Microscopy & Microtechniques Focus

THE ROLE OF MATERIALS DEGRADATION AND ANALYSIS IN THE SPACE SHUTTLE COLUMBIA ACCIDENT INVESTIGATION

Steve McDanels, NASA, Kennedy Space Center, Florida, USA

Delegates at MICROSCIENCE 2006 will have a unique opportunity to learn more about one of the most high profile materials failure programmes ever launched. Steve McDanels, manager of NASA's Failure Analysis and Materials Evaluation Branch at the Kennedy Space Center has been invited to give a special Plenary Session on June 27th, the first day of the Conference. He will detail the light and electron microscopy techniques, as well as their associated chemical analysis techniques, that NASA scientists have employed in their search for the causes of the Space Shuttle Columbia disaster on February 1, 2003.

As well as giving an insight into the depth of the investigation into the Shuttle mission STS-107 disaster, McDanels will talk about NASA's continuing return to flight efforts and the impact the investigations are making on the design and construction of the next generation of space vehicles.

At MICROSIENCE 2006, McDanels will release the latest findings from the investigation. Here, in a special preview, he sets out the scope of the investigation and the findings so far.

> *“THE ANALYSIS OF THE RECOVERED DEBRIS WAS NOT RESTRICTED TO JUST VISUAL EXAMINATION IN THE HANGAR”*

Author Details:

Steve McDanels,
NASA, Kennedy Space Center,
Florida, USA
Steve.mcdanels@nasa.gov

Shuttle Transportation System Mission STS-107 began with the launch of the Space Shuttle Columbia from the NASA Kennedy Space Center on January 16, 2003 *(Figure 1)*.

Figure 1. Launch of the Space Shuttle Columbia on STS-107

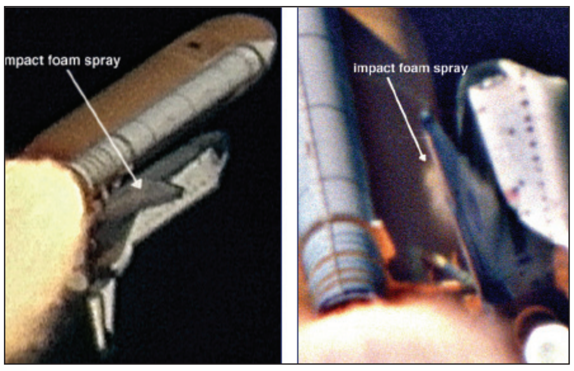


Figure 2. Foam impacting left wing of Columbia during ascent

A review of high resolution still and video imagery recorded during the launch indicated that a piece of foam from the External Tank struck the underside of the left wing during ascent *(Figure 2)*.

The last communication from the Columbia took place during re-entry, at 8:59:32 a.m. (EST), on February 1, 2003; by 9:00:18 a.m. (EST) the Orbiter had begun to disintegrate *(Figure 3)*. Because the Columbia was travelling in excess of Mach 18 at an altitude of approximately 63,400 m (208,000 ft) when she began to break apart, the resultant debris field was nearly 1,030 km long by 16 km wide (640 miles long by 10 miles wide). Approximately 84,000 pieces of debris were eventually collected, weighing nearly 38,555 kg (85,000 lb), corresponding to roughly 38% of the Orbiter's dry weight.

The debris which was recovered was then delivered to the Kennedy Space Center *(Figure 4)*. There, the remnants were further identified and evaluated, and pieces from primary areas of interest were placed in a reconstruction hangar, where an outline of the Orbiter had been superimposed on a floor grid to facilitate the reconstruction process.

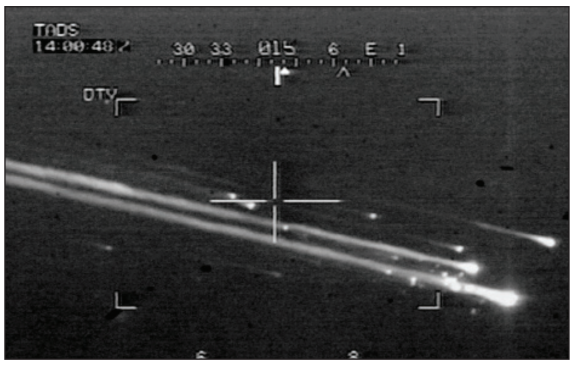


Figure 3. Danish AH-64 helicopter photo of the Columbia disintegrating

It should be noted that there are 22 reinforced carbon-carbon (RCC) panels on the leading edge of each wing. RCC panels from the left wing, outboard of RCC panel 8, i.e., panels 9-22, were recovered further west than the panels inboard of RCC panel 8. The further west an item was located indicated that the piece of debris departed the Orbiter earlier in the breakup.

