THE SPACE SHUTTLE *COLUMBIA* ACCIDENT INVESTIGATION: TOOLS, TECHNIQUES, AND RESULTS

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OVERVIEW

The loss of the space shuttle *Columbia* resulted in the largest aerospace accident investigation in history. Nearly 20,000 people were ultimately engaged in the efforts by the time the primary investigation into the mishap concluded. Although the vast majority of those participating were involved in debris recovery over an area of approximately 17,000 square kilometers (approximately 6,500 square miles), a cadre of scientists, engineers, and technicians from across the United States performed macroscopic and microscopic examinations of the debris, along with microanalytical evaluations, to determine the depositional characteristics of metallic deposits found adhering to portions of the debris. The characteristics of these deposits, such as layering sequences and compositions, were instrumental in determining the sequence of events leading to the disintegration of the vehicle.Body text, body text

1. BACKGROUND

The space shuttle *Columbia* launched (Figure 1) from the Kennedy Space Center in Florida on January 16, 2003, at 10:39 a.m. EST. Approximately 81 seconds into the ascent, a piece of debris, likely foam from the external tank, struck the left wing of the *Columbia* (Figure 2), although the exact location of the impact, and resultant damage, could not be immediately determined. It was later estimated that the debris struck at an impact velocity of mach 2.46.

FIG 1. Space Shuttle *Columbia* Lift Off

FIG 2. Debris Strike on Left Wing

Sixteen days later, on February 1, 2003, the *Columbia* had completed the space-based portion of its mission and was beginning its descent back to Earth. One minute and twenty-four seconds into the peak heating portion of the re-entry, a left main landing gear brake line indicated a temperature rise in that region; shortly thereafter, numerous additional sensors in that area likewise indicated an increase in the localized temperature. Nearly seven minutes later, at approximately 8:59 a. m. EST, loss of signal occurred between the *Columbia* and Mission Control; within forty-five seconds the orbiter began to disintegrate (Figure 3).

FIG 3. *Columbia* disintegrating

At the time of the disintegration, the *Columbia* was traveling in excess of Mach 18 at an altitude of 208,000 feet/63 KM. Because of the combination of altitude and velocity, the resultant debris field was over 645 miles/1,038 KM long and 10 miles/16 KM wide.

2. PROCEDURES

Immediately after the loss of the *Columbia*, a contingency was declared, and an accident investigation board was convened. A multitude of teams and subteams were formed to support various aspects of the investigation, including a Debris Recovery Team, a Materials and Processes (M and P) Failure Analysis Team, and a Debris Reconstruction Team. The Debris Recovery Team was comprised of over 16,000 volunteers who expended nearly 1.5 million hours scouring the debris field for remnants of the vehicle. The recovery effort lasted nearly four months, resulting in the retrieval of approximately 84,000 pieces of orbiter debris, weighing approximately 85,000 pounds/38,555 kg, roughly 38% of the Orbiter's dry weight. The Debris Reconstruction Team, located at KSC, was composed of nearly 150 people who expended nearly 150,000 hours in the reconstruction phase.

The M and P team had to answer several major questions: Did a breach occur in the left wing of the orbiter, and if so, where? Also, what was the sequence of events following the breach, which ultimately led to the loss of the vehicle? In order to answer these questions, a plan of investigation had to be devised.

After pieces of debris were recovered and preliminarily identified in the field, they were then delivered to the Kennedy Space Center for a more thorough identification and evaluation. Of the nearly 84,00 pieces of debris that were ultimately recovered, approximately 1,000-2,000 pieces were determined to be of particular interest- pieces, it was hoped, that would yield the most valuable and salient information with respect to the cause of the catastrophe. These pieces, consisting of right and left wing leading edge remnants, tiles, underside components, etc., were placed on the floor of a hangar that had been designated as the vehicle reconstruction site. The hangar floor itself had a gridwork of tape applied to it in order to facilitate the reconstruction effort. The pieces of debris meriting additional examination were placed on the floor, in their approximate locations corresponding to their original location on the orbiter (Figure 4).

