The Reconstruction and Failure Analysis of The Space Shuttle Columbia

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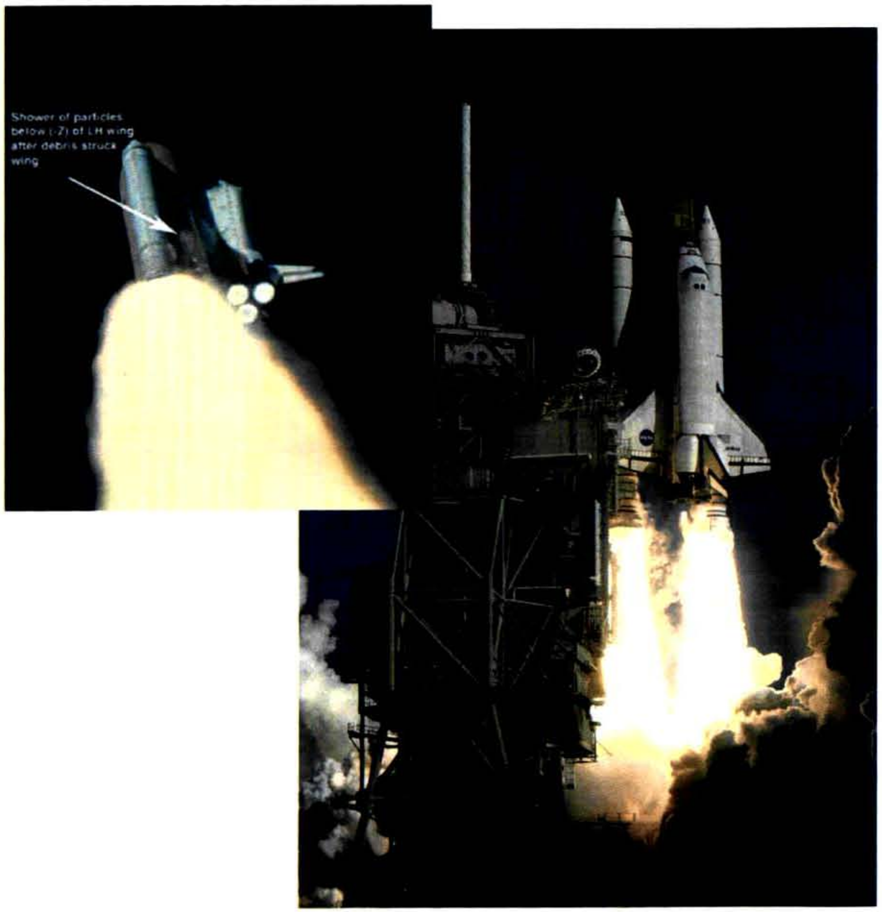
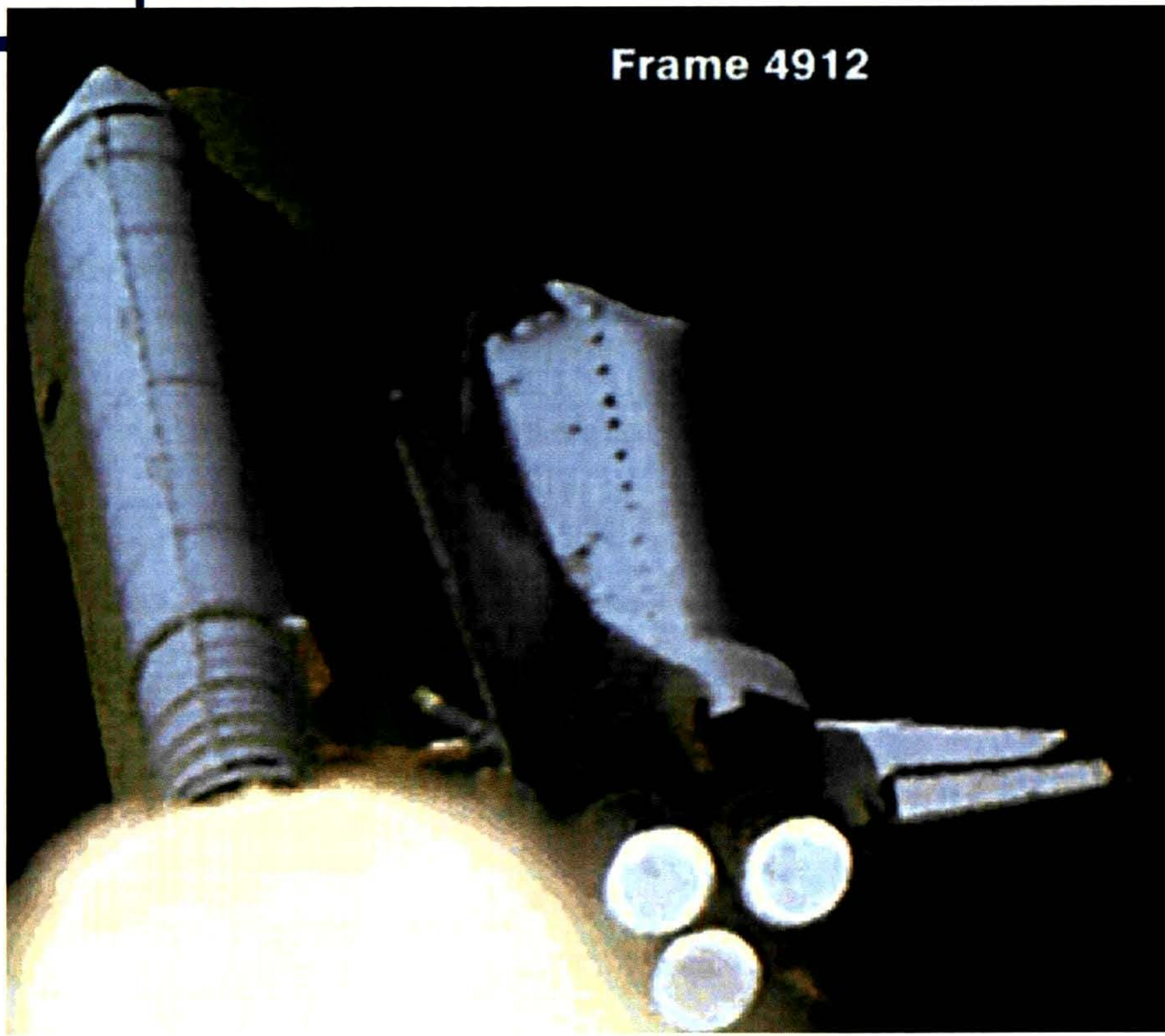
STS-107 Timeline



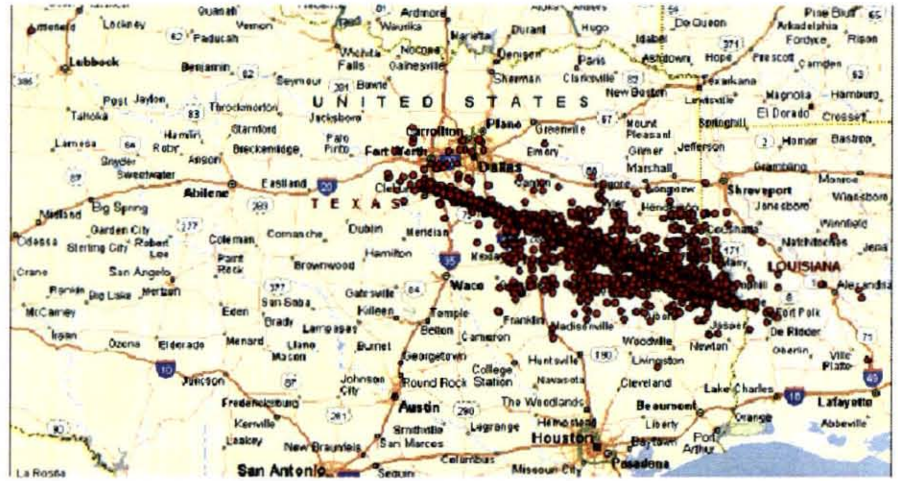
- Launch – January 23, 2003 at 10:39 AM
- Launch + 81.9 seconds, External Tank left bipod foam strikes Columbia's left wing
- February 1, 2003 8:15:30 am, Commander Husband and Pilot McCool execute de-orbit burn
- Entry interface (approx. 400,000 ft), 8:44:09 am
- Over California first signs of debris shedding observed at 8:53:46 am
- Approximately 1 minute 24 seconds into peak heating region of re-entry interface, 8:52:17, an off-nominal temperature in the left main landing gear brake line sensor
- First sign of trouble reported in mission control, at 8:54:24 when four hydraulic sensors were indicating "off-scale low".
- Loss of signal from Columbia recorded at 8:59:32 am.
- Videos made by observers on the ground at 9:00:18 am revealed that the Orbiter was disintegrating

Foam Impact



Recovery

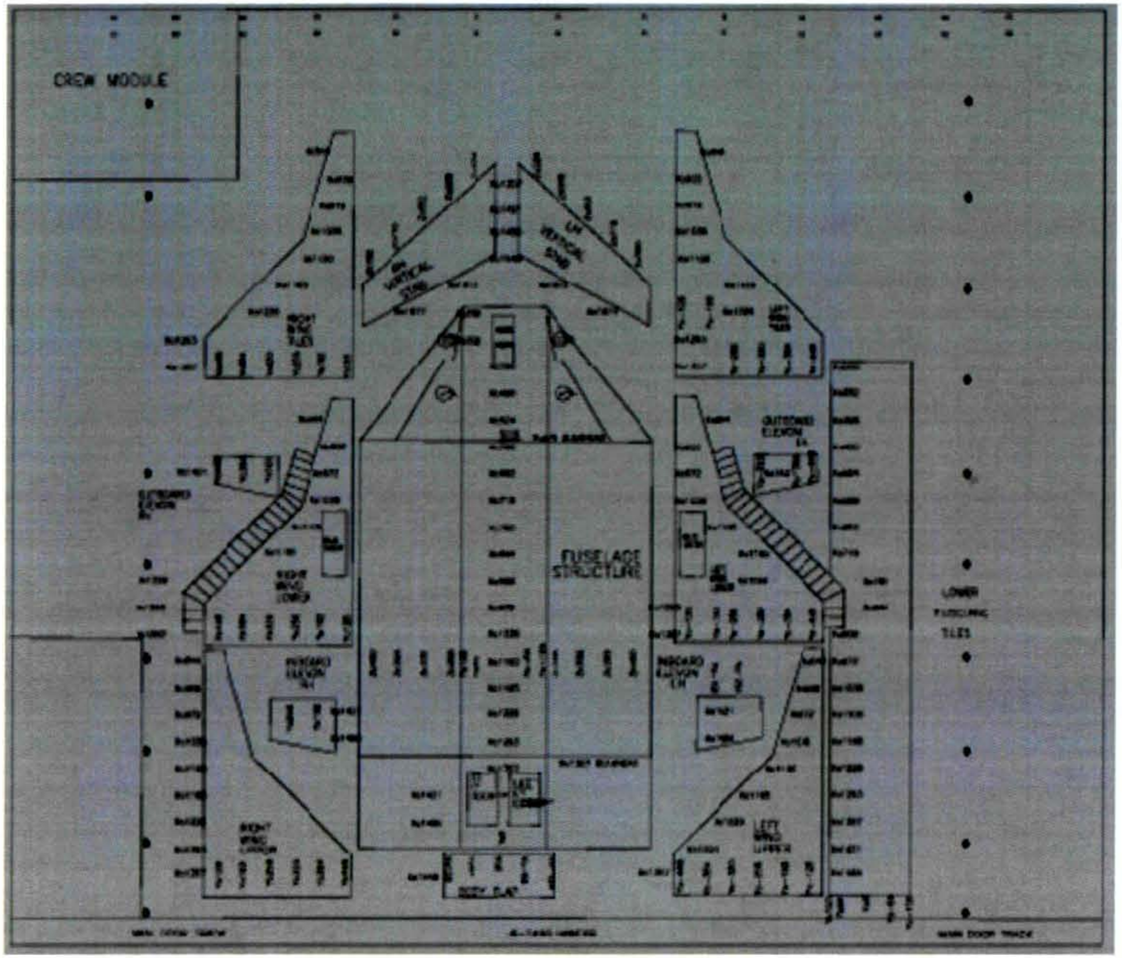
- Columbia was traveling at Mach 18 at an altitude of 208,000 feet at time of break-up
- The size of the debris field was 645 miles long and 10 miles wide
- Each piece of debris was photographed, analyzed for potential hazards, given a unique identification
- Each piece's location was noted and a preliminary identification was attempted
- Debris was then sent to one of several stationing locations before being sent to the Kennedy Space Center for reconstruction
- Over 83,900 items were recovered representing an estimated 38% of Columbia by weight



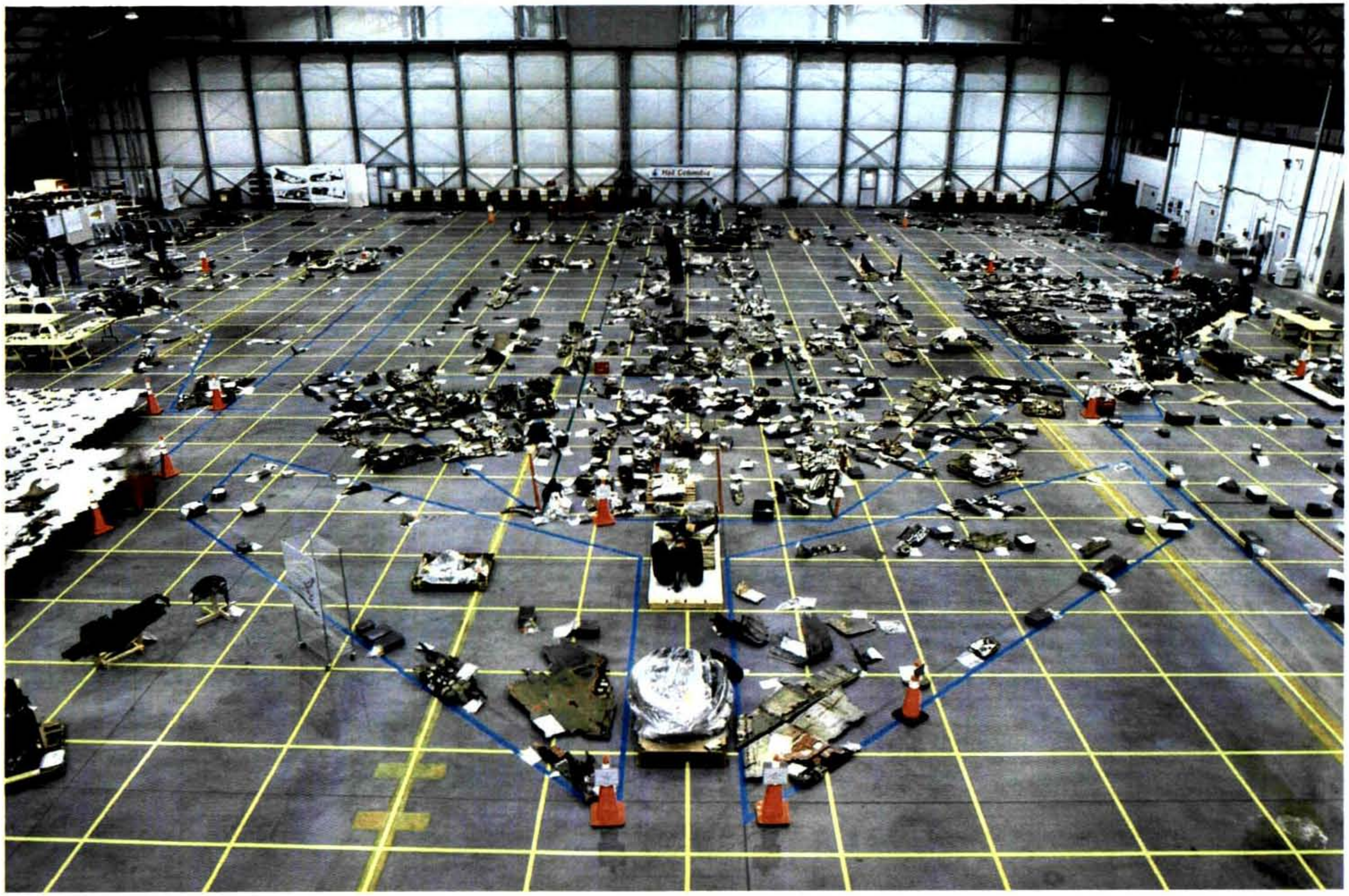
Reconstruction

- Reconstruction is a common aircraft accident investigation tool used to trace damage patterns and failure clues to aid in the determination of probable cause
- A 2-D Reconstruction plan was developed before the arrival of the debris
- The option for possible 3-D reconstruction was deferred until the amount of debris and initial observations were made

