the most probable cause of the damage to the RCC leading edge.