STS-107 Columbia Reconstruction Report

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EXECUTIVE SUMMARY

The Columbia search and recovery effort began February 1st, 2003. Expectations anticipated debris collected in east Texas and Louisiana would provide evidence critical to the Columbia accident investigation and aid in the development of the most probable failure scenario. In the first several days following the Columbia accident, a team formed and planning began for the reconstruction of Columbia. The Space Shuttle Program selected Kennedy Space Center's Shuttle Landing Facility Reusable Launch Vehicle hangar as the optimal reconstruction facility, based on its size, available technical workforce, access to the vehicle ground-processing infrastructure, and its proximity to materials science laboratories. This became known simply as the Columbia hangar.

In the planning phase, the Reconstruction Team established several critical processes for safe handling and management of the debris. These processes included receiving, handling, decontamination, tracking, identification, cleaning and assessment of the debris, each with an emphasis on evidence preservation. The team was comprised of engineers, technicians, inspectors and managers from the National Aeronautics and Space Administration, United Space Alliance, Boeing, and the National Transportation Safety Board.

The reconstruction effort spanned a period of five months in which 27 tractor-trailer loads of Columbia debris were shipped from Barksdale Air Force Base in Louisiana to KSC. As of June 30, 2003, the recovery forces collected an estimated 38 percent of the Orbiter's dry weight. The amount of debris received weighed approximately 84,900 pounds and comprised 83,900 items. The majority of items were no larger than one half square foot. More than 40,000 items could not be positively identified and were placed in the category of unknown metal, tile, electrical, tubing, structure, composite, plastic or fabric. The remaining balance of debris was instrumental in steering the investigation toward a root cause —with the 876 pieces associated with the left wing being the most critical.

Initially, a two-dimensional reconstruction of the Orbiter outer mold line was developed to facilitate assessment of the debris. As debris was positively identified, the left wing leading edge became the investigation's main focus area. This initiated a three dimensional reconstruction of the left wing leading edge panels 1 through 13. In addition, a virtual reconstruction of the Orbiter left wing leading edge was performed. A full-scale left hand wing was also built on tables to display lower surface thermal protection tiles and structure. These reconstruction techniques used in conjunction with material sampling and failure analysis, allowed the investigators to extract the greatest amount of information possible from the debris.

In general, most recovered debris exhibited a combination of thermal damage and mechanical overload failure. Items with high ballistic coefficients showed much greater levels of ablation, while others failed because of aerodynamic forces or ground impact. Specifically, the condition of the left hand wing leading edge provides compelling evidence of an initial breach in the transition region that resulted in catastrophic damage.

The Columbia Reconstruction Team concludes that the initial breach occurred in the lower surface of left hand Reinforced Carbon Carbon wing leading edge panel eight. The breach allowed plasma flow into the wing leading edge cavity, which melted the insulation and structural members in the transition region. The upper leading edge access panels were likely lost due to hot gas venting. Shrapnel from the disintegrating left wing impacted the vertical tail and left Orbital Maneuvering System pod. The plasma penetrated the left wing with one of the exit points being through the trailing edge. The wing's structural capability was diminished to the point where it failed aerodynamically allowing the wing tip and elevons to break off. This resulted in vehicle instability thus increasing aerodynamic and thermal loads on the Orbiter's left side, which caused vertical tail and payload bay door failure. The vehicle orientation rotated to allow thermal flow to penetrate the left mid and aft fuselage sidewall at the wing footprint. In the right wing, the hot gas flow is from the inboard side. Internal thermal loading combined with increased aerodynamic load caused dynamic break up and separation of the upper and lower right wing skin panels. The breakup of the remaining fuselage continued from aft to forward until aerodynamic loads caused final disintegration of Columbia.

As with any undertaking of this magnitude, critical success factors and lessons learned can be gleaned from the organization and execution of such an effort. The goal in documenting this information is to positively influence the organization and execution of future accident investigations. With this intent, the critical success factors that were accumulated over the entire recovery and reconstruction efforts are discussed at the end of this report.

Accident Background

On February 1, 2003 at approximately 0800 Central Standard Time the Orbiter Columbia broke up over east central Texas during re-entry into the earth's atmosphere. The Orbiter was returning to Kennedy Space Center (KSC) at the completion of mission STS-107. At the time of breakup, the Orbiter was traveling at about Mach 18 at an altitude of approximately 208,000 feet. The debris field was scattered over an area of eastern Texas and western Louisiana and measured approximately 645 miles long by 10 miles wide. The debris was recovered and shipped to KSC for examination in the Columbia hangar. It is estimated that approximately 38% (comprised of over 83,900 individual items) of the Orbiter, by weight, has been recovered to date. The debris field is depicted in figure 2.1 – Debris Field.

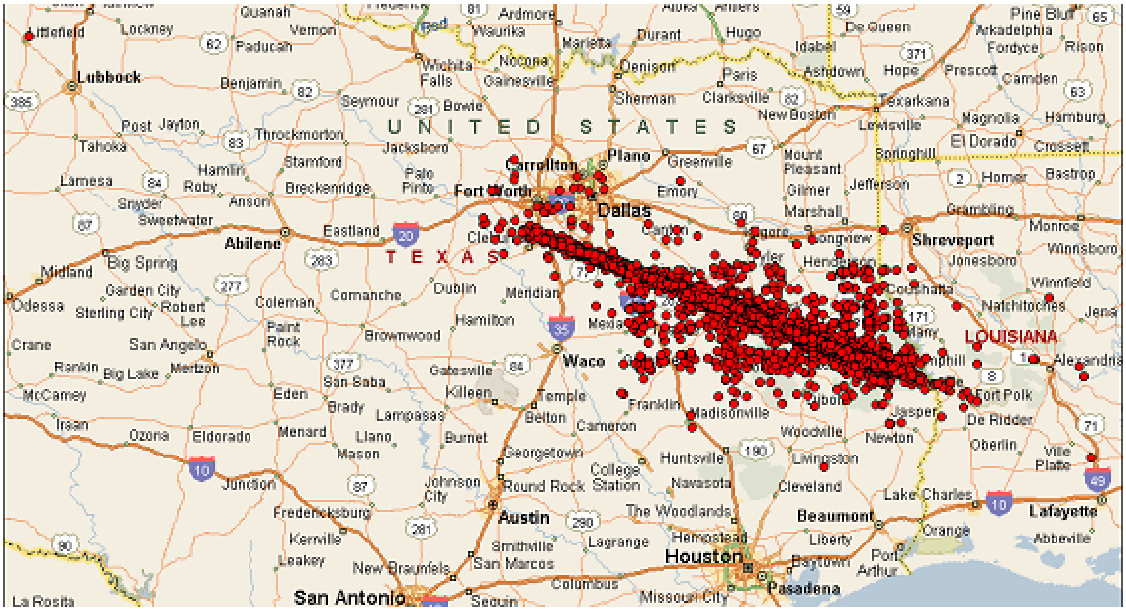


Figure 2.1 – Debris Field

Purpose of Reconstruction

Aircraft accident investigators typically perform a partial or total vehicle reconstruction to trace damage patterns and failure clues to aid in determining the accident's probable cause. This is especially useful when the recorded vehicle data does not provide significant insight into the causes and contributing factors or when an in-flight structural breakup occurs scattering parts over a large geographical area.

Reconstruction may take on many forms, but essentially involves placing the recovered debris into its original position prior to the occurrence of the structural failure. In some cases the reconstruction is performed in a two-dimensional (2-D) representation, and in other cases the debris is reconstructed three-dimensionally (3-D) in custom designed fixtures.

In virtually all aircraft accident investigations, a 2-D layout of at least a section of the vehicle is performed and only when enough information cannot be obtained through this method is a more costly 3-D reconstruction performed. Thus, the 2-D reconstruction planning must begin before the debris arrives at the reconstruction site. Planning for the 3-D reconstruction can be done months or even years later if required.

An essential decision to make before performing a 2-D layout is how to best utilize the available reconstruction space and how to intelligently represent a 3-D vehicle on a 2-D layout grid. Usually, the initial accident reports and preliminary data dictate the reconstruction scheme.

In most aircraft reconstructions, the fuselage layout is split at either the upper or lower centerline then opened up to show either the internal or the external surface. The 2-D layout grid has an expansion factor, usually set at 10 percent to 25 percent, allowing sufficient room for investigators to examine each piece of debris from all angles.

Damage patterns can be discerned as the reconstruction grid is populated. It becomes possible to study the damage's continuity or lack of continuity on associated pieces. As an example, if a wrinkle in one skin panel section continues across a break or tear, it is possible to conclude that the forces necessary to cause the wrinkle were applied prior to the break or tear. The continuity of smears and score marks across breaks provides additional evidence and aids in differentiating between in-flight, post-breakup, and ground impact damage. Overall, relating the damage between individual debris pieces determines failure patterns, including directional indications of force application (for example, the manner and direction in which rivets, screws and bolts were sheared).

Many times differences between adjacent or symmetric (i.e., left vs. right) debris pieces provide valuable clues that lead to determining the initiating event. All significant debris pieces are documented and the most relevant are further analyzed by various sampling and forensic techniques. Because the failure modes and signatures of typical aerospace construction materials are known, an accurate assessment of the overall failure scenario can be made based upon the debris and material assessment results.

The National Aeronautics and Space Administration (NASA) Deputy Administrator gave direction to perform the reconstruction at the KSC. This was the triggering decision for the creation of the Reconstruction Team and the activation of the Reusable Launch Vehicle (RLV) Hangar at the Shuttle Landing Facility (SLF) as the Columbia reconstruction site. Initially based on plans contained in SFOC-GO0014, KSC, Space Shuttle Program, Salvage Operations Plan, the Reconstruction Team structure was adapted for the Columbia contingency and debris reconstruction effort. NASA maintained primary responsibility for the Columbia reconstruction effort with support from United Space Alliance (USA), Boeing, the National Transportation Safety Board (NTSB), and other various support contractors. The team organization chart is shown in Figure 3.1 - Mishap Investigation Team (MIT) - Reconstruction.

Staffing the Reconstruction Effort

For the majority of the reconstruction period, approximately 75 personnel supported operations on each of two 8-hour shifts, 6 days a week. Technical experts from KSC and Johnson Space

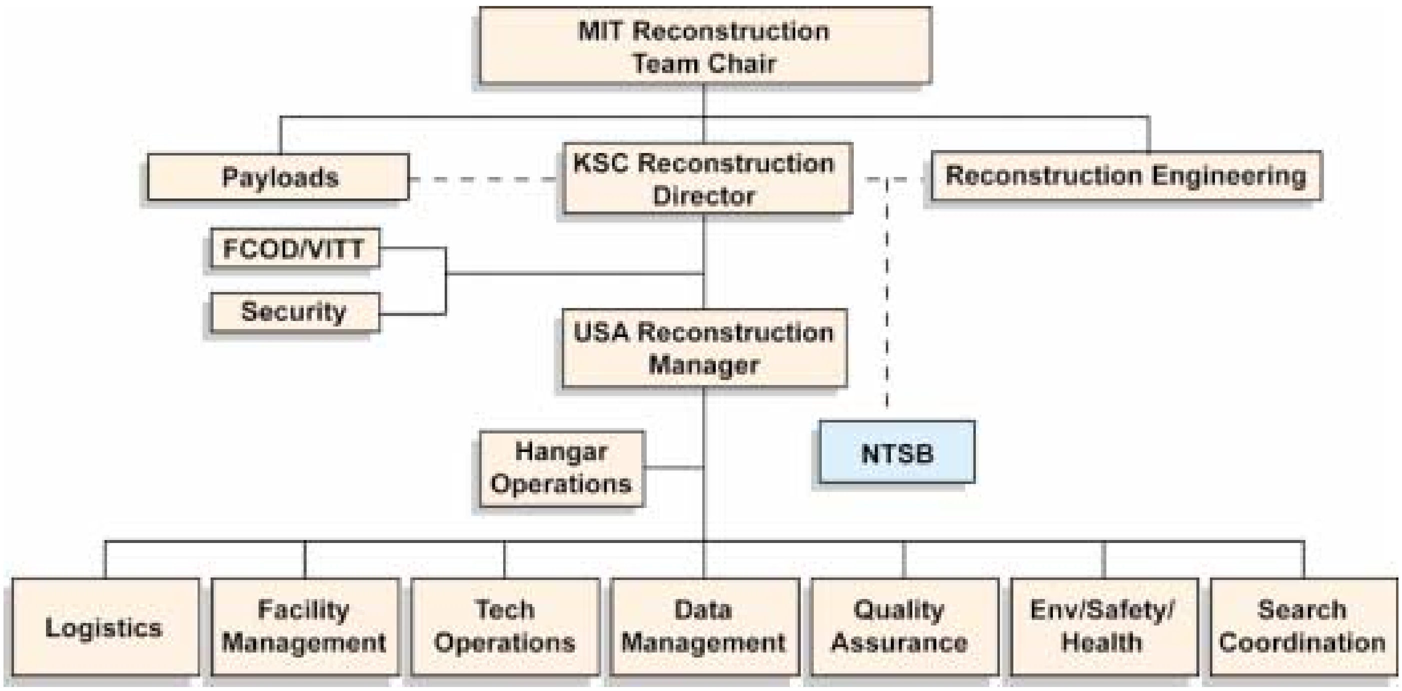


Figure 3.1 - Mishap Investigation Team (MIT) - Reconstruction

Center (JSC) were deployed to the Columbia hangar and assigned to staff the Floor Support, Technical Disciplines, Crew Module Support, Payload Support, Material and Process Engineering, or Data Management processes.

FLOOR SUPPORT

Floor Support consisted of Environmental Safety and Health personnel, Logistics Specialists, Receiving Technicians, Quality Inspectors, Material Handling Technicians, and Industrial Engineers. All were employees from the USA Integrated Logistics, and USA Orbiter/Launch Operations directorates. These personnel constituted approximately 60% of the daily workforce.

Environmental Safety and Health personnel were responsible for determining if detectible levels of hazardous propellant residue were present on the debris. This group verified each truck and box was safe for handling before entering the Columbia hangar. NASA, USA Safety and Health, and Space Gateway Services (SGS)/CHS Environmental Health and Services employed these personnel.

Logistics Specialists, under the supervision of a first line manager, controlled the truck off-loading and the uncrating of all materials received at the Columbia hanger. Orbiter technicians were used in the receiving areas to unpack and clean debris. Quality Inspectors verified debris associated field notes, separated multiple items under one tracking number into individual tracking numbered items and photographed each item.

Material Handler Technicians facilitated the movement of all material from one location to another. All items moved to the reconstruction grid, or material storage bins and shelves, were inventoried and recorded by material handlers.

Periodic audits of debris location within the Columbia hangar were performed to verify process integrity and accuracy. Industrial Engineers performed these independent assessments of debris handling and storage. In addition, a Grid Manager was utilized to control all movement of items to and from the reconstruction grid.

TECHNICAL DISCIPLINES

USA, Boeing, Rocketdyne, and NASA supplied the engineering support for the Columbia reconstruction effort. The engineering team leadership was comprised of NASA JSC Resident Office, USA Orbiter Element and USA Ground Operations. NASA/JSRO manager and USA Orbiter Sub-System Area Managers (SAMs) provided technical and processing leadership, including 3-D laser imaging and debris assessment respectively. USA Ground Operations provided administrative leadership. Engineering personnel made up approximately 30% of the total Reconstruction Team and consisted of the following disciplines:

- Structure Engineer - responsible for vehicle airframe debris
- Mechanisms Engineer - responsible for landing gear hatches and mechanisms
- Thermal Protection System (TPS)/ Thermal Control System (TCS) Engineer - responsible for Orbiter thermal protection debris such as tile, thermal blankets, gap fillers, etc.
- Hypergolic Engineer - responsible for Orbiter Orbital Maneuvering/Reaction Control System (OMS/RCS) components and safing of hypergolic contaminated debris
- Fluids Engineer - responsible for evaluation of non-hypergolic fluid systems debris such as main fuel cells, engines, radiators, etc.
- Electrical Engineer - responsible for evaluation of Electrical Power and Distribution, Instrumentation, and Avionics debris such as black boxes,

wiring, etc.

- APU /HYD Engineer - responsible for Auxiliary Power Unit (APU) and Hydraulic (HYD) Orbiter systems
- Flight Crew Systems (FCS) Engineer - responsible for processing & identification of items with which the crew directly interfaced
- SpaceHab/Payload - responsible for SpaceHab and STS-107 Payload related debris

An Engineering triage team was established and consisted of one engineer per shift for each discipline. Engineers were chosen to be members of this team based upon their multi-system experience and expertise. The triage team members were given the leadership responsibilities for processing and identification of the debris. Other system engineers, experienced senior technicians and quality personnel supported the engineering identification effort. The structures and thermal protection systems required the largest support groups.

A subset of specific engineers performed assessments of key identified items on the grid in support of the scenario teams at JSC. This group created fact sheets with detailed descriptions of the items and significant characteristics for each. Presentations were made to the Orbiter Vehicle Engineering Working Group (OVEWG) for these items on a weekly basis.

After the bulk of debris was processed into the Columbia hangar, the Debris Assessment Working Group (DAWG) was established. This team began a system wide engineering analysis of the debris to determine how the major structure and TPS elements failed. The DAWG was comprised of Boeing sub-system engineers, USA SAMs, USA system specialists, senior NASA system engineers and NTSB investigators.

CREW MODULE AREA STAFFING

The crew module organizational structure was dictated by a combination of the work force available at the Columbia hangar, the need for privacy for crew sensitive items, and the engineering experience needed for assessment.

KSC FCS technicians and KSC Vehicle Integration Test Office (VITO) personnel performed the first line of engineering assessment and held primary responsibility for conducting audits to verify debris was correctly handled.

The formal engineering assessment team consisted of engineers from the KSC FCS division (both USA and NASA) and members from the VITO (both KSC and JSC). Specialist engineers were brought in as required from JSC and Boeing Huntington Beach, CA for unique sub-system assessments.

The Flight Crew Operations Directorate (FCOD) at JSC assigned astronauts to the reconstruction effort, with them responsible for overall management of the crew module workforce. They provided a continuous on-site astronaut presence at the Columbia hangar. Other astronauts rotated to KSC for help in debris identification and determining stowage locations.

The crew module lead was responsible for working with Columbia hangar management, agency management, FCOD and the Crew Module Investigation Team to ensure appropriate handling of the debris while maintaining privacy and security.

PAYLOADS

KSC, Goddard Space Flight Center (GSFC), Boeing, and SpaceHab personnel supported payload recovery efforts. The core group consisted of two NASA Payload Management representatives, one NASA Operations Engineer, and NASA and Boeing engineers with extensive payload experiment backgrounds. This core group coordinated activities with the NASA Accident Investigation Team (NAIT), the KSC Reconstruction Team, the Shuttle

Payload Integration Office, and the payload developers. The engineers led the payload debris identification efforts.

SpaceHab provided several personnel on a rotational schedule that allowed debris to be analyzed by various disciplines. Initially two to four SpaceHab personnel supported first shift daily. In April, as the debris flow slowed down, SpaceHab was able to reduce this support to two days a week.

A team of three to five GSFC engineers traveled to KSC as needed to identify items from the Fast Reaction Experiment Enabling Science, Technology, Applications and Research (FREESTAR) payload. This small team visited approximately once each month for several days at a time.

MATERIALS & PROCESSES (M&P) ENGINEERING

The M&P team was formed to support the reconstruction effort with representatives from USA, NASA, and Boeing from JSC, KSC, MSFC, and Huntington Beach, CA. In addition to supporting the reconstruction engineering team, the M&P team supported the Hardware Forensics Team (HFT), the DAWG and the OVEWG.

Areas of responsibility included the following:

- Development of cleaning procedures and the actual cleaning of debris
- Submitting requests for disassembly of debris
- Development and execution of sampling procedures
- Performing nondestructive testing in the Columbia hangar and writing the test procedures and reports
- Performing analysis of debris items, or deposits on debris items, including writing the test procedures and related reports
- Performing failure analysis and writing related test plans, requests and reports

The team used laboratory resources from KSC (NASA, USA and Boeing NASA Shuttle Logistics Depot (NSLD)), Marshal Space Flight Center (MSFC), JSC, Glenn Research Center (GRC), Langley Research Center (LaRC) and Boeing Huntington Beach to support analytical activities. In a few select cases, laboratories outside the NASA community were used to perform unique analysis.

DATA MANAGEMENT STAFFING

The Columbia Reconstruction Data System (CRDS) development team consisted of multiple USA organizations. There was a core group that worked on-site, full-time while the remainder of the team worked remotely on an as-needed basis. The team consisted of a project leader, web page curators, web administrators, a database administrator and the Documentum support team.

The project leader's role was to act as an interface to the management team. By being intimately involved with the overall reconstruction process development, the project leader was able to define and prioritize software requirements to meet users needs. After software development, the project leader also validated the software to ensure it performed as expected prior to promoting to a production environment. The project leader was the overall system administrator and Responsible Data Manager (RDM) and approved all data access permissions after coordinating with the appropriate disciplines.

The web page curator team initially consisted of two fulltime, on-site, programmers from the Corrective Action Engineering group. These individuals were chosen due to their expertise and familiarity with Orbiter hardware. This background enabled them to perform rapid code development. In April, the web page curator's responsibility transitioned from Corrective Action Engineering to Applications Engineering Services.

The web administrators handled the

web server support. Their responsibility was to ensure the web servers were up and running, promote web software to the production environment, and provide access permissions when requested by the CRDS Project Leader/System Administrator. They also assisted in troubleshooting.

The DataBase Administrator (DBA) was responsible for overall maintenance and supportability of the Structured Query Language (SQL) Server database. The DBA was also the point of contact and responsible for all the interfaces with external databases, such as the Shuttle Interagency Debris Database System (SIDDS).

The Documentum Support Team was responsible for the storage and retrieval of all photographs and supporting debris documentation. User interfaces were developed by this team to easily load photos and documents into the proper folder structure. In addition, web pages were developed by this team to quickly and easily retrieve the photos and documents.

External Interfaces

MISHAP RESPONSE TEAM

The initial NASA response to the loss of Columbia was the establishment of the Mishap Response Telecon chaired by the Mission Management Team. The Mishap Response Telecon managed and coordinated all activities for the first 24 hours. The telecon became the Mishap Response Team (MRT) the day after the accident. Representatives from all program elements, as well as other federal agencies, departments, and military units participated in assisting with the recovery efforts and supported the MRT.

The KSC Rapid Response Team (RRT) consisting of 40 people, under the auspices of the MRT, arrived at Barksdale Air Force Base (BAFB) within 12 hours of the accident. KSC's initial support was two-fold; First, the senior leadership in Texas and Louisiana presented plans for the debris recovery in the field and second, KSC leadership presented their status on supplying personnel for that effort. The RRT evolved into two distinct teams; one responsible to continue the planning and recovery of the Orbiter debris, and one established to begin the reconstruction of the Orbiter debris itself. Planning for the formation of the Reconstruction Team began at this point. The Reconstruction Team at KSC was formed less than 1 week after the Columbia accident upon the decision of the NASA Deputy Administrator.

The chain of command that initially had the Reconstruction Team reporting to the MIT evolved over time, given the geographic separation of the Recovery Team in Texas and the Reconstruction Team at the Columbia hangar. The Reconstruction Team was recognized as a distinct and separate entity and began reporting directly to the MRT. This was also necessary because the ground search ended and the MIT was phased out two months before the reconstruction effort concluded. The Reconstruction Team provided its status to and received direction from the MRT for the remainder of the reconstruction/investigation.

COLUMBIA ACCIDENT INVESTIGATION BOARD

Concurrent with the above, the NASA Administrator activated an independent investigative body, the Columbia Accident Investigation Board (CAIB). By policy, the Board controlled the debris and began to assemble the members and support staff required to conduct an investigation into the accident.

The MRT received direction from the CAIB and continued the NASA investigation into the accident using all of the functional elements and organizations normally reporting to the Space Shuttle Program (SSP).

COLUMBIA TASK FORCE

Recognizing the need for a formal interface, the Columbia Task Force (CTF) was established shortly after the CAIB and became the forum for resolving all matters between the Board and the MRT. The CTF had no specific investigative responsibilities, but was an administrative body that controlled a number of work tasks and ensured appropriate managers were aware of their tasks and priorities.

NASA ACCIDENT INVESTIGATION TEAM

After approximately 7 weeks, the MRT was reformulated into the NAIT to reflect the same three-team structure and responsibilities the CAIB had adopted. The NAIT Team 1 (Materials) lead was the Deputy Center Director of KSC. The Team 2 (Operations) lead was the Deputy Center Director of JSC, who also acted as the overall NASA lead. The Team 3 lead (Engineering) was the Director of Engineering at JSC.

Representatives of the CAIB, NAIT, OVEWG, NTSB, and the Astronaut Office were co-located with the Reconstruction Team to facilitate communication and expedite all necessary paperwork.

TECHNICAL SUPPORT

Many companies and government organizations were called upon to provide special expertise to the Reconstruction Team. These included:

- Michelin: Tire identification
- Goodrich: Landing gear identification
- Aerospace Corporation: Re-entry science
- NASA Glenn Research Center: Wiring
- NASA Langley Research Center: High temperature materials
- Federal Bureau of Investigation: Tile identification
- Honeywell: Avionics identification
- SpaceHab: SpaceHab item identification

Other teams active in the investigation called upon the Reconstruction Team for their knowledge of the debris and what it showed. These included:

- OVEWG
- Failure Scenario Teams
  STS-107 Unexplained Anomaly Closure Team

Columbia Hangar

The hangar located on the south end of the SLF runway adjacent to the Orbiter tow way was used as the primary facility for the receipt, processing, and investigation of the Columbia debris recovered from the field. Originally built for the RLV, this 50,000 square foot facility allowed ample room for a 2-D, 110 percent scale layout of the Orbiter airframe outer mold line (OML) and TPS. Forty thousand square feet of the available hangar space was dedicated to the 2-D grid, while the remaining 10,000 square feet was used to accommodate storage and processing areas. The hangar is pictured in figure 4.1 – Columbia Hangar.

The east wall of the Columbia hanger provided staging for items associated with TPS, Internal Structure, and Reinforced Carbon Carbon (RCC), as well as the sub-system personnel. The west wall of the hanger provided areas for the following sub-system personnel and hardware:

- Avionics
- Main Propulsion System (MPS)
- Purge, Vent & Drain (PVD)
- APU
- Orbiter Electrical (OEL)
- OMS
- Environment Controls and Life Support Systems (ECLSS)
- Payloads and SpaceHab

One bay along this wall, plus the southwest corner of the facility, was used for the 3-D laser scanning effort. Large storage boxes lined the south end of the hanger providing storage for unknown materials made of metal, fabric, plastic, or related to electrical, and payload bay door (PLBD) debris items.

A separate area was constructed within the facility for recovered crew module debris and served as a visible barrier allowing the debris to be handled with discretion.

Clamshell

A 13,000 square foot facility termed Clamshell 4 was chosen to provide auxiliary storage in addition to the Columbia hangar. The purpose of this facility was to store large system components not directly relevant to the

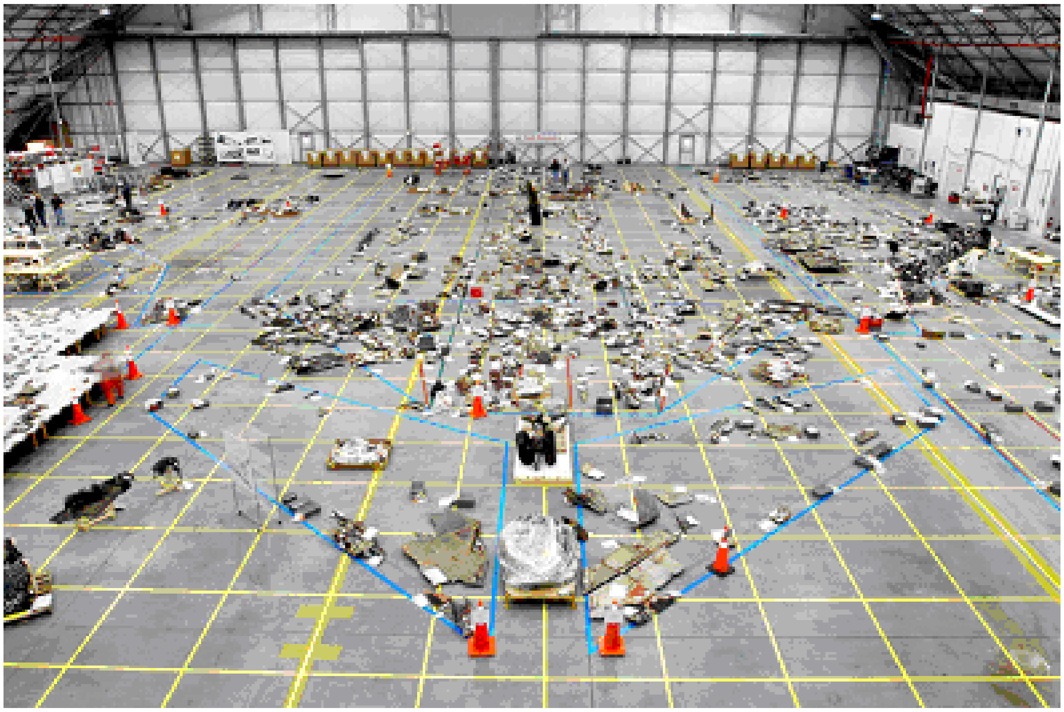


Figure 4.1 – Columbia Hangar

Figure 4.2-Clamshell Auxiliary Storage

investigation. This additional storage capacity allowed for growth in the main facility processes and work areas. The Clamshell is pictured in figure 4.2 – Clamshell Auxiliary Storage.

Certain debris items were selected for storage at the Clamshell including:

- Space Shuttle Main Engine (SSME) items
- Power Reactant Storage and Distribution (PRSD) tanks
- MPS helium Tanks
- APU tanks
- SpaceHab/FREESTAR items
- Unknown TPS items

Midfield Park Site Decontamination Area

It was determined that a facility separate from the Columbia hangar was required to cope with any debris contaminated with hypergolic fluids. This facility, known as the SLF Midfield Park Site Decontamination Area, was capable of handling this type of debris. The decontamination facility included waste and rinsate drums, hard-line breathing air, protective equipment, and an impound storage cage. The decontamination area is pictured in figure 4.3 - SLF Midfield Park Site Decontamination Area.

The SLF Midfield Park Site Decontamination Area was set up in accordance with current KSC requirements (FSOP 6100 USA Florida Safety Operating Plan and KHB1710.2 KSC Safety Practices Handbook) and approved for use by both NASA and USA.

