Nondestructive Testing As a Tool in the Space Shuttle *Columbia* Accident Investigation

Steven J McDanels
NASA
Kennedy Space Center, Florida, 32899, USA
321.861.8969
321.867.1407
Steve.mcdanels@nasa.gov

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.

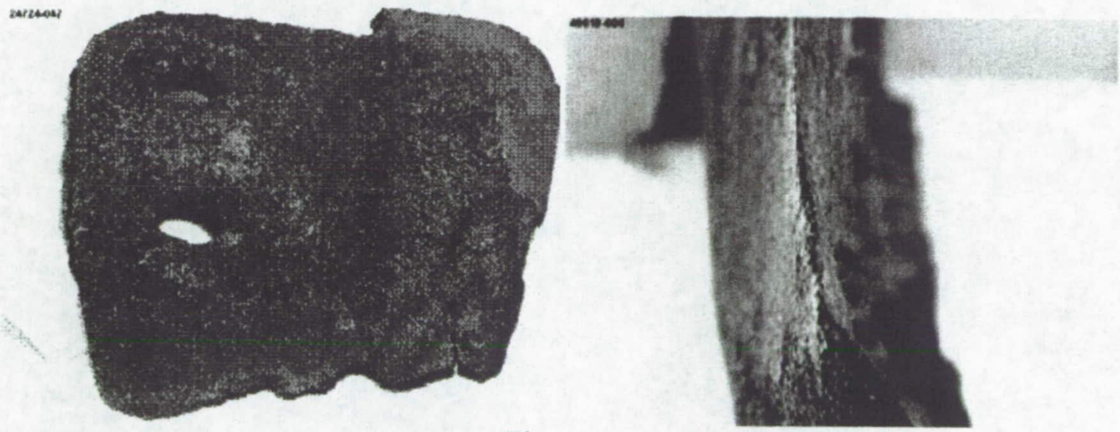


Figure 1
Visual Examination of *Columbia* Left Wing Leading Edge Panel Piece Showing Evidence of Erosion, Excessive Heating, and Mechanical Damage (right) and Knife Edging (left).

.

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).

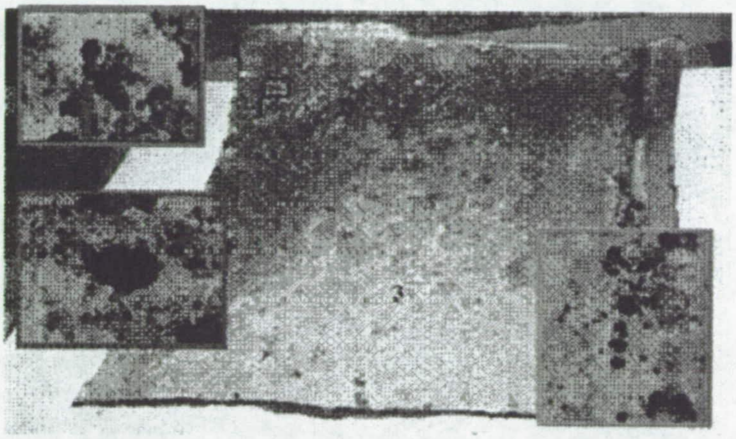


Figure 4
Inverse Radiograph of a Left Hand RCC Upper Apex Displaying Three Distinct Deposition Types and Locations

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*.

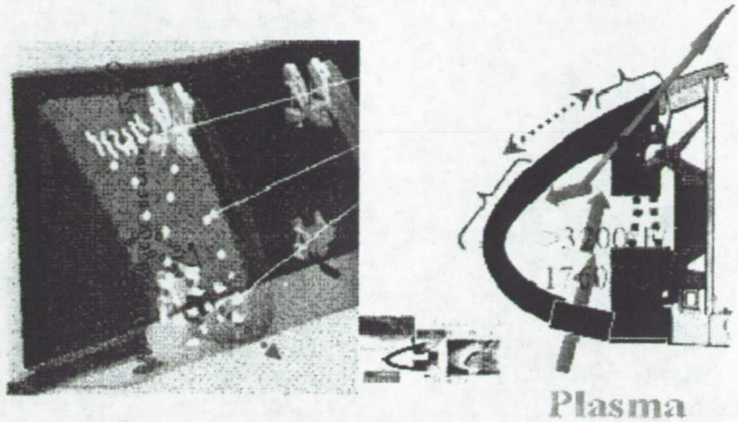


Figure 5
Schematic Representation of Events within the Left Wing Leading Edge of the Space Shuttle *Columbia*

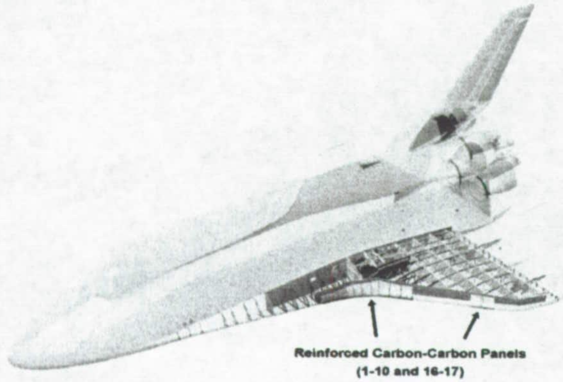
Since the shuttle fleet returned to flight in 2005, several condition monitoring upgrades have been implemented. Sixty-six accelerometers, recording over 20,000 measurements per second, were placed in each wing to detect impacts during launch and to evaluate the magnitude of any strike. Additionally, 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.

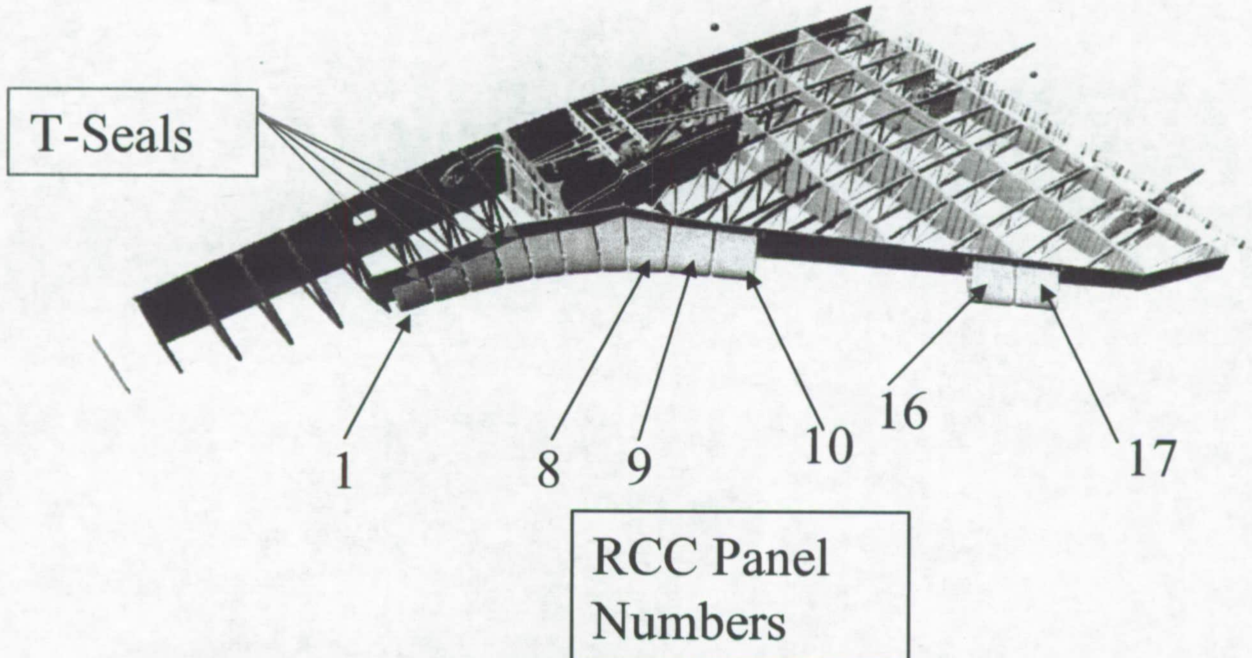
Emphasis Placed on Left Hand Wing Leading Edge