Reconstruction Plan

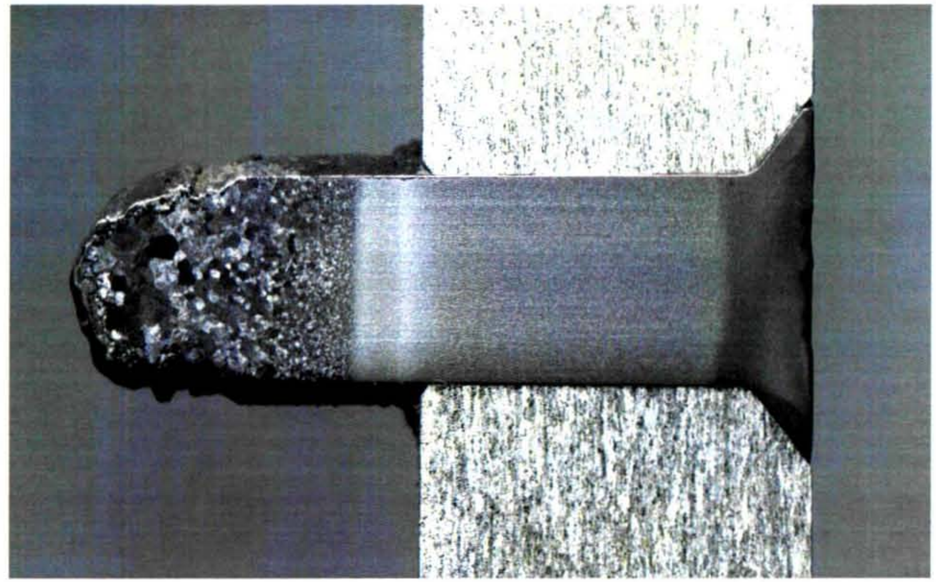


Reconstruction Hanger



Pathfinders

- Six items with similar thermal and mechanical damage to left wing components were selected for failure analysis
- Purpose was to develop failure analysis procedures for debris hardware and to obtain exploratory lab data
- Areas of interest included fracture surfaces, high temperature erosion and melting of fractures and other protrusions, various metal deposits, and various degrees of tile discoloration and deposits.



- The results of the tests and analyses were intended to provide guidance of future failure analyses and provide a basis for debris damage interpretation.

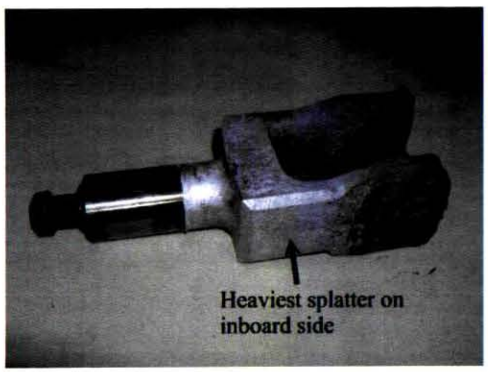
Aluminum Pathfinder

- Intergranular fracture primary failure mode

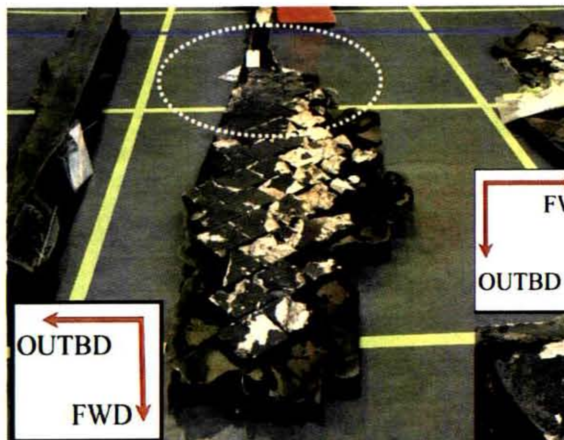
Early Analysis – Left MLG Door Area

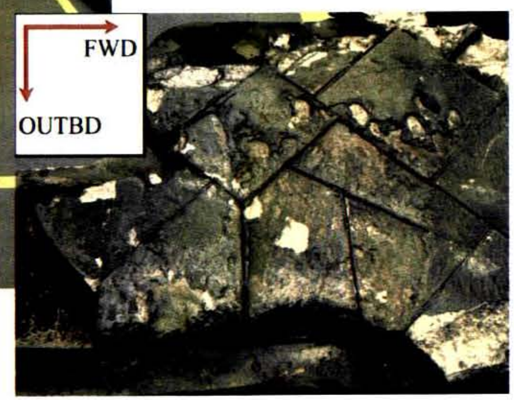
MLG Tires

LH MLG Strut



MLG Door Up-lock



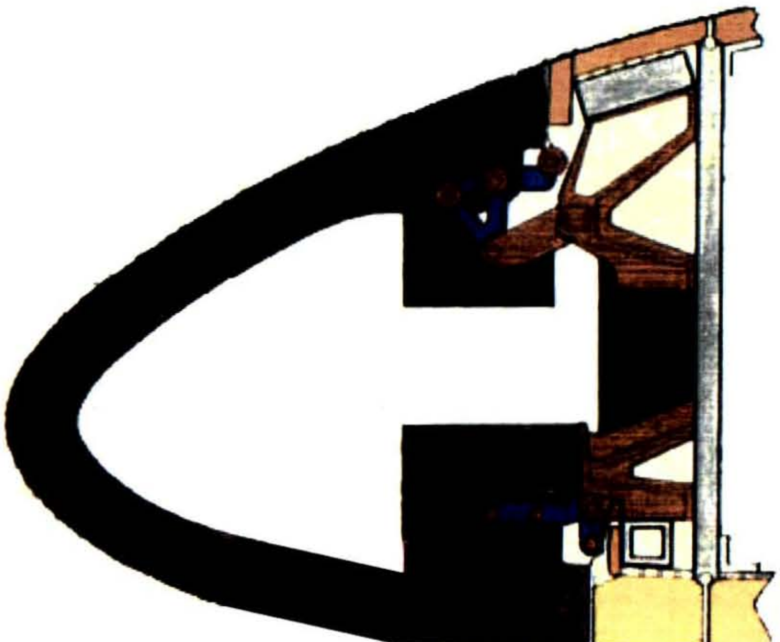


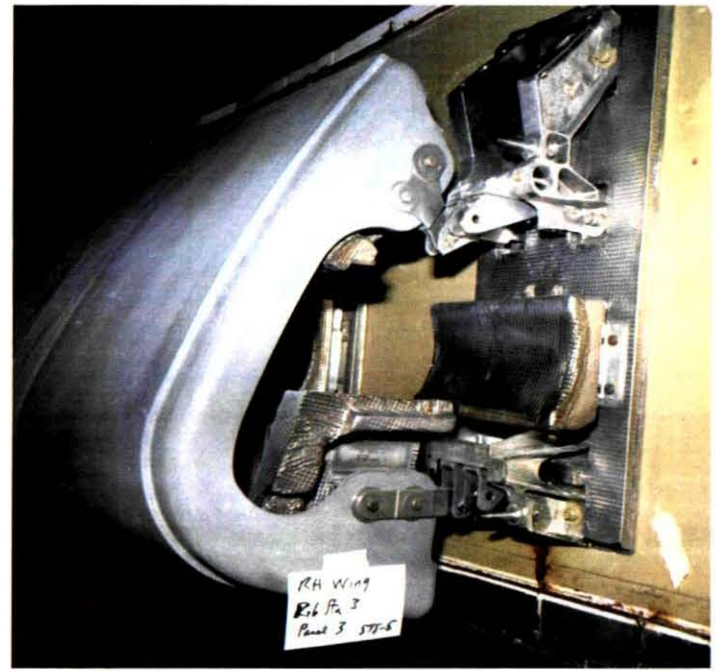
Skin Panel

Emphasis Switched to 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 (MADS Recorder)
- 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

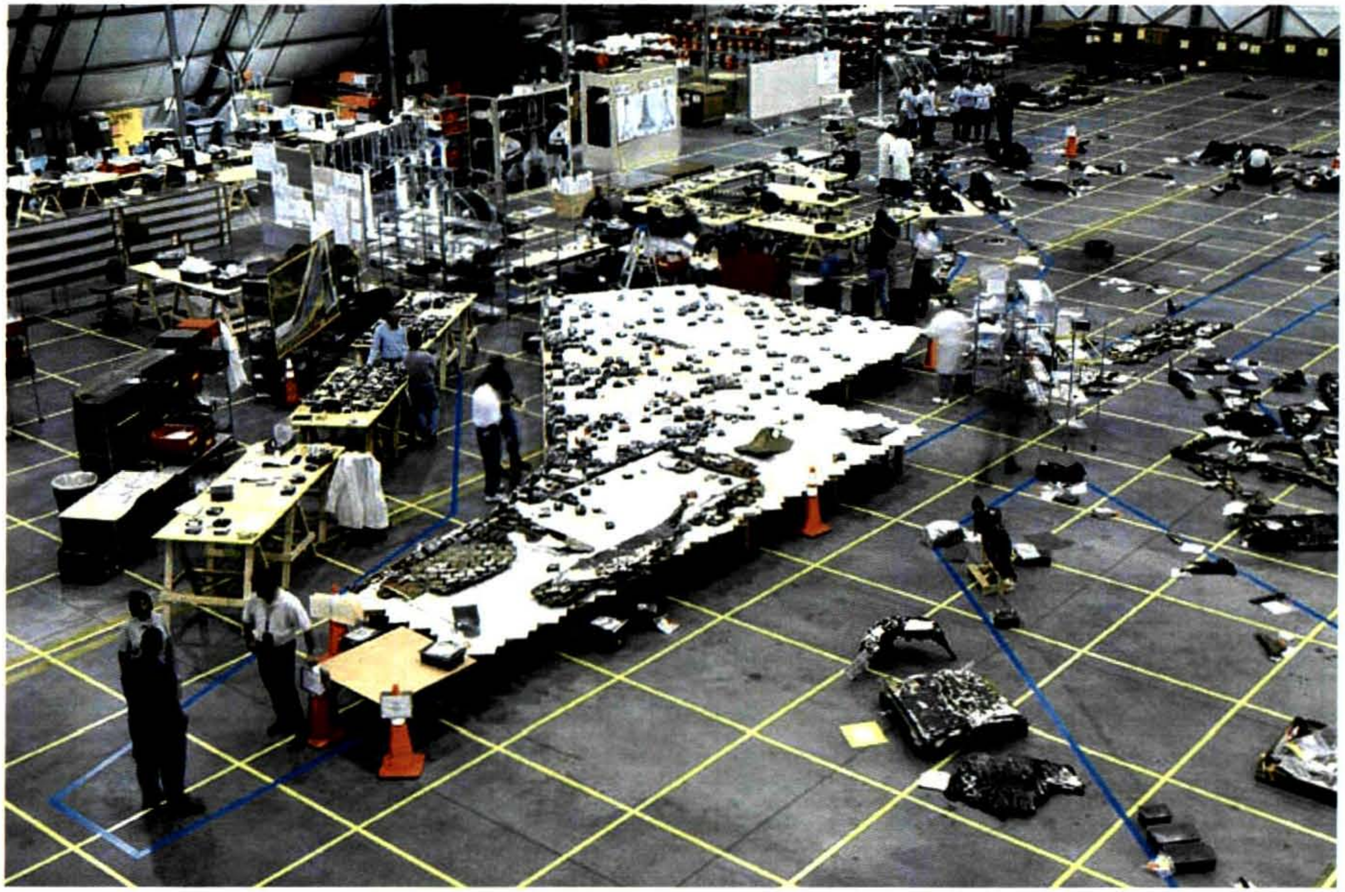
Wing Leading Edge Subsystem (LESS)