All hazardous waste was processed and removed from the area in accordance with current KSC requirements when the recovery effort was completed and the SLF Midfield Park Site Decontamination Area was no longer required. The site was then disassembled.

Figure 4.3-SLF Midfield Park Site Decontamination

Columbia Reconstruction Database System

Prior to the database team being formally chartered, a preliminary database application was already being developed. It was deployed to the BAFB recovery site to begin the task of tracking recovered items.

Within 4 days of the accident, the official database team was established. This team was given the monumental task of having a fully operational database system designed, developed, tested and deployed within 1 week of being formally chartered. When the debris began arriving at the Columbia hangar 1 week later, the Columbia Reconstruction Database System (CRDS) was online and ready to support.

ARCHITECTURE

The CRDS architecture consisted of an SQL Server database with a Cold Fusion web page user interface. Documentum, USA's enterprise document management system, was used to store digital photographs, 3-D images, and various documentation files. Documentation files consisted of various Word documents such as fact sheets, .pdf files, and scanned-in files. Both the SQL Server database and Documentum systems were backed up daily. This architecture provided a robust and secure backbone for the CRDS. It also allowed remote sites at BAFB and other NASA facilities the ability to access the data as needed to aid the recovery and investigation operations.

In parallel with the development of the CRDS, numerous other databases were developed to support recovery operations. The CRDS team remained in constant communication with these other teams to ensure seamless data flow between systems. These other databases were later consolidated into what became SIDDS.

All CRDS data with the exception of photos, documents and secure crew module item data, was replicated real-time to the SIDDS. Some SIDDS data was also replicated to the CRDS such as the Environmental Protection Agency (EPA) tracking numbers, field descriptions, and latitude/longitude information.

USER INTERFACE

The CRDS web pages were designed to provide all users with a common look and feel. This provided users changing from one job to another an easy transition with a minimum of training. All users' screens provided access to common information such as engineering assessment and current item location. In addition, all screens provided a complete history of where the item had been, who performed various functions on the item, and date/time stamps of when the function was completed.

The CRDS provided straightforward user access to a variety of information via a standard set of hyperlinks on all web pages. Using this standard set of hyperlinks, any user could view photographs or open related supporting documents. Additionally, items that had a 3-D image rendered could be viewed directly from the CRDS web page.

The CRDS user interface also provided hyperlinks back to the EPA database that was used by the recovery operation. With the proper access permissions, a CRDS user could gain access to additional recovery data, such as photos taken at the recovery sites, along with any other descriptive data contained in the EPA database.

ACCESS CONTROLS

Read access of the CRDS was made generally available to the NASA centers and to contractors involved in the Columbia investigation, provided they were within trusted domains.

The CRDS had controls to assign data entry permissions to authorized personnel. The system administrator granted the permissions upon receiving a written request from the process owners. Personnel with data entry permissions were restricted to the screens pertinent to their job functions. As an example, only users with engineering permissions could access the data entry screens for engineering assessment. Users with FCOD permissions had additional access to view and update secure crew module engineering assessment fields.

In addition to data entry controls, the CRDS provided data access controls for the viewing of information relating to crew module items and Flight Crew personal items. Engineering assessments, crew module photos and documents were considered sensitive and viewing access controls for secure information were established both by network login and Documentum user authentication. Network login user authentication provided viewing access control to the secure database entries and Documentum provided an additional layer of security for secure photos and documentation. Only personnel with the FCOD or CAIB permission level could access secure data.

The CRDS team continually addressed issues by adding new functionality to the system. These enhancements were made throughout the entire life of the reconstruction project. The team continually supported the user community by providing custom reports for data not readily available from the standard query reports provided via the web page. CRDS is continuing to evolve with the addition of archival requirements used to support the long-term storage and study of the Columbia debris.

Two-Dimensional Grid

With guidance from the NTSB, a grid layout was chosen which maximized the amount of Orbiter OML that could be reassembled in the space available in the Columbia hangar. A 2-D layout was chosen over a 3-D layout for reconstruction. This was due to the limitations a 3-D layout would place on accessing each of the items after placement on the grid, as well as the supposition that only a very small percentage of the Orbiter would be recovered.

The outline of the Orbiter airframe sections that were to be reconstructed were laid out on the hanger floor. To aid in placing items in their proper location on the grid, each airframe section was annotated with Orbiter X_0, Y_0 and Z_0 coordinates. Another feature of the grid was that it was laid out at 110% of the actual size, which provided access between the recovered items. This allowed for detailed evaluations of each item for fracture matching and accounted for the deformed condition of the items. Only items with a higher probability of contributing to the Orbiter break up were chosen for reconstruction on the 2-D grid. The OMS pods, the Forward Reaction Control System (FRCS) and most internal system components were not placed on the grid; however, they were placed in storage around the perimeter of the grid for easy access if required. The grid is depicted in Figure 5.1 – Columbia Reconstruction Grid.

The Orbiter layout for the forward, mid and aft fuselage was split along the upper centerline, splayed open, inverted, and then laid on the floor with the TPS surface facing up. A separate grid area was set-aside for any individual lower surface tiles that were no longer attached to the airframe.

Each wing was divided into three separate regions; the lower TPS, the lower structure and the upper structure combined with TPS. The wing sections were positioned adjacent to the perimeter of the forward, mid and aft fuselage grid but not contiguous to the mating surfaces. As the focus of the investigation narrowed to the left wing leading edge, a separate area was added to the left and right hand wing grid that represented the wing Leading Edge Sub-System (LESS) hardware.

Each elevon was assigned a region on the grid separate from its physical location on a wing. The body flap was positioned in its general location with respect to the aft fuselage. The elevons and the body flap components were oriented with the lower TPS surface facing up.

The vertical tail section and the rudder speed brakes were split into a left and right hand region. Each region was placed on the grid with the exterior surface facing up. These two regions were placed at the north end of the hanger near the forward fuselage section.

When the evaluation process of reconstruction began, the mid body lower surface items that mated with the left wing were temporarily relocated to their proper orientation on the left hand wing lower

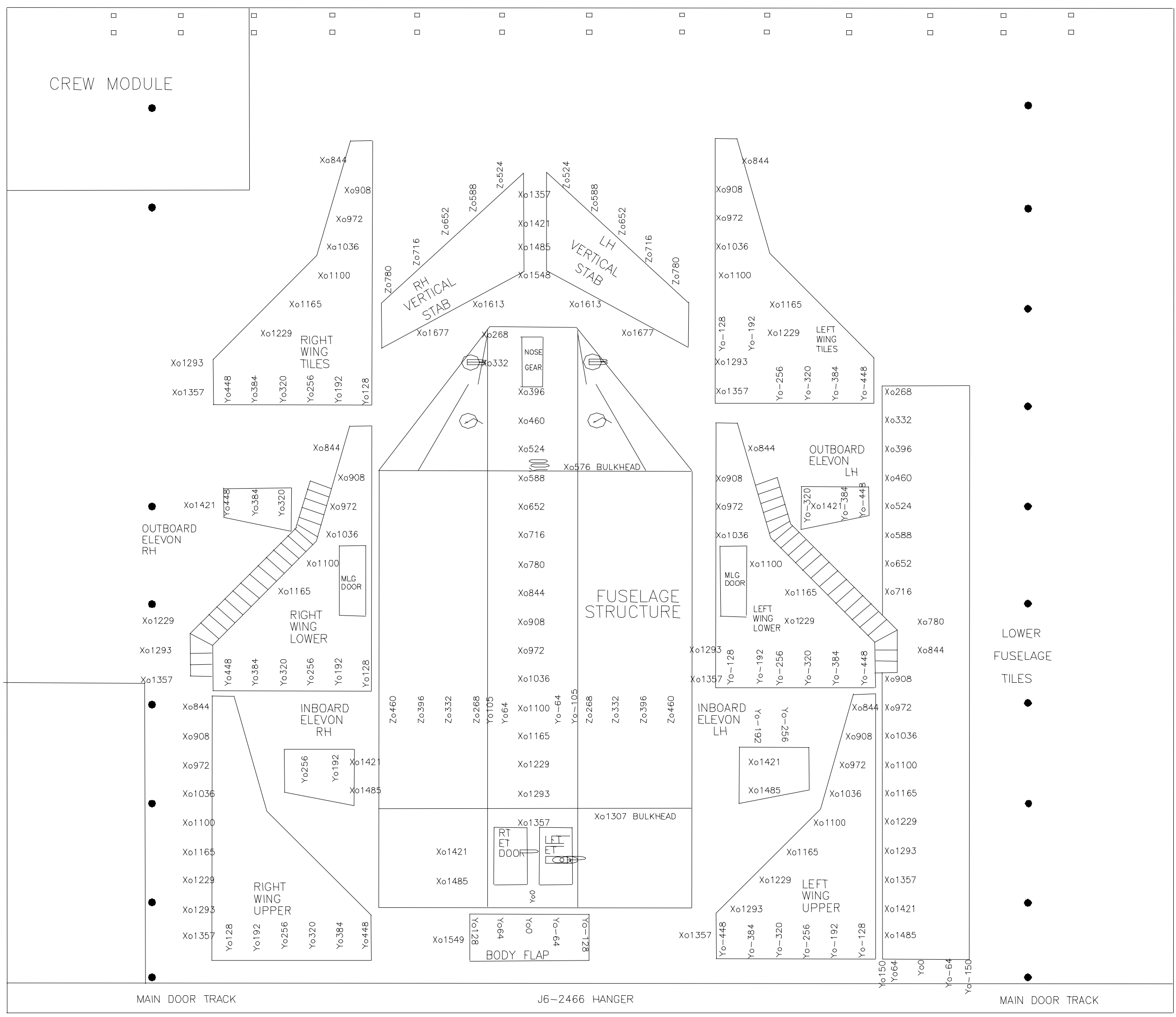
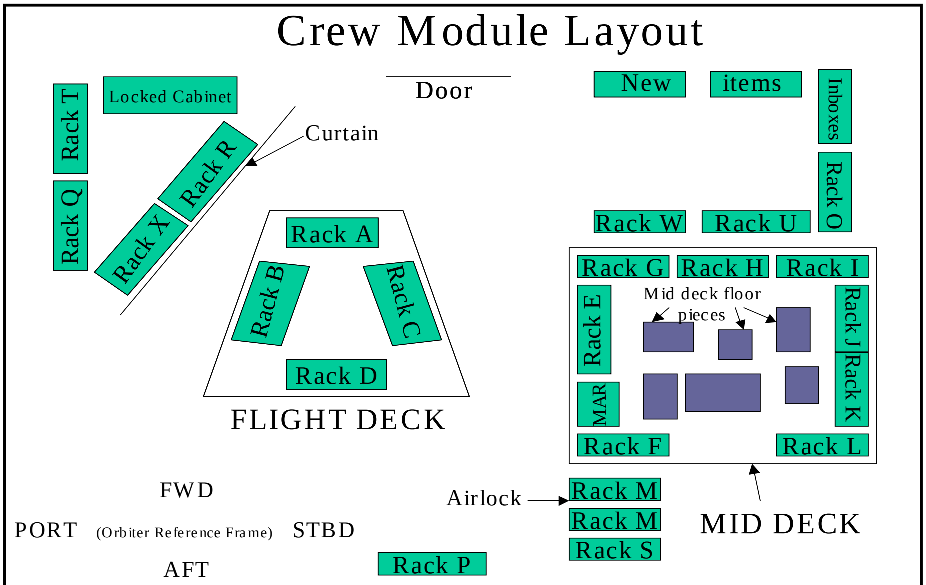


Figure 5.1. Columbia Reconstruction Grid

surface grid or to the tile tables. The tile tables were platforms built up off the floor in the left wing lower surface TPS region of the grid. This allowed engineers to safely place tiles out in the open for evaluation without concern for damage by personnel walking the grid.

After the focus for TPS identification was narrowed to the left hand wing, the lower fuselage TPS region of the grid was partially used for the left and right Main Landing Gear (MLG) hardware and the Wing Leading Edge (WLE) 3-D fixtures.

Figure 5.2. Crew Module Grid



Rack Contents in Crew Module

Rack	Contents	Rack	Contents
A	Flight Deck, forward	O	Crew Module misc structure
B	Flight Deck, port	P	Escape Pole
C	Flight Deck, Starboard	Q	Seats and hardware near or on seats for entry
D	Flight Deck, Aft		
E	MAR contents, galley, port middeck items	R	Crew Escape identified by crewmember
F	WCS, Vol H	S	SpaceHab and EVA tools stowed in PSA
G	MF14 and MF28 lockers		
H	MF43 and MF57 lockers	T	Crew Escape, unidentified by crewmember and on-orbit FCE
I	MF71 and unknown locker fragments	U	Unknown items
J	Unknown locker fragments	W	Identified items unknown stowage location
K	Sleep station and Vol B		
L	Window Shade bag and Aft lockers	X	Agency OFK and Entry FCE
		LC	Locked Cabinet Personal Items and GFE
M	Airlock		

Crew Module Reconstruction

The crew module was set up as a 3-D grid upon recommendations from the NTSB. The 3-D aspect was provided by the use of bread racks to store items in bins. One area of the crew module was set up as the flight deck and another as the middeck. Racks were labeled both with their physical location identification on the Orbiter and also with a simple rack identification. The crew module grid is depicted in Figure 5.2 - Crew Module Grid.

Crew personal and sensitive items were kept segregated even within the crew module area because of their potential emotional impact and also their potential financial value. Personal items and agency Official Flight Kit (OFK) items were kept in a locked cabinet in the segregated area as an extra measure of security.

The initial decision was made to only manage debris that was interfaced by the crew inside the crew module area. The significant structure inside the crew module included the Middeck Access Rack (MAR), panels from the flight deck and the airlock, and middeck floor. Structural floor items set up in the middeck area inside the crew module. As the crew module investigation developed, more structural information was needed. The condition of the water tanks under the middeck floor, the black boxes in the avionics bays, and the physical pressure vessel structure were all collected for analysis. Ultimately the pressure vessel structures were brought into the crew module area of control. As there was insufficient room in the crew module area to store all items, items that were pulled off the structures racks were stored first in large boxes and eventually on bread racks. Bulkheads were reconstructed for short periods of time so that photos could be taken and to allow the investigators to evaluate them; for space reasons they were piled up on pallets between evaluations.

M&P Sampling and Analysis

SAMPLING

A sampling plan was developed to ensure that samples obtained from the Orbiter debris yielded the most data possible while maintaining the integrity of the debris. This plan defined sampling type by criticality, destructive and nondestructive debris sampling, and preservation of samples.

Sampling criticality was divided into two classifications. Type II sampling was defined as sampling conducted on a critical surface, such as a fracture surface, a uniquely damaged area, or a single point source of contamination. By default, Type I sampling was defined as those that did not meet the Type II criteria. The level of approval required for sampling depended upon the classification.

Several destructive and non-destructive sampling techniques were developed. These included coring for debris which was either on or embedded in tile, removal of metal deposits from the structure or RCC surface by a clean laboratory scalpel or forceps, and removal of a small portion of the debris item by cutting with a diamond blade.

Preservation of debris samples was an important aspect of sampling. Photos of the debris item were taken prior to taking a sample. The sample orientation relative to the original item was maintained and documented. Also, work instructions defined packaging requirements to prevent sample contamination.

Various techniques were used in determining a location for sampling on a debris item. The prevalent methods used throughout the reconstruction effort were stereomicroscopy and real-time x-ray analysis.

Stereomicroscopy was used to locate areas of interest on a debris item and to determine if further analysis was required. It was also used during actual removal of samples from the debris item and in conjunction with photo documentation. This sampling technique aided in the identification of part numbers or serial numbers that were not visible to the naked eye.

Also in support of sampling, a real-time x-ray technique was established. This technique used a standard x-ray source and an amorphous silicon plate for detection. X-ray images were collected real-time on a computer and enhanced to provide an aid in selecting debris items for sampling and the sample location. This technique was calibrated using aluminum and Inconel of various thicknesses allowing the team to locate contaminants in or on a debris item composed of either high or low atomic mass.

Debris items sampled included RCC, tile, and metallic components. As the investigation progressed, the majority of the sampling was done in support of analysis for left WLE items.

ANALYSIS

The M&P team employed standard forensic analysis techniques in both the Columbia hangar and laboratories. Some non-destructive testing was conducted within the hangar using stereomicroscopic examination, x-ray, and eddy current. Analytical techniques developed and evolved throughout the investigation as results from previous analyses gave the team insight into the types of information that could be gleaned from the debris. Initial analyses consisted of the following:

- Optical macroscopic and microscopic examination
- Polarized light microscopy-crystalline characterization
- Scanning Electron Microscopy (including low-vacuum) with Energy Dispersive X-Ray Spectroscopy (SEM w/ EDS) including semi quantification and dot mapping
- X-Ray Photoelectron Spectroscopy or Electron Spectroscopy for Chemical Analysis (XPS or ESCA)

- Metallographic sectioning, mounting, polishing
- X-Ray Diffraction (XRD)
- Fourier Transform Infrared Spectroscopy (FTIR)

As the investigation progressed the following techniques were included:

- Exemplar technique
- Neutron activation
- Microprobe with Wavelength Dispersive Spectroscopy (WDS)
- Auger spectroscopy

A number of laboratories were used for the various analyses. These included NASA laboratories at KSC, MSFC, JSC, LaRC and GRC, USA laboratories and Boeing Huntington Beach laboratories. In addition to these locations, several industry and university laboratories were used during the investigation including Batelle, Caltech, and North Carolina State University.

Forensic analysis techniques played a significant role in the analysis of left hand MLG components, WLE structure and selected left wing tiles.

Three-Dimensional Physical Reconstruction

LEFT WING LEADING EDGE

The evaluation of the WLE hardware, as it was laid out on the grid, quickly reached a point where no further useful information could be ascertained. It was decided to reconstruct this region in 3-D and a local prototype lab was tasked with fabrication of 3-D support fixtures for the WLE hardware. These fixtures consisted of a transparent Lexan sheet that was shaped to the contour of the RCC panel and Tee OML. Metal braces supported the Lexan and connected it to a support sub-frame. This connection was made with quick disconnection pins allowing the Lexan and bracing portion of the fixture to be rotated for access to the interior of the RCC panel. The sub-frame was attached to a heavy metal stand through a pivoting arm that allowed the RCC items to be viewed either right side up or inverted like the grid orientation. The stand was mounted on castors to make the fixtures as mobile as possible. Each fixture contained two or three adjacent RCC panels.

The RCC panel items were attached to the contoured Lexan sheets using several different methods that ensured no damage to the RCC material resulted. The spar fittings were also attached to the fixtures to maintain continuity for the evaluation of the RCC hardware. A picture of these fixtures is depicted in figure 5.3 - Left Wing Leading Edge Physical 3-D Fixtures.

A complete 360-degree evaluation of each item was possible for the WLE hardware using the fixtures. This allowed the investigators to clearly visualize each RCC panel/tee and their relationship with adjacent panel items, which was nearly impossible in the 2-D layout. The 3-D fixtures allowed an accurate assessment of the percentage of recovered RCC material for each location to be made. Direct comparisons between related areas on different panels were also possible.

Figure 5.3. Left Wing Leading Edge Physical 3-D Fixtures

Due to the cost and manpower required to fabricate the fixtures and the emphasis placed on merely a small portion of the WLE, only RCC panels 1 through 13 were built-up into 3-D fixtures. For the remainder of the RCC panels, foam blocks, plastic backing material and tape were used to cobble the items together into a facsimile of an RCC panel and Tee.

RIGHT WING LEADING EDGE

To support the comparison of the right hand WLE to the left, the right side was also reconstructed in 3-D. However, due to the same limitations noted above, no right hand WLE panels were placed in fixtures. The same materials and techniques used on the left hand WLE panels 14 through 22 were used for all the panels on the right side. An example of this technique is depicted in figure 5.4 - Right Wing Leading Edge Physical 3-D Reconstruction.

LEFT WING LOWER TILE

Initially, when a tile was positively identified or identified to an approximate Orbiter location, the tile was placed in a tote box on the grid at the corresponding X_0 and Y_0 location. This method however failed to provide a visual trend of the overall wing TPS. Additional tools were required to assist TPS engineers with the debris assessment process and to allow investigators to visualize the entire lower surface. Thus, 22 moveable tables, sized to allow for easy access and handling, were built to replicate the lower left hand wing surface. A picture of the tile tables is shown in figure 5.5 – Left Wing Lower Tile Tables.

The tables were covered with a full-scale tile map that displayed the part number and cavity size of each tile. The tables were covered with Lexan to prevent degradation of the maps. Troughs were added to the WLE to hold the lower LESS carrier panels. Structural seams were added to the table to establish visual indicators for screed and rivet patterns.

These tools allowed each positively identified tile to be correctly placed on the table and provided visual data to help with the evaluation of scenarios. Placing the positively identified tiles on the table also assisted in the identification of other tiles by matching their damage character-istics to the characte-ristics of the previously identified tiles.

Figure 5.4 - Right Wing Leading Edge Physical 3-D Reconstruction

Figure 5.5 – Left Wing Lower Tile Tables

Virtual Reconstruction

At the time of the Columbia accident, NASA was engaged in the Digital Shuttle Project to document the as-built configuration of the Orbiter using scanning devices. After a demonstration of Digital Shuttle's capabilities, scanning was adopted as a Reconstruction Team technique. The initial purpose was to provide a 3-D virtual reconstruction visualizing Columbia debris items in their proper location on the Orbiter. Later it was also used for debris identification.

Two scanning methods were utilized during the reconstruction effort depending upon the complexity of the debris to be scanned. The MENSI Corporation scanner used a tripod-mounted laser scanning head that projected a focused laser beam to image the object and was primarily used to scan skin panels and TPS carrier panels. The Advanced Topometric Optical Scanner (ATOS) used a digital white light to scan the object and was used for debris with complex shapes requiring higher definition. Examples of debris item placement can be seen in figures 5.6 - Left Wing Leading Edge Virtual 3-D Lower View and 5.7 - Left Wing Leading Edge Virtual 3-D Upper View.

After scanning each item, post processing was required. Post processing is the manual process used to refine the scan results into usable solid body Computer Aided Drafting (CAD) rendering of an object. A key result of post processing was that the specific location for each debris model was determined within the Orbiter X_0, Y_0 and Z_0 coordinate system. These coordinates were then used to properly locate objects in the CAD environment in order to achieve a 3-D virtual reconstruction of the Orbiter. DELMIA Corporation CAD software was used to accomplish this task.

While the combined processing produced the 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 look angles around the perimeter of the object and electronically mapping the photographs onto the scanned image.

The scope of the scanning effort evolved as the investigation matured. At one time the scope included scanning of both wings, the leading edges, and the mid-body. However, the final product featured only the left wing and its leading edge with the items in RCC panels 5 through 10 texture mapped. Several factors influenced the content of the final product:

Figure 5.6 - Left Wing Leading Edge Virtual 3-D Lower View

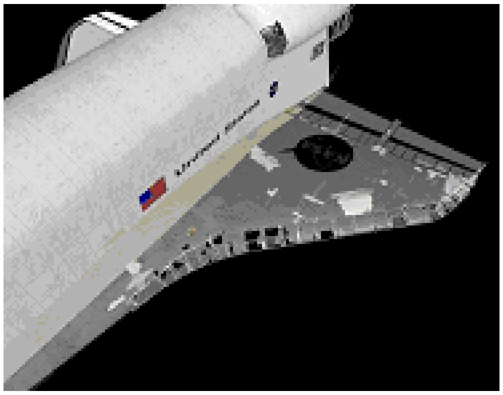


Figure 5.7 - Left Wing Leading Edge Virtual 3-D Upper View

- The focus of the investigation upon the left wing
- The intensive time and effort to scan, post-process, and rig
- The desire to texture map key items
- The addition of debris identification

The first debris identification effort was for "The Littlefield Tile", a small triangular tile fragment that was the western most piece of debris recovered. Geometric matching determined it was a left wing upper surface tile located about 24 inches behind RCC panel 9. Over the course of the investigation, no additional tile identifications were made using this process, however 20 RCC items were scanned to aid in the identification process. The identification effort eventually yielded positive identification of four RCC items and narrowed the possible locations of the other 16 RCC items.

The visualization objectives of scanning were achieved by producing a movie on CD-ROM and DVD with fly around scenes of the left WLE, left wing upper and lower surfaces, and interior views of the left wing including phantom displays of the unrecovered internal structure. The movie also had views of the left WLE RCC panels' interior surfaces.

Identification Tools

ELECTRONIC MAPS

Electronic Maps (E-Maps) is a 3-D computer model originally designed for tracking tile waterproofing and TPS inspection status. However, the tool was used during reconstruction to visualize the OML of the debris recovered. The 3-D model could be rotated or zoomed in or out to accommodate any view angle or level of detail desired.

E-Maps was modified for the reconstruction effort to allow tracking of positively identified RCC and OML structural components placed on the grid. Using color codes, the Reconstruction Team was able to designate three categories of debris; structure with tile, structure only, and tile only. Technicians used a laptop computer to collect the data from the grid. The lap top data was later downloaded to a data collection server. As the tools matured, downloading was accomplished using a wireless network that had been installed in the Columbia hangar.

Another modification made to the E-Maps tool provided a visual indication of where the items were recovered. By importing recovery latitude and longitude data from the CRDS, the E-Maps system showed where the debris was found in comparison to the Orbiter flight path. An example of this is depicted in figure 5.8 - Columbia Reconstruction E-Maps Computer Model.

THERMAL INFORMATION PROCESSING SYSTEM

The Thermal Information Processing System (TIPS) database tracks all TPS component installation and repair information. The following tools were programs controlled by TIPS, used

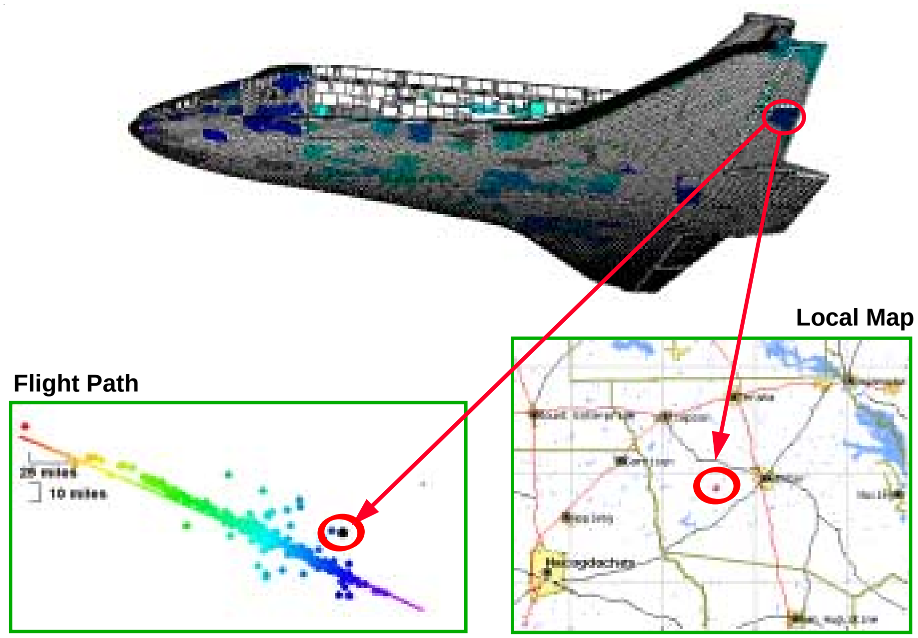


Figure 5.8. Columbia Reconstruction E-Maps Computer Model

essentially for TPS identification purposes:

Multiple Document Interface for Gap Fillers (MDIGAP95)

MDIGAP95 is a graphics program that provided information on tiles and gap fillers installed on all Orbiters. The database is updated each day during Orbiter processing for all configuration changes to tiles and gap fillers. The database that tracked Columbia's components was preserved immediately following the accident. This allowed the system to be used for the reconstruction efforts.

MDIGAP95 data consisted of Order Control Numbers (OCNs), and unique part tile part numbers, tile thickness at the center of the tile and Strain Isolation Pad (SIP) thickness. All of the above data allowed engineering to perform a data search on a partially identified OCN or part number, and then match it with the corresponding tiles that had similar SIP and tile thickness. This provided a list of tile part numbers that the item could represent.

To further support the tile identification effort, the MDIGAP95 database was modified to provide information relating to corner thickness and sidewall angles. Since many lower surface tiles have similar thicknesses, distinctive sidewall angles provided another path in which engineering could isolate a distinct tile characteristic, thus narrowing the possibilities of potential tile numbers.

Shuttle Configuration & Information Display (SCIDS95)

SCIDS95 allowed the capability to enter a tile part number to view 3-D graphics with Orbiter X_0, Y_0 and Z_0 coordinate information for all points. From the X_0, Y_0 and Z_0 point data, engineering could calculate any of the tile sidewall lengths as designed per drawing. This design length was then compared to the item being evaluated. SCIDS95 data combined with the information from MDIGAP95, efficiently narrowed the search for a potential positive identification of a tile.

SCIDS95 also provided the location of structural seams and spar locations in relationship to a tile. Since the majority of tiles recovered were from the lower surface of the vehicle, some structural seams and spar lines provided a distinguishing footprint on the bottom of a tile. SCIDS95 allowed engineering to narrow the location of a tile by the seam or spar line and the tile's thickness.

Columbia Reconstruction Identification Database

During standard vehicle processing, the TPS community does not have access to the master TIPS database. This database contains information pertaining to tiles such as tile thickness, material type, a inner mold line (IML) footprint, specific repair types and screed installations. The standard method used to gain access to this information is to call or e-mail TIPS personnel. However, with the reconstruction efforts and the Columbia portion of the database preserved, it was possible to provide read only access to engineering for some portions of the database. This provided another tool for the tile identification team to perform data searches on key characteristics of an unidentified tile to narrow the search for potential part numbers.

Automated Work Control System

Automated Work Control System **(**AWCS) is the system used by the Thermal Protection System Facility (TPSF) to track the fabrication of TPS components. The system was used during the reconstruction effort to find a gap filler part number when only the OCN was known. MDIGAP95 was then used to find the exact location on the Orbiter.

TILE THICKNESS MAPS AND SIDEWALL ANGLE CHARTS

Tile thickness maps are items that are used during standard vehicle processing. The maps are color coded with the tiles' thickness for each Orbiter. With the reconstruction effort, the maps were used to see trends in tile thickness for identification purposes.