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

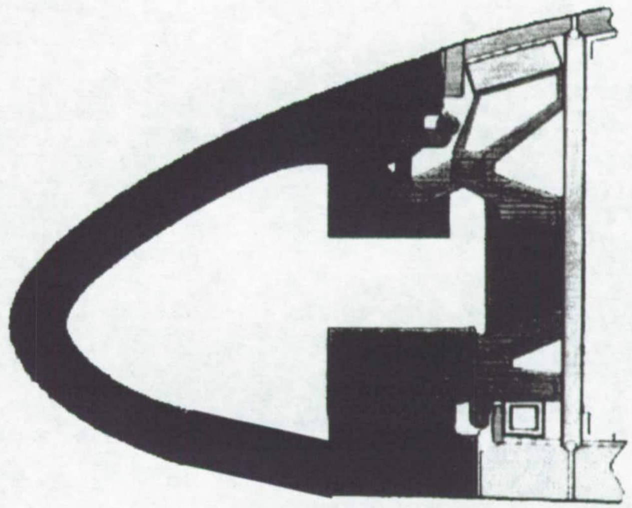
Wing Leading Edge

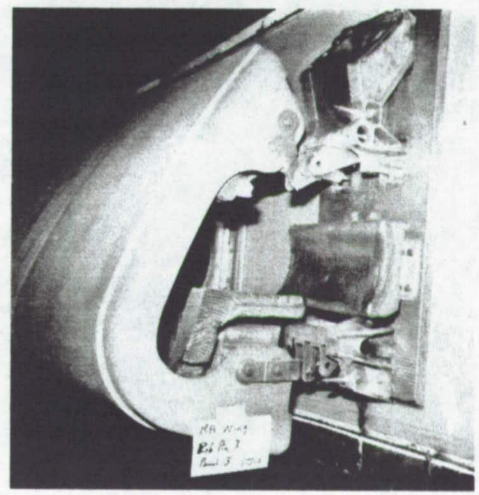




LESS Observations

- 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)

Upper C/P (Slump)

1	2	3	4	5	6	7	8	9	10	11
14906		19041	51033	21066	22510	50314	50386T			

Fitting

1	2	3	4	5	6	7	8	9	10	11	12
		853(4)	788(4)	54043 (4)	50950 (4)					12322 (4)	

T-Seal

1	2	3	4	5	6	7	8	9	10	11	12
	32171		24430 49830	17974	26229		22467 60875		63764		36492 38226

RCC (Slag / RCC attach holes intact / Erosion)

1	2	3	4	5	6	7	8	9	10	11	12
			L	L		M	H	H	M	L	
518 16563	2023F 52089 34389 1847 47937	47918 24736 32044 732	17969 29288 36519	54[illegible]9 57123 57135 36536 37770 55083 26009 36530 36512 24[illegible]2	32055S 59527 61137	31985 26014 23663	2200 17957 18477 43709	7025 27543 29741 49619 52018 61143	29233 34713 43388	34664 26027S	

Fitting

1	2	3	4	5	6	7	8	9	10	11	12
	717(2)	708(2) 431(2)		823	64805 (3)				9413 (2)		

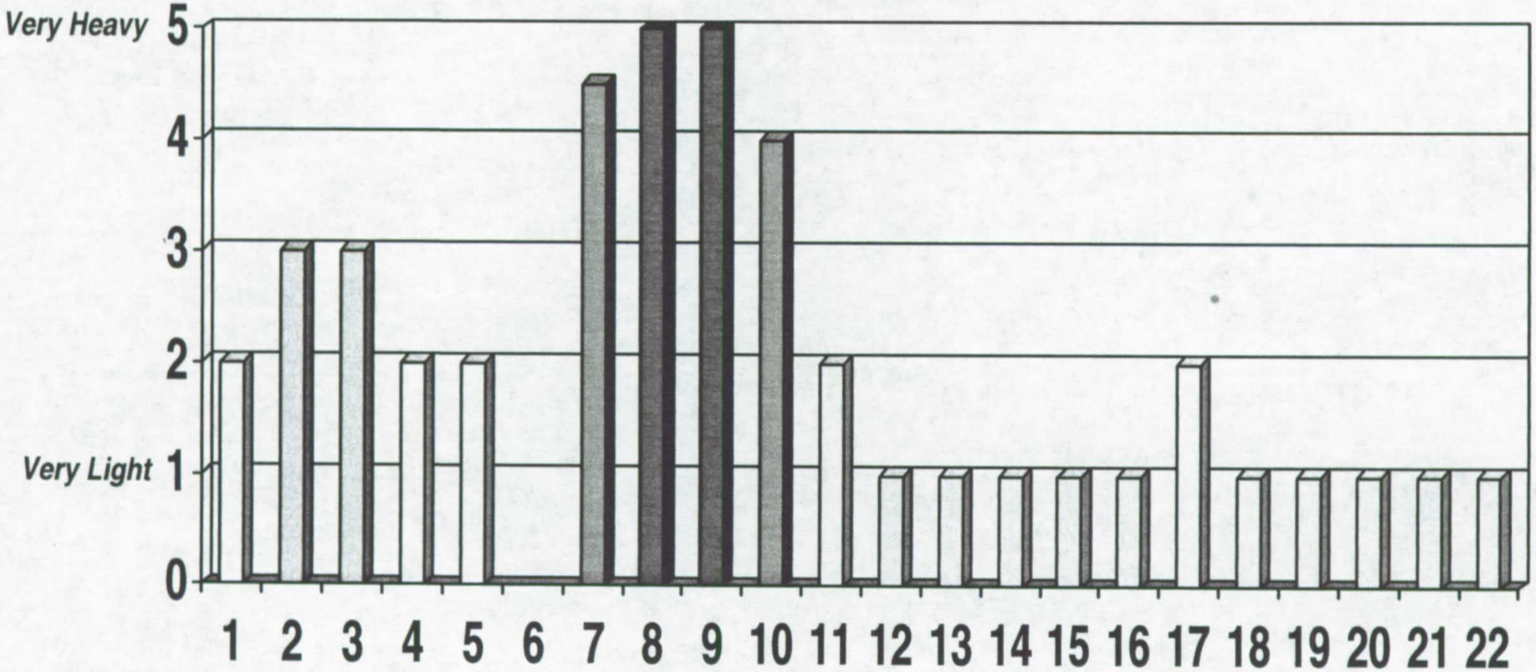
Lower C/P (Slump)

1	2	3	4	5	6	7	8	9	10	11
24086	24543	26022	24082 52885T 56168T		58297	1399 27589T	38991T 26569T	166921 225711	27563	108 24794T 48598T 51645T