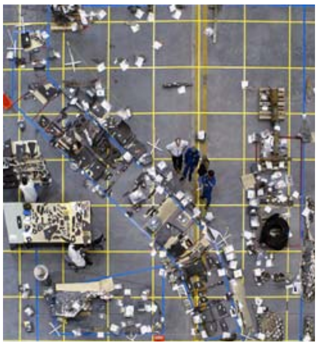

FIG 4. Remnants of Panels 1-22 of the Left Wing Leading Edge

At the onset of the investigation, only completely nondestructive methods of inspection were permitted to be employed. Therefore, the investigative team was limited to visual and low-power macroscopic examination. Magnifying glasses and loupes were utilized during this initial examination... This examination helped determine the effects of thermal damage on various components (Figure 5).

FIG 5. Thermal Degradation Evidence of Hot Gas Flow Exiting Design Slot Indicates Significant Breach Was Into Panel 8

It was decided that looking at any metallic materials that had been melted and subsequently re-solidified would help reveal the sequence of events immediately prior to the disintegration of the *Columbia*. Specifically, looking at the order and sequence of deposition, location of the various deposits of certain materials, and the dispersion and spatter patterns would help the investigators ascertain which components melted, and in what order; this would correspond to the failure sequence of the various components originally located within the left side wing leading edge. By working backwards in this manner, it was believed that the original area of damage could be determined.

As is typical in any investigation, whether a routine failure analysis or the most wide scale mishap investigation in aerospace history, sampling, testing and analysis was conducted sequentially from the least invasive to the most destructive. After only a few samples were harvested from the various remnants, it was soon evident that more surface-sensitive techniques such as XPS and ESCA would only divulge what had been deposited last in the sequence of events immediately preceding the loss of the orbiter, and not help determine the underlying compositions. Likewise, XRD could help show what, if any, compounds were present, but could not furnish the ratios of compounds or their layering and sequencing characteristics. The samples which were subjected to the above methods tended to be loosely adherent "slag" deposits. Although the term "slag" is a metallurgical misnomer in this case, that is the terminology that was used throughout the investigation. It was evident that the interior portions of the left wing leading edge were more heavily covered with slag deposits near panels 8 and 9. The further away from that region- the less slag was found.

As the forensic investigators were permitted to begin destructively harvesting samples, more intrusive techniques were employed. 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, nondestructive radiography was enlisted. For ease of understanding 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. In typical radiography, denser materials appear lighter and less dense materials appear darker. The opposite holds true in inverse radiography; denser constituents appear darker and less dense materials appear lighter (Figures 6 and 7).

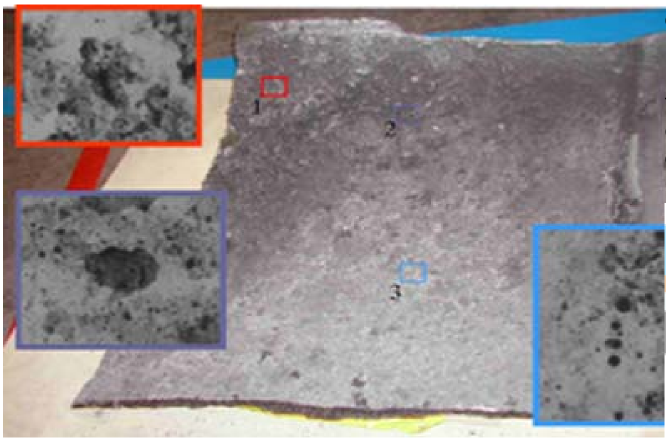

FIG 6. Inverse Radiograph Of The Left-Hand Reinforced Carbon- Carbon Panel Number 8 Upper Apex Displaying Three Distinct Deposition Types and Locations

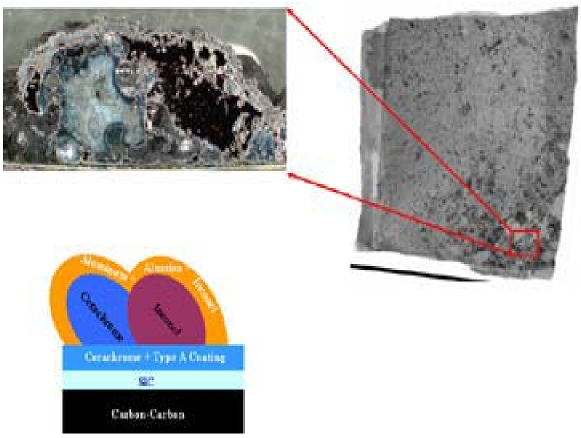

FIG 7. Inverse Radiograph, Metallographic Cross Section, and Schematic Analytical Representation of Panel 8 Piece