The ability to identify the wing tiles became crucial once it was determined that the lower left wing was the critical area of investigation. Since lower wing tiles have distinctive sidewall angles, charts depicting actual design sidewall angles were created. This was used when a tile was determined to belong to the lower wing region. The sidewall angle of the debris item was compared to the sidewall angles charts. This was essential in facilitating the tile's potential location. The TPSF supplied the sidewall angle charts and thickness maps.

CONFIGURATION VERIFICATION ACCOUNTING SYSTEM

The Configuration Verification Accounting System (CVAS) was developed to track all configuration changes to hardware on the Orbiters. After the accident, Columbia's database was also preserved. This allowed the reconstruction effort to utilize the database in the identification of both TPS and non-TPS components. CVAS aided in the identification process by providing any necessary information from part numbers to document numbers.

SHUTTLE DRAWING SYSTEM

The Shuttle Drawing System (SDS) is a system that provides on-line access to all Boeing controlled engineering drawings and Engineering Orders (EOs). During the reconstruction effort, SDS was utilized to help identify components with distinct design features such as rivet, rib or seam patterns, screed, or instrumentation.

Receiving and Process Flow

A receiving and processing flow was developed prior to arrival of the first debris truck at the Columbia hangar. An overview of the Receipt & Processing Flow activities is depicted by figure 6.1 – Receipt and Processing Flowchart and the flow of debris items within the hangar is shown in figure 6.2 – Hangar Work Area Debris Flow.

SHIPPING AND TRANSPORTATION

Barksdale AFB in Louisiana served as the central collection facility for all debris being collected at the various field recovery sites in east Texas and Louisiana. As debris was received at the BAFB hangar facility, a data record for each item was entered into the CRDS and assigned a KSC tracking item number. A paper traveler that included the KSC item number, associated bar-code and descriptive information was then printed and attached to the item.

Some items were not entered into the CRDS during times when there was a significant backlog at BAFB in order to expedite items to KSC. Instead, the shipping box containing multiple items was entered into the CRDS and assigned an item number for tracking purposes.

Debris items were packaged for shipment at the Barksdale collection site. Typical packaging of debris involved bagging or bubble wrapping individual items before boxing or crating. Larger items were palletized for shipment.

As debris was collected at BAFB, a delivery schedule was established for shipment of the debris to KSC. Lone Star Trucking Company performed the transport of the debris from BAFB to KSC. At first, two trucks departed Barksdale every Monday and Thursday

RECEIPT & PROCESSING FLOW

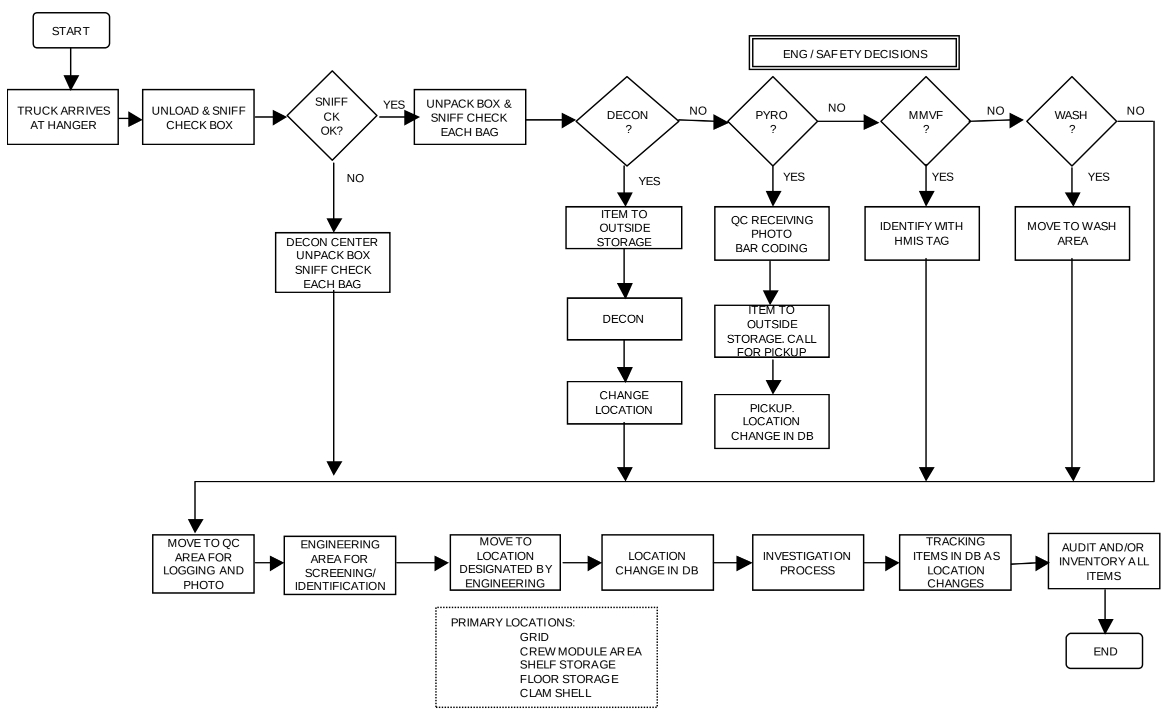


Figure 6.1 – Receipt and Processing Flowchart

with arrival scheduled at KSC every Tuesday and Friday. Several months into the recovery effort, as the amount of debris collected began to taper off, the frequency of shipments was reduced to one truck twice a week, then eventually to an as needed basis.

As items were loaded onto the trucks for shipment to KSC, shipping reports were generated from the CRDS to inventory what was on the truck. Each truck arrived with a shipping manifest.

Crew module debris items required special handling due to their sensitive nature. These crew module items included crew personal items, valuable items such as mission patches, and generally most crew escape items. Therefore, a process was set up in the field to segregate and protect those types of debris to ensure they were not exposed to public or media viewing and to prevent theft. Items identified in the field as sensitive were packed in boxes and labeled. These boxes were carried in the cab of the transport truck from Barksdale AFB to KSC.

There were some debris items that were thought to be biologically hazardous, thus these items were sent directly from the field to JSC. After being cleared as safe to handle, these items were boxed up separately, labeled and sent to KSC.

Weighing of Debris

After the arrival and processing of the first shipment of debris at KSC, the program levied a requirement to determine the weight of the recovered hardware. To avoid having to weigh each item individually, a statistical analysis was performed on the next several shipments of debris to determine the weight of the shipping pallets, storage boxes and packaging material. Using the inventory list of the first shipment, a close approximation of the total weight of non-debris items was established. A detailed review of photos of all the items in the first shipment was performed and several specific items were weighed. The approximate total debris weight was calculated using this data.

For all subsequent shipments, the loaded weight of each truck was determined at the Logistics Facility prior to unloading at the Columbia hangar. The weight of each shipping container, standard pallet, and truck trailer was subtracted from this value. All non-standard pallets were individually weighed and the weight of all packing materials for each shipment was determined. The weight of these items was also subtracted from the total.

The combined weight of all the debris shipments was calculated to be approximately 84,900 pounds. This represents 38 percent of Columbia's 223,900 pound dry weight.

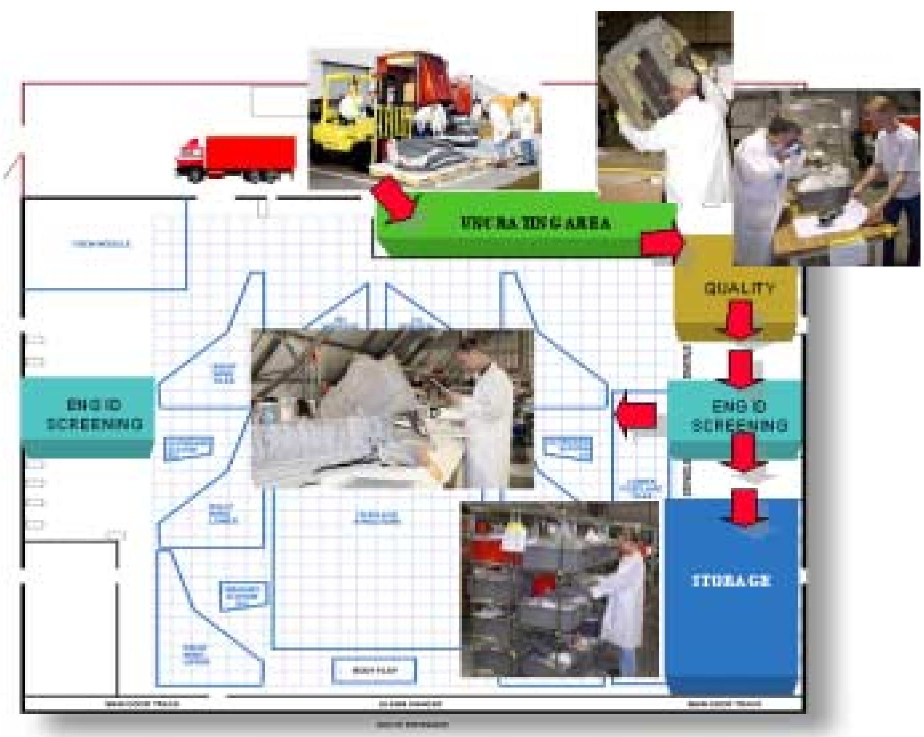


Figure 6.2 – Hangar Work Area Debris Flow

UNCRATING

After the debris arrived at the Columbia hangar, all containers and items were screened in the unloading/unpacking zone for hazards or contaminates. Toxic Vapor Checks (TVCs) were performed on all boxes and containers down to and including zip lock bags before processing any items. All items deemed safe to handle were unpacked and unwrapped. Any items identified as pyrotechnics or crew module received special handling.

Debris suspected of containing Man Made Vitreous Fibers (MMVF) was sealed in plastic bags or wrapped in plastic wrap to contain any hazardous particulates. The term friable was also used to describe these items, which refers to any item that is easily broken into small fragments or reduced to powder. Hazardous Material Inventory System (HMIS) tags were then affixed to notify personnel of the possible hazards involved, all items deemed safe to handle were unpacked and unwrapped. All items were then checked against the manifest/shipping document to assure receipt of all items. External packaging and wrapping materials were then broken down and weighed. The weight was used for the final calculation of received materials.

QUALITY RECEIVING

Database Entry

After the debris was uncrated, it was transferred to the quality receiving area where it was photographed and appropriately tagged. A data record was generated or updated for each debris item using the CRDS. Items previously entered in the CRDS at Barksdale were checked in at the hangar with minimal data entry. New records for items not previously entered into CRDS at Barksdale were created at this point in the process. When multiple items contained in the same box or bag were identified with a single tracking number, the items were separated and assigned individual item numbers referenced to the parent item number. This was referred to as the parent/child relationship.

Data records included item description, time and date of arrival, location of recovery area (longitude and latitude), and date and time of recovery. EPA and SIDDS tracking numbers that were generated at the field recovery sites were entered when available.

Bar-coding

A bar-code was generated for each piece of debris. The bar-code label was attached directly to the debris item or affixed to the packaging containing the item. The bar-code labeling system improved efficiency throughout the process when accessing CRDS screens.

Both pen and gun type scanners were used in the reconstruction process. Personal Digital Assistants (PDAs) with bar-code scanning capability were also used in the reconstruction process. The PDAs were used primarily for audit and inventory purposes.

Photographing

All debris items were photographed as part of the receiving process with 4 mega-pixel digital cameras. The photos were linked to the debris item data record using the CRDS. Photos of items related to the crew module were uploaded to a password-protected partition in the database. Additional photos were added upon request of any Reconstruction Team member.

Because of the secure photo requirement, crew module debris was not photographed at the quality receiving area like all other debris. It was routed to the crew module area and verified as either crew personal or non-personal. Once it was identified as not personal, a photograph was taken within the crew module and the photo was uploaded to the secure area of the CRDS. The number of quality receiving personnel asked to perform this function within the crew module area was kept to a minimum to maintain the appropriate level of sensitivity.

MOVEMENT AND RELEASE OF DEBRIS

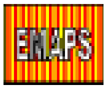
As the debris items moved through the process, their location was tracked using the CRDS. In addition, when a part left the Columbia hangar, the quality assurance personnel made an entry in the CRDS to record authorization for item removal. Upon debris return, an additional entry was made.

The CRDS was utilized to track the current locations of all items and the complete running history of all item locations. Using the CRDS, the handlers assigned items to a grid location, storage location, or sent them to engineering or quality assurance for further disposition.

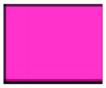
Grid Management

A method of tracking the movement of debris on and off the grid was required. Flags were the tools developed to help manage the movement of the debris. When a flag was used as a placeholder for an item temporarily removed from the grid, the item number and name of the person removing the item were recorded on the back of the flag and the item location in the database was left unchanged. The following flags were used:

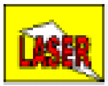
NEW - This flag was placed with new items on the grid that had not been entered into the E-Maps program. This flag was removed when E-Maps personnel began evaluating an item.



EMAPS - This flag was placed with items on the grid that were being evaluated by E-Maps personnel. The flag was removed when E-Maps had been updated to show the inclusion of the noted item.



HOT PINK - This flag was placed with items on the grid that had been evaluated by E-Maps but the location could not be positively identified.



LASER - 3-D Laser Imaging personnel used this flag as a grid placeholder when an item was temporarily removed for 3-D image processing.

CAIB - CAIB team members used this flag as a grid placeholder when an item was removed from its original grid location as part of the investigation process.

ENG - Engineering personnel used this flag as a grid placeholder when an item was temporarily removed for further evaluation.

PROCESS EVAL - This flag was placed with items on the grid that were being audited as part of Process Evaluation. This flag was removed when Process Evaluation for the item in question was complete.

The Grid Manager and the Industrial Engineering group performed periodic audits of the debris location within the Columbia hangar to verify system integrity. Using the CRDS, a material handler compared the location of the debris in storage to the location stored in the database, correctly relocated any debris found in the wrong location, and then updated the database accordingly.

A quality function was developed to ensure database entries were truly standardized. The VITO had developed a cue card for 'Level 1 Audit' procedures for the crew module to check for standardization. These procedures were adopted for the broader hangar operation. The audit ensured entries were standardized, that accurate latitudes and longitudes were entered, that items were logged in and that photographs were in the proper part of the database. After the audit began, new items that came in were audited before placement on the 2-D grid. This method ensured that at least two individuals looked at the database entry; the original data entry personnel and then the auditor.

Debris Release Process

Any time a debris item or sample of a debris item was removed from the Columbia hangar premises, a sample release form (SRF) or impound release form (IRF) was required. A SRF required the approval of Quality and the Reconstruction Engineering Lead while Quality and the NASA Reconstruction Director approved an IRF.

Contaminated debris was either entered into the CRDS and temporarily stored outside the Columbia hangar until pick up, or was moved directly to the decontamination site with accountability recorded down to the major package level (i.e., box).

As the engineering teams identified debris items for transfer to the clamshell for storage, the database was updated to indicate that the debris had been relocated. Quality personnel issued a release form before a material handler moved the item to the truck. This process was repeated for each item being transferred. Once at the clamshell, the items were offloaded with their new location recorded for later entry into the CRDS.

Debris Requiring Special Receiving

CREW MODULE DEBRIS RECEIVING

Boxes of debris labeled "Crew Module" were segregated as soon as the truck arrived. Members of the crew module team were on hand as a designated receiving technician opened each bag to check for hazardous contents. Once the TVC was complete, the box was taken to a cordoned area with quality and handling personnel. Quality would print out bar-code labels and enter the description based on guidance from the crew module person. This was to ensure that field descriptions did not contain sensitive information that could identify the item in the public part of the database. The handler would then check out the item directly to the crew module.

The field recovery process did not capture all personal or sensitive items; therefore these items would sometimes arrive mixed in with the other debris. Receiving technicians would immediately contact crew module personnel and ensure that those items were expedited to the crew module area. Non-sensitive items followed the standard process through receiving.

BIOLOGICAL DEBRIS

Initially, biological debris was screened by medical personnel in the field or sent to JSC for medical screening. Upon arrival at KSC, this debris had already been verified safe for handling and was routed through the normal receiving process and then stored along with the other systems debris. This debris did not require any special provisions other than the use of normal Personal Protective Equipment (PPE) during handling.

Toward the end of the recovery effort, medical screening at JSC and in the field was suspended. KSC then adapted the receiving process to have resident medical personnel screen the biological debris as it arrived in the receiving area before it continued through the normal hangar processes. This was done to ensure that no biological hazards existed and that no incidental remains entered the process.

PYROTECHNIC DEVICES

Pyrotechnic devices were identified and segregated from other items, placed in ammo cans, then relocated to the pyrotechnic storage Conex outside of the hangar until they could be transported to an impound area within the Ordnance Storage Facility. Pyrotechnic engineering was notified for pick up and safing of the items. Expended pyrotechnic items were then returned to the Columbia hangar.

KSC work authorization documents controlled traceability and all work associated with the identification, transport, impounding and disposition of pyrotechnic components. Proper authorization was obtained from the Prevention/Resolution Team (PRT) representative prior to disposition of pyrotechnic components.

Engineering Identification Process

After the debris receiving process was completed, items were routed to the engineering identification area of the hangar. Items initially identified by the Engineering Triage Team as Orbiter debris were further categorized as either airframe (Tile, RCC or Airframe skin) or non-airframe. Duplicate engineering identification areas were established on the east and west sides of the hangar.

All non-airframe debris items were routed to the west identification area with a non-airframe traveler attached to facilitate movement of the items through all sub-systems. After determining an item did not belong to a specific system, engineers put a check in the box by their system and passed the item on to another system. When ownership of an item was established, the component was identified with the appropriate system and the CRDS was updated. The item was then placed in storage in the appropriate system bin.

When ownership of an item could not be determined, as evidenced by a check in all boxes on the traveler, a material handler put the item in the ‘Unidentified’ storage area. The traveler was retained with the item for future verification that the component had been evaluated by all systems.

Airframe items were routed to the east identification area of the hangar and evaluated by engineering to determine their exact location on the Orbiter. Items positively identified (using drawings, maps, etc.) were entered in the CRDS and routed to their final location on the grid (wing, mid fuselage, body flap, etc.) and updated by E-Maps personnel. A red tag was placed on an item if it was identified only to a particular section of the grid and not to a final, positive location. The red tag clearly distinguished these items from positively identified items and allowed items to be maneuvered on the grid until final placement was determined. Airframe components not readily identified were placed in a staging area until they could be placed on the grid and/or additional expertise could be contacted to assist with the identification. Red tagged, staging area, and positively identified debris items were all updated in the CRDS.

The remaining items that could not be identified were updated in CRDS as belonging to one of the following unknown categories and routed to storage:

- Metals
- Tubing
- Electrical
- Fabric/Composite
- Non-Orbiter
- Structures
- TPS
- Plastics

Database entries throughout the

process reflected the effort to identify items and their stowage locations. Part and serial numbers were used when known. The concept of key words for search functions was understood early and was incorporated into a standardized entry format. The standard format for an item was established by each engineering discipline. Keywords that were meaningful to each sub-system were used consistently in the engineering description field, which would allow for database searches of like items.

CLEANING

M&P Engineering provided cleaning procedures and instructions to support the reconstruction triage and engineering efforts. Triage procedures for the cleaning of tiles, blankets, RCC, composite structure, metals, non-metals and electrical components were provided. Specific procedures to aid in part identification were written for tile, printed circuit boards, and MLG components.

Cleaning procedures were documented in a procedure titled 'Detailed Cleaning Methods to Aid Identification and Engineering Analysis'. A one-page summary of triage cleaning instructions was also prepared and posted in the hangar.

TILE IDENTIFICATION

Approximately 7,000 tile items were recovered. Due to the varying degree of damage, several different methods were used during the tile identification process. First, identifiable tiles were sorted in triage by longitude. 96 degrees longitude was chosen to segregate the tiles that may have initially come off the lower left wing, which was the critical area of focus for the investigation. Any tiles found west of 96 degrees longitude were retained in the engineering area for evaluation. These tiles were then sorted by vehicle locations. All tiles, except the wing and tiles west of 96 degrees longitude, were routed to storage. Material handlers entered the possible vehicle location, as identified by engineering, in the CRDS and then routed the tile to the appropriate storage bin. If an unidentifiable tile fragment was received, it was routed directly to unknown tile storage.

The potential wing tiles found west of 96 degrees longitude were first evaluated to determine if a part number could be read. Part numbers were visible on some tiles or could be retrieved by a simple cleaning of the part using Isopropyl Alcohol (IPA). Black lights used with IPA sometimes allowed faded impressions of the part number to be read. When part numbers were not detectible, distinct tile features such as thickness, sidewall angles and repairs were used to aid with the identification process. Engineering drawings were used when there was a distinct design feature on the tile, such as a rivet or seam pattern on the IML, instrumentation, or insert holes. The TIPS database provided a history of each tile that included most repairs and bond and removal dates. Documented repairs often provided enough of a signature to use as an identifier. The TIPS database allowed engineering to perform a data run of a particular repair of the tile within a specific thickness and footprint. This information would then aid in reducing the number of potential part numbers for a specific tile.

Initially, when a tile was positively identified or identified to an approximate location (distinguished by a red tag), the tile was placed in a tote box on the grid at the corresponding X_0 and Y_0 location. This method however failed to provide a visual trend of the overall wing TPS. Full-scale TPS tile tables were used to allow each positively identified tile to be placed in its exact location, therefore trends became more apparent. Placing the positively identified tiles on the table assisted in the identification of other tiles by matching their damage characteristics to the characteristics of the previously identified tiles.

CREW MODULE

Once an item was identified as possible crew module debris and routed to that area of the hangar, various sub-system engineers familiar with the equipment in the cabin reviewed the debris. A series of inboxes were used for each sub-system and items for review were placed there. If an item did not belong to a sub-system that engineer marked the part accordingly and passed it to the next inbox. If a part completed this process and remained unidentified it was placed on a rack for unidentified parts. Frequently, identification was not possible beyond the type of material used (i.e. metal, fabric, foam, etc.). The crew module team also examined the hangar unknown part bins looking for any additional crew module items.

When an item was positively identified, an effort was made to identify its stowage location within the cabin in the event that information proved useful to the investigation. Positive identification proved challenging because some payloads were stowed on the middeck and some Government Furnished Equipment (GFE) was stowed in SpaceHab. In some cases, items with multiple onboard copies, like Payload and General Support Computers (PGSC) or Photo TV equipment, had more than one possible stowage location.

PAYLOADS

The initial MRT direction to the payloads identification team was to simply separate payload debris from Orbiter debris to better facilitate the prime Orbiter structural focus of the investigation. However, the identification effort quickly grew to identifying specific payload assemblies where possible. This positive identification not only provided a certainty that the item was not to be included in the Orbiter investigation, it ultimately led to unexpected recovery of science.

Positively linking payload debris to one of 80 experiments flown on STS-107 was challenging and complicated. Due to the diversity of experiment owners, experiment configuration information was not located in centralized drawing systems or databases. The recovery team called on payload integration offices and payload developers to provide drawings or photos documenting the original configuration of the experiments. Hardware developers provided photos that included the assembly stage through final closeouts. SpaceHab provided their module drawing and payload closeouts photos. Payload identification was aided by the Boeing Engineering Action Center, especially when part numbers or other identifications were visible on debris.

In addition, payload developers were brought in, when appropriate, to help identify their unique internal hardware items. In some cases, when specific experiment debris was positively identified, payload developers were able to facilitate science recovery efforts. KSC initiated global CAIB/NAIT approval for researchers to access their hardware debris for science recovery.

Search and Recovery Coordination

The accurate and prompt relay of engineering assessments of the significant recovered items from KSC back to the recovery command center at Lufkin was crucial to the debris search effort. The reconstruction effort provided daily updates to the recovery team in an attempt to assist in search prioritization. The accuracy of data published in Lufkin depended heavily on the prompt relay of engineering assessments from KSC for the significant parts recovered in Texas and Louisiana. By working closely with

Weston, EPA's contractor, KSC supported the recovery team by investigating, verifying, and correcting inconsistencies in the recovery location data. Comparing the results from data mining in both the EPA/Weston and the KSC databases allowed KSC to find and correct any errors or mismatches located in either database. By tracing actual field data sheets on the recovered items in the hangar, KSC was able to correct hundreds of data entry errors in both databases. Correcting latitude and longitude inconsistencies was vital to the success of planning the search and recovery efforts.

SIGNIFICANT RECOVERED ITEMS LIST

The product used to facilitate the exchange of information between reconstruction and recovery was the Significant Recovered Items List (SRIL). This product was used by the Lufkin Command Center to methodically and continuously refine plot strategies for further air and ground searches. The SRIL became the single source of accurate recovery information and engineering assessments for the majority of the left wing recovered debris. The search areas were extended beyond the initial corridor as a result of daily engineering assessment updates to the SRIL.

KSC supported the recovery efforts of the Columbia Recovery Office (CRO) for the western states with a separate list of recovered items, named CRO SRIL. This list closed the feedback loop to the CRO for items found in California, Nevada, Utah, and New Mexico. As items were received and assessed, the list was updated and distributed via email to the CRO at JSC.

FAST TRACK PROCESS

The fast track process was initiated to prioritize the handling and assessment of significant recovered items, particularly left wing components and items found outside the main debris field. This process was also used to expedite the identification of items from the same areas on the vehicle as cameras, film, and recording devices. By tracking this debris, search teams could extrapolate the most probable location of these critical recording devices.

When an item was assessed in the field as possibly fitting the description, the item was tagged as "Fast Track" and sent to KSC on a priority basis. These parts were segregated on the transportation trucks to ease identification upon arrival at the Columbia hangar. Fast tracked items received priority processing through the receiving and engineering assessment processes in order to expedite a final description of the item and relay that information back to the recovery team.

DEBRIS PLOTTING CAPABILITY

Unique maps were used daily by the air, ground, and water search groups in Texas to triangulate locations of key components and successfully locate related items. These plots were created using updated assessments supplied by the Reconstruction Team via the SRIL.

At the Columbia hangar, debris plots were developed upon request by the search or investigation teams. These maps were used to verify and correct latitude and longitude data for recovered items. Plotting the pick-up points and times of certain EPA/Weston field teams helped correct possible latitude and longitude debris errors.

Plots based on item type were developed for engineers performing analysis on initial vehicle break-up scenarios. Other plots of particular recovered items helped engineers in the hangar identify and assess individual items based on their proximity to each other or by where they landed in the search corridor.

Recovery locations located outside the search corridor required verification due to the inconsistencies in the Global Positioning Satellite (GPS) latitude and longitude formats initially entered in the EPA/Weston Database. The plotting enabled a quick determination of which points required investigating. Although a great deal of effort was spent on trying to decipher the correct location, the daily plots were not 100 percent accurate.

Engineering Assessment Process

The engineering team personnelused a variety of assessment methods. The majority of engineering assessment was accomplished in the hangar. Offsite testing and M&P analysis was performed when required.

In most cases, an engineering assessment of the debris could be performed via visual examination. When necessary, stereomicroscopic (30-500X) examination was performed for part identification or to analyze fracture surfaces or heat-damaged features. A variety of traditional Non-Destructive Evaluation (NDE) techniques were also available in the Columbia hangar. Sampling of numerous debris items was performed and the samples were analyzed at offsite laboratories. In a few select cases, failure analysis was performed at offsite laboratories on debris items or extractions from debris items.

DISASSEMBLY

When required for debris identification, sampling or failure analysis disassembly instructions were provided via a Reconstruction Documentation Sheet (RDS). The debris configuration was recorded and photographed prior to disassembly. Detailed steps annotated disassembly and assembly procedures. Where applicable, the debris was returned to a pre-disassembly configuration.

RECONSTRUCTION DOCUMENTATION SHEET

An RDS was a form used to document any work that was performed on a debris item. The RDS included instructions to properly perform any activity from simple disassembly through destructive testing. The RDS was titled and identified by the KSC assigned item number.

As steps in the RDS were worked, personnel performing the work either signed or initialed the step indicating completion of the step. After completion of the final step in an RDS, it was returned to the library for record retention.

Approvals for working an RDS were:

- Systems Engineer
- MIT representative
- CAIB representative

WORK AUTHORIZATION

Work authorization approval guidelines were established early in the reconstruction process. For non-intrusive tasks such as NDE, disassembly for identification purposes, and non-destructive sampling, a RDS approved by the system engineer, MIT local representative and CAIB resident were sufficient. In all other cases, approval of the OVEWG, MIT, MRT and CAIB was required. A Test Approval Request (TAR) was utilized to document this authorization. When the NAIT was formed as the replacement for the MIT/ MRT, it became the authority.

FACT SHEETS

Engineering generated fact sheets on key or critical debris items without supposition of cause. Fact sheets documented physical observations and laboratory results of a debris item. All fact sheets were posted in the CRDS and were available to all investigators. For example, fact sheets contained the following information:

- Zone and item number
- Part number and nomenclature
- Associated items
- Location drawing
- Physical observation
- General condition
- Materials (design & foreign)
- Deformation
- Fracture features
- Thermal effects
- Environmental effects
- Photos or critical sketches/drawings
- Sampling or NDE Results

DEBRIS ASSESSMENT WORKING GROUP

The DAWG, with guidance from the NTSB, was a team comprised of airframe engineers from NASA, USA and Boeing, and M&P engineers. The charter of the DAWG was to determine what the hardware revealed independent of telemetry, photographic and video data, derived hypothetical scenarios, and timeline evaluations. The DAWG compiled system summaries from all Orbiter sub-systems and generated airframe and TPS reports of all the major regions of the Orbiter. From these evaluations, a failure scenario based solely upon the debris evidence was developed.

Environmental Safety and Health

NASA and USA Safety and Health reviewed the Columbia reconstruction process and assessed the hazards associated with the Orbiter and the handling of its components. Plans were put in place to mitigate both physical and health hazards to an acceptable level. Where applicable, engineering controls were incorporated into the process and the appropriate PPE was identified and required for use.

The health hazards identified included, but were not limited to, the handling of hypergolic contaminated items, contacting liquid chemicals and handling friable materials. Hypergolic propellants are fuels and oxidizers which ignite on contact with each other and need no ignition source. For Orbiter systems the fuel is Mono-Methyl Hydrazine (MMH) and the oxidizer is nitrogen tetroxide (N_2O_4). Friable materials are those that are easily broken into small fragments or reduced to powder.

The physical hazards identified included, but were not limited to, the handling of non-contaminated debris, handling of ordnance and handling high pressure systems. Special procedures were established for each of these hazards.

The NASA Environmental Program Branch and USA Environmental Management reviewed all processes and walked down the reconstruction impoundment areas to identify potential environmental compliance concerns in an effort to limit liability with state and federal regulations.