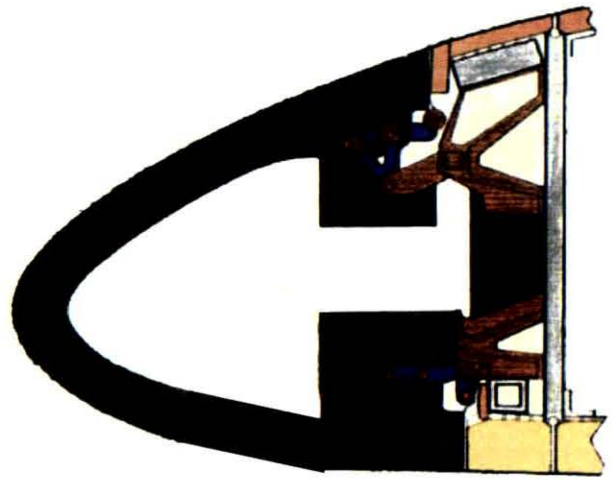
3D Reconstruction of Left WLE

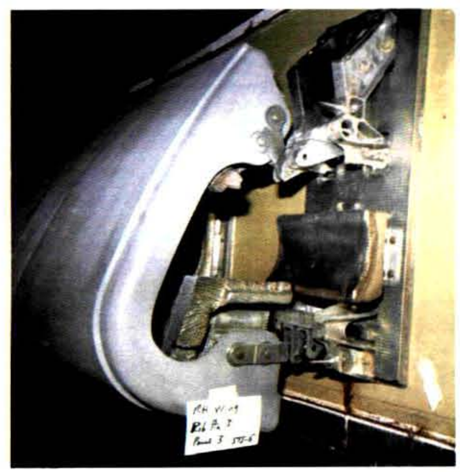
Left Wing Tile Table



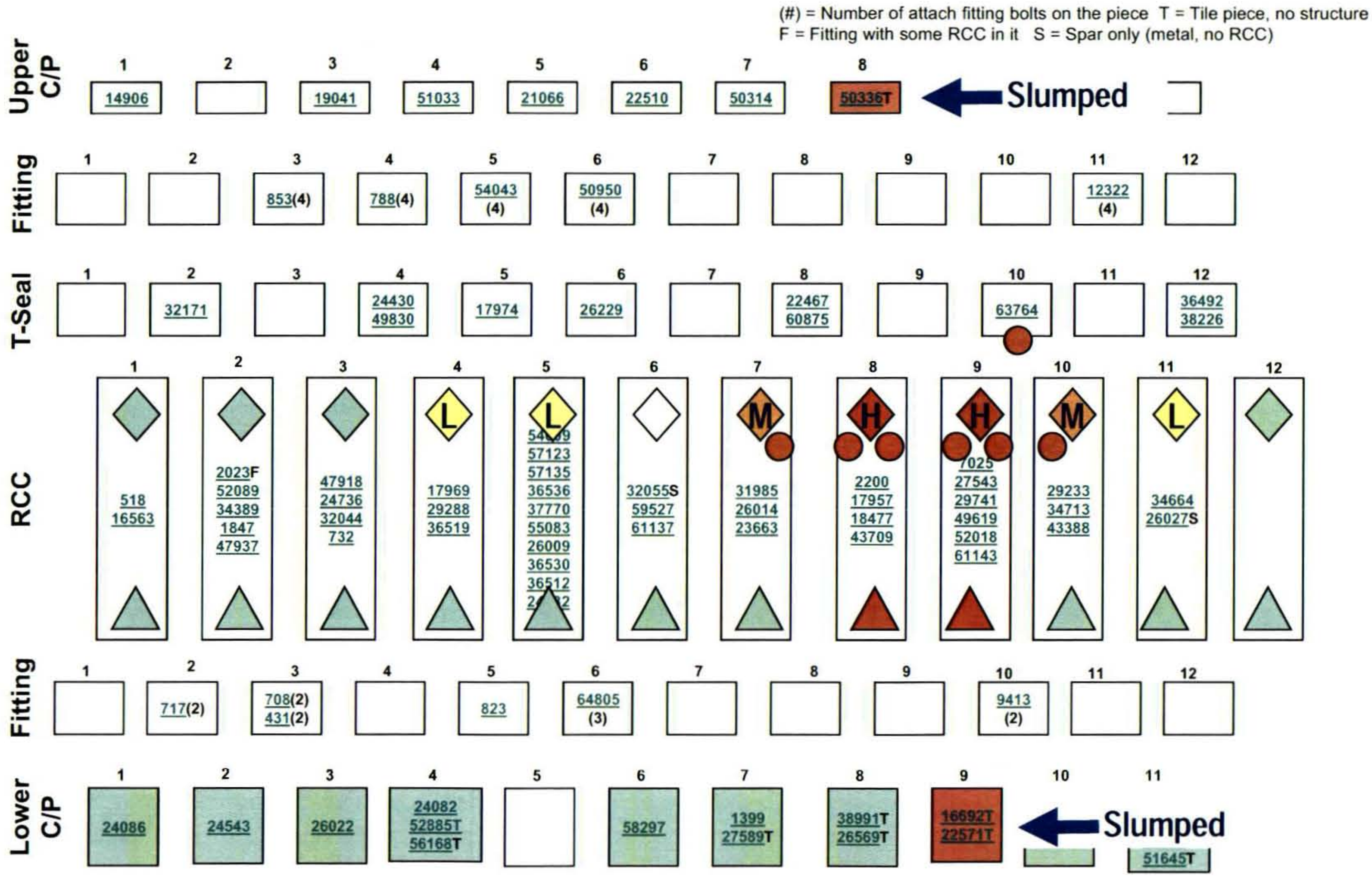
LESS Observations

- 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

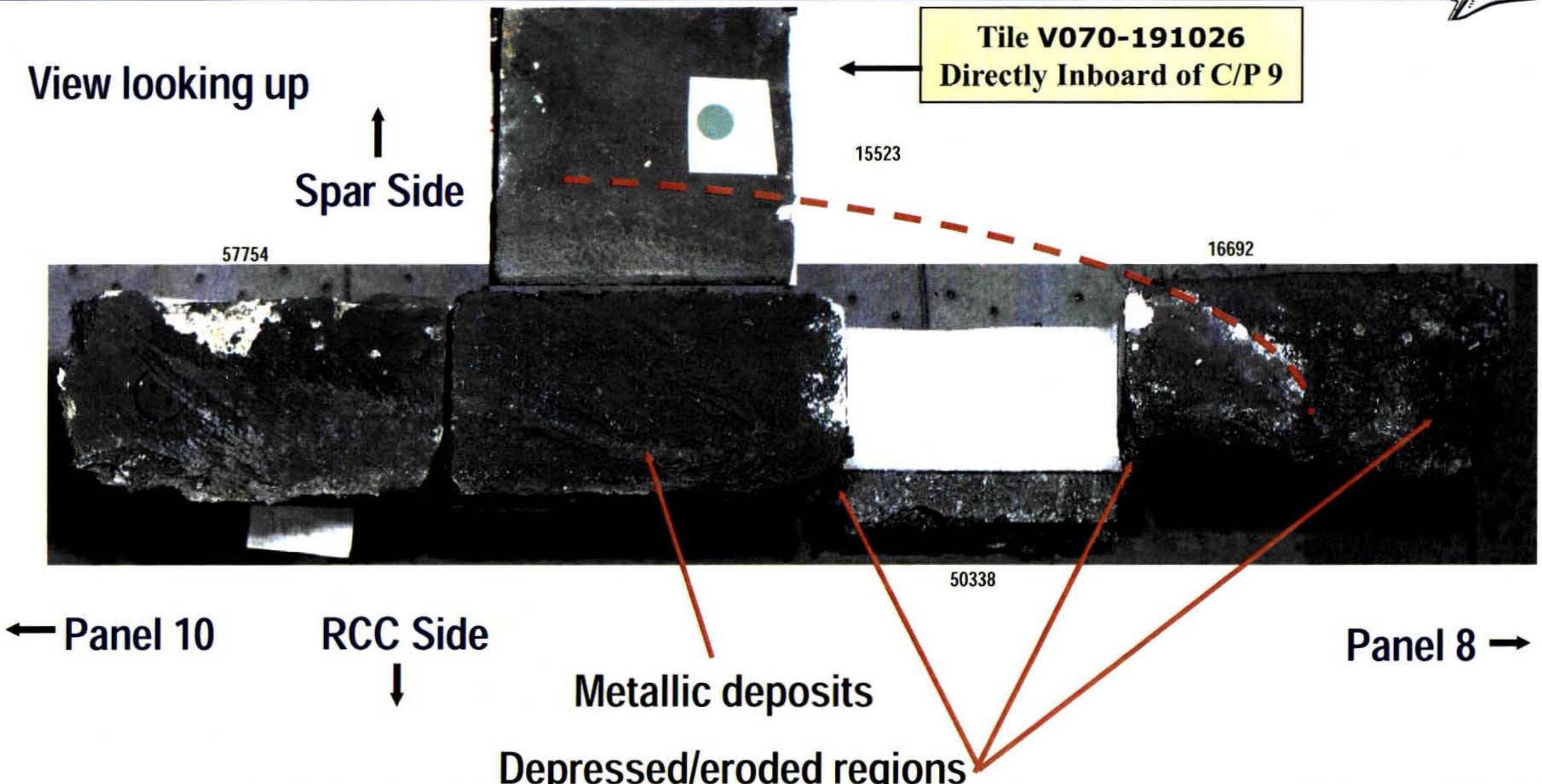




Left Hand Wing Debris Points to RCC 8/9 – Slumped Tile



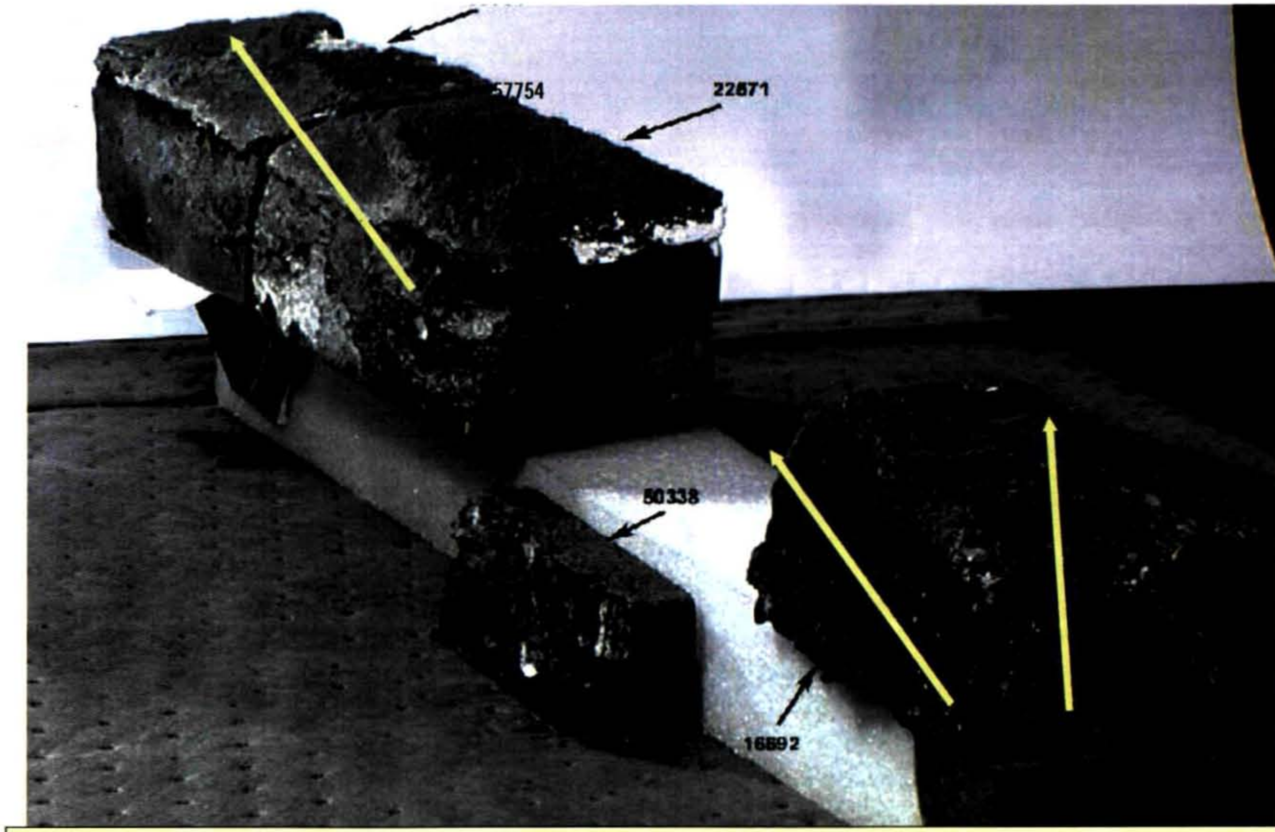
Reconstructed View of LC/P 9 Tile with I/B Tile



Flow Patterns Indicates C/P 9 Was Not Dropped Down Into Flow

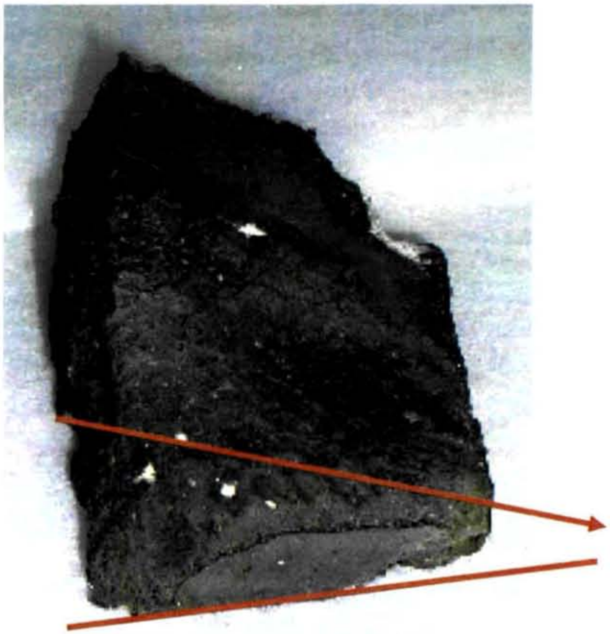
Open question: Location of Plasma Flow From Panel 8 to tiles on 9?

Reconstructed View of Lower C/P 9 Tile



Slumping and erosion patterns suggest plasma flow across the carrier panel tile (from 8 toward 10)

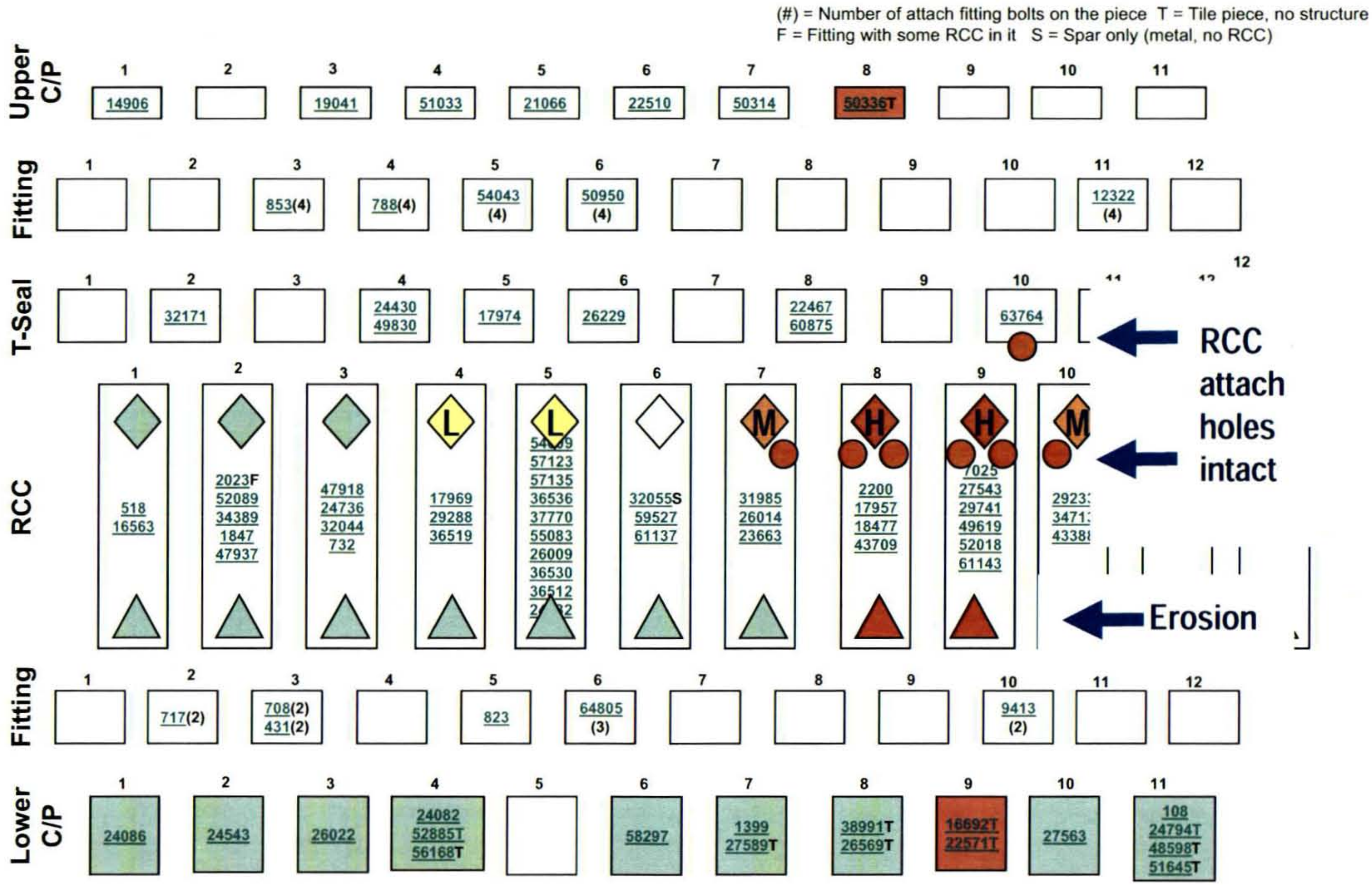
Carrier Panel 8 - Upper



Item 50336 (V070-199715-074)