USA
United Space Alliance
BOEING

Relative Metallic Deposition on L/H Wing Materials

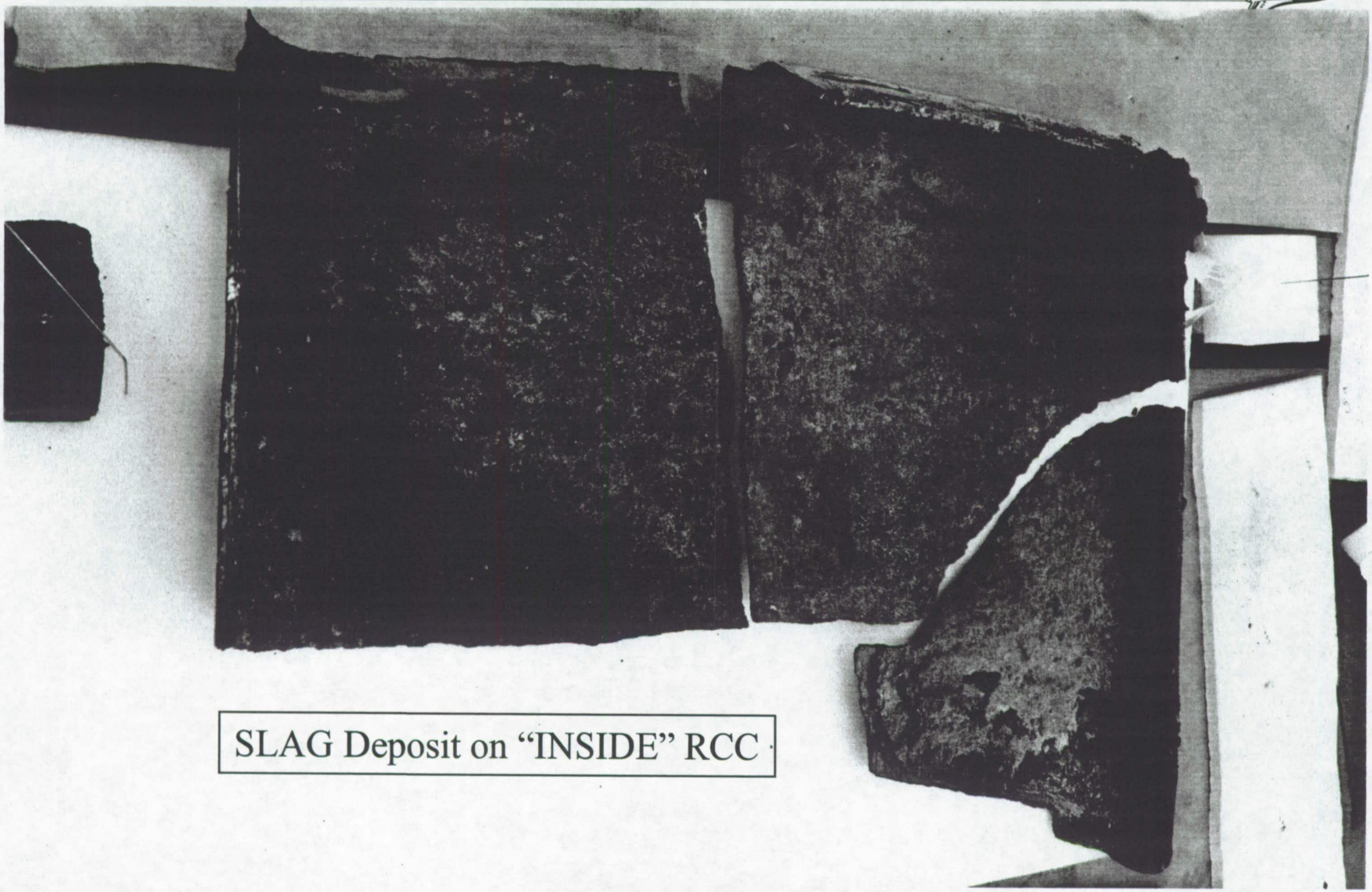
Qualitative deposition assessment:
from "Very Light" to "Very Heavy"



Distribution of metallic deposition <u>volume</u>
was centered around panels 8 & 9

NASA
USA United Space Alliance
BOEING

Slag Deposit Example, LH RCC 8



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

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

Repeatability and Reproducibility of results emphasized

Analysis Approach

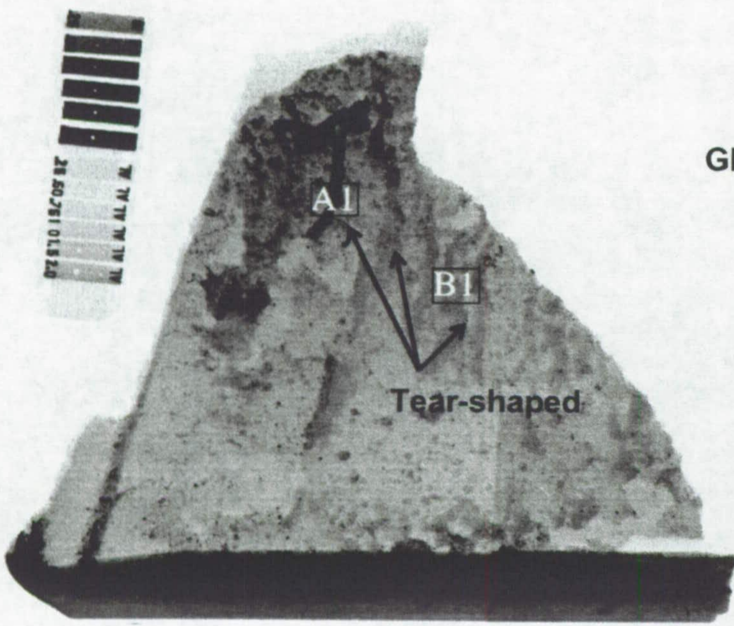
- Radiograph RCC panels & Tiles
- Strategically locate samples - minimize the sample count. Two samples of each feature.
- Use diagnostic techniques (X-section, SEM, Microprobe, XRD) to identify:
  - Content of slag
  - Layering of slag
- Use "Interpretation Criteria" to correlate deposit analysis <==> WLE source material

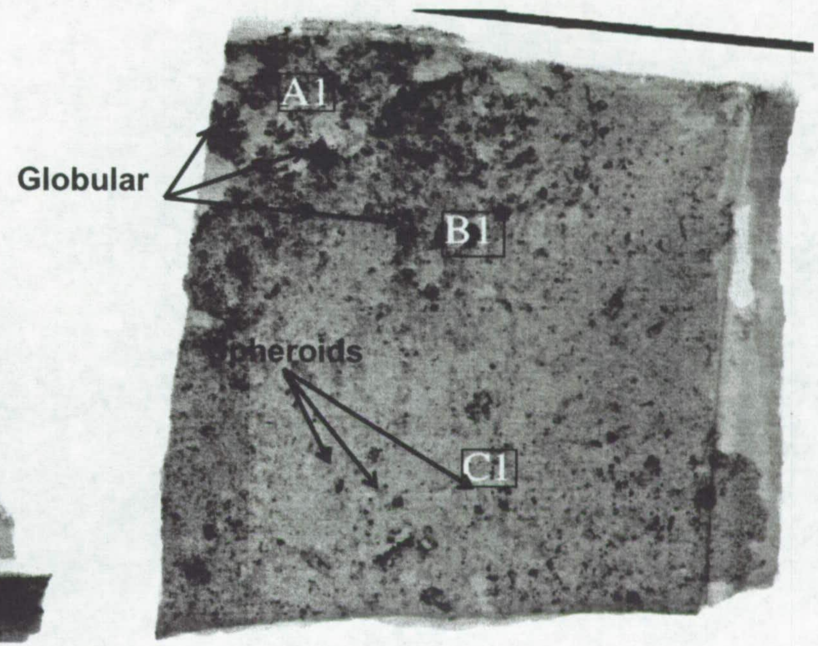
Apply results to ALL radiographs and visual features to answer the high level questions.