The USA Environmental, Safety & Health organizations supplied the reconstruction engineering team with a checklist to review when writing debris handling work steps so that all potential safety or environmental issues could be addressed prior to the process being implemented.

PERSONAL SAFETY

Training

The KSC workforce is required to maintain a mandatory level of safety training for normal vehicle processing. In addition to this mandatory training, all personnel obtaining access to the Columbia hangar, with either a permanent or temporary badge, were required to review a safety briefing. This briefing described all potential safety and environmental hazards within the hangar and the individual's responsibilities upon entering the hangar. After the briefing, individuals were required to sign a course attendance roster verifying their understanding of safety requirements. Only then was a hangar access badge issued.

Personal Protective Equipment

PPE was identified for each process and posted throughout the hangar. All PPE requirements were defined in the component handling PPE matrix, which was part of the safety training briefing.

Typical PPE requirements for performing TVCs on trucks prior to unloading and for unloading trucks included the use of Pylox or Kevlar gloves, Tyvek coats, safety glasses, hydrazine dosimeters, and steel-toe shoes. Similarly, the PPE required for personnel opening bagged components, handling friable materials, handling components with liquid, handling non-contaminated components, or using less than or equal to 4 oz of chemical for cleaning purposes consisted of the use of Kevlar gloves, Nitrile gloves, goggles and aprons, safety glasses and Tyvek coats.

Additional PPE requirements were established for personnel emptying the High Efficiency Particle Air (HEPA) filter vacuum or for personnel cutting RCC or TPS material. Typical PPE requirements consisted of the use of Nitrile gloves, safety goggles, Tyvek coats, and air purifying respirators.

COMPONENT MONITORING

Toxic Vapor Checks

TVCs are performed using a meter which can detect trace levels of hazardous chemicals. TVCs performed at the Columbia hangar by Environmental Health personnel were to determine if debris was contaminated with fuel and/or oxidizer residue.

Any items that were identified as having detectable levels of hypergolic propellant residue were immediately routed to either a fuel or oxidizer cabinet located outside of the hangar and transported to the SLF Midfield Park Site Decontamination Area for further evaluation.

Particulates

All debris items that were determined to contain MMVF (i.e. glass fibers) were clearly marked with the hazard and contained in a tote tray or wrapped in plastic when appropriate. All areas where MMVF items were handled or stored were routinely cleaned with approved HEPA vacuums to keep the particle count to a minimum.

Sample monitoring of the hangar and the various personnel identified to be in Similar Exposure Groups (SEGs) was performed by Environmental Health Services. The personal sampling plan for fibers, respirable particulate and silica was set up to perform four personal samples per SEG per shift. Sampling of various SEGs continued throughout the reconstruction effort.

It is policy at KSC to use the most stringent guidelines of the Occupational Safety and Health (OSHA) Permissible Exposure Limit-Time Weighted Average (PEL-TWA) and the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value-Time Weighted Average (TLV-TWA). The area monitoring of the hangar and the personal monitoring of the employees did not reveal any violation of the exposure limits for the criteria stated above.

DECONTAMINATION OPERATIONS

All items identified as possibly hazardous or contaminated were routed to the SLF Midfield Park Site Decontamination Area for further evaluation. There, technicians performed more detailed toxic vapor checks to determine if the suspect parts were truly contaminated or just off-gassing residual vapors that may have been trapped in the plastic bags during transportation.

The SLF Midfield Park Site Decontamination Area was set up to handle decontamination operations for both fuel and oxidizer contaminated debris. Detailed procedures to decontaminate the debris were developed, which reflected operations routinely performed during flight processing. Safety and Environmental Health closely monitored all SLF Midfield Park Site Decontamination Area operations.

The SLF Midfield Park Site was chosen as a decontamination area due to its remote location and ease of modification to an impoundment site. NASA Environmental requested that the area around the site be sampled prior to and at the completion of the decontamination activities to ensure that the Columbia reconstruction process caused no ground contamination.

Although no actual decontamination operations were performed at the SLF Midfield Park Site Decontamination Area, some wastewater was generated by the removal of mud from the debris. The final ground sampling after deactivation of the site indicated no contamination.

WASTE STREAMS

An Environmental Phase 1 Site Assessment of the Columbia hangar was performed prior to the beginning of reconstruction operations and a closeout assessment was performed when all reconstruction operations were completed.

Waste Containment

USA Environmental Management evaluated all processes that occurred inside the Columbia hangar and at the SLF Midfield Park Site Decontamination Area for possible waste generation. All possible waste streams were collected and sampled prior to disposal. Processes were reviewed for waste minimization practices before receiving Environmental Management approval. One drum of waste water was generated during reconstruction operations and was treated as hazardous waste.

Wash Down Area

A wash down area was set up on the north side of the Columbia hangar to allow mud to be washed from some of the larger debris using water. A wash down area was established and approved by the Florida Department of Environment Protection (FDEP) prior to use. The wash down area consisted of a heavy-duty plastic tarp laid on the ground and surrounded by petroleum absorbing booms and a turbidity barrier. A third layer of protection at the wash area was provided by placing hay bales around the perimeter of the turbidity barrier for support.

Chemical Usage

Prior to use, all chemicals were approved by the CAIB through coordination with USA M&P Engineering, Environmental Management, and Safety & Health. Cleaners were limited to water, Spirit 126, and IPA. No aerosols or other cleaners were allowed inside the hangar without prior approval from the above organizations. Limiting the chemicals used during the reconstruction process prevented incompatibility issues with the debris, minimized the type of PPE required for the operations, and mitigated the waste streams to non-hazardous waste only.

Security

AREA SECURITY

The designated debris impound areas included the Columbia hangar, the north facility apron area adjacent to the hangar, the recovery/salvage related temporary storage buildings and containers required to support the reconstruction effort. Additional controlled areas included the SLF Midfield Park Site Decontamination Area, Landing Aids Control Building (LACB) and the clamshell.

PHYSICAL CONTROL

Physical security measures included secure core locks, deadbolts, security seal eyelets, a designated key custodian, and an eight-foot chain link fence at the north side of the hangar. The fence controlled both personnel and vehicle access to the hangar. Entrances outside the fenced area were locked and sealed. Security Officers provided armed access control to this area.

All Conex trailers and dumpsters were located within the secured area. The on-site Security Officer and the Access Control Monitors (ACMs) conducted periodic checks of the security seals.

Six Closed Circuit Television (CCTV) cameras were installed in various locations inside the Columbia hangar. Videotapes were routinely collected by a NASA Special Agent and stored in a combination safe. Additionally, a video monitor capable of displaying all camera angles was installed in the guard shack at the personnel access point to the Columbia hangar.

PERSONNEL CONTROL

Personnel requiring access were properly badged for KSC and were also placed on a hangar access list. An additional badge, approved by NASA KSC Security, was issued for personnel on the list. Three badge designations were used: “Permanent”, “Temporary”, or “CAIB”.

For personnel who would be at the hangar nearly full time, a "Permanent" badge was issued with their name written on it. Permanent badges were kept until the work at the hangar was completed. Personnel at the hangar three days or less a week were issued a "Temporary" badge. This badge allowed the same access as the permanent, however was surrendered at the end of the day. The third designation was a "CAIB" badge, which was a brightly colored full-access permanent badge that allowed for quick identification of CAIB members.

SGS Security Officers provided 24/7 access control and security to the Columbia hangar and surrounding fenced area. One officer ensured all personnel requiring entry to the hangar were in possession of the proper badge or under the control of a properly designated escort. The officer also verified appropriate hand receipts were obtained prior to removing debris and other controlled equipment from the hangar and that no prohibited items were brought into the hangar.

In addition, USA provided three ACMs to control access and provide security inside the LACB and Columbia hangar. The ACMs issued permanent and temporary badges and conducted badge exchanges for temporary personnel from the Action Center inside the LACB. They logged temporary badged personnel in and out of the hangar, and ensured appropriate hand receipts were used when necessary. ACMs also checked all interior hangar security seals and assisted with the opening and closing of the hangar.

SECURITY PROCEDURES

Designated debris areas were established as NASA Limited Areas and were controlled as such. Limited area signs were posted conspicuously around facility perimeters and on fences in accordance with KHB 1610.1 (as revised), KSC Security Handbook.

Introduction and removal of material or packages into or out of the designated area, or sub-component areas, of this operation was controlled by a system that identified the individual(s) moving the item(s), and accountability/ tracking of the item(s) moved. This system was determined and managed by designated authority specified in SFOC-GO0014, KSC, Space Shuttle Program, Salvage Operations Plan.

Unless approved by the Reconstruction Director, the following items were prohibited inside the Columbia hangar:

- Briefcases, backpacks, lunch boxes, or other such containers
- Cameras and laptop computers
- Food and drink items
- Flammable devices

Media events inside the Columbia hangar were supported with one SGS Security Officer and/or a NASA Special Agent. Mutually agreed upon media areas were cordoned off with ropes and stanchions. These areas provided the media access to the debris without compromising security and safety requirements.

Public Affairs/Media Support

As the Columbia debris began arriving at KSC, the Center's Public Affairs Office (PAO) was asked to coordinate with the Reconstruction Team concerning all media requests concerning the reconstruction effort.

While the debris grid was being populated, KSC PAO worked closely with managers to organize media tours through the hangar, assist with interviews with designated managers, and respond to numerous media questions concerning reconstruction. The NASA News Chief at KSC was assigned to be the single point of contact to coordinate media interview and hangar tour requests.

Working under CAIB guidelines, PAO

and the Reconstruction Team held weekly media events in the hangar and hosted reporters and photographers who desired access. Every other week, the Reconstruction Chairman met with the press and during this event provided them with details, on the record, regarding the progress of reconstruction efforts.

PAO also supported routine events involving reconstruction efforts by providing extensive photographic and TV coverage of the activities for release to the media and the general public. The images were provided to the media via PAO dissemination methods (i.e., web, NASA TV uplink, press releases, etc.).

Events routinely photographed and documented included the weekly truck deliveries of debris and the eventual placement in the hangar, workers in the hangar, CAIB tours, elected representatives and other VIP tours, and media activities in the hangar.

Photography/Video Imaging Operations

Aside from the photo documentation done for the PAO, the reconstruction personnel needed their own photographic support to complete their work. The photographs were used to provide visual documentation of hardware at check in to the CRDS, to support the hangar status briefing to the NAIT and OVEWG, for engineering identification of hardware through electronic transmission to system experts, on-site and off-site engineering routine uses, unique initiatives such as the virtual scanning or the spectral imaging, and the CAIB's investigations.

Initially, the quality receiving personnel within the hangar were capable of supporting the required needs. However, the engineering need for additional support with images for their interim reports and to share information with off-center investigators quickly overwhelmed the process.

Since access to the debris needed to be controlled, any requirement for outside photography or other imaging operations needed to be coordinated through the NASA operations office. Specific requests that could not be handled in house were assigned to KSC contract photographers. Photographic tasks requiring contractor support were overall grid photos, tile table photos, WLE 3-D reconstruction fixture photos and unique engineering request photos.

Contractor photographers became accustomed to taking photographs of the overall grid view, detail shots of each wing, and hangar operational improvements intended to be shared with the entire investigative management team. The support of high-rangers and other personnel lifts were used to get the best image possible. The photographer and the personnel needed to operate the heavy equipment were scheduled twice per week. The same photographer and personnel lifts were also used to take the final report images of each grid area in the hangar.

Additionally some unique initiatives required that engineers take photos. The NASA operations office authorized theses requests on as as-needed basis. An example was the spectral imaging to capture the spectrum reflected by debris excited by lasers. This was in an attempt to aid the debris identification and recovery effort in the field. Another requirement was to support the texture mapping of the laser scanned debris so that a visible image could be overlaid onto the virtual image taken. These images were transported outside the hangar to specialized facilities across the country for processing, but remained protected and impounded due to information technology security requirements levied on the process.

The HFT also required highly detailed images using special equipment. M&P personnel provided dedicated camera equipment to the hangar. This equipment remained secured within the hangar for the length of the investigation.

The CAIB investigators were authorized to use their own photographic equipment within the hangar. To discern and control who was allowed to have personal equipment, all CAIB members were issued orange badges from the reconstruction action center.

Document Control

As additional documentation requirements evolved during the reconstruction process, it became apparent there was a need to establish some form of paperwork storage and control in the hangar. A library was set up to house all paperwork that was not directly attached to the debris.

Team Leaders were authorized to publish plans and procedures in support of the overall Orbiter Reconstruction Plan. All documents were revision controlled and a hardcopy was provided to the librarian. The Quality Assurance Manager was responsible for the librarian function.

The librarian maintained the Orbiter Reconstruction Plan and any supporting documents, as well as the RDS used for testing, sampling, or other activities involved with the investigation of the debris. The library contained hardware debris reports, fact sheets and tile paperwork. The librarian maintained an index of those documents, which provided the title and revision information. Additionally, the librarian verified the minimum signature requirements were satisfied prior to release of the work documents.

General Observations

There were more recovered and identified OML debris items in the forward fuselage area of the orbiter with a bias in favor of the starboard side. Almost every piece of OML debris showed some of heat damage as evidenced by charred filler bar or Strain Isolation Pad (SIP), discoloration of the exposed primer, slag, and/or thermal erosion (ablation) of the fracture edges of structural pieces. Significantly less molten metal and aluminum oxide were present on the debris from the forward end of the vehicle. Very little (<1%) of the Fibrous Insulation Blanket (FIB) survived the break up and even less of the Felt Reusable Surface Insulation (FRSI) was recovered. The High Temperature Reusable Surface Insulation (HRSI) and Low Reusable Surface Insulation (LRSI) tiles are either missing or substantially damaged on all items due to either heating or aero loading or both. Recovered OML structural items were at least partially protected by their TPS during re-entry.

Honeycomb skin panels are notable in their complete absence or in the severity of facesheet loss and core erosion. The recovered pieces were typically skin material that was attached to internal structure or were otherwise shielded during re-entry. Skin panel stringers, located in the forward fuselage, mid fuselage and wings, typically failed due to a combination of thermal and aerodynamic loads as evidenced by either fracture along the upper or lower bend radius or the chemical milling lines. .

Items of relatively high ballistic coefficient show substantial ablation. Examples of this condition include payload longeron fittings, Orbiter/External Tank (ET) attach fitting, Space Shuttle Main Engines (SSME), Main Landing Gear (MLG), and thrust structure components.

With few exceptions, Reinforced Carbon-Carbon (RCC) components (both nose and wing) and their attach hardware appear to have failed as a result of mechanical overload, either in flight or due to ground impact. For those exceptions, thermal damage was a significant factor in the component failure and will be addressed in detail later.

Cumulative tracking of recovered debris by OML location was accomplished graphically with an electronic mapping system. Figures 8.1 through 8.4 show the recovered OML debris as viewed from above, below, and both sides.