Slumping and erosion patterns suggest plasma flow out of leading edge cavity (consistent with vent)

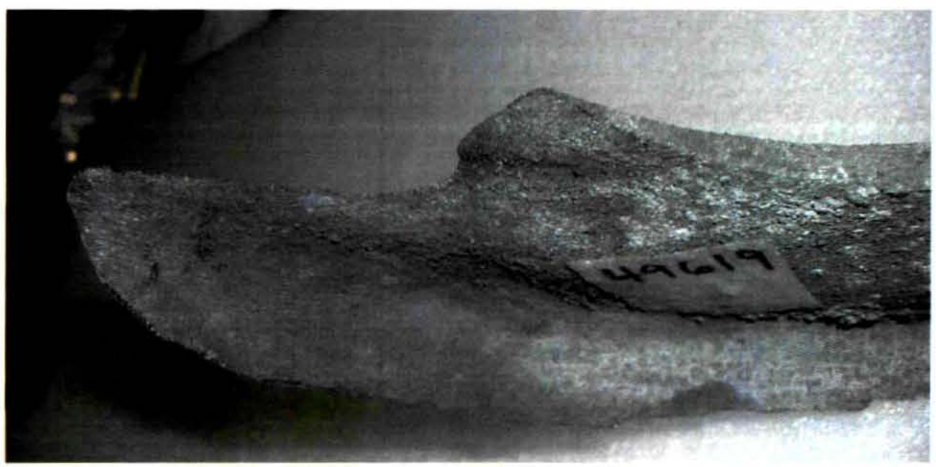
Left Hand Wing Debris Points to RCC 8/9 – Erosion (▲) and RCC with attach hole intact (●)



Erosion on Panel 8 Upper Outboard Rib

Outboard apex

Item 49619



Close-ups of knife edge, note fibers not visible on internal surface of panel due to deposits.

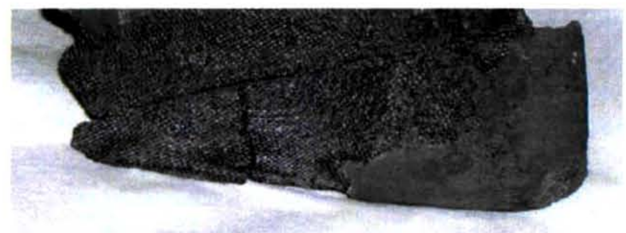
Rib tapers from design thickness of .365″ to .05″.

Erosion on Gap Surfaces of Panel 8 Outboard Lug & Matching Heel Piece

External/Outboard surfaces:

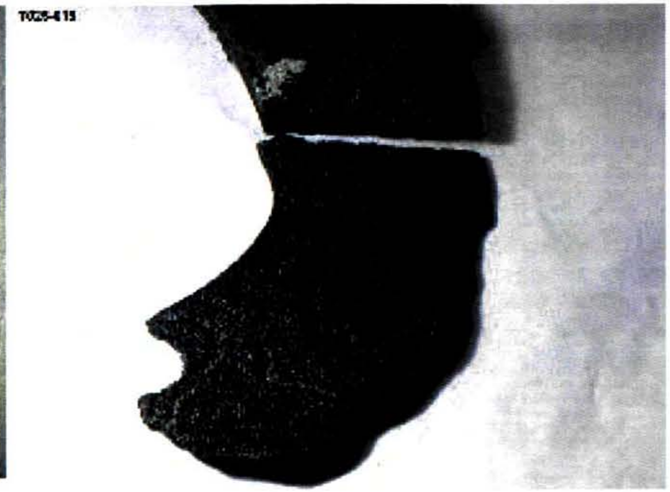
- Matching eroded plies between items 24724 and 58291, shows heat flow external to the panel while panel heel and lug were attached
- Metallic deposits at lug attach points - evidence that metallic deposited after lug no longer attached to fitting
- Inconel bushings missing at holes

Lug fragment tapers from design thickness of .499", to a Knife Edge with a minimum thickness of 0.063"

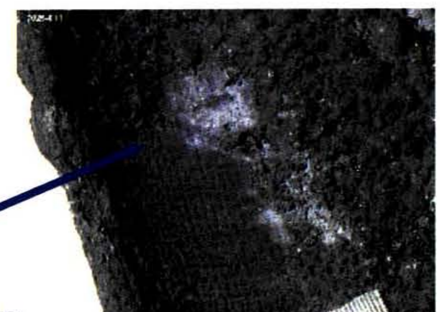


Heel fragment tapers from design thickness of .233", to a Knife Edge with a minimum thickness of 0.052"

Erosion on Panel 9 Upper Inboard Rib

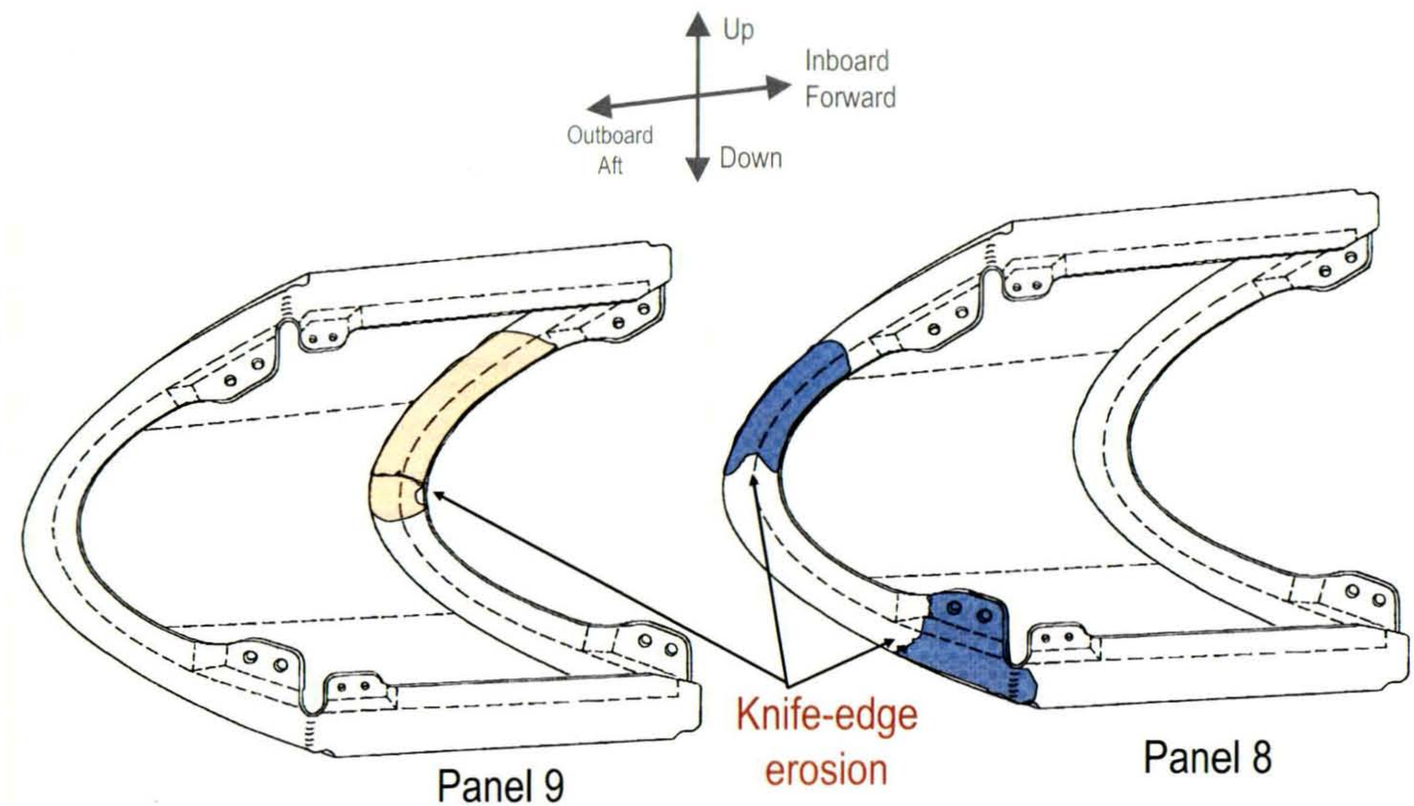


7025 to 52018 interface shows severe thermal erosion – thickness ranges from 0.270 to knife edge of 0.040



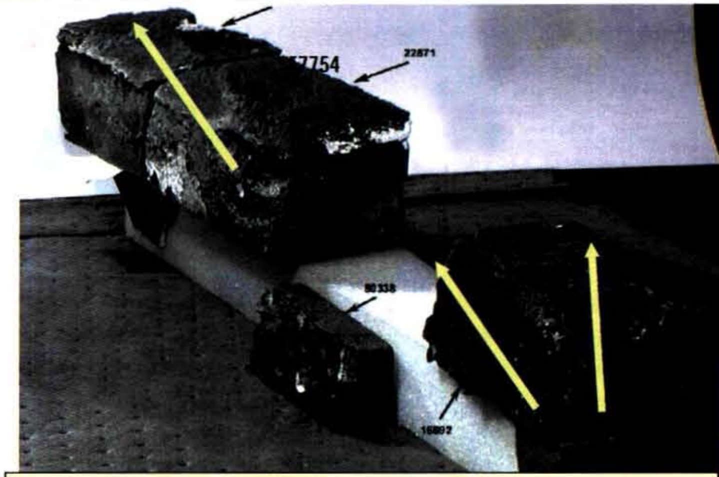
7025 internal side shows presence of metallic deposits

RCC Panels 8 & 9 Erosion Features

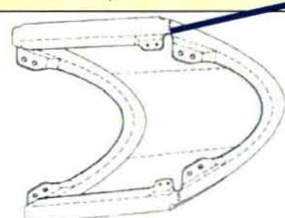


Erosion indicates prolonged exposure in the panel 8-9 joint area.

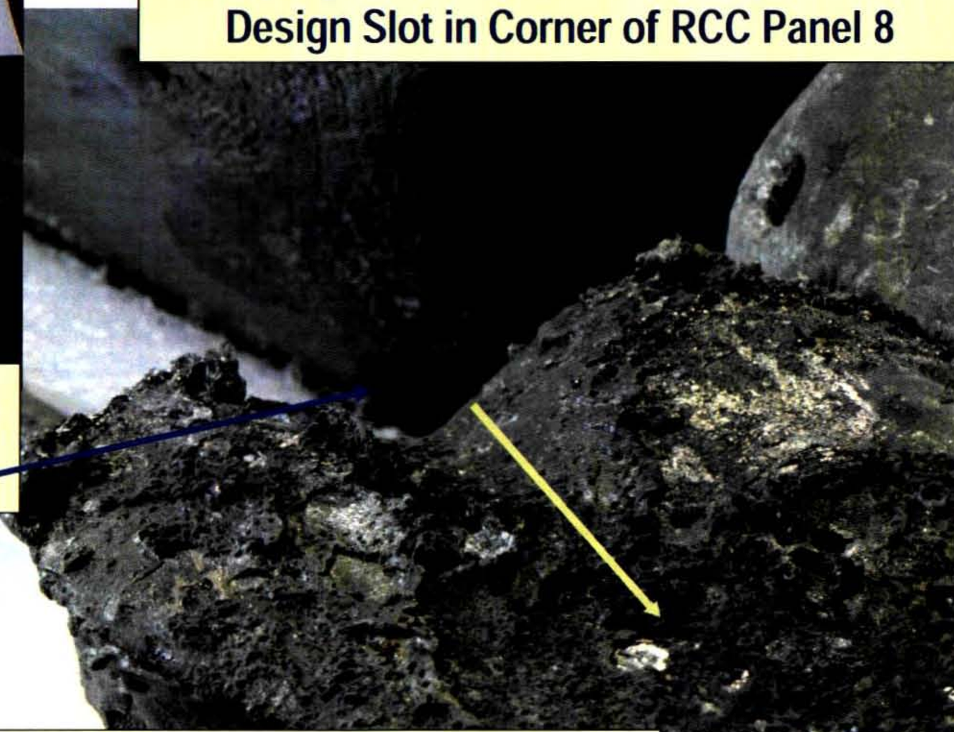
Slumping Source for Carrier Panel 9 Tile was Revealed



Slumping and erosion patterns suggest plasma flow across the carrier panel tile (from 8 toward 10)