NASA USA United Space Alliance BOEING

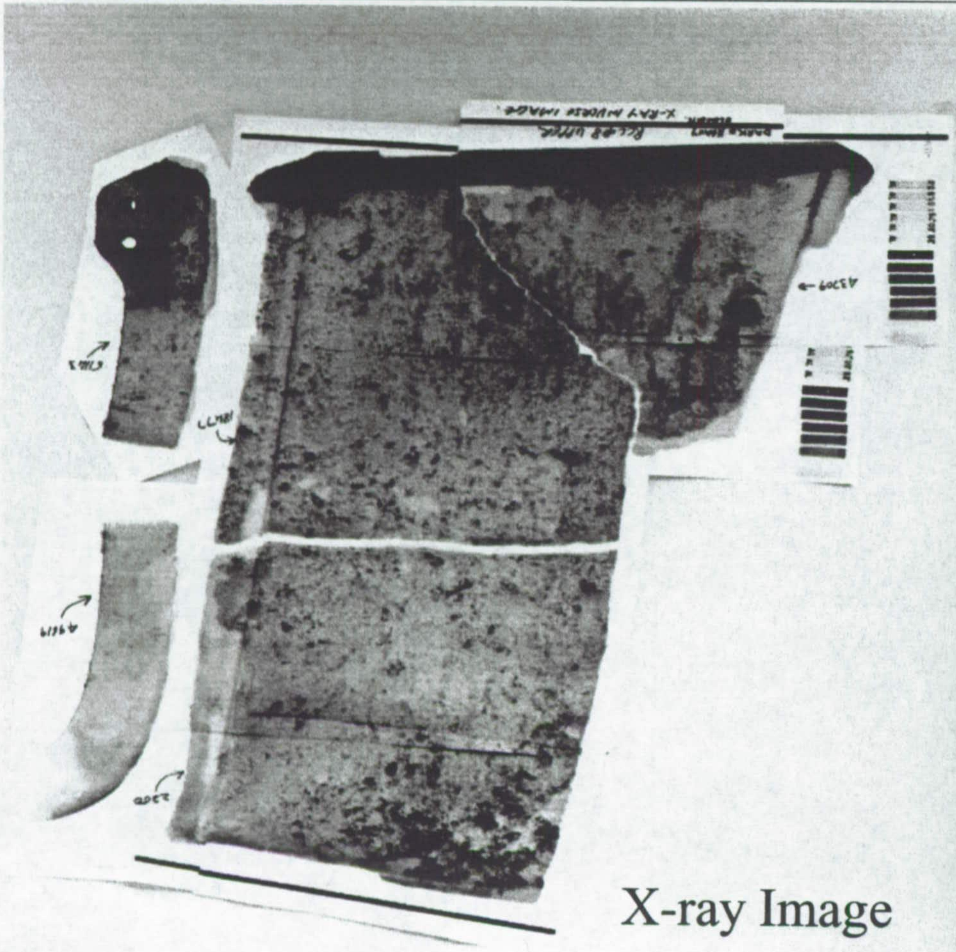
Radiographic Features

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

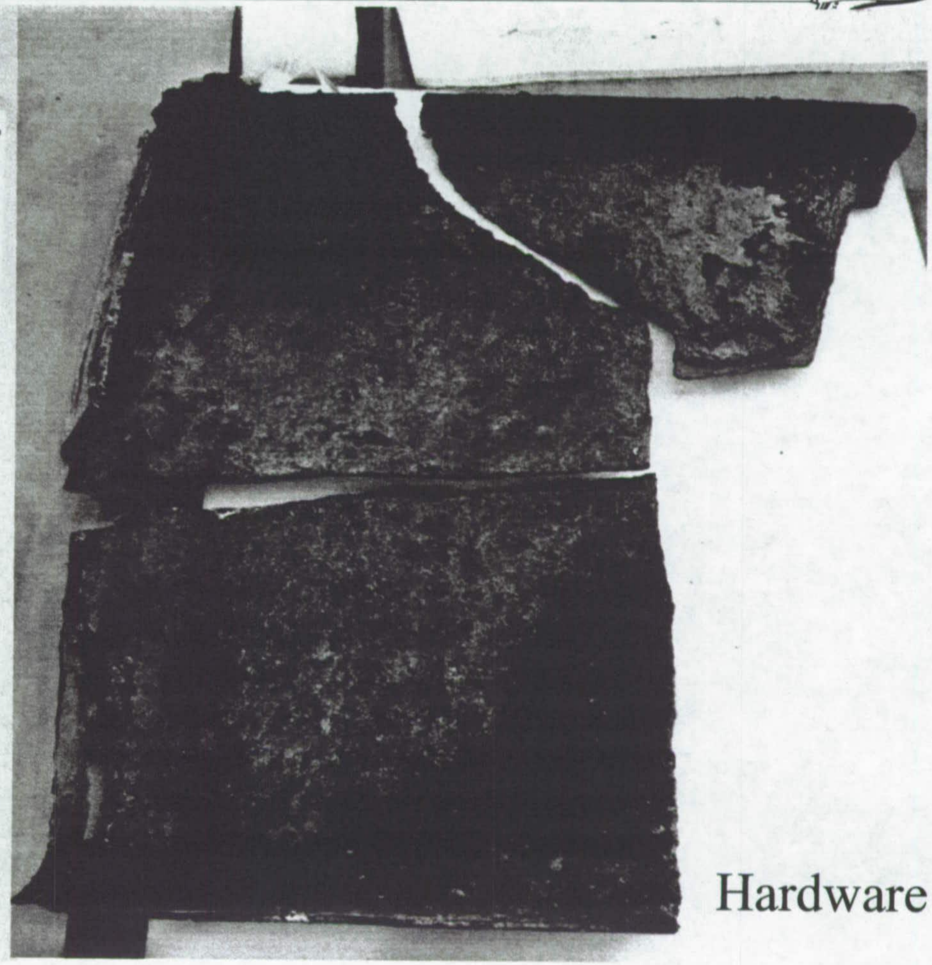




Radiography WLE LH Panel 8

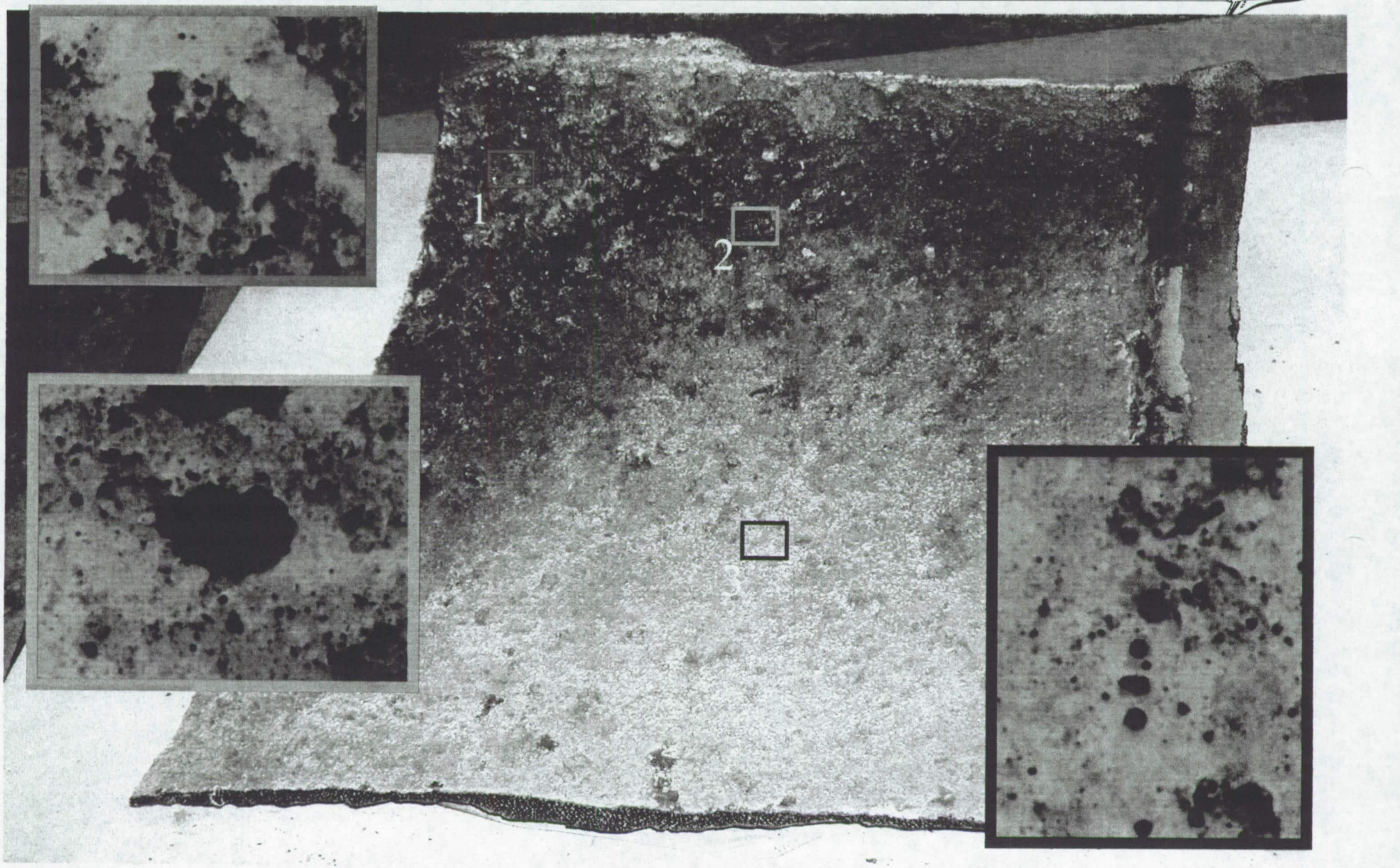


X-ray Image



Hardware

LH RCC 8 Upper Apex

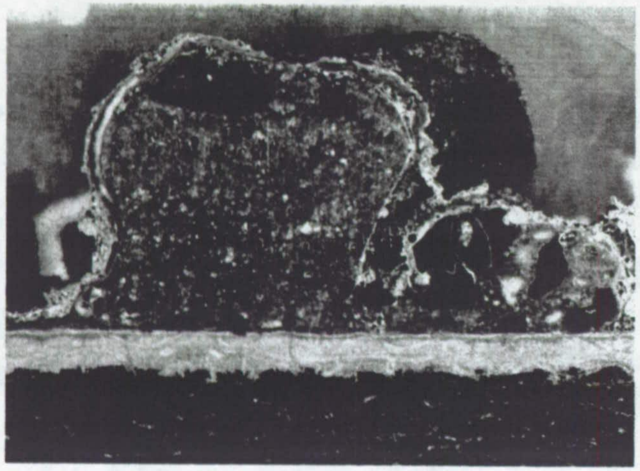


Interpretation Criteria - Examples

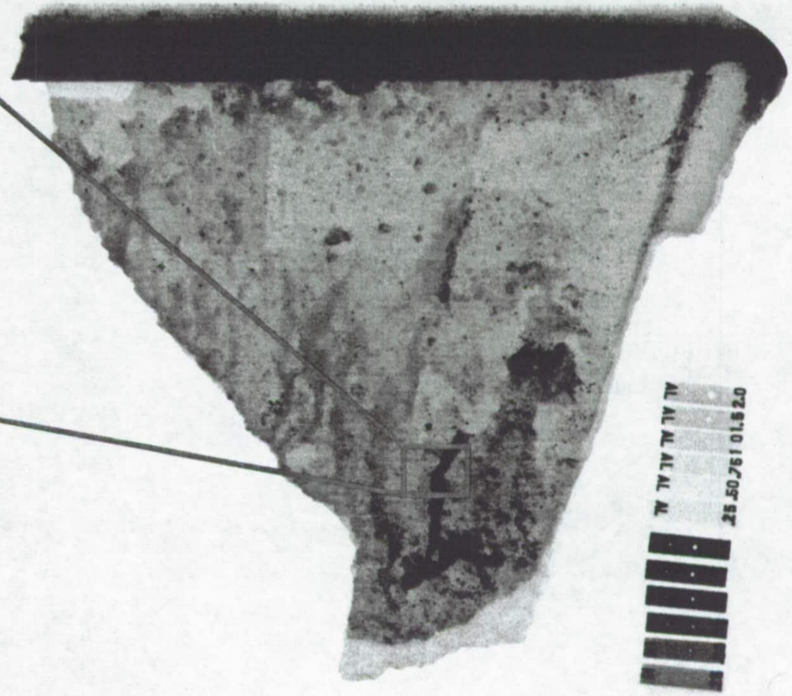
- **How to identify specific alloys in the deposit?**