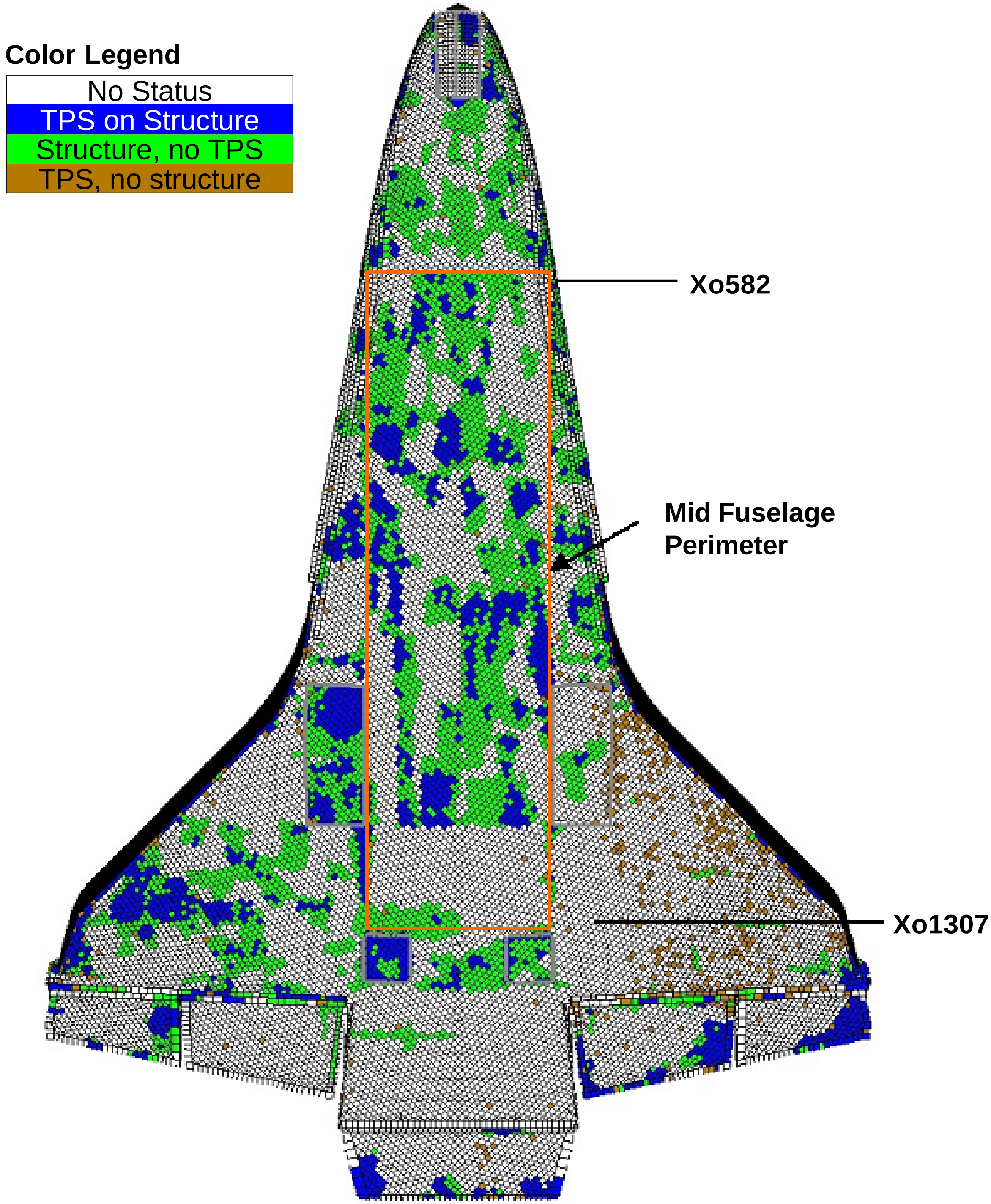


Figure 8.1 Recovered Orbiter Debris - Lower Surface

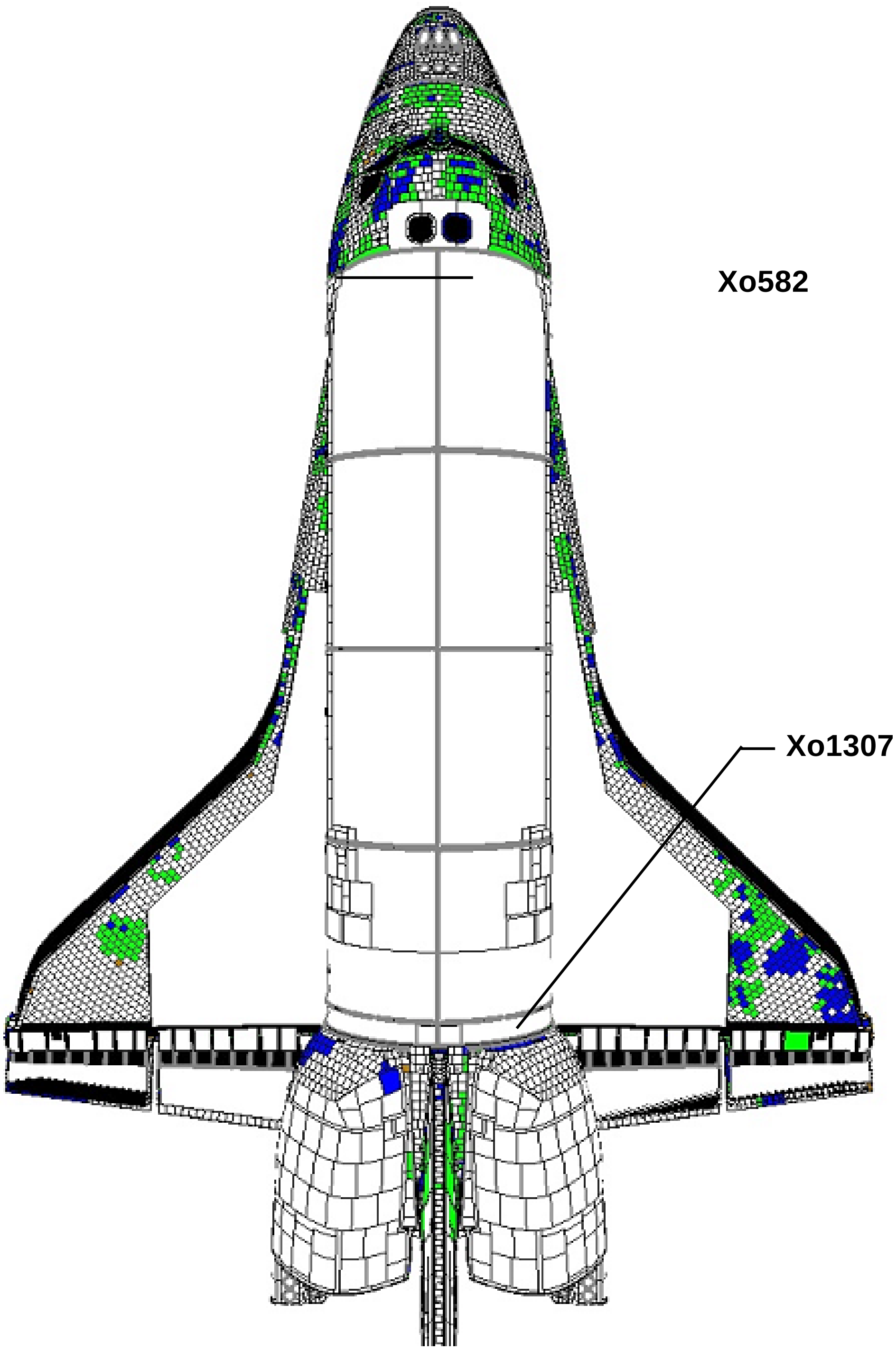


Figure 8.2 Recovered Orbiter Debris - Upper Surface

Figure 8.3 Recovered Orbiter Debris - LH Side

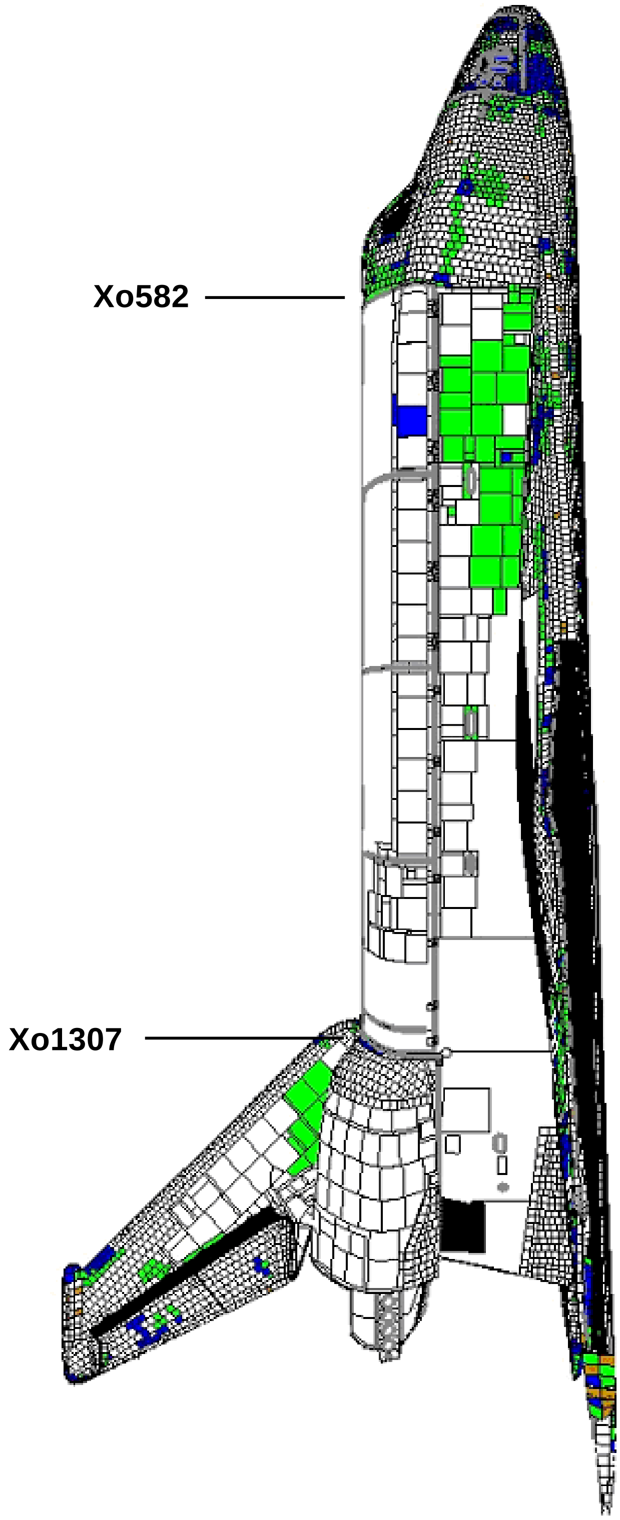


Figure 8.4 Recovered Orbiter Debris - RH Side

Figure 8.5 Forward Fuselage

Figure 8.6 Mid Fuselage

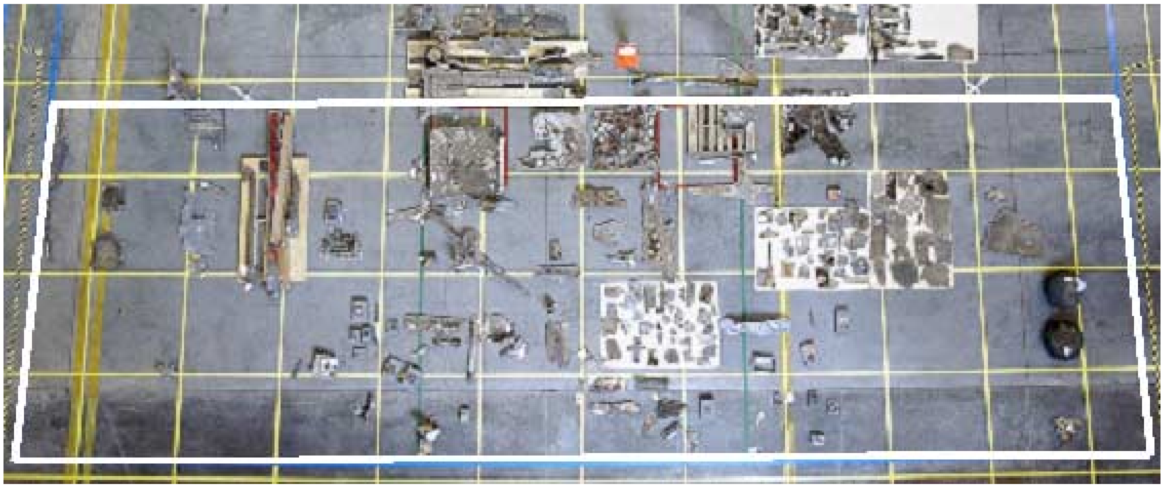


Figure 8.7 Aft Fuselage

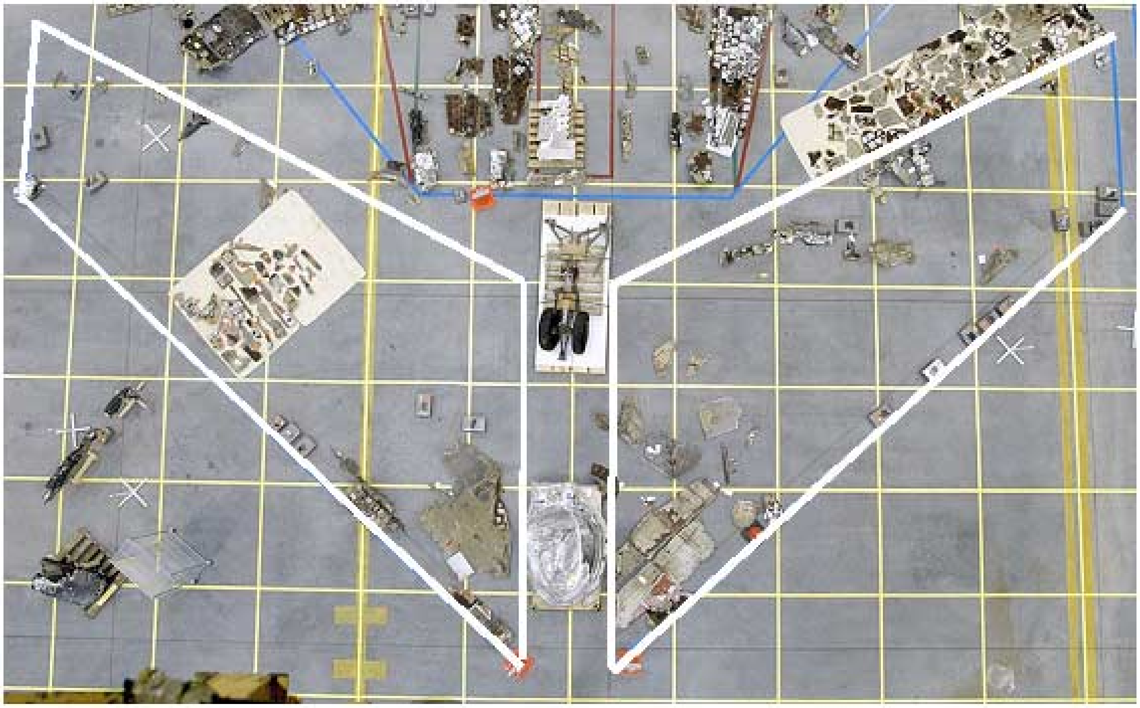


Figure 8.8 Vertical Stabilizer

Figure 8.9 Body Flap

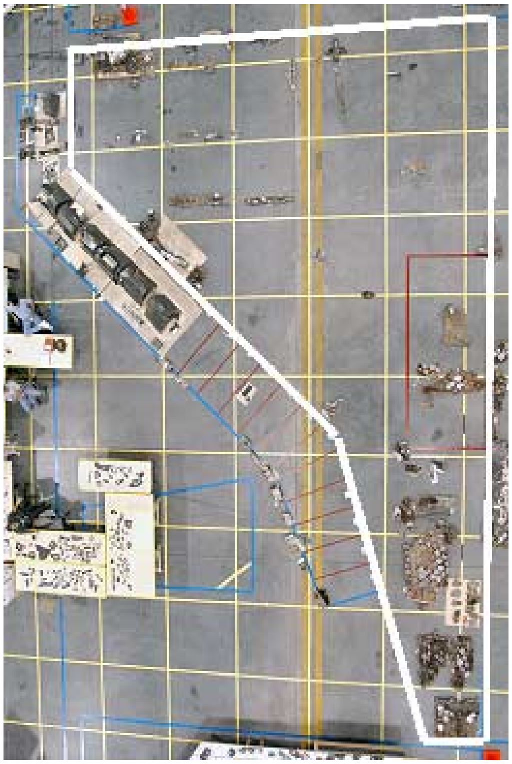


Figure 8.10 Left Wing Lower

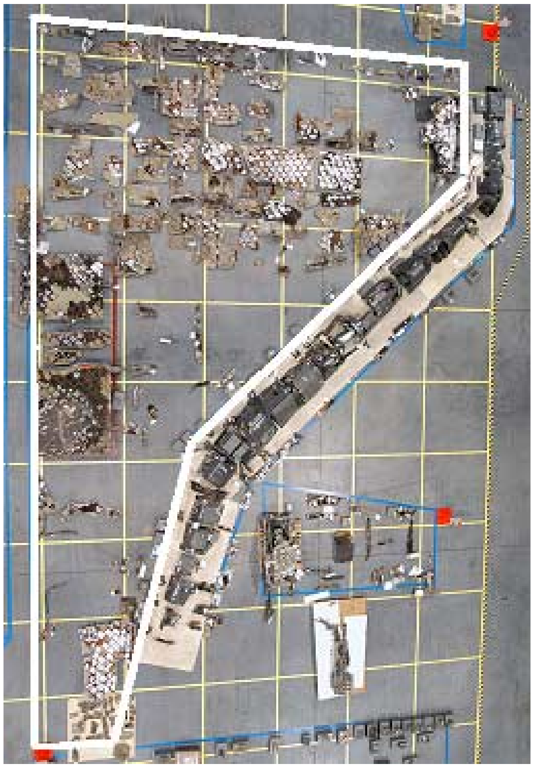


Figure 8.11 Right Wing Lower

Figure 8.12 Left Wing Leading Edge

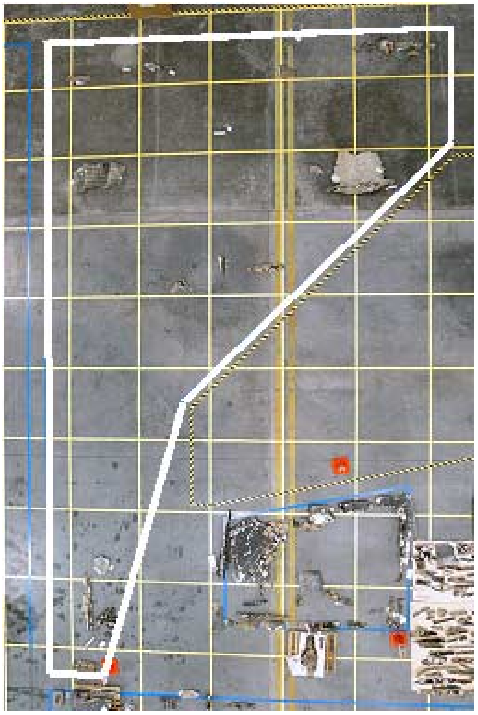


Figure 8.13 Left Wing Upper

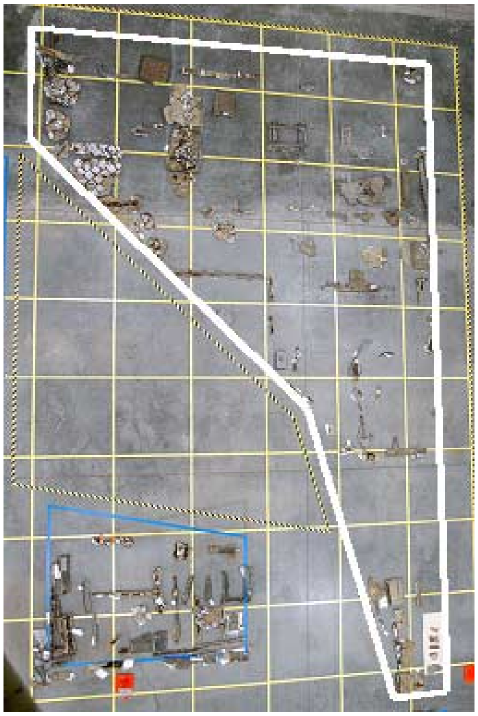


Figure 8.14 Right Wing Upper

Figure 8.15 Left Wing Lower Tile

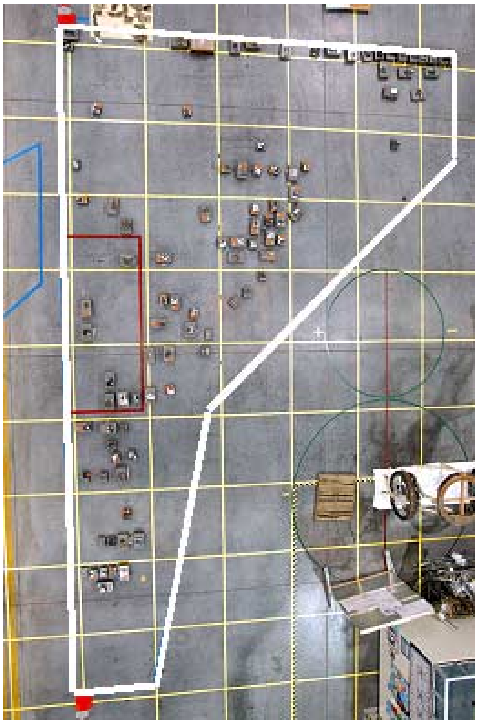


Figure 8.16 Right Wing Lower Tile

Forward Fuselage

The recovered forward fuselage components are predominantly skin/stringer segments and include a few noteworthy subsystem components. The component size ranges from less than one square foot to approximately ten square feet. All observed components exhibit evidence of mechanical overload as the primary failure mechanism. With very few exceptions, heating plays an insignificant role in the component degradation and appears to be during or subsequent to the mechanical breakup. Roughly 40% of the forward fuselage has been recovered with no difference in damage levels comparing left to right or upper to lower. Two recovered RCC components, nosecap and chin panel (1114), show evidence of mechanical breakup with no thermal damage.

Other OML components include the forward Orbiter/ET attach fitting with RCC arrowhead (37046) and the forward half of the left hand nose landing gear door (Item 284).

The left hand and right hand thermal window assemblies (1269, 63978, 583, and 45079) were recovered.

The right hand overhead thermal window assembly (1175) was also recovered.

The overhead window carrier panel (1175) tile damage is unique in that the perimeter carrier panel tiles show outward slumping and glassification on all four edges

Item 284

Item 583, 45079

Item 1114

Item 37046

Item 1269, 63978

Item 1175

Three of the four crew module attach links (1678, 1765 and 2171) were recovered. Three of the four attach lugs for the links were intact, while the left hand lug was fractured.

Several lower surface and sidewall antennas were also recovered. Most OML surfaces show substantial damage to bonded (TPS) components including: particle impacts (nose landing gear door tiles), erosion, ground impact damage, and in-plane failures. Items of high ballistic coefficient (egress hatch window ring frame and crew module link fittings) show evidence of ablation. Very few tile cavities show evidence of failure/loss due to backside heating. In most cases where the cavity is exposed, the failure mode appears to be erosion, in-plane fracture, or lifting/peeling due to aerodynamic loads. In the latter case, the remaining SIP layer shows light charring. There is no evidence of ablation on any of the RCC fracture surfaces. A few metallic fracture locations show broomstrawing. One exposed metal chin panel attach fitting exhibits no discoloration, even though it is located in a high heat region.

Forward Reaction Control System

Twelve primary structural components and all of the forward reaction control system (FRCS) thrusters were recovered. Each of those components exhibits evidence of mechanical overload as the primary failure mechanism. Heating did not appear to play a significant role in the component degradation and appears to be during or subsequent to the mechanical breakup. The recovered FRCS structure items include six internal stringers and six sections of the shell with internal structural members attached. The internal stringers appear to have been torn away from the skin, retaining their attach rivets. The skin sections (792, 82061) typically have fracture edges that follow fastener rows and are not thermally eroded. Approximately 25% of the outer mold line was recovered. In only one location, the

Item 792

Item 82061

Item 2171

062303_01fForward

backside primer is substantially blistered with the corresponding outer surface TPS showing evidence of failure due to backside heating.

Mid Fuselage

Recovered mid fuselage components are predominantly skin panel segments with a few noteworthy structural or subsystem components as well. Roughly 30% of the mid fuselage has been recovered, biased towards the floor area and the front of the vehicle. The component size ranges from less than one square foot to approximately thirty square feet. With very few exceptions, heating played an insignificant role in the component degradation and appears to be during or subsequent to the mechanical breakup.

Most mid fuselage OML components show evidence of mechanical overload as the primary failure mechanism. Out-of-plane deflection is noted on numerous pieces, indicating exposure to high aerodynamic loads both during and after breakup. The midbody floor segments extend all the way to the forward mating plane at Xo582 for nearly the width of the floor. Fracture edges of the sidewall skin segments are generally less heat affected than those of the floor segments. For those locations where skins connect to the midbody main frames, the majority of failures occurred between skin and frame rather than within the frame itself. Very few frame segments have been recovered. Noteworthy components include heavily eroded titanium longeron bridge fittings (266).

The left hand forward (32038) and right hand aft (49366) hoist fittings are significant due to ablation of the titanium.

Three sections (1 left hand and 2 right hand) of the sill longerons were recovered. The mid fuselage sill longerons (105, 266, 54117) are significant as they provide primary mid fuselage stiffness.

Item 32038

Item 49366

Item 266

Item 105

Item 283

The eroded skin panel (283) just inboard of the left hand wheel well, has outward plasma flow from the wheel well region. The point of erosion is located at the forward-inboard corner of the wheel well.

The close-up shows outward flow region at Yo105 and Xo104

Most OML surfaces show substantial damage to bonded TPS components. Damage includes particle impacts, erosion, ground impact damage, in-plane failures, and three locations with glassified tile. Greater amounts of TPS tile remnants are present closer to the vehicle centerline. Almost no tile cavities show evidence of failure/loss due to backside heating. In most cases where the cavity is exposed, the failure mode appears to be erosion, in-plane failure,

primer-to-primer failure, or lifting/ peeling due to aerodynamic load. Several metallic fractures have broomstrawing.

A few mid fuselage items have significant TPS slumping or glassification. An example is the lower wing root to fuselage attachment at Xo1249 (53827), and the inboard edge of the left hand MLG wheel well (9464) at Yo105.

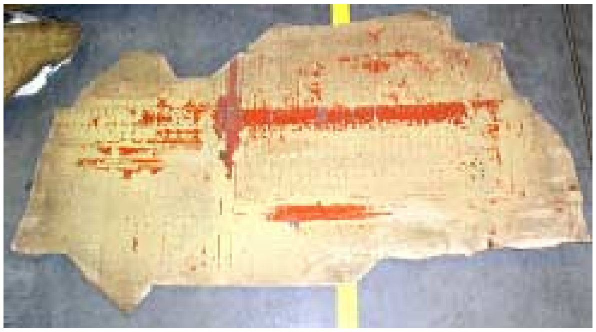
A few lower surface skin segments (52240, 1193) show heavy edge erosion. The aft inboard corner of the left hand wheel well where the Yo105 sidewall and the Xo1191 spar join, are two examples of this condition.

Item 53827

Item 9464

Item 52240

Item 1193



Item 38767

Item 25969

Item 53993

A typical fuselage sidewall segment (38767) has TPS erosion on the outer surface and fractured stringers on the inner surface.

One item which shows localized heating damage is the vent door blanking plate (25969), which is part of the left hand midbody sidewall.

Payload Bay Doors

The recovered and identified payload bay doors (PLBD) items are predominantly skin or skin/rib segments of the door itself, but include a few noteworthy subsystem components as well. The component size ranges from mostly less than one square foot to approximately sixteen square feet (53993). All observed components exhibit evidence of mechanical overload as the primary failure mechanism. Heating plays an insignificant role in the component degradation and appears to be during or subsequent to the mechanical breakup. It is estimated that 1300 lbs. of PLBD hardware was recovered, which equates to approximately 25% of the entire PLBD structure.

The representative sample of PLBD segments that was evaluated exhibits mechanical failure and falls into three major categories. The most prominent category (approximately 80% of all items) consists of small (under one square foot) skin fragments, with or without honeycomb core, that show fracture and ply delamination around the entire perimeter of the item. In many cases, one facesheet is missing and various amounts (up to all) of the honeycomb core is eroded. The second category includes segments of primary PLBD structure, either partial frames or partial torque box, with small fragments of skin attached. Frames are typically fractured into segments of approximately 1/4 to 1/3 of their original length. The least populated category (approximately 10 items) includes multiple partial frames with connecting skin. Typical to all fracture edges, the laminates are degraded/unwoven to individual fabric strands. Numerous subsystem components such as handhold brackets, wiring clamps, latch fittings, hooks, rollers, and linkages remain attached. The subsystem components, which were observed with the representative samples, did not show obvious deformation.

There is very little evidence of thermal degradation. RTV adhesive applications (bondlines, conformal coating) do not show charring or loss of resilience on most items. No thermal erosion of aluminum fastener collars was observed, as noted on numerous other structural items. On most items there is either partial or total erosion of the bonded TPS tiles or blankets. In some cases, only the inner blanket fabric remains installed. A few items have portions of wire harnesses installed with partially melted insulation. The polyurethane coating, which was applied to some inner surface locations, is blistered or has peeled away in some of these locations.

The wing OML assessments were performed by breaking down the wings into smaller zones using main spar locations/ skin splices as the dividing line. The smaller zones help to distinguish between different skin types in the different zones. The wing glove (Xw807 to Xw1009) is aluminum skin stringer assembly combined with a honeycomb leading edge and the intermediate wing and elevons are aluminum honeycomb (Xw1009 to Xw1191). The wheel well (Xw1040 to Xw1191, Yw105 to Yw167), torque box (Xw1191 to Xw1365), and lower trailing edge/ cove (Xw1365 to Xw1387) are aluminum skin stringer assemblies.

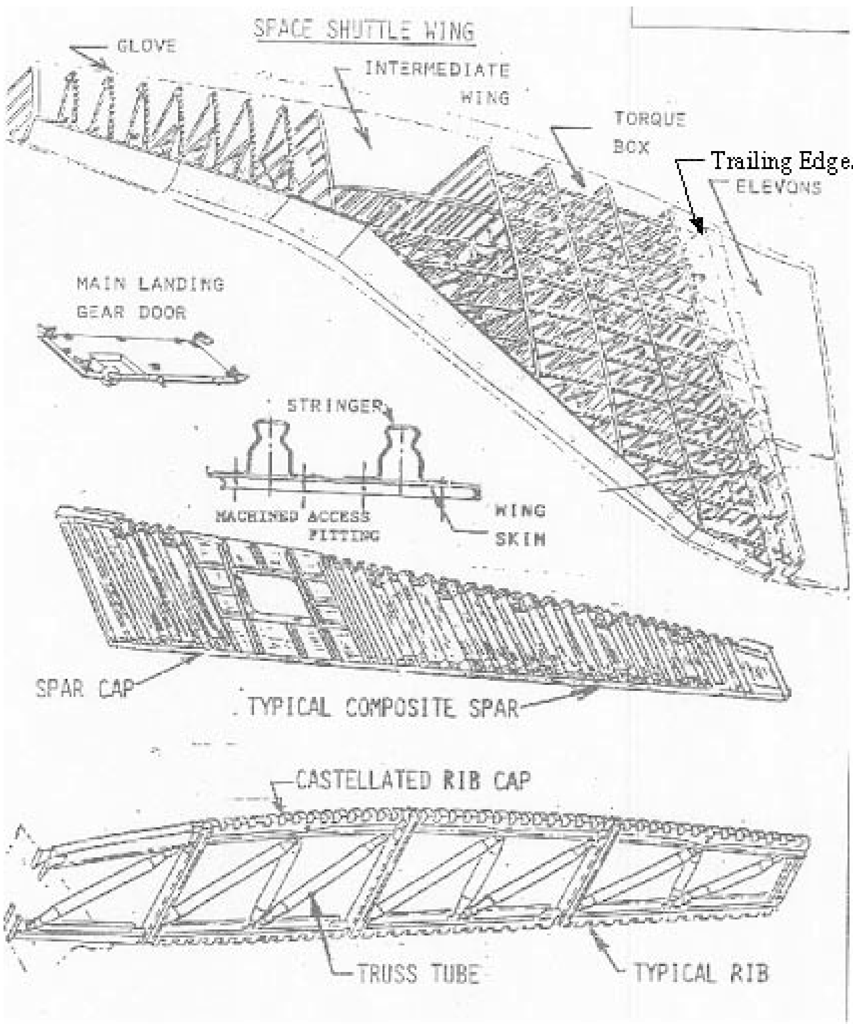
General Observations

Significantly less surface area of the left hand upper and lower skin was recovered compared to the right hand upper and lower skin surface area. Significantly less of the upper than lower skins were recovered for both wings. The intermediate section has less upper and lower skins recovered than either the glove or torque box sections for both wings. A large portion of both wing tips consisting of skin/leading edge spar was also recovered.

The recovered upper and lower right hand skin pieces are generally larger when compared to the left hand skin pieces. The left hand skin pieces are attached to a reinforced splice plate at main spar locations. Internal wing structure such as truss tubes, frames and composite spars were not recovered, except for two large pieces of aluminum right hand wing spar. A significant portion of the upper wing-to-fuselage attach at the right hand wing root (Xw1249 to Xw1365) was recovered compared to one small left hand wing root piece at Xw1191. Almost the entire right hand MLG door (95%) was recovered compared to less than 5% of the left hand MLG door.

Based upon visual inspection of the inner mold line (IML) and OML, the overall condition of recovered left hand skin pieces indicates more thermal damage than right hand skin pieces. Slag is most prevalent in the intermediate and trailing edge/cove areas for both wings.

The left hand wing inboard actuator and the right hand wing outboard actuator were recovered. The amount of recovered skin surface areas of all four elevons was generally the same with most pieces concentrated on the lower side located along the inboard, outboard and aft edges. The right hand elevons have more pieces recovered on the aft-inboard corners compared to the left hand elevons that have more pieces recovered on the aft-outboard corners.



Wing Glove

Right Hand Glove - Fifteen percent of the right hand glove upper and lower surface area was recovered. The upper pieces were mostly one to three square feet and located near the leading edge in the area where tile was installed compared to the lower glove area, which included one large skin piece (8496) that is approximately fifteen square feet. One upper skin piece included a portion of the Xw807 splice for the wing glove to mid fuselage fairing (12553). Structural wing skin doublers in the glove area were still attached to the skin pieces and have numerous areas of local buckling and cracking between the attach rivet rows.

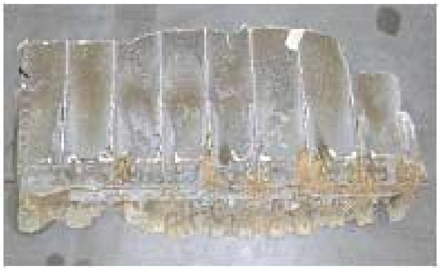
The hat stringers on the IML of the upper and lower glove skin pieces were fractured except in the areas of the splice fittings and ribs. Although only a few smaller items were available for comparison, the lower glove pieces aft of Xw900 show more heat effects on both the OML and IML surfaces, correlating to the proximity of the forward edge (starting point) of the RCC panels.

Left Hand Glove - Twenty-five percent of the left hand glove upper and lower surface area was recovered. The left hand and right hand glove were comparable in that the pieces were located primarily in the same areas with typical failures of the hat stringers on the IML and the wing skin doublers on the OML.

Only four items of upper glove skin were recovered, a portion of the Xw807 glove to fairing splice, a piece of glove honeycomb leading edge, a piece of upper glove skin and the glove bulkhead at RCC panel 1. The left hand Xw807 upper glove to fairing splice piece (734) showed similar thermal damage and slag as a comparable item on the right hand side (12553). Very little honeycomb skin was recovered in the wing areas except a piece of glove honeycomb leading edge (1632) skin, which was approximately two square feet. The OML side of the piece has tile fragments and charring of exposed filler bar. Both the upper and lower facesheets

Item 8496

Item 12553



Item 734

Item 1632

were completely delaminated from the core, and the IML side of the piece has no discoloration of the primer on the fwd side of the rib.

A piece of upper wing glove skin at Xw949 and Yw140 (33611) has overload fractures on the inboard and outboard edges and unique molten fracture surfaces on the forward and aft edges. The molten fracture edges are very porous, and there are tiny impact craters covering the entire part's IML and OML surfaces.

The OML surface has only a slight tile/filler bar footprint and the primer was missing on the IML and OML of this part. The location of this piece is inboard of a recovered left hand leading edge spar piece (83323) with RCC panel 2 upper-fwd attachment, which has medium slag on the IML side.

Item 33611

The glove honeycomb bulkhead piece (24709), which is forward of RCC panel 1, has more thermal damage on the aft side than the forward side. The four internal tiles on the aft side are missing and the FRSI in the four internal cavities is charred black. The forward side has more thermal erosion and slag than the aft side and the honeycomb bulkhead is thermally eroded everywhere except where the structure is reinforced.

Item 24709

The lower glove area was comprised of four large skin pieces greater than one square foot, a piece that included a portion of the Xw807 glove to fairing splice (272) which was approximately six square feet, two smaller pieces of the Xw1009 glove to intermediate section splice (62708, 41798), and one piece located in the lower wing glove skin acreage (2113). This skin piece (2113) was comparable to a right hand piece that was approximately the same size and in approximately the same location with the left hand piece having more heat effects than the right hand piece (8496) on the IML and OML surfaces.

Item 2113

Intermediate Wing

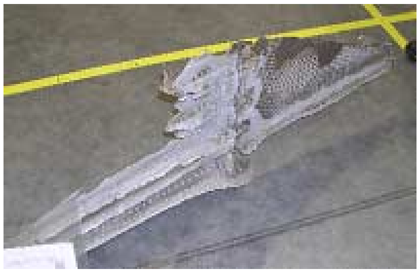
Right Hand Intermediate Wing – Ten percent of the right hand intermediate wing upper and lower surface area was recovered. Recovered pieces were less than one square foot and consist of pieces of honeycomb skin splices at intersections of main spars and ribs.

A portion of the upper Xw1040 spar, Yw198 rib intersection with attached wing skin (68801) was recovered. This area was structurally reinforced because it is one of the wing assembly hoist points, consisting of a four-bolt pattern centered on the intersection. On this item there is medium slag build up, thermal erosion and broomstraw fractures. The entire surrounding upper honeycomb skin is completely eroded away on the edges with heavy thermal erosion on the aft-inboard hoist point fastener.

A lower skin to fuselage splice piece (14880) also shows thermal damage on the fracture edges, including broomstraw fractures and thermal erosion. A rib located at Xw1113 and Yw174 (75613) has medium slag build up and the exposed fasteners are eroded more on the inboard side. The upper and lower intermediate wing have medium slag build up between the Xw1040 to Xw1113 stations, both outboard in the RCC panels 7 and 8, and inboard in the main landing gear door (MLGD) (658).

Item 68801

Item 14880



Item 75613

Left Hand Intermediate Wing – Less than one percent of the right hand intermediate wing upper and lower surface area was recovered. The upper intermediate wing has only two items identified to a location on the grid. The two small items are honeycomb skin splices at intersections of main spars and ribs less than one square foot in surface area. A lower Xw1040 spar, Yw167 rib intersection with attached wing skin (67091) is a structurally reinforced assembly hoist point and the entire surrounding upper honeycomb skin is completely eroded away on the edges.

Item 67091

Although slightly smaller compared to a corresponding piece on the right hand wing (68801) there is very similar thermal erosion on the IML side with the left hand piece showing a heavier slag build up than the right hand. Additionally, both pieces have some shadowing effects on the forward side of the IML. The OML sides of the left hand and right hand pieces were similar with charred filler bar and/or tile fragments fractured at the densification layer.

Item 36264

Item 43698

Item 24812

The other piece is the upper wing skin at Xw1160 and Yw282 rib at its intersection with the wing leading edge spar (36264) adjacent to RCC panel 13. The lower facesheet is missing and the exposed honeycomb core is thermally eroded down to the potting adhesive used around the string of fasteners where the rib attached on the IML side.

The lower intermediate wing is comprised of seven smaller items of honeycomb skin splices at intersections of main spars and ribs. Four pieces are located forward of the MLGD and three pieces are located along the outboard side of the MLGD. No other pieces were recovered in this area. The four pieces forward of the MLGD (74416, 43698, 40982, 41089) and the three pieces outboard of the MLGD (50345, 49482, 24812) all have honeycomb facesheet and core erosion except for the areas along fastener rows where a potting compound was used.

The three pieces outboard of the MLGD were more structurally reinforced than the four located forward of the MLGD and have more thermal erosion and slag deposits on the IML side. One of the pieces outboard of the MLGD is a small portion of the Xw1191 splice plate (24812) located outboard near the wing leading edge at Yw254, which has thermal erosion, and heavy slag deposits on the IML side.

Item 658

Main Landing Gear Door

Right Hand Main Landing Gear Door – Ninety five percent of the MLGD structure was recovered in two small pieces and two large pieces. The large pieces were nearly intact with OML skin/ stringers, and IML skin/ stringers still attached forming the basic box section of the door.

The aft side of the forward piece of MLGD (658) has fracture edges in the lower skin immediately aft of the center hinges, which are deflected out-of-plane. The edge of this door piece has slag uniformly distributed across the entire surface, which is not present on any other edges of this piece or on any other edges of the aft door piece (260). The forward and center hinge fittings are fractured two thirds of the way along the fitting arc length and there are two intact up-lock rollers along the inboard edge, and one intact along the forward edge. The forward side of the aft piece of MLGD (260) has edges in the lower skin thirty-one inches forward of the aft hinge, which are in plane. The aft hinge fitting tore out at the hinge attach point on the wing side, leaving nearly the full length of the aft hinge fitting attached to this piece of MLGD. There is one intact up-lock roller on the inboard edge.

Left Hand MLGD - Five percent of the MLGD was recovered in four smaller pieces of OML skin each less than two square feet in surface area. The pieces are from the center area of the door with the forward fracture edge of the largest piece (32013) located just aft of the center hinge point. Only one of four uplock rollers was recovered.

Torque Box

Right Hand Torque Box – Forty-five percent of the torque box upper and lower surface area was recovered with a majority of the skin pieces belonging to the lower surface. The recovered upper skin pieces are from two main areas; outboard near the wing tip and inboard at the reinforced wing-to-mid fuselage carry-through structure. Structural wing skin doublers in this area are still attached to the skin pieces and displayed numerous areas of local buckling and cracking in between the attach rivet rows. All of the recovered skin have typical failures of the hat stringers on the IML except for two upper skin pieces and three lower skin pieces

Item 260

Item 32013

between Xw1249 to Xw1307, outboard of Yw312. The upper pieces (12213, 78275) and lower pieces (2071, 1446 and 16556) have stringers fully intact with no failures of the hat sections and little discoloration of the primer on the IML side of the skin. The OML of these five skin pieces has more tile remaining and less in plane fractures than the surrounding skin pieces.

Only two identified pieces of internal wing spar at Xw1307 were recovered; the inboard (1421) and the outboard (41670) and a large piece of right hand wing honeycomb leading edge spar from Xw1307 to Xw1365 including pieces of the lower skin. The seven pieces of wing root between Yw105 and Yw123 (1165, 59401, 1550, 77707, 73025, 67930, 37309) include main spar attach bolts between Xw1191 to Xw1249 (59401), main spar attach bolts at Xw1307, and reinforced upper wing skin panels with stringer carry-through fittings (1165). All of these parts have broomstraw fractures and localized heavy thermal erosion.

The piece of honeycomb leading edge spar (59409) is from the tip area forward approximately six feet and has lower skin pieces attached. Many leading edge components are attached to the spar personnel pass through locations with attached structural doublers and small pieces of the upper wing skin splice plates.

Additional primary structure recovered in this area included several pieces from the torque box at the wing root

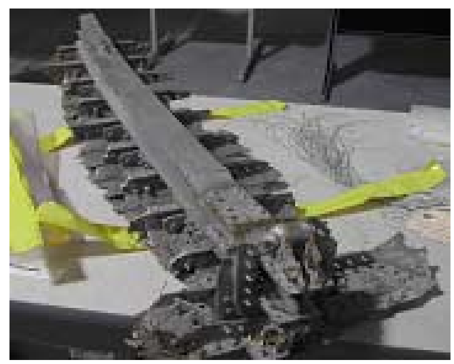
Item 12213

Item 16556

Item 1421

Item 41670

Item 1165



Item 59409

Item 59401

outboard/forward side including RCC fittings, spar insulators and access panels. There are localized areas of heavy slag build up and thermal erosion on the IML side.

Each internal main spar location contains a corresponding splice plate along the upper wing skin OML. Seventy percent and 10% of the Xw1191 splice, 50% and 50% of the Xw1249, 5% and 75% of the Xw1307, and 50% and 70% of the Xw1365 splice plates were recovered for the upper and lower wing respectively. The splice plates are thicker than the adjacent skin and were recovered either still attached to the skin on the forward side, aft side or all by itself with many of the fractures occurring along fastener rows.

Left Hand Torque Box – Less than five percent of each of the upper and lower torque box surface areas were recovered. The pieces are less than one square foot in surface area except for two large skin pieces greater than five square feet. One of the large skin pieces located at Xw1220 and Yw147 to Yw183 (76275) is comparable to a right hand piece (71706) that is in approximately the same location and has approximately the same size. The right hand piece remains relatively flat as compared to the left hand piece, which is bent out of plane in several locations. Although the left hand and the right hand pieces have similar thermal effects based on coloration and slag, the left hand hat stringers have more thermal erosion on the IML. The other large skin piece is from Xw1249, Yw312 to Yw372 (49443) and is comparable to a right hand piece (2287) that is smaller in size and in approximately the same location. In this case the left hand piece also exhibits more heat effects than the right hand when based on coloration, slag, and thermal erosion of the hat stringers on the IML. The remaining smaller items are pieces of upper wing skin splice plates at main spar locations. The recovered pieces of left hand Xw1365 splice plates have a much larger slag build up than the right hand Xw1365 splice plate pieces.