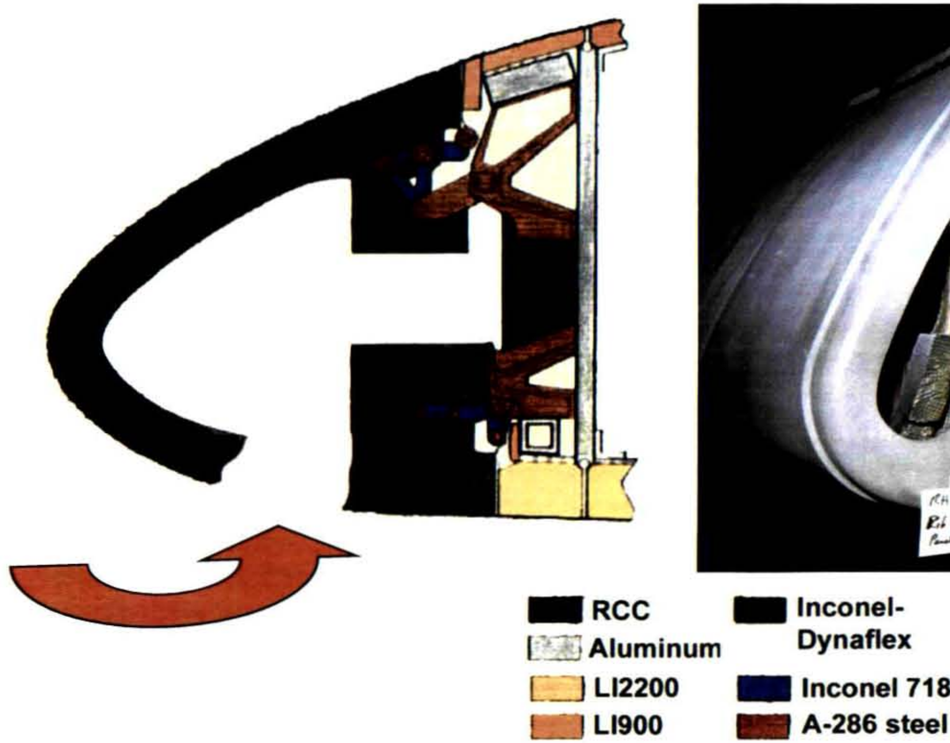
Slumping of C/P 9 Tile #1 Corresponds with Design Slot in Corner of RCC Panel 8



Evidence of Hot Gas Flow Exiting Design Slot Indicates Significant Breach Was Into Panel 8

Debris Indicates Highest Probability Initiation Site

- Wing failure initiated in the panel 8 area
  - Most likely at the panel 8 area near 8-9 joint
  - Condition existed before or shortly after entry interface



Left Hand Wing Debris Points to RCC 8/9 – Metallic Deposits (H)

(#) = 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

1	2	3	4	5	6	7	8	9	10	11
14906		19041	51033	21066	22510	50314	50336T			

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	12
	32171		24430 49830	17974	26229		36492 38226

Metallic Deposits

RCC

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 2[illegible]2	32055S 59527 61137	31985 26014 23663	2200 17957 18477 43709	7025 27543 29741 49619 52018 61143	29233 34713 43388	34664 26027S	

Fitting

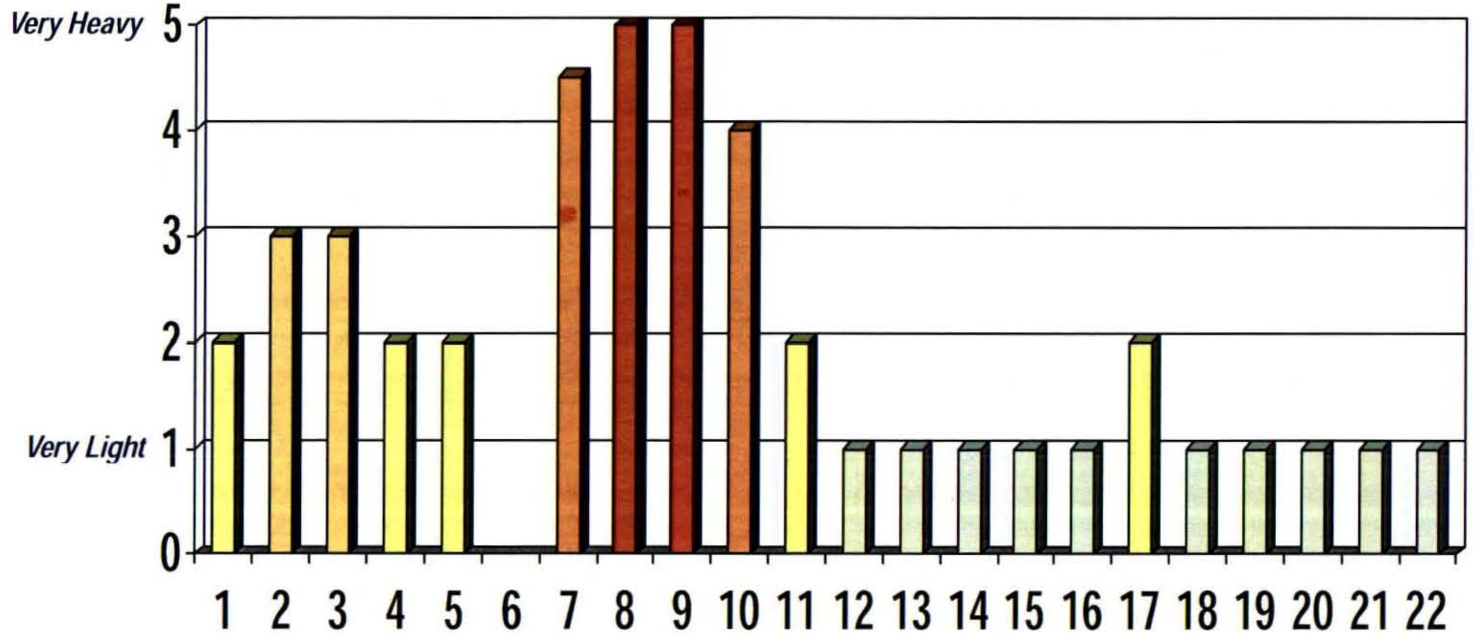
1	2	3	4	5	6	7	8	9	10	11	12
	717(2)	708(2) 431(2)		823	64805 (3)				9413 (2)		

Lower C/P

1	2	3	4	5	6	7	8	9	10	11
24086	24543	26022	24082 52885T 56168T		58297	1399 27589T	38991T 26569T	16692T 22571T	27563	108 24794T 48598T 51645T

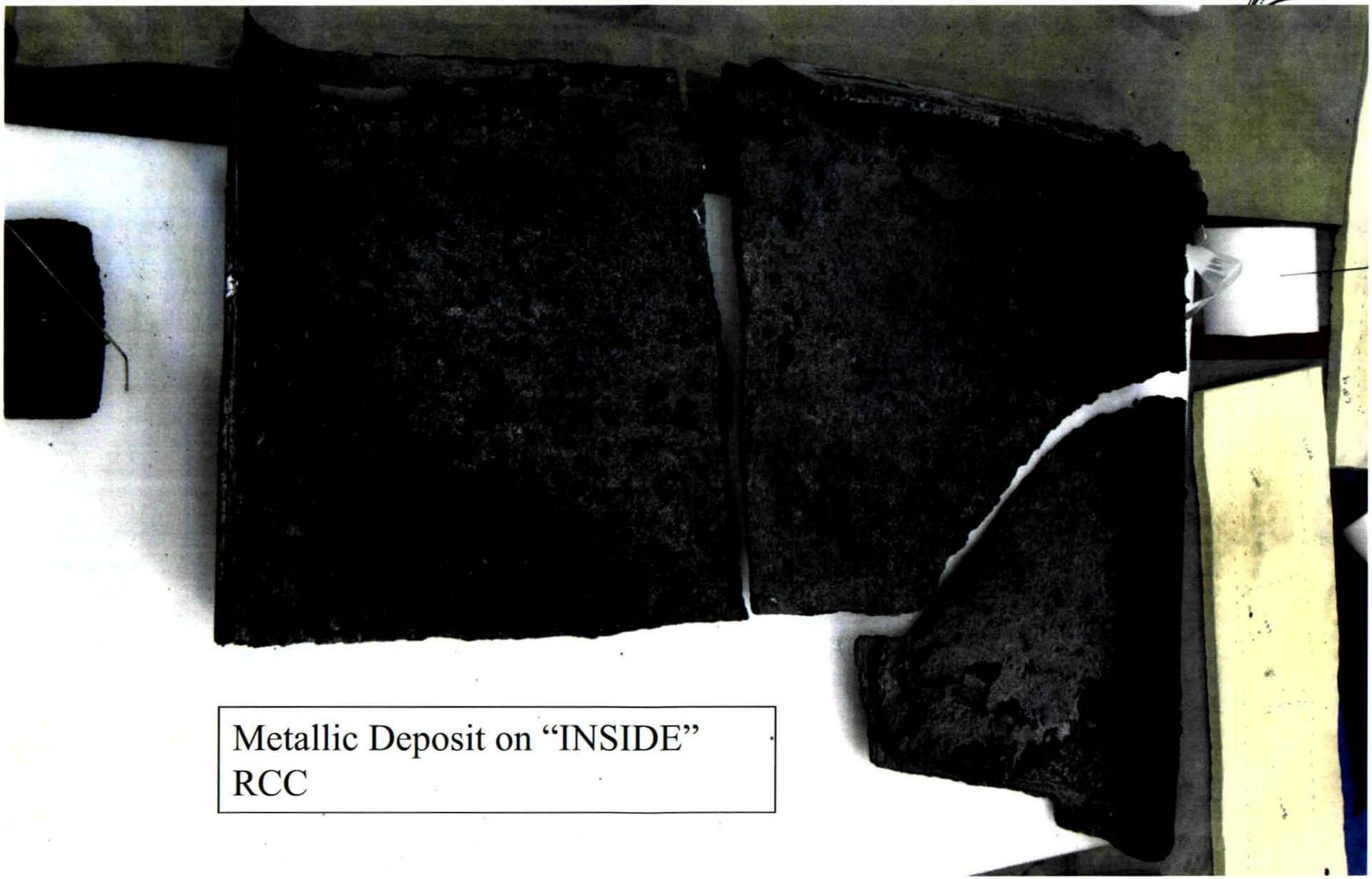
Relative Metallic Deposition on L/H Wing Materials

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



Distribution of metallic deposition volume was centered around panels 8 & 9

Metallic Deposit Example, LH RCC 8



Metallic Deposit on "INSIDE" RCC

High Level Questions

Sample the metallic 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

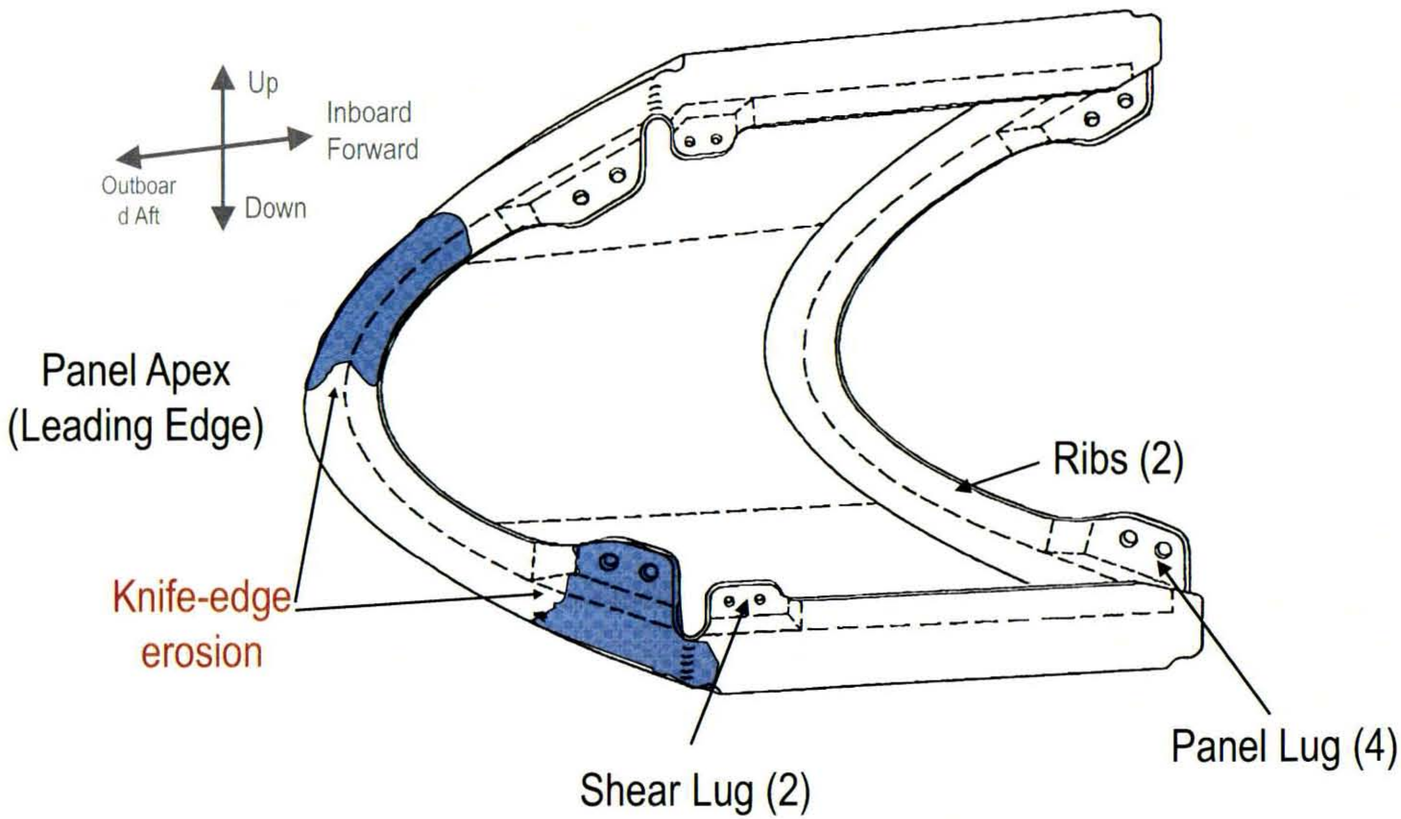
Repeatability and Reproducibility of results emphasized

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 metallic deposits
  - Layering of metallic deposits
- Use "Interpretation Criteria" to correlate deposit analysis <==> WLE source material