  - A286 or IN601, IN718, IN625 can be distinguished based on (Ni/Fe) ratio and evidence and amounts of Mo, Nb, Co and Ti.
  - 2024 can be identified by presence of metallic Al + Cu, Al_2O_3 + Cu.
- **How to identify Cerachrome in deposit?**
  - Cerachrome is approximately 43%$Al_2O_3$53%$SiO_2$3%Cr_2O_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.

NASA USA United Space Alliance BOEING

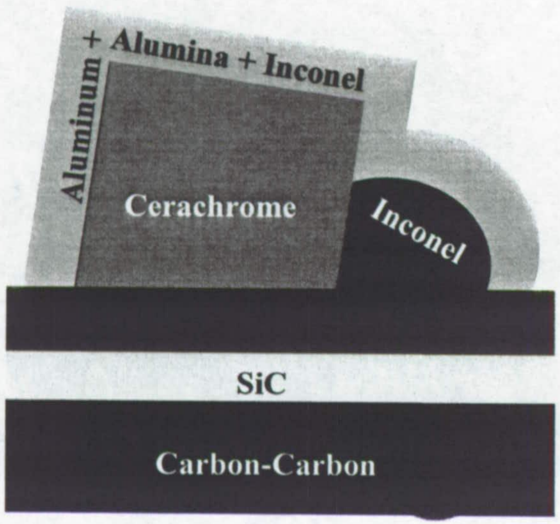
LH RCC 8 – Slag Feature: Thick Tear Shaped