3. RESULTS

The radiographs essentially served as maps to guide the investigators to where sampling should be done. As the samples were located and harvested, they were subsequently subjected to analytical testing to determine their composition. Once removed from their parent piece, the samples were metallographically mounted and cross sectioned, then examined via scanning electron microscope, where energy dispersive X-Ray spectroscopy (EDS) and electron microprobe analysis (EMPA) were utilized. 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.

Four types of deposits were found on the interior of the wing: globular, spheroidal, tubular, and typical (Figure 8). The globular deposits were found mainly on the apex of the interior of the RCC panels and contained re-solidified cerachrome insulating material, which has a melting point of approximately 1,649° C. The spheroidal deposits had a large concentration of Inconel 718, and were found mainly in the interior upper central portion of the panels. The tubular deposits, with their corresponding composition of cerachrome, were found on the upper region of the interior of the panels, opposite the plasma entry point (Figure 9).

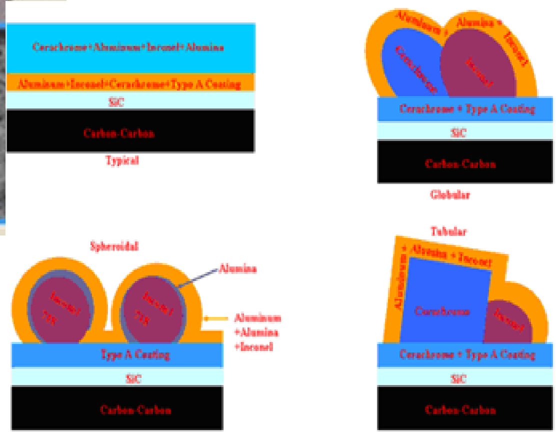

FIG 8. Schematic Representation of Deposit Type and Composition Of Samples From Figure 6. Dr. Greg Jerman, NASA-MSFC

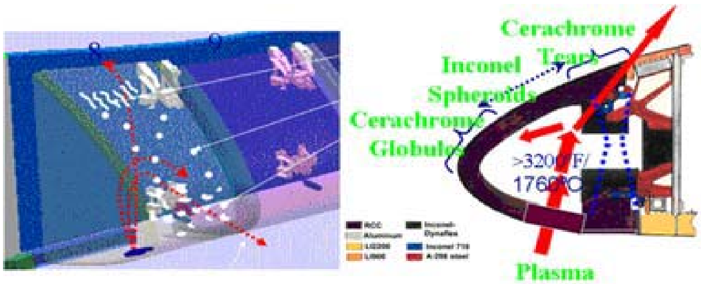

FIG 9. Proposed Breach Location and Impingement Path

4. CONCLUSIONS

The pattern and dispersion characteristics derived from radiography, and the chemical compositions of the cross-sectioned samples, were combined with visual, macrsocopic, and fractographic features found on several pieces of recovered debris to answer the questions posed to the M and P team at the onset of the investigation: Did a breach occur in the left wing of the orbiter, and what was the sequence of events following the breach? The left wing in the panel 8 and 9 area began melting the cerachrome insulating material, which deposited on the opposite side of the interior in tubular deposits. The temperature required to melt cerachrome is sufficient to degrade and erode surrounding heat resistant tiles and interior support hardware. As the hot flow swept inward, it next encountered inconel spanner beams, whose spheroidal deposits were in the central portion of the interior of the RCC panels. The lack of detection of A286 in the chemical analyses indicated that the interior attach fittings were not in the path of the flow, further helping back trace the breach location. When taken together, it became apparent that heat damage was most severe in, and occurred first, near panels 8 and 9 on the leading edge of the left wing, corresponding to the suspected area of the foam strike during ascent.

[1] B. Mayeaux. (2004) *Journal of Materials,* **Vol 56 No. 2**: 20-30