Figure 4. Reconstruction of the Columbia debris at the Kennedy Space Center

The analysis of the recovered debris was not restricted to just visual examination in the hangar; the debris was subjected to myriad quantitative and semi-quantitative chemical analysis techniques in the laboratory, ranging from examination via the scanning electron microscope (SEM) with energy dispersive spectrometer (EDS) to X-ray diffraction (XRD) and electron probe micro-analysis (EPMA), as well as electron spectroscopy for chemical analysis/X-ray photoelectron spectroscopy (ESCA/XPS). The chemical testing was performed to help determine the sequence, order, and pattern of deposition of various types of deposits found on many critical pieces of debris.

ESCA/XPS and XRD were beneficial in determining compounds which were found in the deposits. EPMA and SEM/EDS were useful in understanding and characterising the sequence and ordering of the deposits *(Figure 5)*. Specific alloys could be identified by their respective ratios of nickel and iron, which, along with the presence of alloying elements such as molybdenum, cobalt, niobium, and titanium, helped differentiate and identify alloys such as Inconel 601, Inconel 625, Inconel 718, and A286.

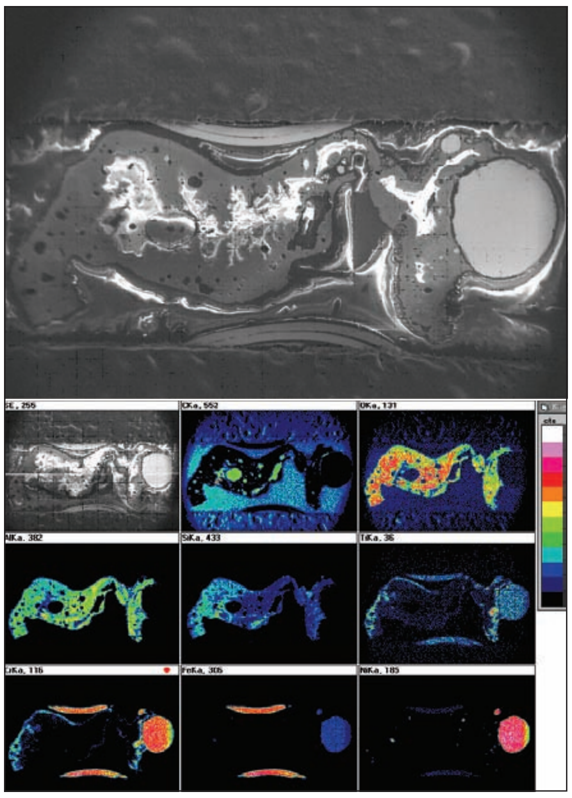


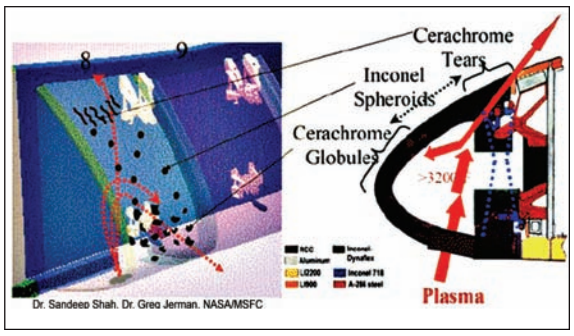
Figure 5. Materialographic cross section of deposit (top) and X-ray dot map (bottom)

Likewise, radiography was performed to help understand the characteristics of the deposits, particularly their relative amount, orientation, distribution, and overall spatter patterns.

The debris was examined to glean any information pertaining to the types of mechanical and thermal damage encountered. A small number of left wing leading edge RCC panel fragments displayed severe "knife-edging" from exposure to high temperature, high velocity plasma. This damage was generally concentrated to debris remnants from left wing RCC panels 8 and 9 of the Orbiter.