Slag Item 43709, Sample 2A1



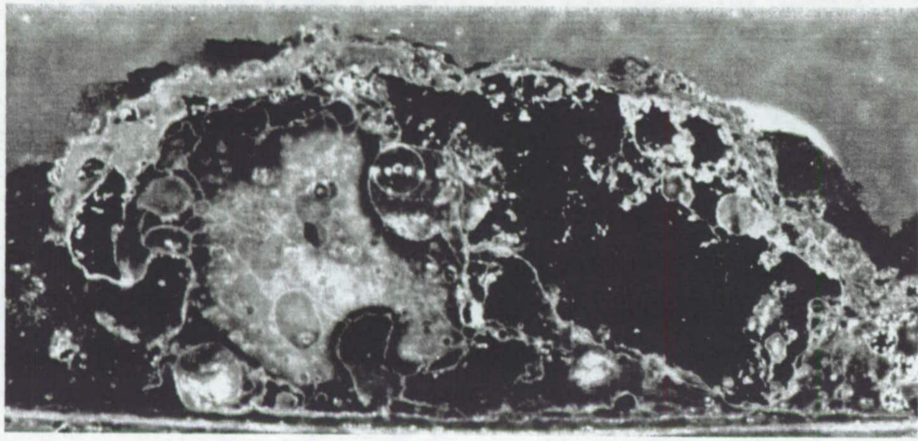
Radiograph of Item 43709



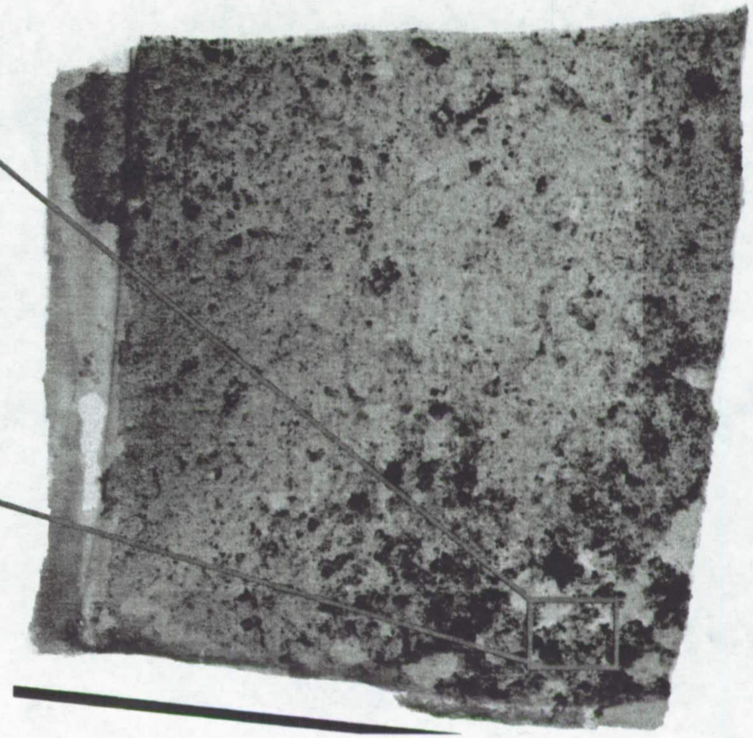
USA United Space Alliance

BOEING

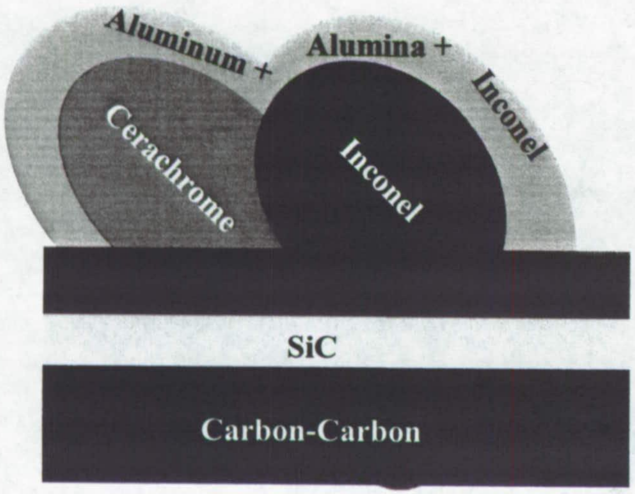
LH RCC 8 – Slag Feature: Thick Globules



Slag Item 2200, Sample 6A1



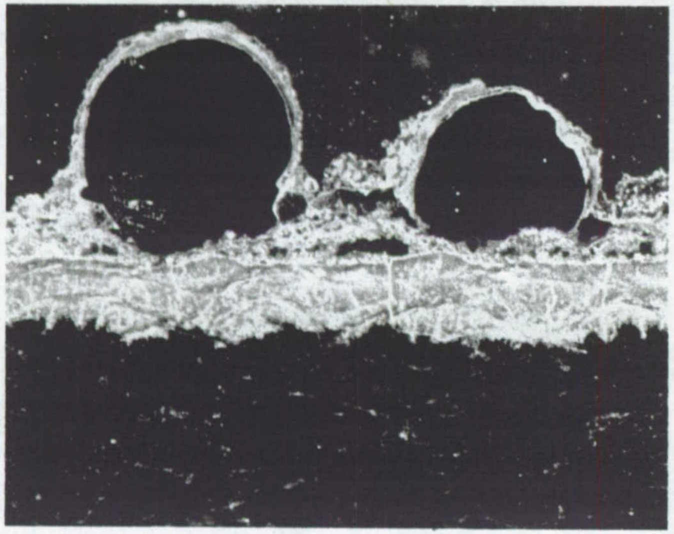
Radiograph of Item 2200



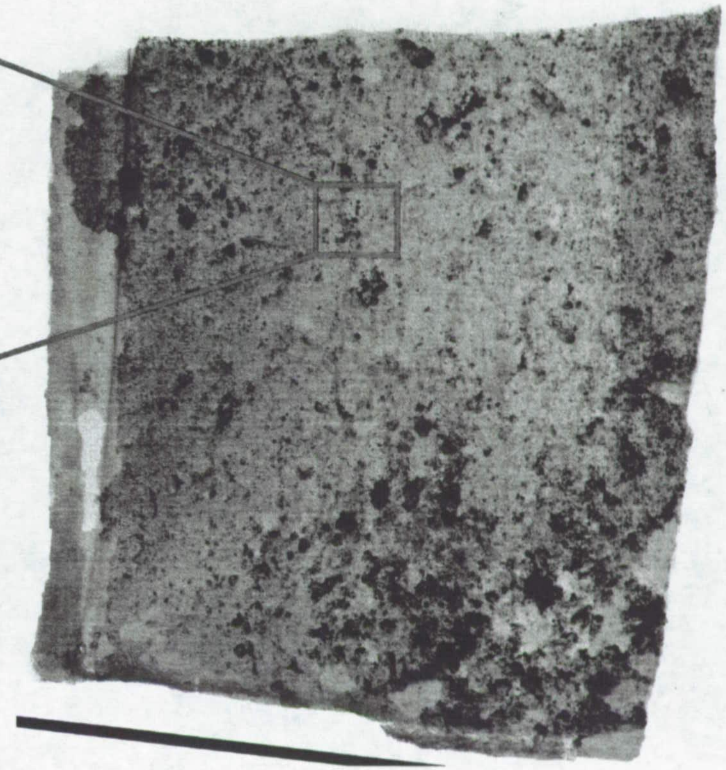
USA
United Space Alliance

BOEING

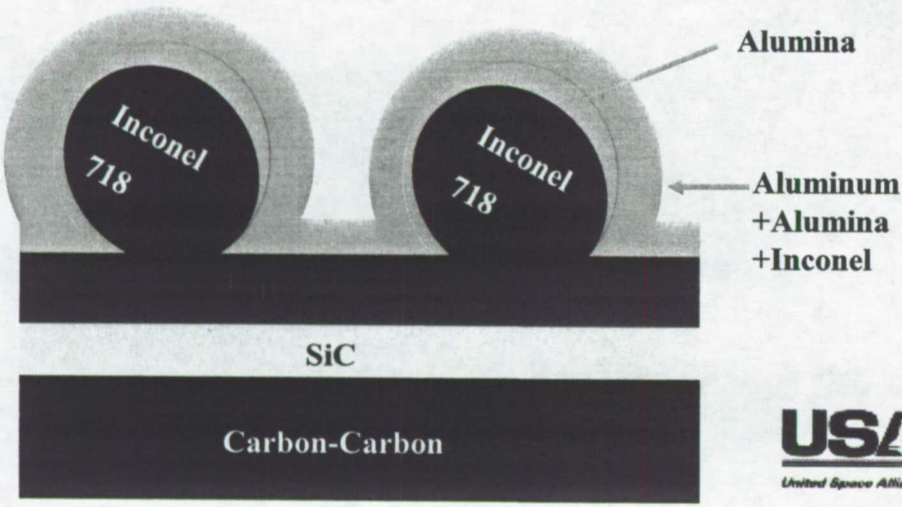
LH RCC 8 – Slag Feature: Spheroids



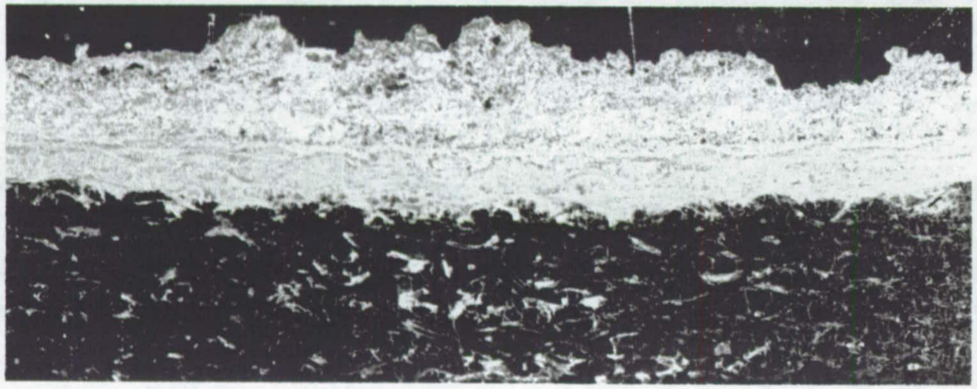