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

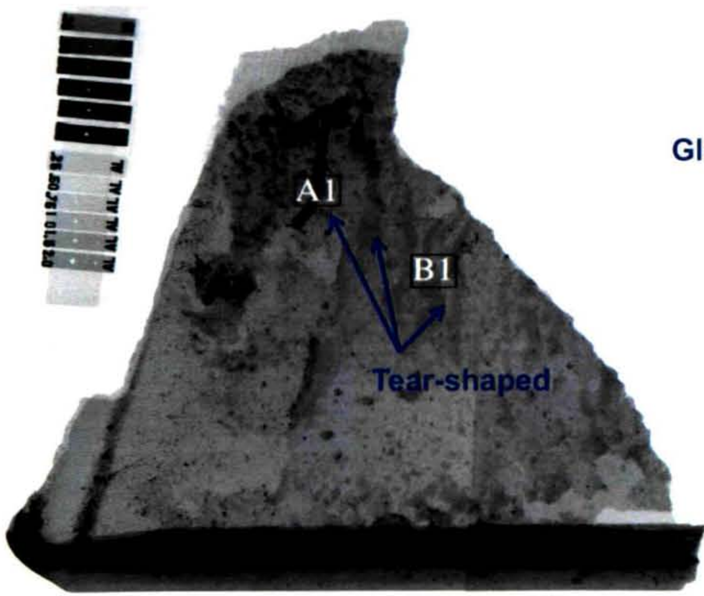
RCC Panel 8 Erosion Features

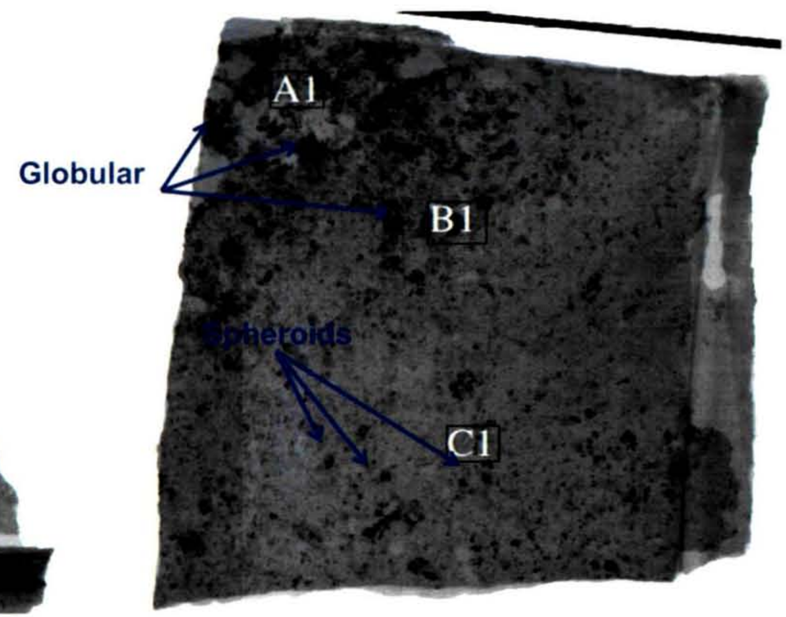


Erosion indicates prolonged exposure to plasma heating

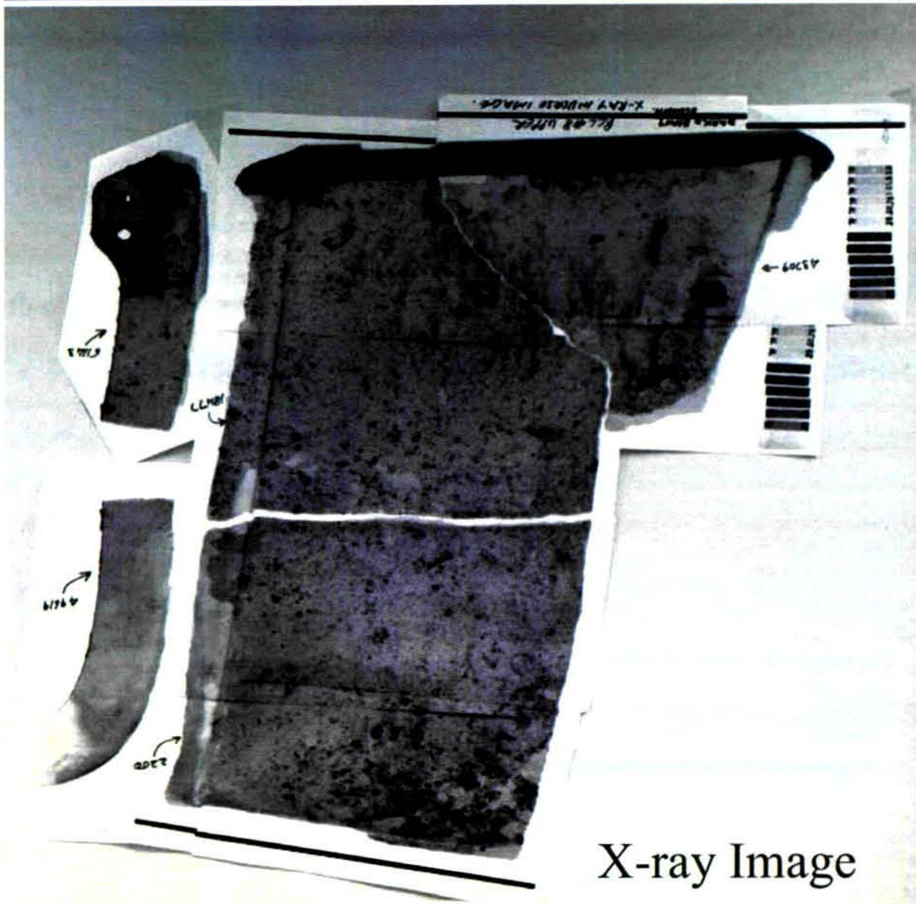
Radiographic Features

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

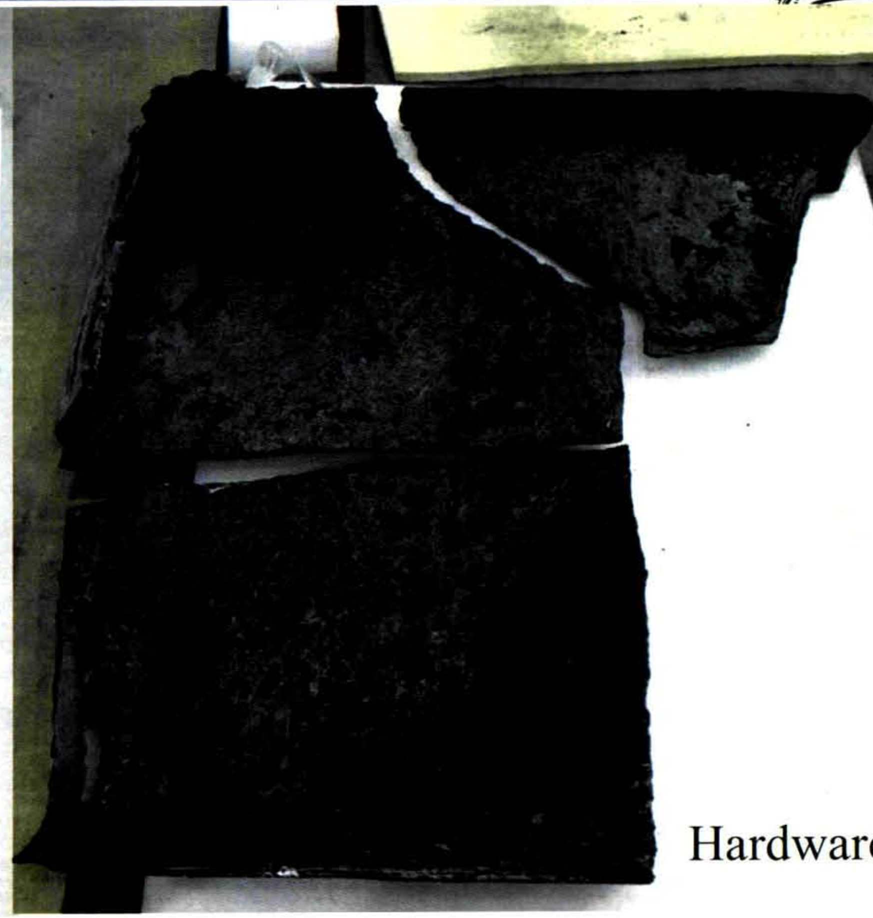




Radiography WLE LH Panel 8

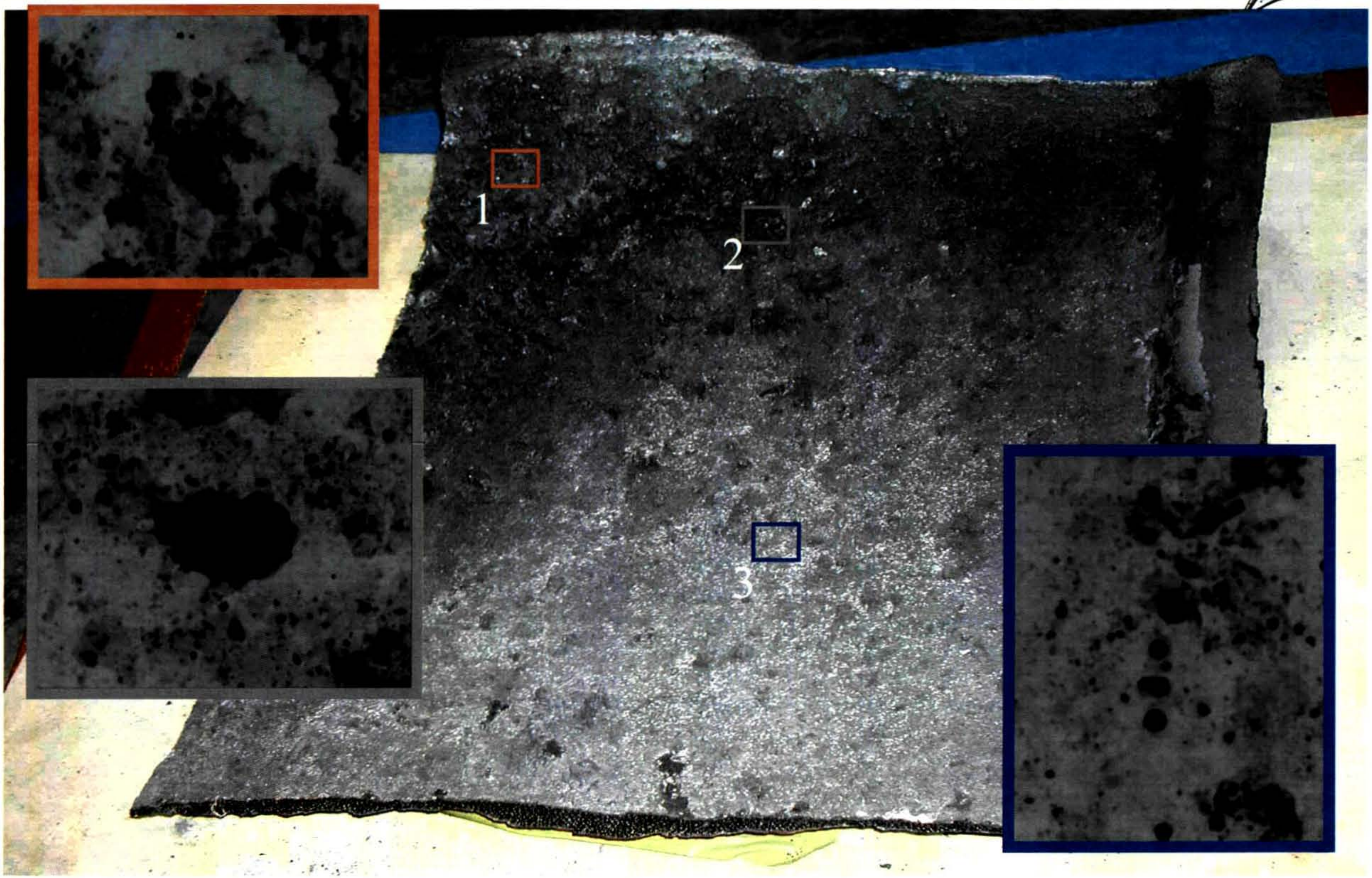


X-ray Image

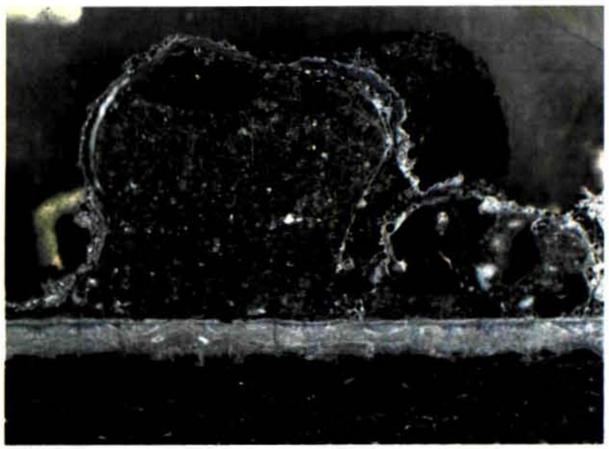


Hardware

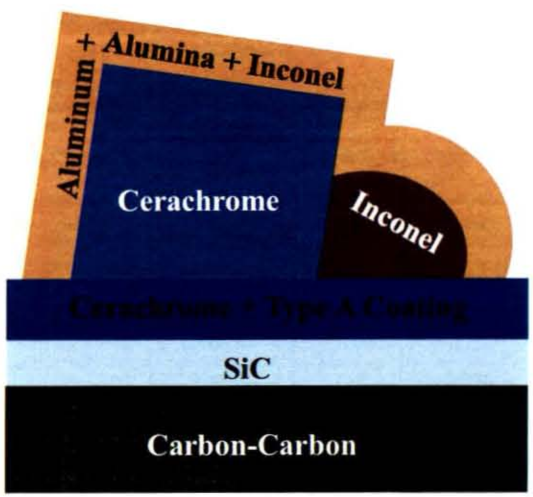
LH RCC 8 Upper Apex

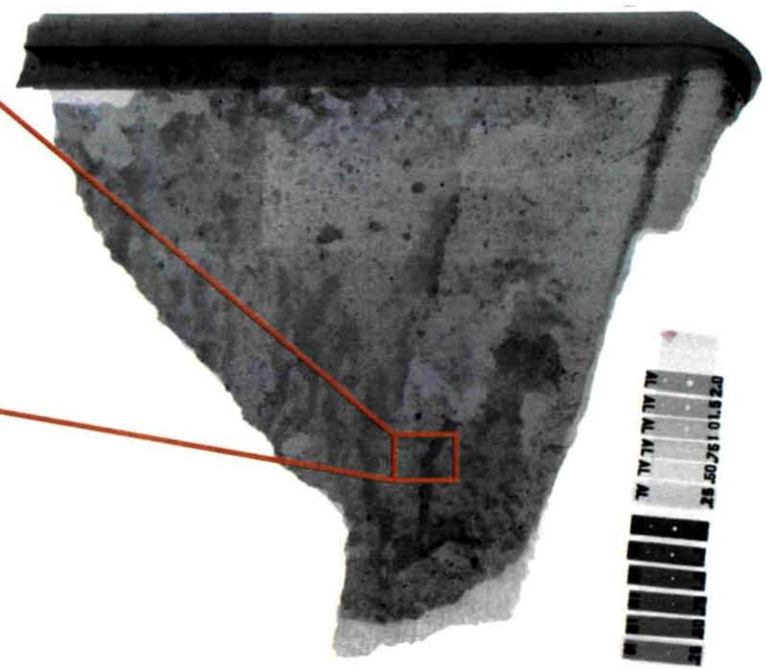


LH RCC 8 – Deposit Feature: Thick Tear Shaped



Item 43709, Sample 2A1

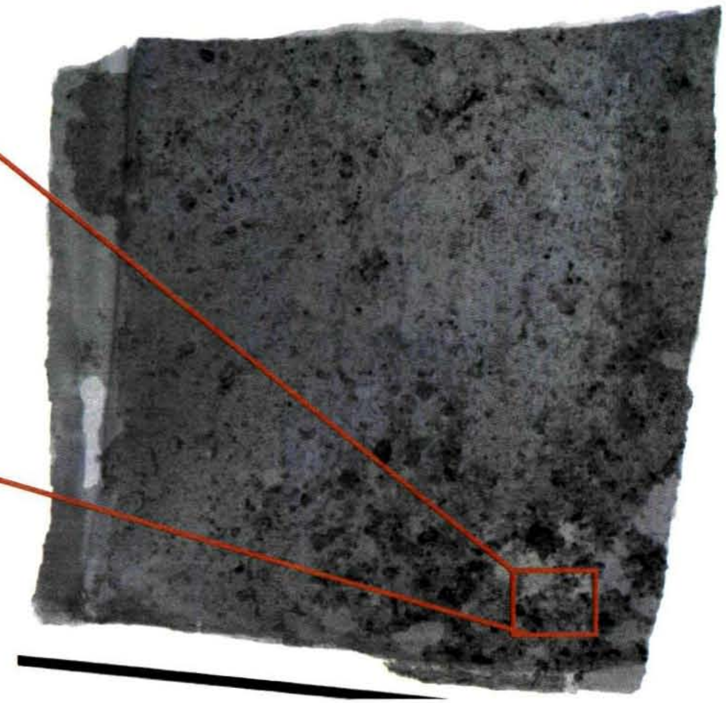




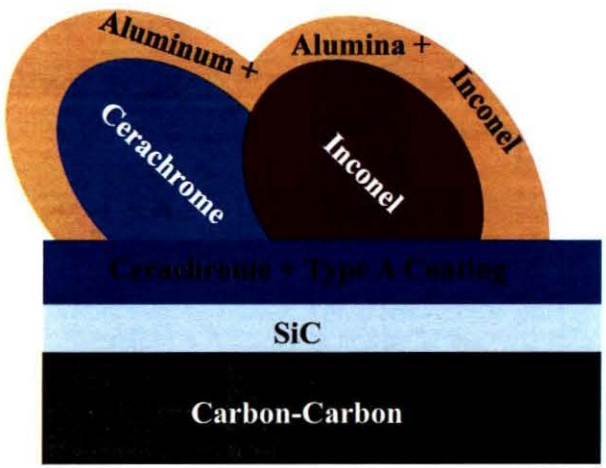
Radiograph of Item 43709

LH RCC 8 – Deposit Feature: Thick Globules

Item 2200, Sample 6A1

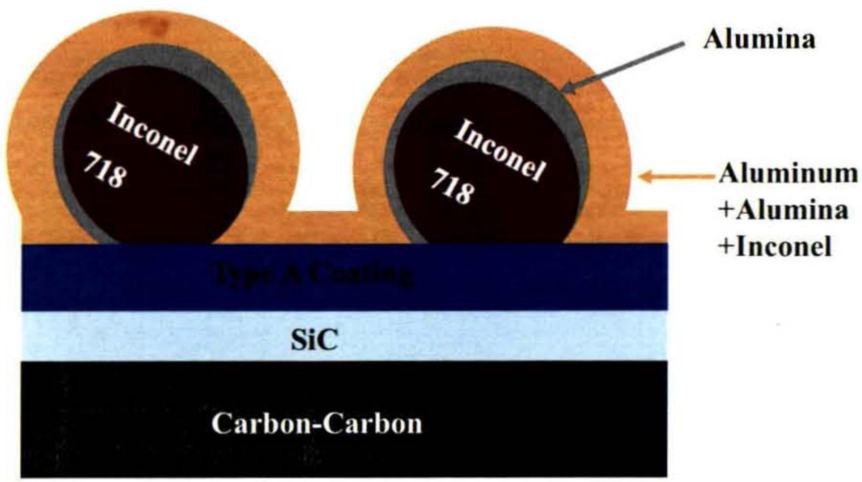


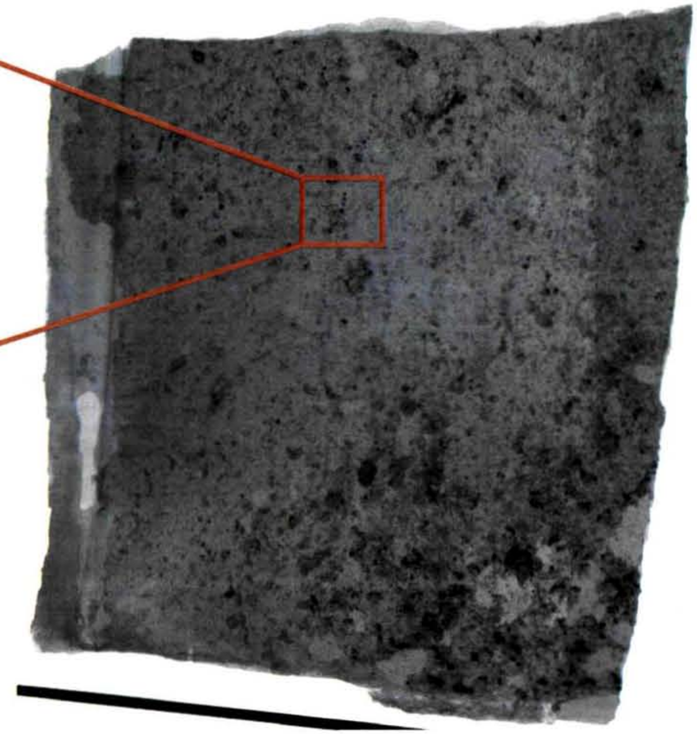
Radiograph of Item 2200