Item 76275

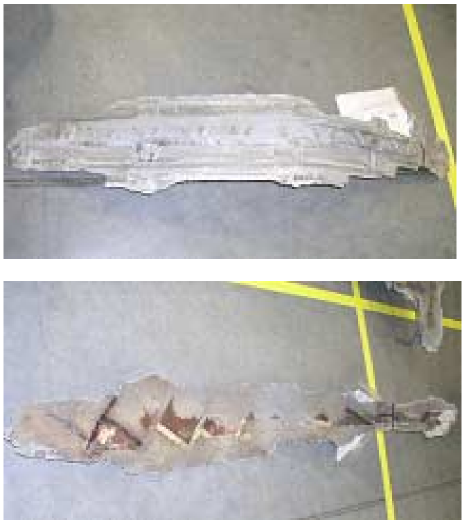
Item 71706 (RH Wing)

Item 4493

The lower skin pieces recovered in the torque box were located outboard of Yw256, except for one, and attached to wing skin splice plates at main spar locations. The piece inboard of Yw256, the Xw1249 splice plate at Yw167 (16647), has medium slag on the IML.

Further outboard along the Xw1249 spar at Yw357 to Yw372 another piece (52816) was recovered that has a medium slag build up on the IML. This piece, although smaller in size, is comparable in location to a piece on the right hand side (2071) which has no slag present, and little primer discoloration. A total of five pieces of the Xw1307 splice plate were recovered. One piece at Yw372 (71799) Item 71799 includes a reinforced hoist point area and

Item 52816



Item 2287 (RH Wing)

Item 16647

Item 71799

Item 2071 (RH Wing)

has heavy slag on the IML side and is comparable to a right hand piece (33194) that is larger but from the same location. The left hand piece has more heat effects than the right hand piece when based on coloration, slag, and thermal erosion on the IML.

Two pieces of the Xw1365 splice plate were recovered that had medium slag on the OML. One located at Yw335 (73945)

Item 33194

Item 73945

Item 67481

Item 780

and the other was attached to the recovered wing tip piece. Ten percent and 5% of the Xw1191 splice, 15% and 30% of the Xw1249, 1% and 10% of the Xw1307, and 10% and 20% of the Xw1365 splice plates were recovered for the upper and lower wing respectively. Similar to the right hand side the splice plates were recovered with skin pieces attached to either the forward or aft sides, or both, with many skin fractures occurring along the fastener rows.

The largest recovered piece was the left hand wing tip (780), which contained several elements including the outboard section of the primary seal tube, lower wing skin sections, wing tip installation, wing trailing edge beam, and a small portion of the wing leading edge honeycomb spar. The OML surfaces of the wing tip piece are less affected by heat than the IML surfaces, which have heavy slag deposits on the forward facing surfaces.

Item 37739

Trailing Edge/ Cove

Right Hand Trailing Edge/ Cove – Thirty percent of the wing trailing edge lower surface area was recovered with most skin pieces attached to the Xw1365 splice plates. The area outboard of the Yw312 wing stub had fewer recovered pieces than inboard of Yw312. Approximately 70% of the wing trailing edge carrier panels were recovered and in every case the wing trailing edge beam structure fracture edges were approximately equivalent to the footprint of the carrier panel (67481).

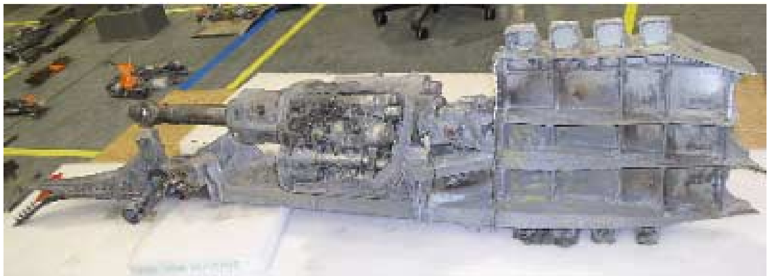
A section of the primary seal tube (37739) was recovered that was forty-six inches long between Yw212 to Yw258. Additional pieces of primary seal tube splices were found attached to the wing hinge fittings at Yw435, Yw342, Yw312, Yw282, and Yw212.

The Yw312 wing stub between the inboard and outboard elevon, the Yw212 hinge point for the inboard elevon, and the Yw387.5 hinge point for the outboard elevon were recovered. The Yw312 wing stub (44937) has a fracture edge approximately fifteen inches forward of the hinge point. The fracture edges are out-of-plane with broomstraw fractures. The outboard surface of this piece of wing stub has heavier slag than the inboard surface. The Yw212 hinge rib piece (56265) is seventy inches long and runs fwd from the hinge point with the fwd fracture edge corresponding to the area where the integrally machined castellated rib attaches to the upper and lower skin. The lower rib cap appears to have the original contour but the upper rib cap is bent ninety degrees upward at a location eighteen inches forward of the hinge point.

The rib melted all along the neutral axis in the center of the web and the rib caps have broomstraw fractures and thermal erosion. The Yw387.5 hinge rib piece (36076) is sixty-four inches long with the hydraulic actuator assembly attached. The forward fracture edges of this piece have out of plane tearing with broomstraw fractures occurring in the integrally machined castellated rib forty-three inches forward of the hinge point. At the actuator forward attach point there is severe gouging in the top surface of the clevis that matches the footprint of the upper surface of the actuator rod end. Additionally the hinge rib has thermal erosion exposing the full length of the fastener, which has erosion of the exposed shank.

Item 44937

Item 56265



Item 36076

Item 59522

Left Hand Trailing Edge/ Cove – Five percent of the wing trailing edge lower surface area was recovered with most skin pieces less than one square foot and attached to the Xw1365 splice plates (ref 7.4 Torque Box). Approximately 5% of the wing trailing edge carrier panels were recovered and in every case the carrier panel failed at the attach fittings, one at Yw312 (59522), one at Yw255 (58088), and one at Yw201 (66765), this is in contrast to the right hand failures, which occurred in the wing trailing edge beam structure (67481). The carrier panels on the left hand wing have medium slag on the fwd facing side compared to the right hand carrier panels, which have no slag.

One section of the primary seal tube was recovered along with the wing tip (ref

Item 1204

7.4 Torque Box) from Yw435 to Yw465. Additional pieces of the primary seal tube splices were attached to the wing hinge fittings at Yw342, Yw312, and Yw212. The Yw342 wing hinge fitting (1204) has heavy slag and thermal erosion on the lower surface directly through the splice tube. This thermal erosion also was also present on a recovered Yw435 right hand wing hinge fitting (1151).

The Yw312 wing stub (44446) has a fracture edge approximately fifteen inches forward of the hinge point. The fracture edge is out of plane with broomstraw effects. The outboard surface of this piece of wing stub has heavier slag than the inboard surface. The thermal effects on this piece were of the same magnitude as a comparable right hand piece (44937), which also has the heaviest slag on the outboard side. The Yw212 actuator (7327) was recovered and had a hole through the outer casing on the upper fwd surface caused by thermal erosion. Its corresponding hinge rib piece (279) is forty inches long and runs forward from the hinge point has a forward fracture edge where the rib attaches to the lower skin. The lower rib cap appears to have the original contour and the upper rib cap is fractured eight inches forward of the hinge point. The web and rib caps have thermal erosion and broomstraw fractures.

Elevons

Right Hand Inboard Elevon – Fifteen percent of the upper surface OML and 10% of the lower surface OML were recovered. The two largest items are the lower surface inboard edge (38891) and the upper surface inboard edge (26197).

The other recovered pieces consist of narrow pieces of honeycomb skins that are attached to a rib on the IML side with a minor presence of slag. A piece of the Yw212 elevon hinge rib (56265, 7.5 Trailing Edge/ Cove) is attached and fractured approximately eighteen inches aft of the

Item 7327

Item 279

Item 1151 (RH Wing)

Item 44446

hinge point. Six elevon cove carrier panels (all or in part), 40% of the primary seal panel, and 15% of the flipper door rub panels were recovered. One of the six carrier panels tore out at the boss on the inboard side and the outboard side was only slightly deformed. The remaining five carrier panels have only slight deformation at either hole location.

Right Hand Outboard Elevon – Thirty five percent of the upper and lower surface OML was recovered. The largest item was approximately eighteen square feet and was located along the inboard edge (75987) and included a portion of the lower elevon skin, inboard sidewall, outboard closure rib, and upper elevon skin. The IML surfaces have no discoloration of the primer and the lower OML surfaces have severely heat damaged honeycomb facesheets consisting of fractured/ missing pieces of outer facesheet and thermal erosion of the core to the inner facesheet. The upper OML surface has less thermal effects than the lower surface that includes the only area of FRSI recovered from anywhere on the wings. The outer room temperature vulcanizing (RTV) adhesive membrane is charred black and the residual Nomex felt is pliable.

The other recovered pieces consist of narrow pieces of honeycomb skins that are attached to a rib on the IML side with a minor presence of slag similar to those on the inboard elevon. A piece of the Yw387.5 elevon hinge rib is attached to the wing hinge rib (36076, 7.5 Trailing Edge/ Cove) and fractured approximately six inches aft of the hinge point. One elevon cove carrier panel, 10% of the primary seal panel, and 15% of the flipper door rub panels were recovered. The elevon cove carrier panel tore out at the boss on the inboard side and the outboard side was only slightly deformed.

Left Hand Inboard Elevon – Five percent of the upper surface OML and 35% of the lower surface OML were recovered. The larger recovered items were located along the aft edge, including the aft-inboard and aft-outboard corners. The other smaller recovered pieces consist of narrow pieces of honeycomb skins that are attached to a rib on the IML side. The twenty square foot aft outboard corner (20583), the adjacent outboard sidewall honeycomb closeout (87) and the aft inboard corner (71626) were recovered. On the two corner pieces the upper OML TPS was missing, except in the trailing edge

Item 87

Item 71626

Item 38891

Item 26197

Item 20583

area, and there is thermal erosion of the honeycomb facesheet and core with broomstraw fractures. The lower OML tile has many tile or tile fragments attached. A piece of the Yw212 elevon hinge rib is attached to the wing hinge rib (279, 7.5 Trailing Edge/ Cove) and fractured approximately fourteen inches aft of the hinge point.

Five elevon cove carrier panels (all or in part), 5% of the primary seal panel, and 10% of the flipper door rub panels were recovered. Three of the five carrier panels tore out at the boss on the inboard side and two had the threaded insert pulled out of the structure at the inboard side. In either case the outboard side appeared only slightly deformed.

Left Hand Outboard Elevon – Twenty five percent of the upper surface OML and 35% of the lower surface OML were recovered. The larger recovered items were located along the aft edge, including the aft-inboard and aft-outboard corners. The other smaller recovered pieces consist of narrow pieces of honeycomb skins that are attached to a rib on the IML side.

The largest piece was the aft outboard corner (35) that is forty square feet and has medium slag on IML fittings and ribs with broomstraw fractures. The upper OML TPS was missing, except in the trailing edge area, and there is thermal erosion of the honeycomb facesheet and core with broomstraw fractures. The lower OML tile has debris peppering and light gray discoloration compared to the inboard elevon piece (20583), and has many tile or tile fragments attached.

Three elevon cove carrier panels (all or in part), 5% of the primary seal panel, and 40% of the flipper door rub panels were recovered. One of the three carrier panels tore out at the boss on the inboard side and two had the threaded insert pulled out of the structure at the inboard side. In either case the outboard side appeared only slightly deformed.

Item 35

Left Wing

Of the tiles that have been recovered, seven percent are identified to the left wing, with the majority belonging on the lower wing section. The lower wing tiles and structure are placed on a full-scale model of the wing, which provides a method of seeing trends. The predominant tile failure mode was from internal wing heating that caused the primer layer between the structure and tile bond line to fail.

There are a greater number of structural pieces with tile remains forward of the MLGD than aft. The tile remnants, resulting from in-plane fractures, consist of silica, charred filler bar, and RTV adhesive. Individual tiles identified in this region do not have signs of slumping or glassification damages, but do have debris impact damages.

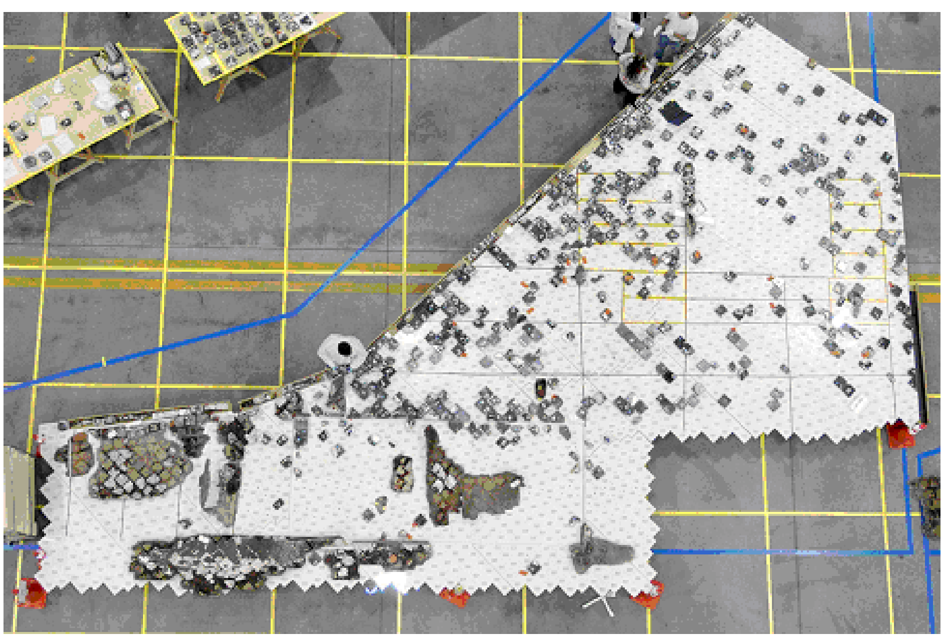
The majority of tiles identified in the MLGD region are concentrated around the perimeter of the outboard edge of the gear door. One tile, (33590), located on the outboard forward corner of the door has excessive heating. The erosion patterns show the flow direction starting from the IML to OML, moving inboard. The midbody structure side, inboard of the MLGD, has 6 tiles (283) with black deposits on the OML. The silica and Reaction Cured Glass (RCG) coating erosion patterns have a thermal erosion signature of an inboard flow direction. The remaining tiles on the gear door have minimal thermal degradation or contamination, with less backside heating effects as compared to the rest of the lower wing.

From the leading edge of the MLGD

Forward of the MLGD

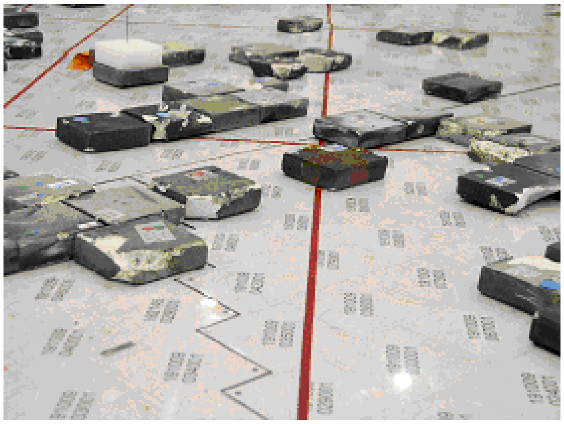
Item 33590

Item 283



Left Wing Tile Table

Forward of Xo-1191



Aft of Xo-1191

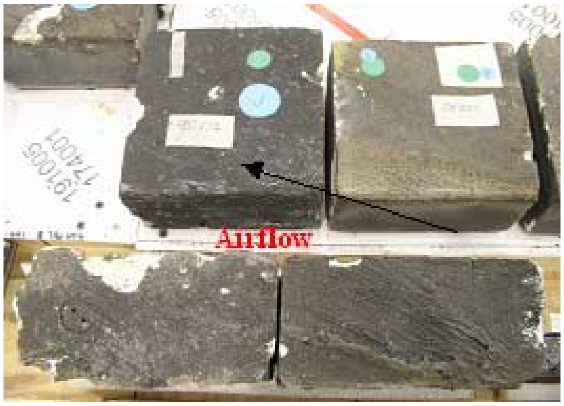
progressing aft, all tiles, except fifteen, failed due to backside heating. The fifteen tiles, which are located on the leading edge of the wing aft of LESS access panel 13, failed by in-plane fractures.

Tiles aft of Xo1191 between Yo198 and Yo254 exhibited minimal signs of thermal degradation compared to those forward of Xo1191. The forward facing sidewalls of these tiles, do however have slumped RCG coating that indicates direct airflow impingement. Tiles from Xo1091 and Xo1191, aft of LESS access panel number 9, have significant thermal related damages, which consist of glassification and erosion.

Adjacent to LESS access panel 9, two leading edge wing tiles (23553 and 15523) have severely slumped RCG OML and sidewall coating. Black deposits are embedded into both slumped regions. The flow patterns are approximately twenty-five degrees outboard of the normal airflow direction. On LESS access panel 9, the two tiles (57754 and 22571) have similar slumping and flow patterns as the two leading edge wing tiles.

Three tiles (43820, 13001, 1858) located inboard of LESS access panel 13 have very unique erosion patterns. These patterns indicate RCG coating was damaged due to a debris impact, which not only exposed the underlying silica but also removed an entire portion of the tile. The remaining silica is severely glassified, but shows a normal reentry directional flow pattern. These features indicate the tile remained bonded to the structure for a substantial period of time during reentry. The remaining silica has embedded aluminum oxide, which is black in appearance.

The tile (85472) is located inboard and aft from LESS access panel number 9 is the third most western tile found in the debris field. The design thickness was



Items 23553, 15523, 57754, 22571

Items 43820, 13001, 1858

062303_01fTPS Wings

Item 85472

2.1 inches, however a debris impact with subsequent heating and thermal erosion resulted in a loss of 70% of the RCG coating and silica material. The remaining portion of the tile consists of white silica, with slight glassification. The tile failed due to backside heating, with no evidence of aluminum oxide deposits, but the remaining OML coating has light brown color in appearance.

There are two open areas on the lower wing that are bounded by three densely populated tiles regions. The open areas, which consist of 40 tile locations, are inboard of Yo-198 and outboard of Yo-226, and forward of Xo1191. Items 1858, 43820, 13001, also border this region.

The most western recovered tile (14768) found in the debris field was a piece of upper wing LRSI tile, with black deposits covering the OML. The tile piece was not positively identified, however 3D evaluation and lab analysis indicated the tile could be placed in one of two locations. Both possible locations on the left and right wing are inboard of Leading Edge Structural Subsystem (LESS) upper wing access panels 8 and 9.

Item 14768

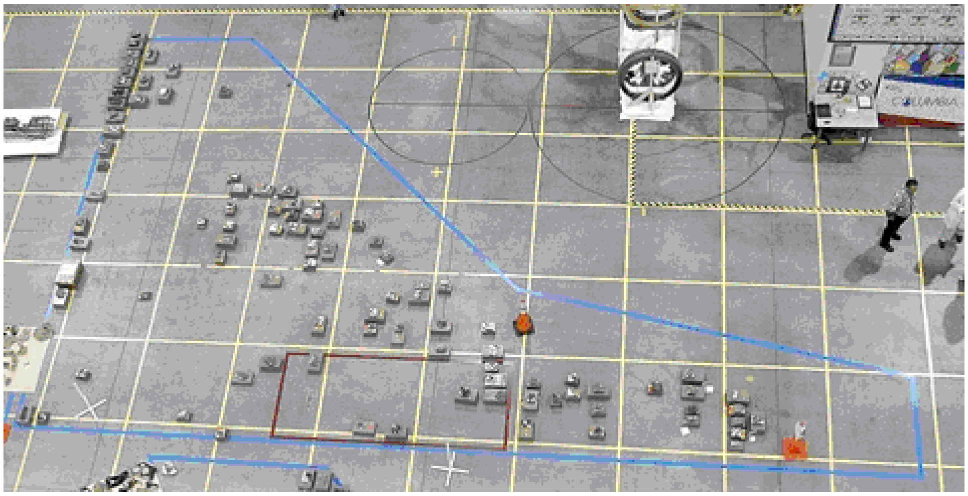
Voids on Left Wing Table

Right Wing

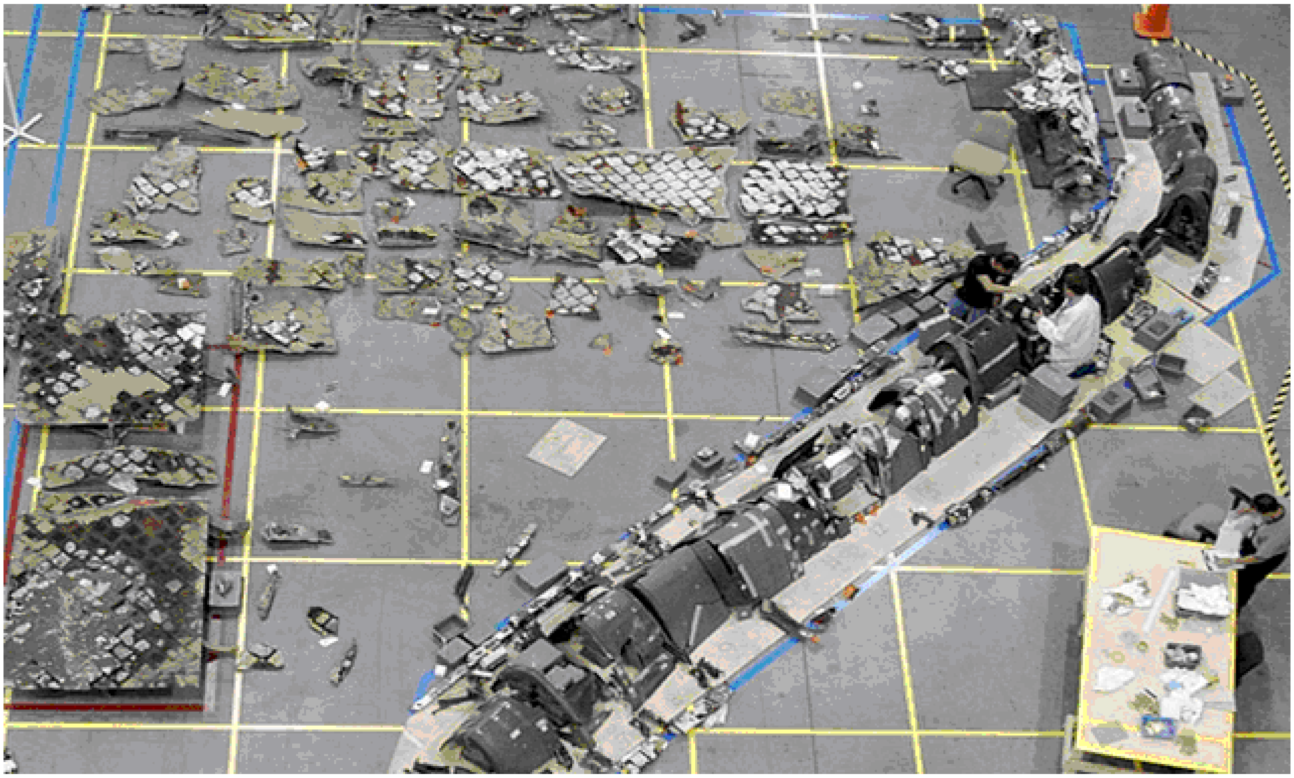
With the focus belonging to the left wing, less than 1% of the recovered tiles have been positively identified to the right wing. The overall right wing tile failure mode indicated less backside heating and more in-plane fracture, in comparison with the left wing.

On the lower wing, from Xo1040 to Xo1191, the MLGD had the majority of bonded tiles and tile remnants. Thirty percent of the MLGD tiles (658) were still bonded and show some shallow OML debris and heating damages. Tiles in this location typically showed a light brown discoloration. The remaining exposed structure has primer slightly charred and peeling with RTV adhesive attached.

There is no evidence of silica remnants on the structure aft of the MLGD, from Xo1191 to approximately Xo 1250. Residual RTV remains on the structure but is charred in some locations. From Xo1250 to Xo1300 and including the wing tip, the tiles failed by in-plane fracture with the remaining silica and SIP adhered to the structure. However, several individual tiles in the



Lower Right Wing Tile Grid



Lower Right Wing Structure

Item 658

region do show evidence of backside heating failures.

Tile failures on the upper wing were a combination of backside heating and in-plane fractures, however, no FRSI was recovered. Structure pieces with tiles still installed (28421 and 1412) are primarily located from Xo1191 aft, inboard from the spar edge. Tiles in this region are less that one-inch thick and were recovered with black deposits on the OML. One instrumentation tile (43000) was positively identified, with 10% of the OML coating intact and the exposed silica having black deposits. Backside heating was the cause of the tile failure.

On the lower inboard and outboard elevons, unusual tile heating occurred on the outboard elevon, inboard edge. The OML Reaction Cured Glass (RCG) coating was separated from the underlying silica (75968). The remaining RCG coating was pooled indicating airflow direction. The color of the RCG coating and silica are unusually discolored exhibiting a light brown gray appearance. The upper surface of the elevons are covered FRSI per design, of which the only recovered portion was on the upper outboard elevon.

Item 75968

Item 28421

Item 1412

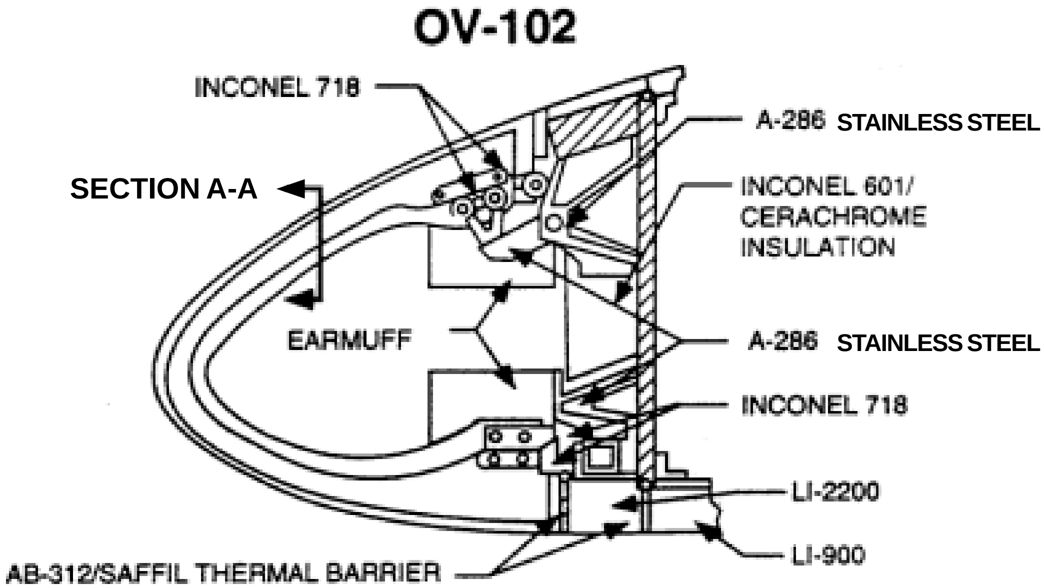
Wing Leading Edge Sub-System

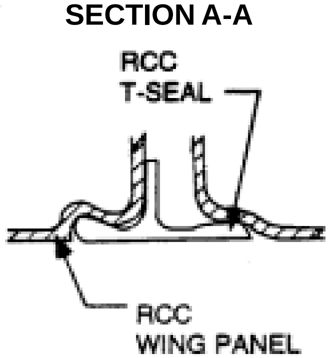
The Wing Leading Edge Sub-System (WLE) consists of 22 Reinforced Carbon Carbon (RCC) panel assemblies per wing, which provides thermal protection to the aluminum wing spar. Each assembly, except panel 22, pairs a panel with an associated gap “tee” seal. The gap seal attaches to its mating panel with two A286 bolts and bushings at clevis attach fittings and mechanically locks on the panel periphery. The gap between installed panels is referred to as a rib splice, which is closed by a gap seal. The gap seals install to the outboard end of the RCC panels, with the exception of gap seal 1, which installs to the spar fittings, using two bolts/sleeves. The rib splice between panel 1, the forward-most location, and the glove is closed by gap seal 1 “L” angle seal, whereas panel 22 does not have a gap seal and adjoins the wing tip.

The larger panels (5-19) contain Inconel 718 spanner beams to carry moment loads on the panels. The spanner beams, Inconel 718 clevis fittings and aluminum honeycomb wing spar are thermally protected with insulators made of Cerachrome batting encased in Inconel-Dynaflex 601 foil.

The panels are installed onto the wing leading edge spar via A286 spar fittings (mounting brackets). Each upper and lower spar fitting is installed to the wing spar with four A286 bolts. Each spar fitting has attach points for adjacent RCC panels, with the exception of rib splice 1 and 23. Each RCC panel attaches to four spar fittings, two lower and two upper, by means of A286 bolts and bushings, which allow panels to slide inboard and outboard along the wing. Adjustable shear pins (two each per panel) located on the upper and lower spar fittings insert into fittings on the outboard/aft heel of the panels to retain the panel’s position in the inboard and outboard direction.

Upper and lower access panels attach to the spar to seal the gap between the RCC panel and wing spar/tile. The upper LESS access panels are 2024 aluminum honeycomb and install with four (two inboard and two outboard) A286 bolts. The lower panels are extruded boxes made of either 2024 or 6061 aluminum and installed with two (one inboard and one outboard) A286 bolts.





062303_01WLE Sub-sys

General Observations

RCC material recovered

- Left Wing – Panels 65 %, Gap Seals 45%
- Right Wing – Panels 70%, Gap Seals 70%

Spar Fittings (or portions) recovered – 23 possible

- Left Wing Upper – 16 Lower – 15
- Right Wing Upper – 17 Lower – 18

Access Panels (or portions or individual tiles) recovered – 22 possible

- Left Wing Upper – 17 Lower – 19
- Right Wing Upper – 18 Lower – 21

The majority of the RCC panels/seals have fracture surfaces without thermal erosion. The WLE has been categorized into three different regions for evaluation based on the heat damage.