Slag Item 2200, Sample 6C1



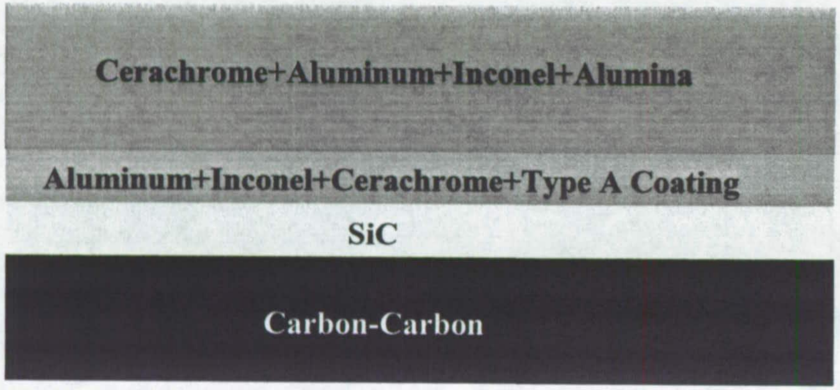
Radiograph of Slag Item 2200

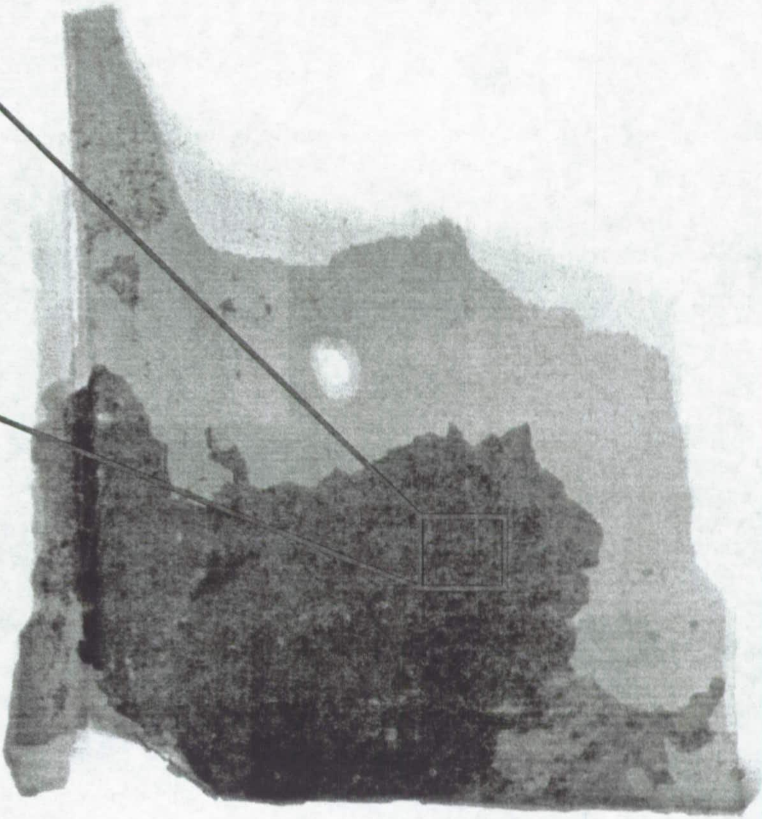


LH RCC 8 – Slag Feature: Uniform Deposit



Slag Item 16523, Sample 4A1





Radiograph of Item 16523

Significant Findings - Sampling LH RCC Panel 8

- Large amounts of melted ceramic cerachrome insulator
  - High temperature >3200ºF
- 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

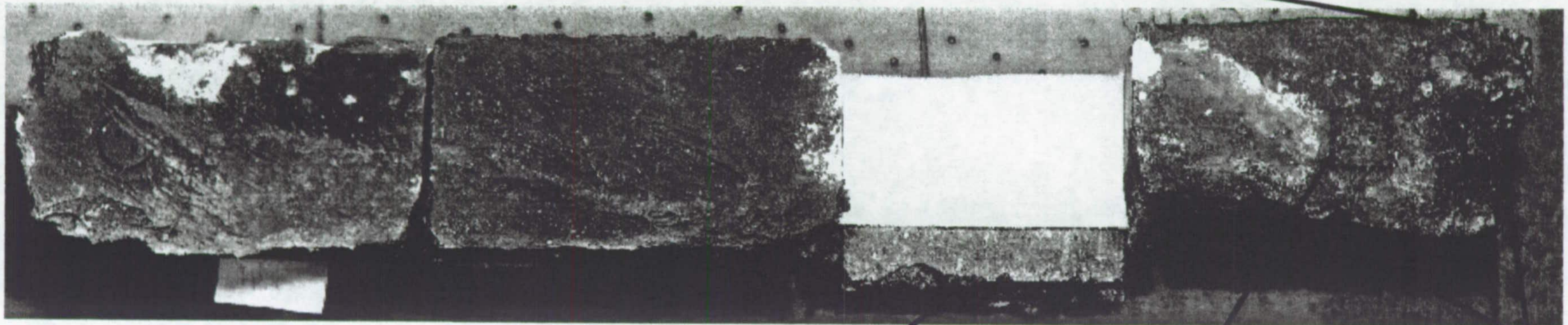
Slag distribution & shape suggests plasma flow direction and deposition duration