LH RCC 8 – Deposit Feature: Spheroids

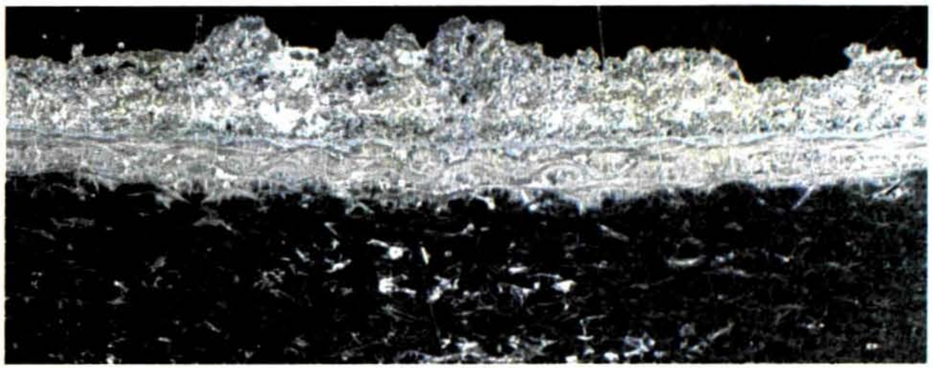
Item 2200, Sample 6C1



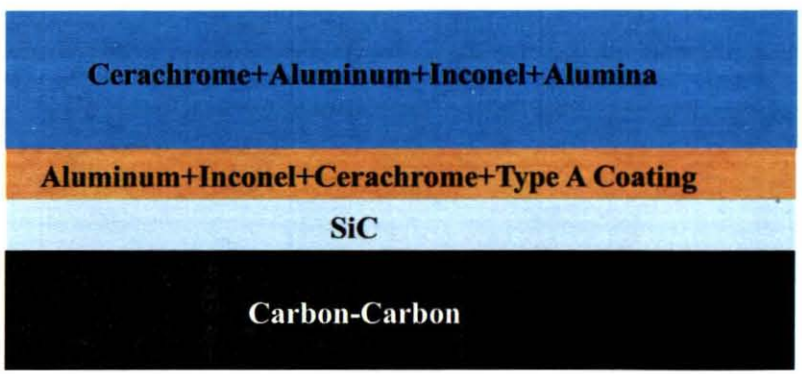


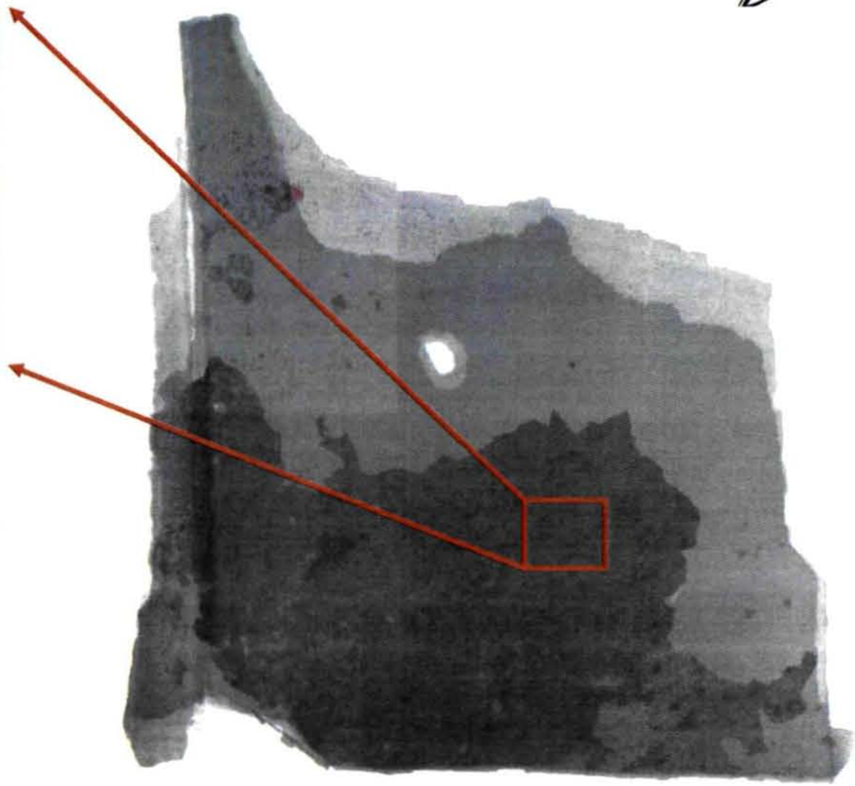
Radiograph of Item 2200

LH RCC 8 – Deposit Feature: Uniform Deposit



Item 16523, Sample 4A1





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 metallic deposits
  - Breach location away from spar fittings
- Cerachrome + Inconel in first deposited layers
  - Melting of spanner/foil/fittings + Insulator
- Aluminum deposition secondary event

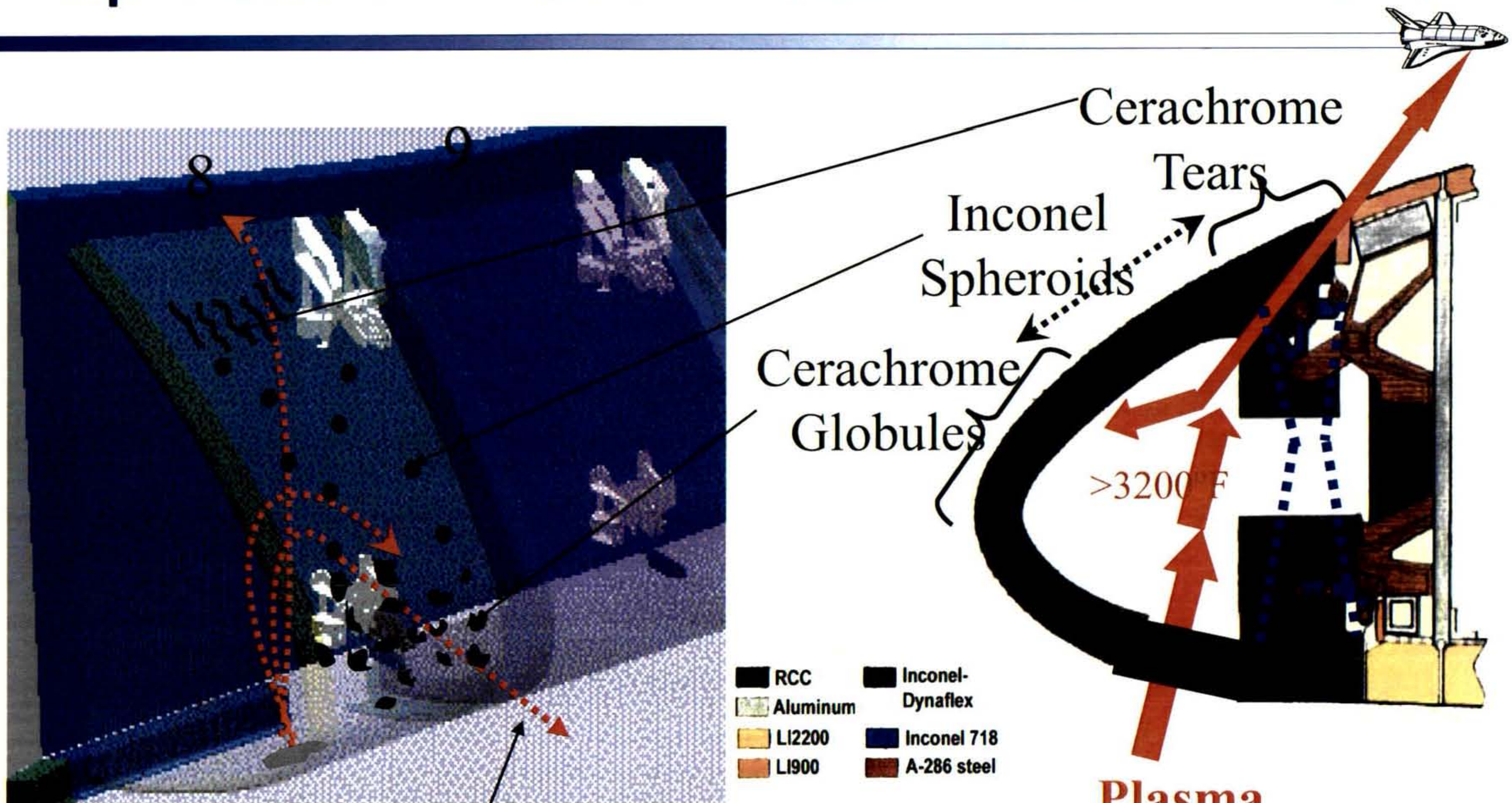
Layering of metallic deposits suggests plasma impingement location

Distribution & shape of metallic deposits 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 metallic deposit layers contain aluminum
  - CONCURRENT Spar/Inconel/Insulator melting
- Metallic deposits are is generally uniform and relatively thin
  - No region where melting was concentrated
    - i.e. plasma heating for short periods