- Glove region (Rib Splice 1-7 / Xw 923-1055) medium heating
- Transition region (Rib Splice 7-12 / Xw 1055-1152) high heating
  - LH Panel 8 & 9 severe heating
- Torque box region (Rib Splice 12-22 / Xw 1152-1365) light heating

This observation is supported by the quantity, size and condition of metal hardware, including wing spar sections. More hardware from the torque box region was recovered than from glove and transition regions, with the least amount found for the transition.

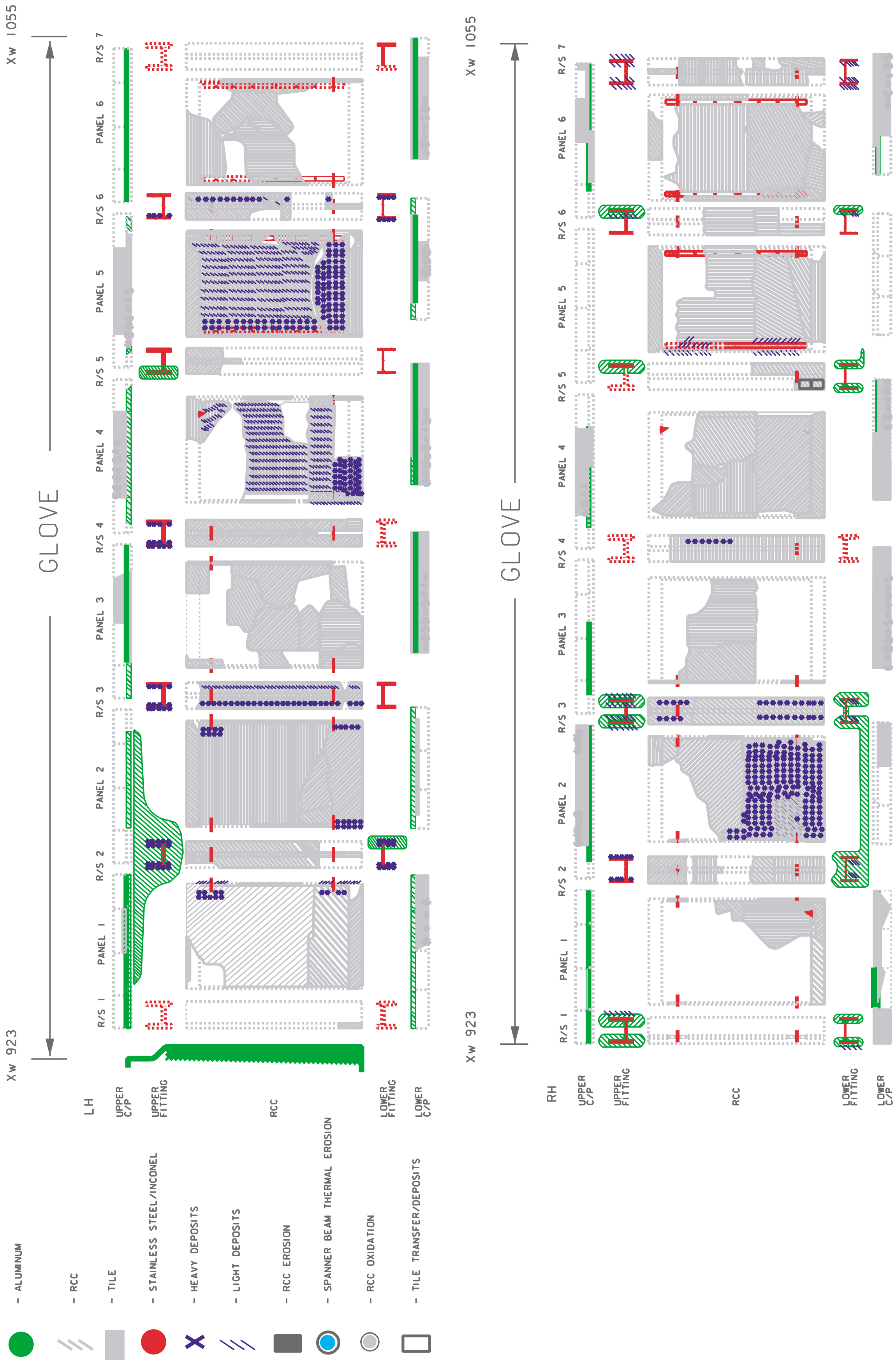
Fewer upper than lower LESS access panels and/or tile were recovered and had more damage. Inspection of the LESS access panels attaching hardware shows thread engagement met design requirements. The primary failure mode for the lower panel attach is bolt pull through whereas the upper is honeycomb core pull through (36).

The maps on the following pages depict the identified recovered wing leading edge components and their condition (left hand, top; right hand, bottom).

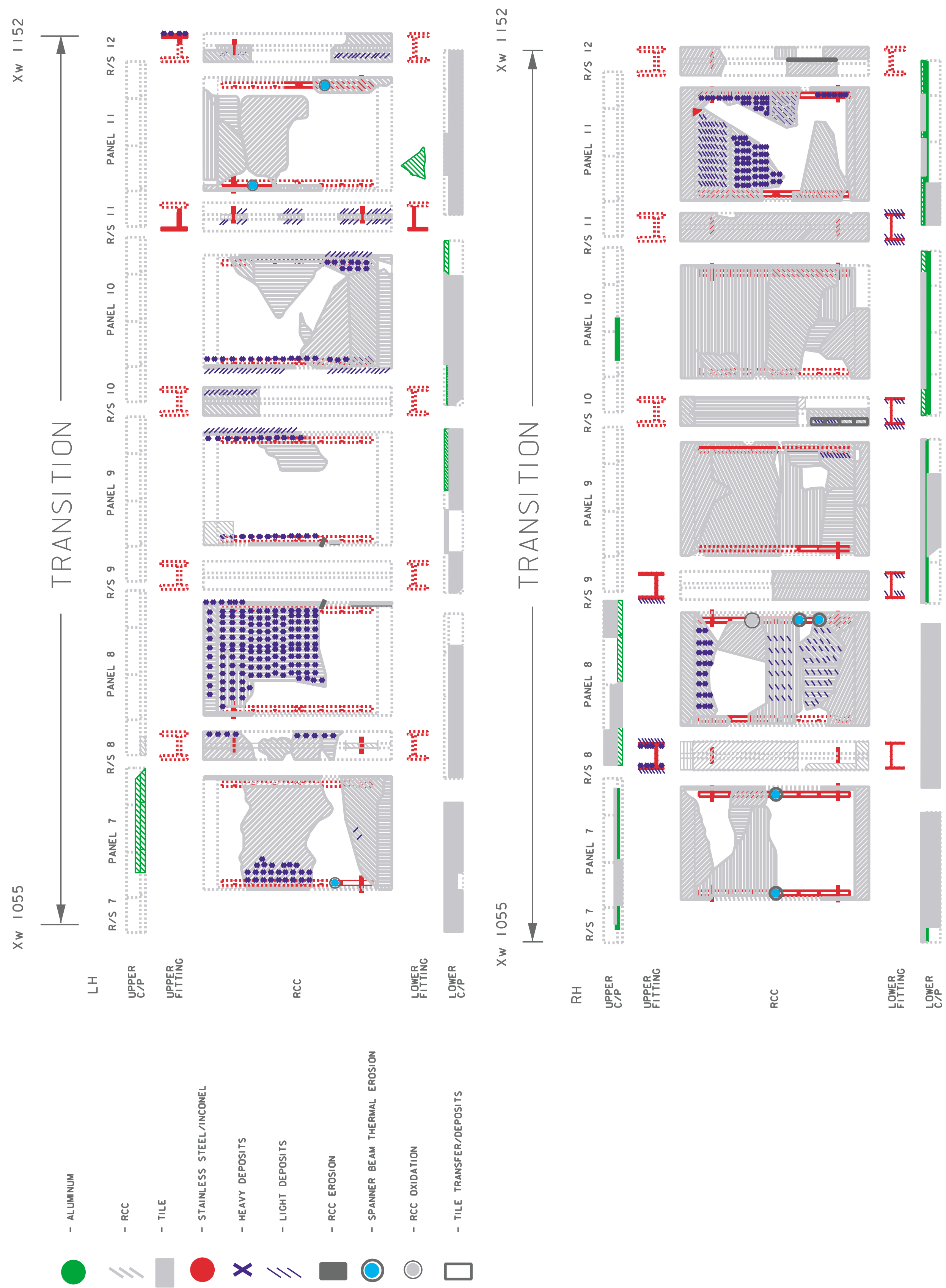
Upper core pull through

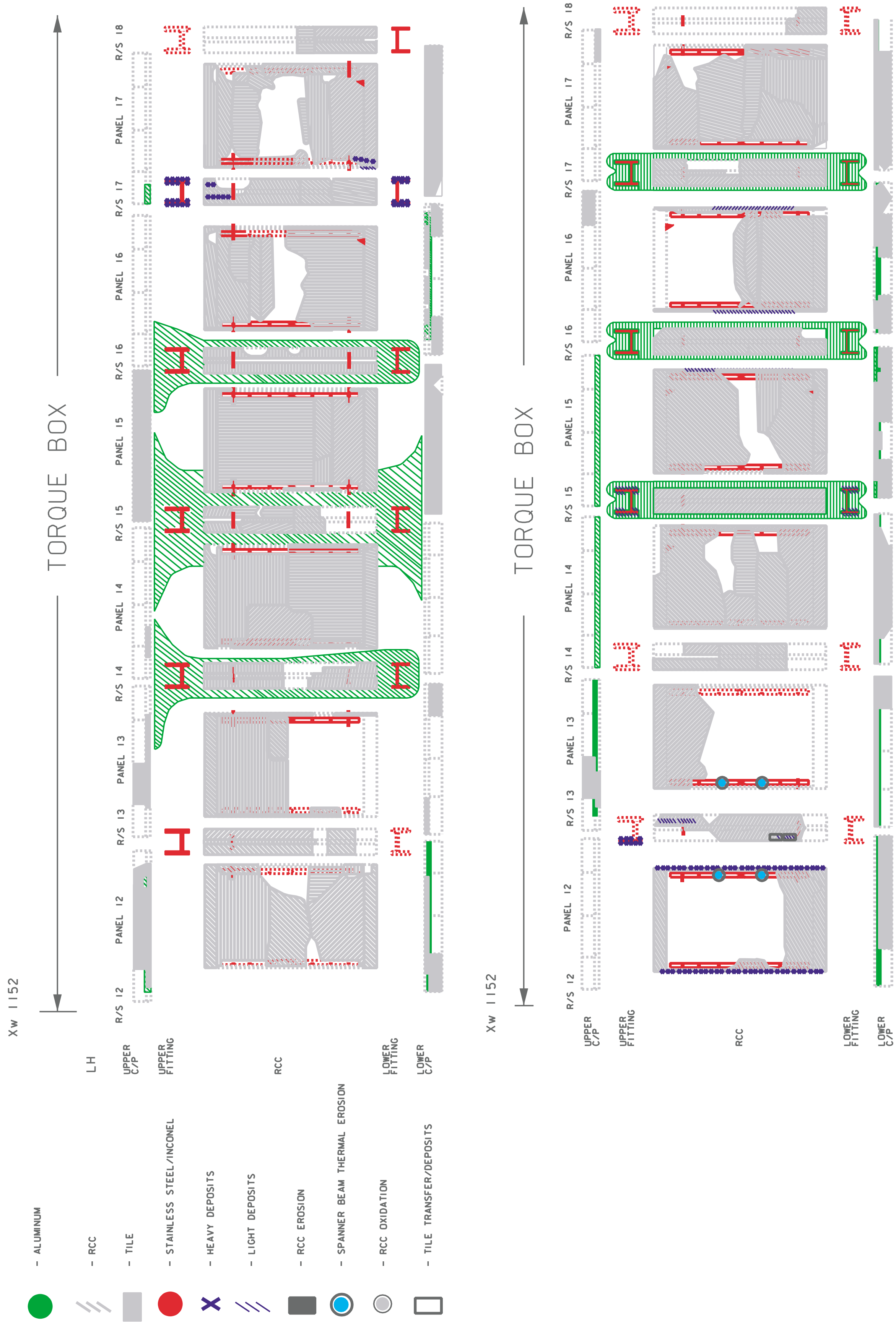
Item 36 LH Spar Fitting 21

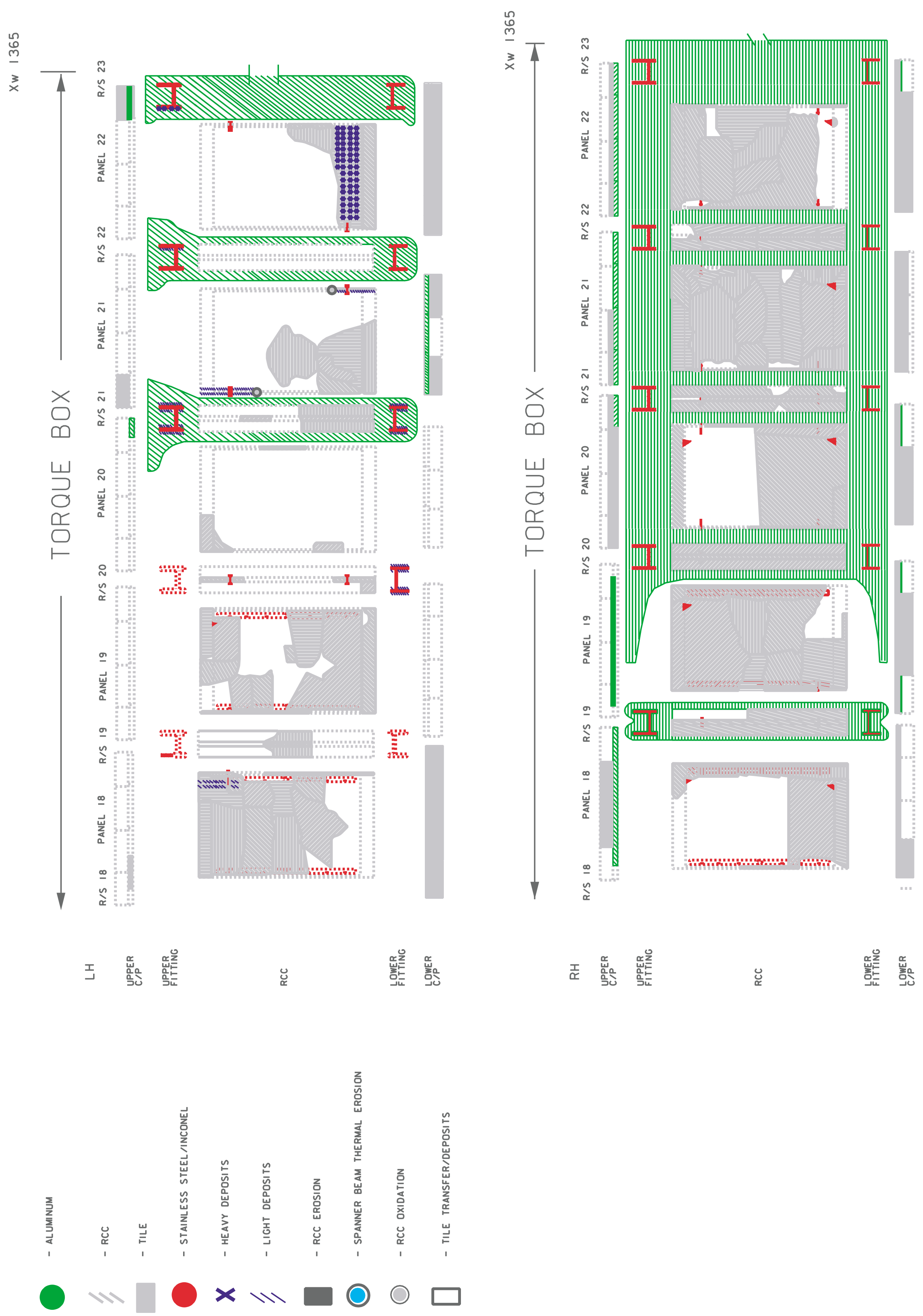
Lower bolt pull through



062303_01WLE Sub-sys


TRANSITION
Xw 1152
Xw 1055
LH
RH
UPPER C/P
UPPER FITTING
RCC
LOWER FITTING
LOWER C/P
R/S 12
PANEL 11
R/S 11
PANEL 10
R/S 10
PANEL 9
R/S 9
PANEL 8
R/S 8
PANEL 7
R/S 7
- ALUMINUM
- RCC
- TILE
- STAINLESS STEEL/INCONEL
- HEAVY DEPOSITS
- LIGHT DEPOSITS
- RCC EROSION
- SPANNER BEAM THERMAL EROSION
- RCC OXIDATION
- TILE TRANSFER/DEPOSITS


TORQUE BOX
TORQUE BOX
Xw 1152
Xw 1152
R/S 12
PANEL 12
R/S 13
PANEL 13
R/S 14
PANEL 14
R/S 15
PANEL 15
R/S 16
PANEL 16
R/S 17
PANEL 17
R/S 18
LH
UPPER C/P
UPPER FITTING
RCC
LOWER FITTING
LOWER C/P
- ALUMINUM
- RCC
- TILE
- STAINLESS STEEL/INCONEL
- HEAVY DEPOSITS
- LIGHT DEPOSITS
- RCC EROSION
- SPANNER BEAM THERMAL EROSION
- RCC OXIDATION
- TILE TRANSFER/DEPOSITS



062303_01WLE Sub-sys

Glove Region (Rib Splice 1-7)

Item 21066, 22510

All of the left hand and right hand LESS access panels for the glove region were recovered with the exception of the right hand 5 upper and lower panels. The damage to the upper panels varied from relatively intact panels with tile to only portions of aluminum facesheet, as depicted with left hand panels 5 and 6 (21066 and 22510).

The unusual finding in this area is right hand lower panel 4 (68729, 75915, 80558) with slumped tile similar to left hand lower panel 9 tile.

There are fourteen spar fittings per side in the glove region. Ten fittings, five upper and five lower, were found for the left hand side. Twelve fittings, six upper and six lower, were found for the right hand side. Upper and lower 1, upper 7 and lower 4 left hand spar fittings were not recovered. The right hand upper and lower spar fittings for rib splice 4 were not recovered. There are pieces of the aluminum wing spar attached to the spar fittings. The fittings and outer facesheet of wing spar have a non-uniform splattering of molten aluminum deposits

Item 68729, 75915, 80558

Item 75915, 80558

though the remaining pieces of silicone barrier on the spar are still pliable. The inner spar facesheet is virtually free of metallic deposits.

Per design, in the glove region only panels 5 and 6 have spanner beams, two per panel. Entire or partial spanner beams were recovered for each location on the right hand panels. Panel 5 outboard and 6 inboard spanner beams for the left hand side were recovered. The inboard spanner beams for panel 6 on both left hand and right hand sides along with left hand 5 were free of deposits or thermal erosion. The spanner beam for right hand 5 exhibits deposits consistent with the deposits found on RCC panel 5. Right hand panel 6 spanner beam has spar side thermal erosion. Pieces of Inconel foil from the insulators are scattered throughout the glove region.

All the RCC pieces in the glove region have fracture surfaces without signs of thermal erosion, though some of the fracture edges have substrate oxidation. The majority of the RCC lug clevis attach fittings were recovered. Uniform thin deposits on the interior of the panels contain Inconel, Ceracrhrome and aluminum at all deposition layers. The largest source of aluminum is the wing

Item 83323
LH Splice 2

Left Hand RCC Panels 1, 2, and 3

Left Hand RCC Panels 4, 5, and 6

spar, with the aluminum access panel providing a secondary source.

The highest concentration of deposits on the panels is the lower portion of right hand RCC panel 2, which coincides with a missing lower access panel 2. Fracture sequencing can be determined based on deposit levels. Panel 2 and its associated gap seal have a heavy concentration of metallic deposits on one side of a fracture while the mating fracture surface is completely free of deposits. This condition is found on the gap seal (64823, 58575, 18474) where the middle

Items 64823, 58575, 18474

Items 58575, 18474

Item 64725

Item 50336

section is free of deposits and the upper and lower portions have a heavy coating of deposits.

Gap seal 5 lower portion has tile coating transferred to the outer surface of the seal (64725). Similar tile deposition is also found on right hand gap seal 10 and 13.

A gap seal rotation test confirmed that a de-pinned (not fastened) upper attach point will allow the seal to pivot about the lower attach point. An apex region through crack in a gap seal is required to allow a portion of the gap seal to pivot about the upper attach point. This pivoting could allow contact with tile, thus transferring material.

Transition Region (Panels 7-11)

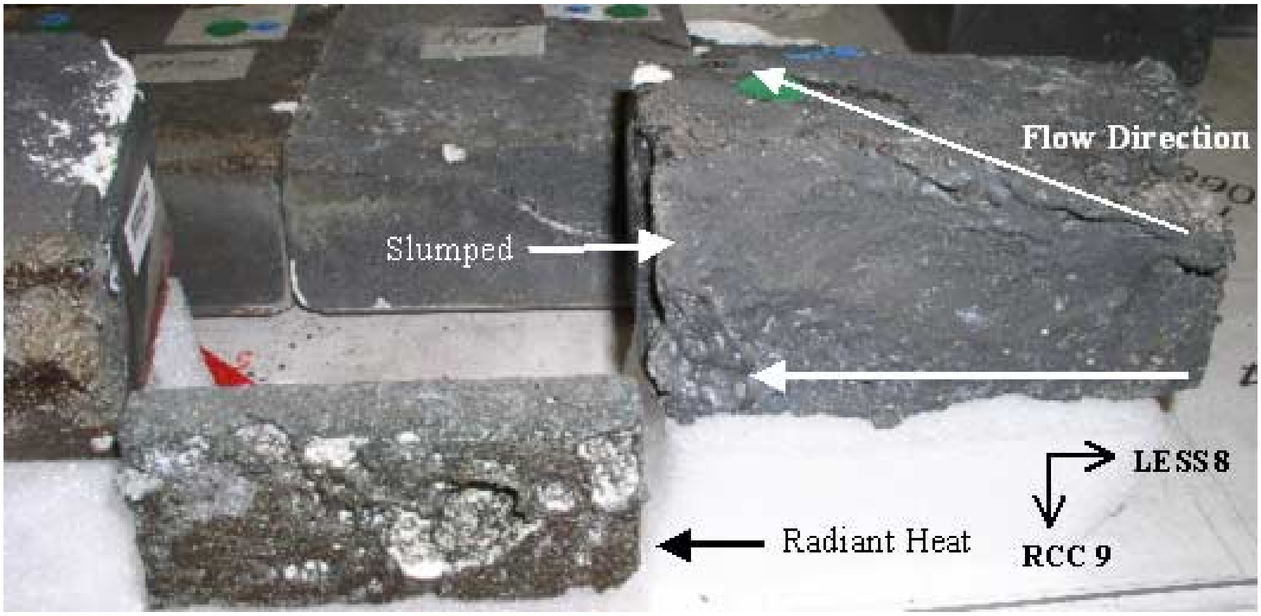
There are ten LESS access panels, five upper and five lower, per side in this region. The condition of the right hand panels is consistent with the panels in the other regions. Each lower access panel location for left hand and right hand side is represented either by tile, panel or combination of the two. Three right hand upper access panels are represented, of which panel 10 is facesheet only. The upper left hand transition area is void of access panels and tiles with the exception of the inboard interior tile for panel 8 (50336). The tile exhibits radiant heating and has deposits of Inconel, aluminum, carbon and Cerachrome.

There is no heat damage on any of the right hand panels. The only heat damage to the lower panels is to the tiles for left hand panel 9 (16692, 50338, 22571, 57754) on the surface adjacent to the RCC. Though the tiles exhibit severe heating, a portion of the aluminum access panel, as well as panel 8 and 10, survived with minimal heat effects.

Panel 8 - Lower Access Panel Tile

Panel 9 - Items 16692, 50338, 22571, 57754

Panel 10 - Lower Access Panel Tile



The slumping and erosion of the tiles for panel 9 originates in the inboard forward corner, which aligns directly with the design notch in the heel of RCC panel 8 as shown above.

There are ten spar fittings per side, five upper and five lower. Six of ten right hand fittings were recovered, upper 8, 9 and lower 8, 9, 10 and 11. The right hand fittings have minor splattering of metallic deposits. No left hand spar fittings were recovered for rib splice 8 through 10 and only portions of the fittings for rib splice 11 and upper 12 were recovered.

Nine of the ten spanner beams on the right hand side were recovered, six of which are complete assemblies. Only portions of three spanner beams were recovered for the left hand side, none in panels 8, 9 or 10. Spar-side thermal erosion occurred on several of the recovered spanner beams as shown below:

- Right hand 7 inboard & outboard (55085 & 32087)
- Right hand 8 outboard, two locations (66897)
- Left hand 7 inboard upper (83639)
- Left hand 11 inboard (70376)

The only insulation material found is a piece of Inconel foil for the outboard


Item 55085


Item 83639


Item 70376

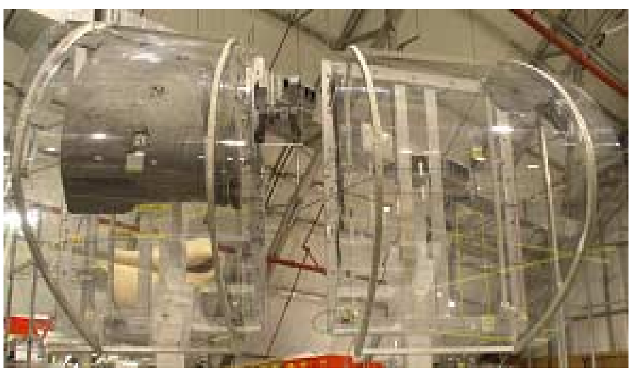
Left Hand RCC Panels 7, 8 & 9

spanner beam insulator on right hand panel 9. There wasn't any insulation recovered in the transition region for the left hand side.

There is significantly less RCC material and internal components on the left hand side than the right hand side, particularly in the transition region.

The lower acreage of left hand panels 8 and 9 are completely void of RCC material.

Per design there are twenty-four lug clevis fittings for panel and gap seals per side. Fifteen fittings are represented for



Left Hand RCC Panels 8 & 9

Right Hand RCC Panels 9 & 8

Left Hand RCC Panels 10 & 11

Right Hand RCC Panels 11 & 10

the right hand side and only eight fittings for left hand side, plus a bolt without clevis fittings for panel 10. The split bushing from the lug is fused to the bolt.

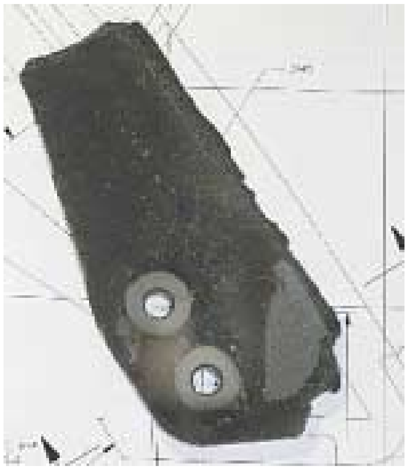
A failure unique to the left hand transition region is the absence of hardware for the upper lugs. All other location failures consisted of lug break up or clevis fitting to spar fitting overload. For the locations listed in the table to the right, the lugs were recovered with varying degrees of missing hardware.

The heaviest concentration of deposits for the left hand and right hand wings is on the internal surface of RCC panel 8. On the left hand side the heaviest concentration of deposits in this region is on panels 7, 8 and 9, with panel 8 being the most dense overall for both wings.

Deposit samples were analyzed to determine composition and the layering effect. The deposit layers indicate internal component melting timeline and can be used to determine the breakdown sequence of the leading edge. Deposits on all four panels consist of Inconel, Cerachrome and aluminum. Right hand panel 8 and left hand panels 7 and 9 have

Panel 8

Panel	Lug Location	Item	Hardware Condition
7	Outboard	26014	Missing all hardware, except split bushings
8	Inboard	17957	Partial clevis, split bushing, aft bushing, no bolts
8	Outboard	61143	Missing all hardware, slag deposits in holes
9	Inboard	N/A	Lug was not recovered
9	Outboard	29741	Missing all hardware, including gap seal hardware
10	Inboard	34713	Missing all hardware, except one bolt with split bushing



Item 26014

Deposits on Item 2200

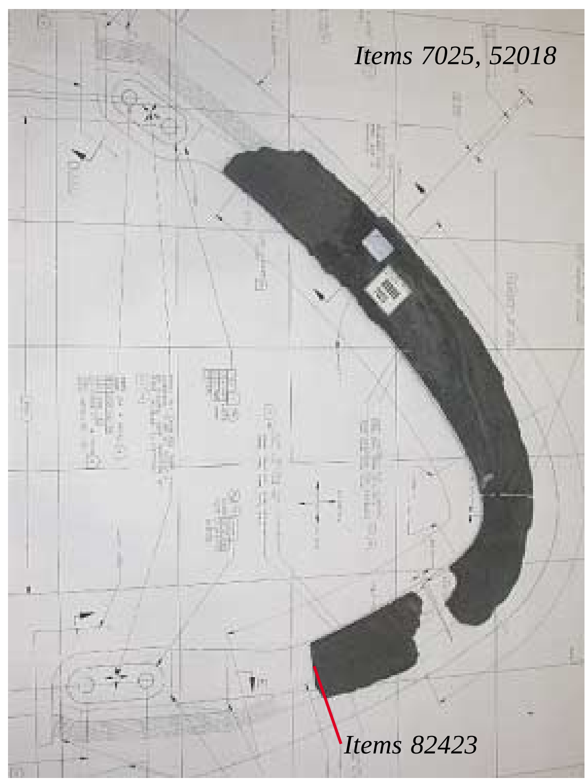
traces of aluminum on the initial deposit layers. There is no evidence of aluminum in the initial layer for left hand panel 8, with some aluminum deposits in the secondary layer and significant levels in the last deposit layer. Though not on the first layer, A286 deposits were found on left hand panel 9, however no A286 deposits were found in left hand panel 8.

No RCC erosion was found on the right hand wing. There is oxidation of RCC material on both wings. The outboard rib on right hand panel 8 has oxidation on the spar side of the panel (1419). The only erosion found on any of the RCC panels is the outboard rib and heel of left hand panel 8 and the inboard rib of left hand panel 9.