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

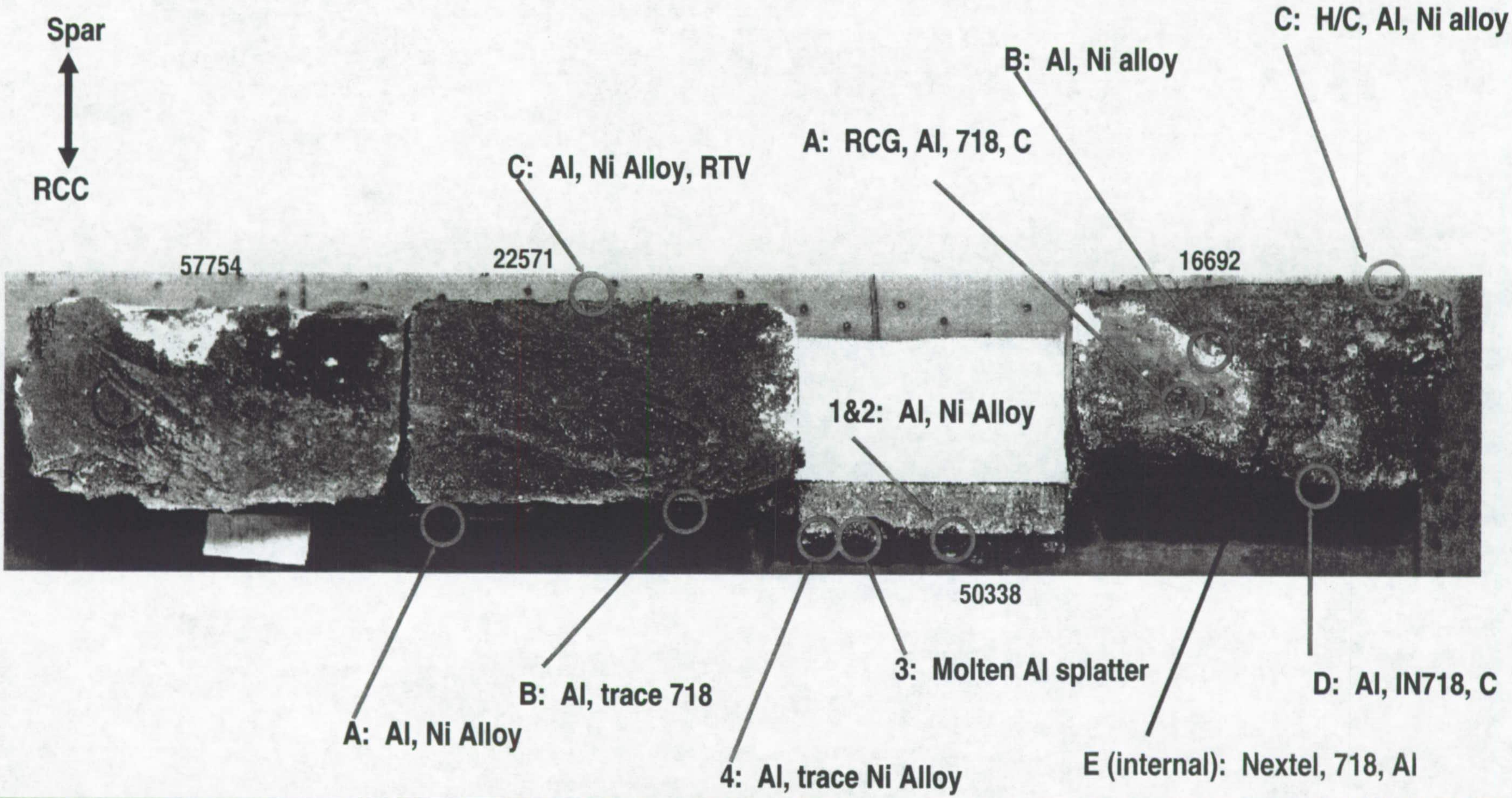
NASA USA United Space Alliance BOEING

LH RCC Panel 9 Lower CP Tiles



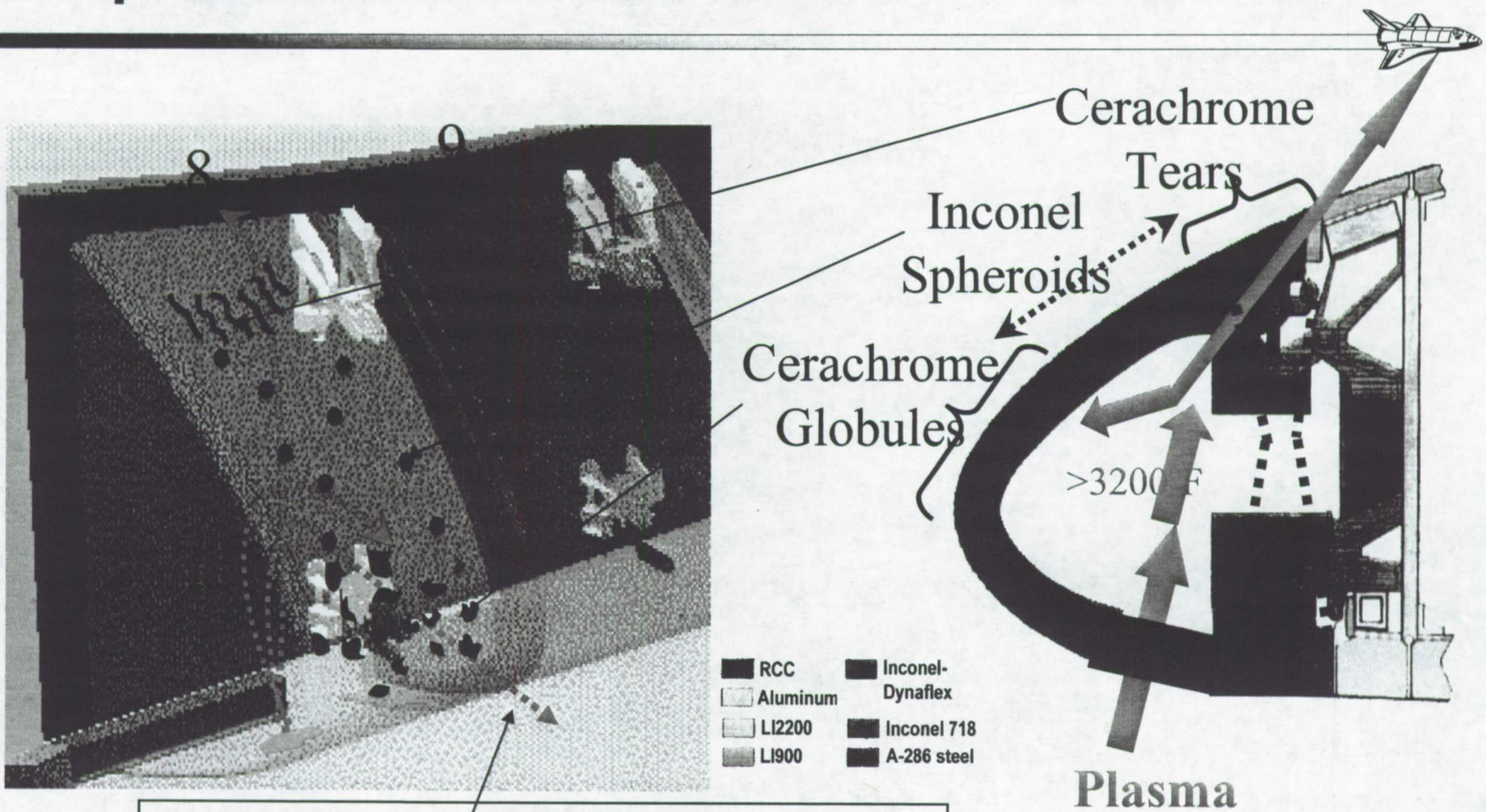
Realtime X-ray, Sidewall View

Sampling – LH Panel 9 Lower CP Tiles



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

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

NASA USA United Space Alliance BOEING

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.