Proposed Breach Location and Plasma Flow



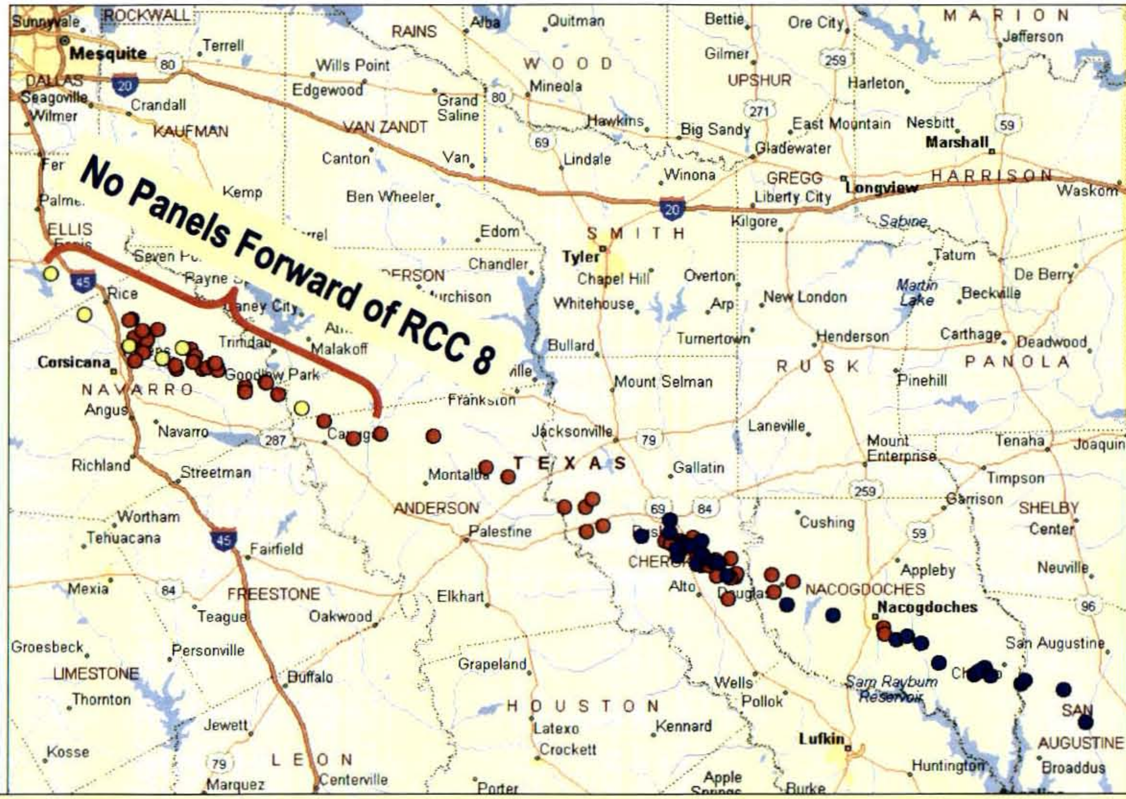
Flow Exiting through RCC 8 on to lower Carrier Panel 9 tiles

Corroborating Information - RCC Panel Debris Locations

Left Wing RCC

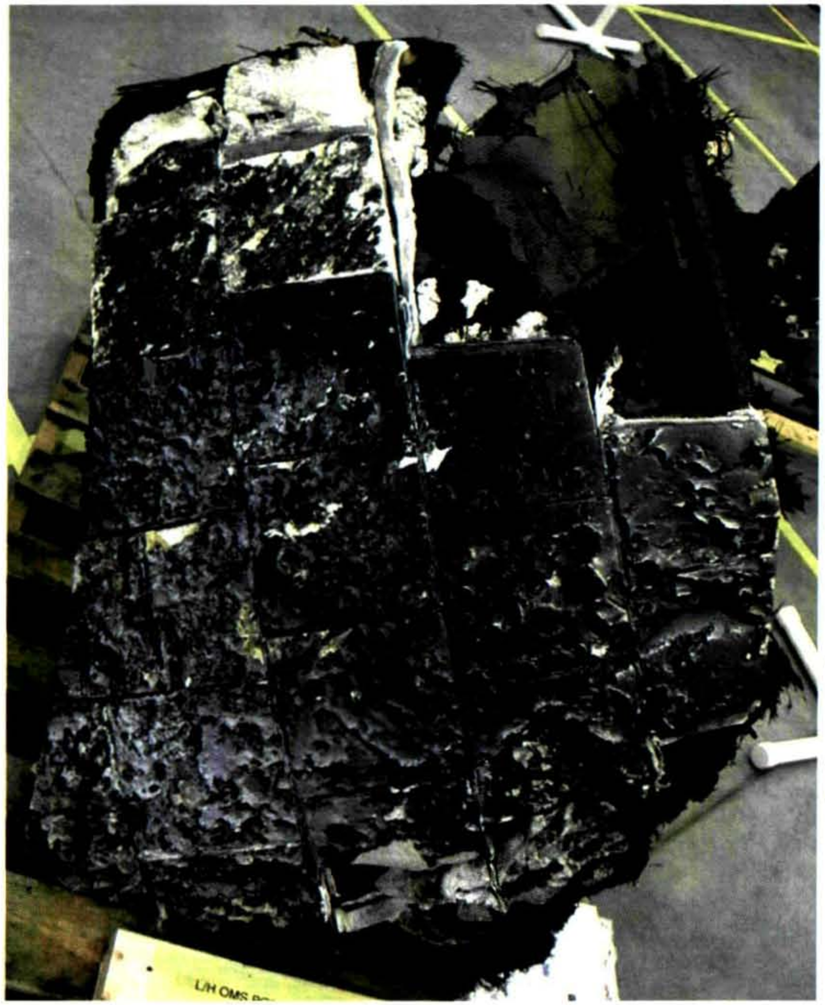
Left Wing Eroded RCC

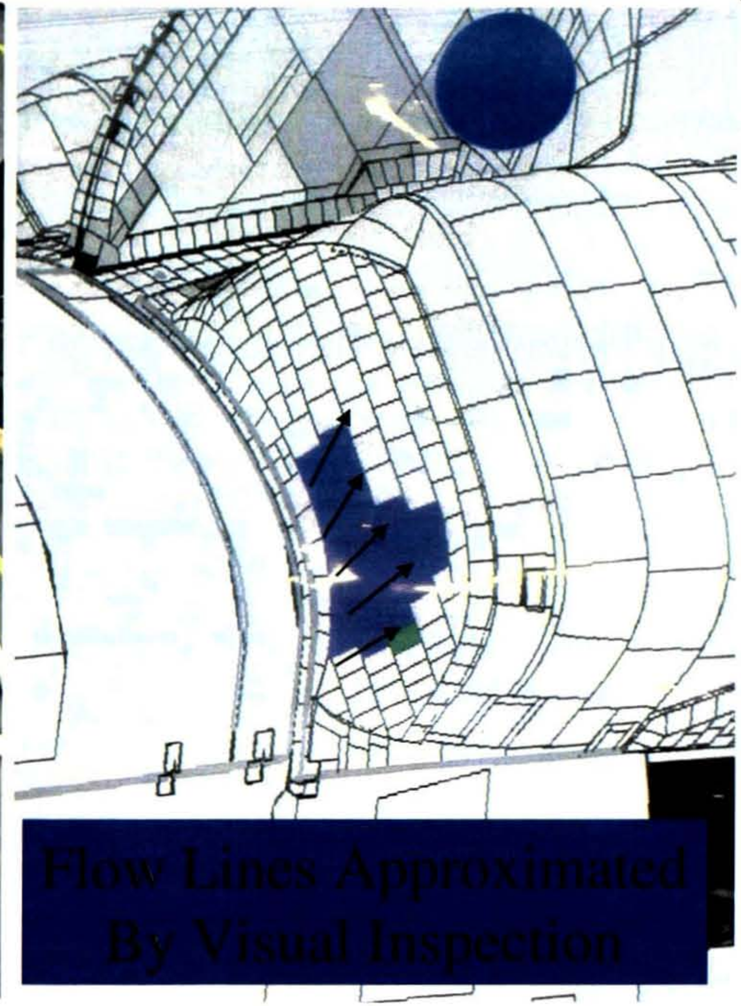
Right Wing RCC



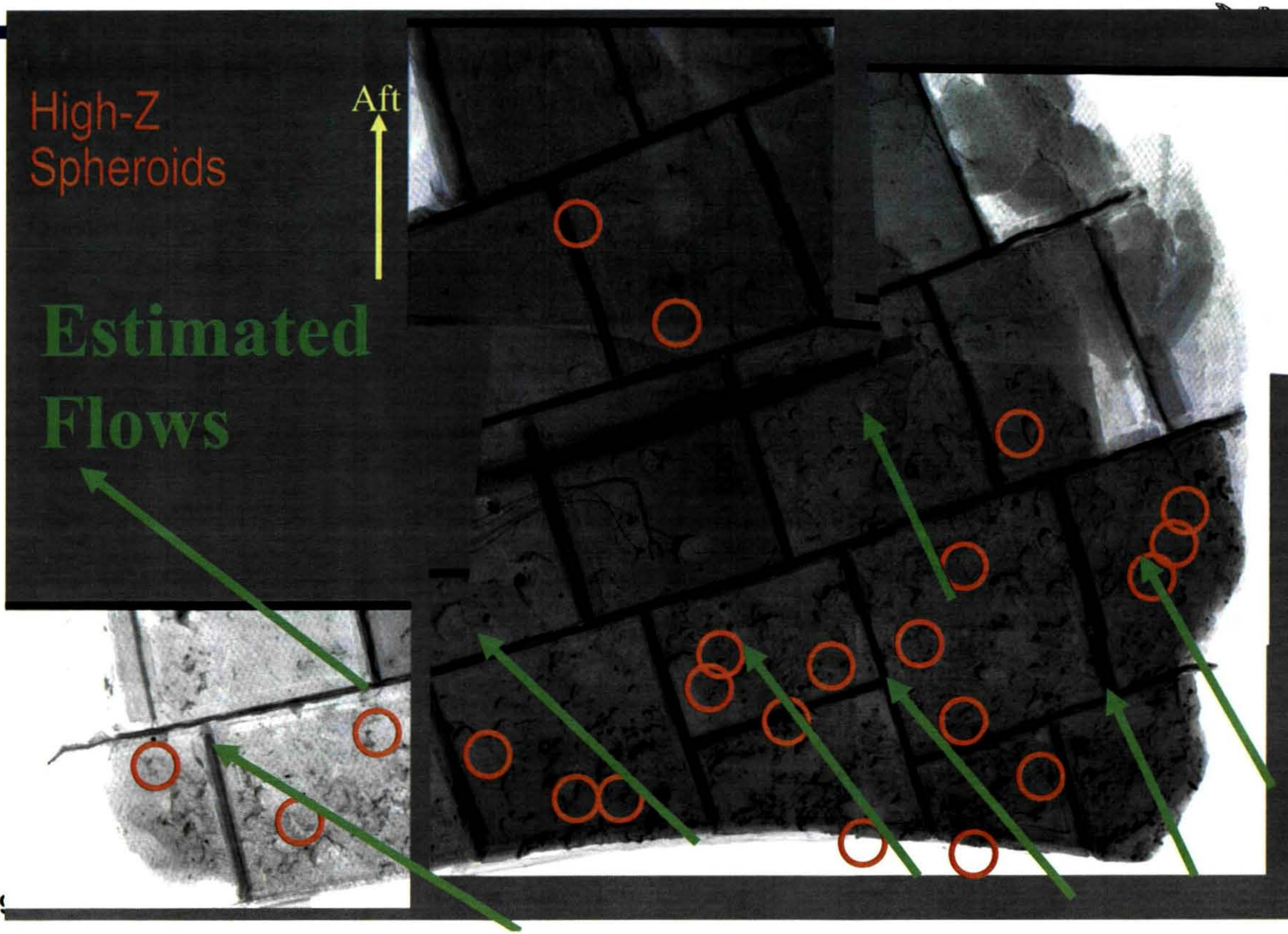
- Panels at RCC 8 and Aft Dropped First
- All Eroded RCC Pieces (in 8 & 9) Found to the West
- R/H Wing Panels and L/H Wing Panels 1-8 Found to the East

Corroborating Information – LH OMS Pod Analysis

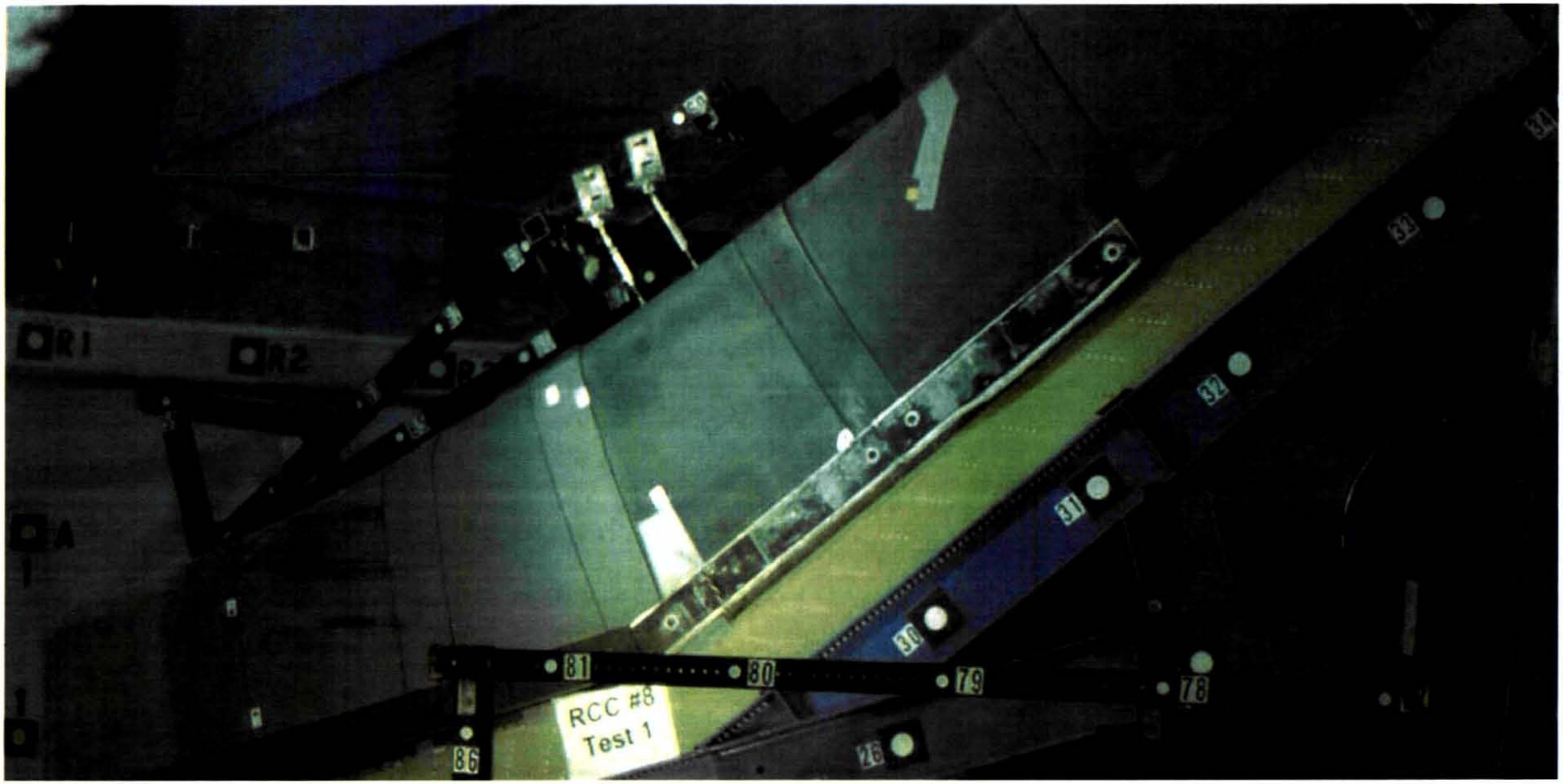




Corroborating Information – LH OMS Pod Analysis



Corroborating Information – Impact Testing



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.