The combination of the recovery location (further west versus east), chemical analysis, and damage evaluation helped the investigators determine that the likely location where a breach occurred was in the outboard region of left wing RCC panel 8. The RCC fragments from this area displayed the most severe "knife-edge" attack, indicating they were exposed to the plasma stream for the longest duration. Based upon the presence of melted cerachrome, a ceramic insulating material used inside the structure of the wings of the Orbiter, it was estimated that the temperatures encountered during re-entry were in excess of 1760° C (3200° F). The lack of A286, and the presence of Inconel 601, in the initial layers of deposits indicated that the breach occurred lower on the RCC panel rather than in the upper region, corresponding to the video and photographic evidence obtained during the launch.

The information evidenced by the debris was also crucial in ascertaining the path of impinging plasma flow once it had breached the wing *(Figure 6)*. As the plasma began penetrating the leading edge panels, the Inconel 601 foil-covered cerachrome insulation blankets began to melt and vaporise within the wing. Hardware adjacent to the RCC panel 8 region, including wing carrier panel tiles directly aft of the breach, began to slump and melt. Hardware, including adjacent RCC panels, began to erode downstream of the breach. This type of damage was not observed on panels upstream, or inboard, of the suspected breach location in panel 8. Eventually A286 and Inconel 718 leading edge attach hardware began to melt and weaken in the path of the plasma flow. Ultimately, the impinging plume compromised the wing leading edge spar, whereby the left wing could no longer withstand the extreme loads imparted to it during the final re-entry of the Columbia.



Dr. Sandeep Shah. Dr. Greg Jerman. NASA/MSFC

Figure 6. Likely breach location and subsequent plasma flow path

After the Columbia Accident Investigation Board (CAIB) issued its findings, the major portion of the investigation was concluded. However, additional work remained to be done on many pieces of debris from portions of the Orbiter which were not directly related to the initial impact during ascent. This subsequent work was not only performed in the laboratory, but was also performed inside the Vehicle Assembly Building at the Kennedy Space Center, where the Columbia debris is now housed. Portable analytical equipment, including X-Ray fluorescence (XRF) and Fourier transform infrared spectroscopy (FTIR) devices, have been used recently to characterise deposits and features on pieces of debris which could not otherwise be brought to a laboratory for analysis. Likewise, acetate and silicon-rubber replicas of various fracture surfaces were obtained for later macroscopic and fractographic examination. Rather than concentrating on wing leading edge components, this subsequent investigation included the Columbia's windows, bulkhead structures, and associated components. The findings from this portion of the investigation are not yet ready for publication; however, the information will be available for the MICROSCIENCE 2006 conference.

Many improvements, changes, and augmentations have been incorporated into the Space Shuttle since the loss of the Columbia. Technicians have been retrained to improve the quality of sprayed-on insulation. The External Tank has been modified to minimise the likelihood of foam shedding during ascent. Increased still and video observation has been instituted to help ensure no damage occurred during lift off, and if any damage is detected, it can be evaluated real-time. Impact detection sensors have been installed on the most susceptible wing leading edge components, the RCC panels. Likewise, impact-susceptible areas have been hardened and reinforced to help resist damage. A boom arm with a laser imaging system will allow what had been until now inaccessible and obscured areas of the Orbiters to be examined in orbit. The list goes on, but every change, improvement, or delay has all been instituted with one goal in mind: To ensure that the Space Shuttle is as safe as possible.

As the Space Shuttle begins what may be the final stage of its historic career, the lessons and information learned from its service will prove invaluable in designing, constructing, and building any successor vehicle. The next generation vehicle will incorporate many of the characteristics and features which made the Space Shuttle a successful space launch system, and will utilise improvements based upon the experience of a quarter century of Shuttle flights.

ACKNOWLEDGMENTS

The efforts, findings, and analyses of the following Principal Members of the Materials and Processes Team constitute the bulk of this paper: **Dr. Brian M. Mayeaux**, NASA/Johnson Space Center; **Thomas E. Collins**, Boeing/Huntington Beach; **Dr. Gregory A. Jerman**, NASA/Marshall Space Flight Center; **Steve McDanels**, NASA/Kennedy Space Center; **Dr. Robert S. Piascik**, NASA/Langley Research Center; **Richard W. Russell**, NASA/Johnson Space Center; and **Dr. Sandeep R. Shah**, NASA/Marshall Space Flight Center.