Item 82423, does not have sufficient geometry or remaining surfaces to

Item 1419

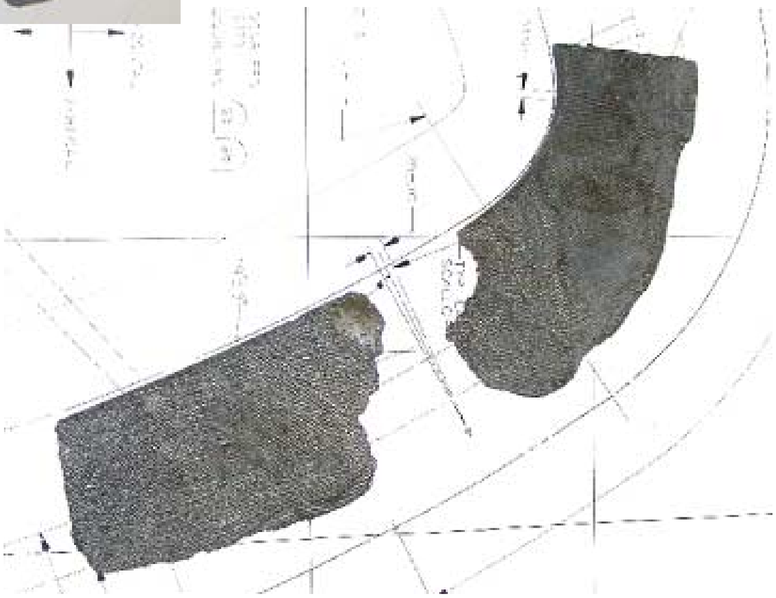
Panel 8



Panel 9

positively confirm its location. The piece of RCC rib has been located on panel 9 based on a fit that matches the drawing profile and erosion pattern. The erosion on 82423 is identical to the erosion on 52018. The edges of the piece have been eroded down to a knife edge.

The erosion is on the upstream side of the ribs, indicating a downstream flow direction. The rib on each piece is eroded down to a knife edge. The lug holes, to accommodate clevis attach fittings for panel 8, are oversized by means of erosion. The bolts and split bushings were not recovered.



There are two pieces of left hand lower gap seal (35201, 17943) that still need location confirmation. Comparing wear, deposits, near fracture match and upstream erosion the pieces appear to be related. The pieces dimensionally fits in several locations, most eliminated due to recovered items. The remaining locations

Items 17943, 35201

Items 1616, 5338

are rib splice 9 and 10. The best fit based on surroundings is rib splice 10. The erosion on the gap seal does not match the erosion on the ribs of the RCC panels at rib splice 9. The deposits on the seal pieces, does match the deposits on panel 11 at rib splice 10.

Right hand gap Seal 10 and panel 9 lower portion have tile material on the outer surfaces (1616, 5338) similar to gap seal 5 in the glove (64725) and 13 in the torque box (59454) regions.

Torque Box Region (Rib Splice 12-23)

The torque box region of the wing leading edge has less thermal damage than the other regions. There are eleven each upper and lower LESS access panels per side. Twenty-one of the twenty-two panels for the right hand side and eighteen of the left hand panels are represented. Left hand panel locations 16-22 are completely void of panels or are represented by a single tile or small piece of honeycomb. The right hand panels outboard of rib splice 17 have virtually no discernable heat damage.

There are twenty-two spar fittings in the torque box region per side. Seventeen (nine upper and eight lower) fittings were found for the right hand side. Eighteen (nine upper and nine lower) fittings for the left hand side were found. Compared to the glove and transition regions, larger pieces of aluminum wing spar were recovered in this region. On the left hand side metallic deposits are on the spar fittings (68) whereas on the right hand side the deposits are on the wing spar inner facesheet (59409, 9544). The silicone barrier on the outer facesheet of the right hand wing spar is free of metallic deposits and remains pliable.

Item 68 LH Spar Splice 15

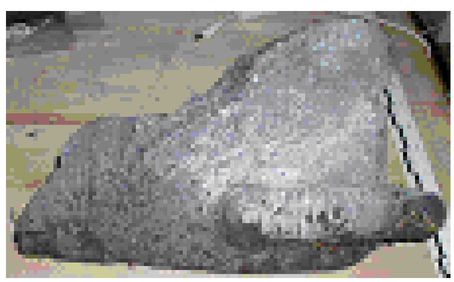
Items 59409, 9544 RH Spar Splice 22 & 23

Per design, there are sixteen spanner beams for panels 12 through 19. Panels 20, 21 and 22 do not have spanner beams. Thirteen of the sixteen beams for the right hand side have been recovered, with panel 13 inboard beam exhibiting spar-side thermal erosion (65539). Nine of sixteen beams (some partial) were recovered with some showing overload damage. The majority of the insulators found on the wing leading edge were in the torque box region, particularly on the right hand side. Right hand insulators found inboard of rib splice 17 experienced minor heating and aero damage, whereas insulators outboard have no heat damage and only ground impact damage.

Right hand gap Seal 13 lower portion has tile material on the outer surface of the seal (59454).

The RCC in the torque box regions do not exhibit any thermal erosion however do have some areas of oxidation as shown on left hand panel 21 (6024).

Item 59454



Item 6024

Aft Fuselage

The total percentage of the aft fuselage OML surface area recovered was approximately fifteen percent, with tile/tile fragments present only on the largest pieces. More right hand than left hand pieces were recovered. The skin pieces have fracture edges that are minimally affected by heat, except for the large ballistic coefficient items that have severe heat erosion. Many of the skin panels located in the aft fuselage were smaller and could not be specifically located within the grid. These items are waffle pattern aluminum structure with fracture edges all around and some light slag on the IML side. The largest items from the aft floor area were located fwd of Xo1365.

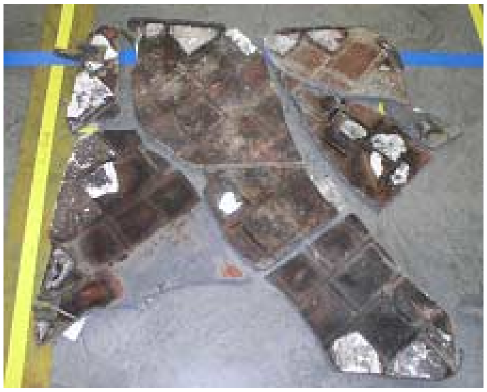
These items included the right hand and left hand ET door, two large skin pieces (35834, 76544) on each side of the vehicle centerline, and a portion of the lower Xo1307 bulkhead. The recovered pieces of structure on the left hand side have more heat related effects than those on the right hand side, except for the internal thrust structure items of high ballistic coefficient. Numerous tiles were identified as possible aft tiles; however, their final location was not determined due established priorities. The only tiles that were assessed were on the largest of the recovered pieces. The exposed filler bar/ remnants were more charred on the left hand recovered pieces than the right hand.

Item 35834

Item 76544

No flow directionality could be discerned from any of the assessed tile.

The right hand ET door (53830) is fully intact with fracture edges at each of the two hinge points. Approximately sixty percent of the tile is still bonded. The OML surface and the primer on the IML of the door is not discolored. In comparison, seventy-five percent of the left hand ET door was recovered, in seven pieces, and has only five percent of the tile fragments attached. Two large floor skin pieces recovered accounted for nearly the entire area between the left hand and right hand ET doors. The right hand piece (76544)



LH ET Door

Item 53830

1307 Bulkhead

Item 1181

Item 36055, 42928, 24846

included the aft ET door latch mechanism. The forward ET door latch mechanism was also recovered in a much smaller skin piece.

The large portion of the right hand Xo1307 bulkhead was recovered, which included wing-fuselage attach structure, mid-aft fuselage attach structure, a portion of the sidewall, a portion of the Xo1307 bulkhead, ET socket structure, and the LO2 blast can assembly attached with separation hardware contained within. This item has heavy slag deposits and heat effects on the aft facing surfaces. The forward facing surfaces were shadowed, evidenced by minimal slag deposits and no discolored primer.

The corresponding part on the left hand side is much smaller in size and consisted primarily of just the ET socket structure (31154) itself. The left hand item has extreme thermal erosion on all edges of the piece.

Two additional recovered primary structural items were the right hand (49596) and left hand structure (63994) surrounding the aft outboard corner of the ET door. The right hand piece has less overall heat effects than the corresponding left hand piece.

The titanium thrust box beam (2485) is an example of extreme heat exposure, characterized by splaying into a flat piece as compared to the intact titanium box beam (36072).

Four additional recovered pieces of primary structure each having heavy thermal erosion and melting on the edges are a thrust structure strut, beam, and strut attach points (36055, 42928, 1181, 24846).

The RH sidewall hoist point (49366) includes a portion of the mid-to-aft fuselage and attach fittings. This piece has heavy thermal erosion from the aft side evidenced by missing and melted collars

Item 49366

Item 63994

Item 31154

Item 2485

Item 49596

on the exposed fasteners.

The right hand OMS pod attach point 3 (41387), includes a piece of the OMS Pod structure and the aft fuselage OMS deck structure still clamped up by the attach bolt, nut and associated bushings.

Oribital Manuvering System Pods

The oribital manuvering system (OMS) pod structure is manufactured of graphite epoxy skin and Nomex core composite and skin/aluminum frame segments. The majority of recovered items, typically less than one square foot in size, have ply delaminations and fractures. The debris has evidence of mechanical overload as the primary failure mechanism. Heating plays an insignificant role in the component degradation and appears to be subsequent to or during the mechanical breakup. RTV adhesive applications (bondlines, conformal coating, etc.) do not show charring or loss of resilience on most items. No thermal erosion of aluminum fasteners was observed. The most significant component recovered is a composite skin segment from the left hand pod leading edge (1334). This skin segment has damage to the thermal protection system, consisting of tile slumping, debris peppering and metal deposits embedded in the tile.

Vertical Stabilizer and Rudder Speed Brakes

The estimated percentage of recovered vertical tail (including items known to be vertical tail but not specifically located with the tail grid) was 5 to 10% of the total surface/OML area.

Sixteen primary structural items recovered and assessed. The tile damage on the left hand is more prominent than the right hand side and includes both heat deformation and debris peppering.

Two leading edge items have sections of left hand and right hand outer skin, the tip cap (1633) and the leading edge forward cover (52092). The forward cover has a prominent flow pattern in the upward direction at an approximately 60 degrees from the leading edge spar plane. Items lower on the vertical stabilizer show more signs of heat damage than items that are higher and aft.

Two of the three

Item 1334

Item 52092

Item 1633


Item 2199


Item 56262

primary structural attach points between the vertical fin and the fuselage were recovered, the forward attach fitting (2199) and the right hand rear attach lugs with shear ties. The fractures occurred in the surrounding tail and fuselage structure and not with the primary attach bolts.

The items higher on the stabilizer have fracture surfaces that exhibit over load related failures. In contrast, the fracture surfaces of the items in the lower region have a broomstraw condition. The right hand rear attach lugs and shear ties (56262) have heat related failures on the IML side with buckling and broomstraw fracture surfaces.

Body Flap

Twenty to twenty-five percent of the body flap has been recovered including approximately three hundred tiles that have not been identified to their exact location. The item size ranges from less than one square foot to approximately fifteen square feet. The recovered items are primarily the right and left outboard aft corners and the trailing edge. The other identified structural components are predominantly aluminum honeycomb skin, ribs, rib caps, and spar segments. The structural items primarily have signs of mechanical fracture initiated by mechanical overload as the failure mechanism. There is no apparent difference in damage levels comparing left to right or upper to lower. Very few tile cavities show evidence of failure/loss due to backside heating. There is evidence of tile slumping on the left outboard aft corner (64059) and trailing edge wedge (85253). The slumping on the trailing edge wedge tile shows a flow direction that is almost perpendicular to the flight vector, running outboard to inboard and tile damage includes apparent particle impacts.


Item 64059


Item 85253

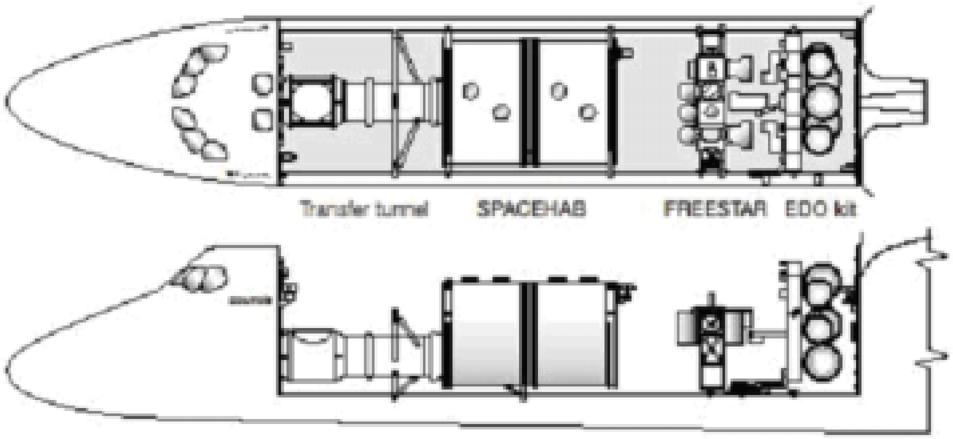
PAYLOADS

The following paragraphs provide a general summary of the payload configuration, and the general condition of what has been recovered/identified for each major element.

The STS-107 Mission payload hardware consisted of a forward extension, Spacehab tunnel, Spacehab Research Double Module (RDM), and Fast Reaction Experiments Enabling Science, Technology, Applications and Research (FREESTAR). The Spacehab tunnel consists of a core tunnel section, a 7.87-inch forward tunnel section, a flex section at each end, four supporting trunnions on strut support structures and a keel fitting mounted on an aft strut support structure. In addition to the subsystems, the Spacehab module manifested two large rack-based experiments (Vapor Condensation Distillation (VCD) and Combustion Module-2 (CM-2)) and a large stowage rack (MESS). It also housed a large contingent of middeck-style locker-based experiments on the forward and aft bulkheads. The FREESTAR payload carried several experiments in five various containers, most of which were Hitchhiker or Get-Away Special (GAS) cans.

There has been only one item identified from the forward extension. It was an interior panel of the plenum box assembly that had ECS duct openings and a location for a tunnel light switch. The panel was torn away from the element during breakup and appears to have been exposed to very minor heating.

Several items have been identified from the tunnel assembly. The 7.87-inch forward tunnel section was identified nearly intact with the forward trunnion strut attach points and two partial struts attached. The ring for the forward flex section is attached but the rubber portion is burned adjacent to the ring and the opposite ring is missing. The portion of the tunnel that connected to the aft of this section appears to be melted and has fracture surfaces. The rear strut attach ring of the tunnel was recovered with two partial strut sections attached. The upper strut attach bracket is torn from this flange leaving an incomplete ring. Another flex section ring with a partial thermally degraded assembly was recovered but not positively identified as the remnants of the forward or aft flex section. One complete adjustable strut and several partial sections of struts have been recovered, as well as four trunnion assemblies and the keel assembly, each with partial struts attached. All of the tunnel assembly items recovered appear to have been exposed to extreme temperatures and heating effects.



(Note: the above picture is missing tunnel forward trunnions)

On the Spacehab RDM, only sections of the heavier bulkhead and intermediate adapter flanges have been recovered with one to two inches of thermally eroded skin attached. A total of three trunnions have been recovered, one of them mounted to a long tie-beam. Two of the trunnion assemblies were twisted from the shell and their support structure appears to have been exposed to high temperatures. In most cases the titanium parts survived intact, minus any chrome plating as applicable. Both view ports (one from each module) have been recovered nearly intact and again one to two inches of thermally eroded skin is attached.

Three partial connector bracket feedthroughs and a vent valve assembly feed-through have also been recovered and experienced multiple fractures.

The items inside the RDM were of a much lighter construction than the external structure with a few exceptions (CM-2 structure, MESS rack, etc.). Most of the hardware is broken apart, almost to the component level. Items have thermal damage ranging from severely eroded to only lightly degraded.

The MESS rack was heavy in its construction and a large percentage was recovered with minimal thermal damage. The Structure of Flame Balls at Low Lewis-Number (SOFBALL) experiment module (EMS) was recovered nearly together (received in a box with one tracking number) and have significant evidence of burning or heat exposure. Only a portion of the Laminar Soot Processes (LSP) EMS was recovered and it has impact damage as well as severe thermal damage. Very little has been identified from the Mist EMS with the only significant item being the gate valve assembly.

From the CM-2, only 40% of the fluid/gas supply single rack has been recovered. None of the recovered plumbing or valves or gas bottle support structures have been positively identified. From the Experiment Package, the front and rear end caps of the combustion module were recovered as well as the instrumentation ring. The front cap has severe thermal erosion with a large hole in the center while the other two items are intact with minor thermal damage. Most of the other components identified from this rack saw a significant amount of heat, are severely eroded and had slag deposited on them.

Only the major sub-components of the VCD rack experiment were recovered including the Distillation Assembly, Pressure Control and Pump Assembly (PCPA), and Fluid Control and Pump Assembly (FCPA). The VCD components predominately show structural impact damage.

The state of most of the smaller, lightweight items that were stowed inside the Spacehab module ranges from burned and melted to near pristine condition. Items in stowage that were protected by several layers of containment have minimal damage. The majority of the items show moderate to extreme evidence of heat exposure. Smaller metal items like the test tube racks are slightly bent or broken.

Some payload items that flew stowed in the middeck of the Orbiter were recovered in better condition than the items in the mid body. Twelve of the fourteen canisters from the Biological Research in Canisters (BRIC) experiment, the entire double drawer Experiment Insert assembly from Biopack, and several Zeolite Crystal Growth (ZCG) autoclave examples, most with very little damage were recovered.

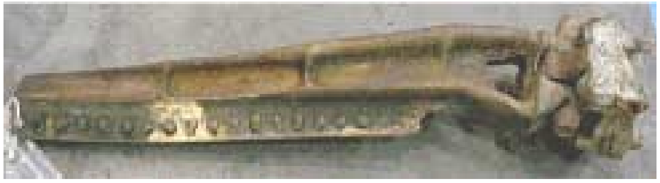
Very little of the MPESS structure or the MPE support equipment for FREESTAR was recovered. Three diagonal brace interface points and some splice plate sections have been found but none of the tube structures. For the MPE, three of the dogbone structures and some of their single bay pallet plate has been identified along with the avionics mounting plate from which the cover and components are missing. Only one trunnion and support block has been recovered/identified. The five canisters each had an upper and lower end plate and four each of these have been recovered along with sections of the middle shelves and the structural ribs around the can. The critical viscosity of xenon (CVX-2) avionics package canister was recovered without its protective shell and one end plate but a great deal of internal components remained including the internal shelf mounts. The electronics have heavy thermal damage. All of the recovered mechanisms and electronics were unidentifiable.

CREW MODULE

General Observations - Approximately 45% of the original crew module mass was recovered. Some major structural elements recovered, included portions of the forward and aft crew module bulkheads, window frames, mid-deck floor components, airlock and hatches. About 70% of the flight-deck panels, and 80% of the mid-deck floor were recovered. Less than 20% of locker metal structure and fragments of the plastic and composite material of the locker trays were recovered. The mid-deck Access Rack (MAR) was found nearly intact. Although some foam, fabric and paper were recovered, the bulk of the items recovered consisted of metal, plastic and composite materials. It is estimated that less than 30 % of items stowed in the lockers were recovered. The EVA tool and suit debris (stowed mostly in the airlock for entry) were weighed, with 40% of the original mass was recovered.

The condition of the recovered debris items varied widely; from highly melted, twisted and torn, to near pristine. Overall, the damage distribution of crew module debris is consistent with surrounding debris from the forward fuselage structure. Debris recovered from the crew module experienced noticeably less aerodynamic heating than other portions of the vehicle. Heating was sufficient to burn away nearly all exposed thin sections of the exterior pressure shell (including bulkhead areas), and exposed thin section areas of internal components. Although some recovered debris has significant thermal damage, evaluation of heat patterns do not suggest any evidence that an internal cabin fire occurred before vehicle break-up. Primary and secondary structure elements suggest that structural failures occurred at high temperatures evidenced by broomstraw fractures.

Item 1765



Item 1678

Five major attach points that suspend the crew module inside the forward fuselage were recovered, port & starboard crew module to fuselage side fittings, double strut Y-link attaching the lower center Xo576 bulkhead to the Xo582 frame, and the single Z-link attaching the Xo378 bulkhead to the Xcm200 bulkhead.

Both the port and starboard side fittings were recovered with evidence of high heating. Each fitting exhibited failures at both its crew module interface and Xo582 frame interface. The crew module interface failed at the longeron tab on both the port and starboard sides. On the Xo582 frame interface, the starboard side (1765) experienced a lug tensile failure while the port side (1678) fittings pulled through the Xo582 frame.

Both the port and starboard side struts of the Y-linkage failed in tension at the clevis end fittings. The port side failed in proximity to the Xo582 ring frame, the starboard side in proximity to the Xo576 bulkhead.

The Z-link failed at the attach point to the Xcm200 bulkhead. The joint failed by a combination of both fastener tensile failure and fastener insert pullout.

Item 54057

Electrical Power Distribution and Instrumentation

The electrical and avionics debris items have varying levels of damage. For example, general purpose computer 3 (GPC 3) was badly dented, missing its front panel, and two internal cards but was otherwise intact. The Orbiter experiment (OEX) recorder (54057) has damage, but data could be extracted from the tape. Most of the recovered line replacement units (LRU) were pieces that had to be identified from either coldplate numbers or from pictures of internal components supplied by various sources including NASA space logistics depot (NSLD) and NASA.

LRU's that were easily identifiable from connector layout or part numbers were limited to the following:

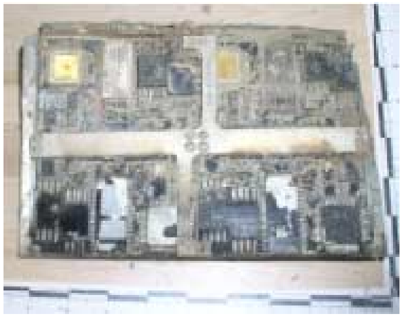
- Multiplexer demultiplexer payload forward 2 (MDM PF2)
- GPC3
- Electronic assembly-1 (EA-1), EA-2 and signal processing assembly (SPA) from the KU-band system
- Heads up display electronics (HUDE) 1 and 2
- Caution and Warning Unit
- Measurement and Acquisition Data System (MADS), Pulse Code Multiplexer (PCM) and Frequency Division Multiplexer (FDM)

Most of the circuit cards (44309) were damaged from exposure to excessive heat. This damage was evident by missing solder traces, loose components normally held in by solder, missing components. In the most extreme cases the boards appeared to have been heated so much that the resin holding the fibers together, have burned away leaving charred, frayed material. Many of the circuit cards were also broken and only pieces remained.

Only a very small fraction of the wire connectors and coaxial cables were recovered.

The LRUs in the aft avionics bays appear to have suffered from more heat and damage than those in the forward. No LRUs were recovered intact, and the cards from the advanced master event controllers (AMECs) (15132), aero-surface amplifiers (ASAs), ascent thrust vector control (ATVC) controllers, and cryogenic controllers were badly damaged. Identifiable LRUs were recovered, but in all cases they were missing their external skins and were identified by internal components.

The recovered LRU cases were heated to temperatures high enough to cause the aluminum to melt. Most part number, serial number, decals and other identifying markings on circuit cards were damaged or destroyed by exposure to high heat.



Item 44309

Item 15132

Flight Controls and Hydraulics Systems

Flight Controls and Hydraulics Systems - Less than one third of the space shuttle flight controls system was identified as part of the recovered hardware. Two of the four elevon actuators, two of the six engine thrust vector control (TVC) actuators, one of the four body flap rotary actuators, and none of the rudder speed brake rotary actuators were recovered. Some gears and housing pieces of the rudder speed brake and body flap power drive units were recovered. Other than one hydraulic circulation pump, the only hydraulic system pieces recovered were from the aft and had been attached to the Xo1307 bulkhead. Many other line replaceable unit (LRU) parts such as electronic boxes and miscellaneous tubes could not be identified without destructive testing. Fluid lines, wiring, LRUs (electronic boxes) and most of the actuators are among many items missing or destroyed. Only one LRU reaction jet driver forward (RJDF) was recovered mostly intact. Most of the cold plates, which have pieces of the LRU's structural housing attached, and some LRU cards could be identified.

Pieces with high ballistic coefficients represent most of the recovered items. Small items such as valves or thin hydraulic tubing were most likely ablated or not recovered. As a result of its relatively low melting point, very few aluminum components were recovered but the titanium or stainless portions of some those items remained.

The largest pieces recovered from the flight controls system were two main engine TVC actuators, the right outboard elevon actuator (36076), and left inboard elevon actuator (7327).

Most items exhibit damage from mechanical overload, thermal erosion, and ground impact except for the left inboard elevon actuator and some hydraulic fittings. These have slag from other areas caused by plasma flow.

Item 36076

The majority of the remaining items were pieces of pumps, tubes, flex-hoses, electronic components, reservoirs, and water spray boiler parts. In general, most of the flight controls and hydraulics system hardware is charred and muddy. Very little hydraulic fluid was found except within the actuators themselves. All three SSME hydraulic accumulators were recovered in good condition. The only non-SSME hydraulic accumilator that was recovered still contained 1700 psi gaseous nitrogen (GN2). Two water spray boiler GN2 tanks were found undamaged and intact.

Item 7327

Forward fuselage flight control components such as the star tracker and both air data probes along with a number of LRUs appear to have less damage than similar hardware from other areas.

Landing Gear Systems

General Observations - The left MLG assembly (tires and gear structure) has significantly more thermal damage than the nose gear and right main gear assemblies. More of the nose landing gear (NLG) hardware was recovered than either the left hand or right hand MLG.

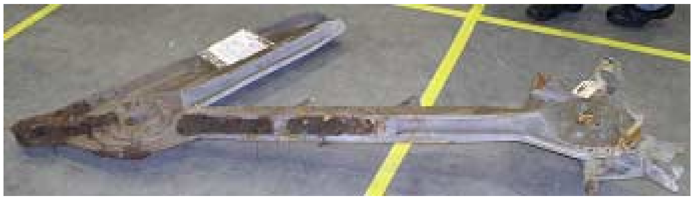
Overall, the nose landing gear hardware is in better condition than the MLG hardware. Only some of the items with high ballistic coefficients have significant heat damage. The gear itself

NLG

Left MLG

Right MLG

Item 9226



Item 565

Item 2187

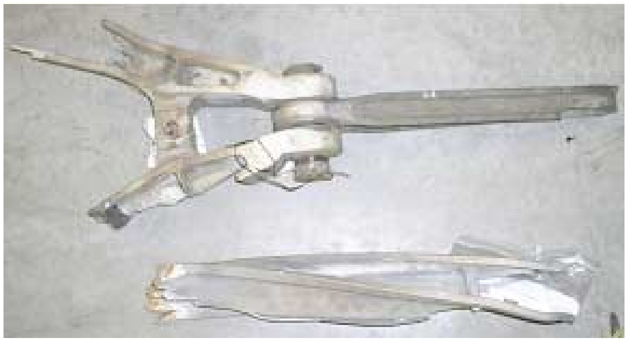
(9226) is intact to the point that hydraulic fluid was present and GN2 was almost at flight pressure after recovery. The nose wheel steering actuator has some heat damage. The left hand (aluminum) trunnion is still attached to the gear and the visible support ribs have high temperature web fractures. Both deflated tires are intact and attached to the wheels, which remain on the axle. The left hand wheel is intact and the right hand wheel is mostly intact, however, the inboard bead had broken free. Half of the fracture bead was recovered. The retract link tang is attached to the strut with about three inches of the link remaining.

The three remaining trunnions (565 and 2187) were recovered as two debris pieces. The main ribs between the trunnions are mostly intact and the webbing on the ribs shows a combination of heat effects and overload failures. Half of the door uplock cam assembly (1803) was recovered as well as several hinges

Item 1803

Item 561

Item 2540/2218



for the doors. Only minimal evidence of thermal exposure is present. A large portion of the upper and lower drag brace assembly (2540 and 2218) was recovered. Both parts have broomstrawing and overload failures.

Several pieces of the wheel well box structure were recovered and only superficial heat discoloration of the koropon is present. Parts of the uplock assembly were attached to these box parts and predominantly show evidence of overload failure. An example is item 561.

With the exception of the upper cylinder and the lower piston, only a small percentage of the left hand MLG was recovered. Most of the hardware shows signs of high temperature exposure. The lower piston assembly (1257) exhibited melting and thermal damage on the lower end. The outboard axle threads are gone with melted surfaces where they begin on the axle. There are burn through areas just aft of the jack pad and at the lower scissors mount. Both ends of the scissors mounting pin are melted. More than 95% of the bronze/aluminum portion of the upper end of the piston is missing. Sawtooth fractures and melting are visible. The piston barrel is in relatively good condition. The forward side of the piston barrel has much less chrome damage and less evidence of melting (bronze/aluminum material) than the aft side.

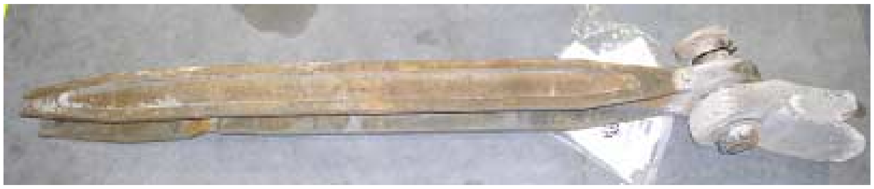
On the upper cylinder (12697), the gland nut threads are melted for two-thirds of the circumference and the uplock lug is melted away. The lower lug of the downlock link is attached and melted. One leg of the clevis is more than 80% melted away. The upper portion of the cylinder has extensive melting and distortion. The upper scissors pin and fitting are intact. The aft side of the upper cylinder is in better condition than the forward side, which shows more chrome damage and more overall heat damage.

Item 1257

Item 12697

The lower drag/lock brace (24823) has minimal thermal damage. The upper pin and outboard mating clevis are still attached. The attached clevis piece, and the adjacent clevis piece (81992) recovered separately, are both thermally damaged. These two are the only aluminum parts recovered for the left hand MLG that is not protected by other hardware during flight. The lower end of the brace demonstrates a typical over-stress condition.

Several brake assembly rotor and stator components were recovered with



Item 24823

conditions ranging from intact to fractured small pieces. The left hand outboard brake body (1805) was recovered and has extensive thermal damaged.

The tires were recovered separated from any other structure. The left hand outboard tire (197 and 210) is split into two pieces around the circumference and directed heat is evident on the inboard side of the tire. The inboard tire (2168 most probable location) is in good condition with only minor thermal damage to the entire outer surface and a split in the body.

Very little of the right hand MLG was recovered, in stark contrast to the recovery of almost the entire right hand MLG door, mostly intact. The tires were recovered separate from any other structure. Both tires are in good condition with only minor thermal damage to the entire outer surface and are in very similar condition to the inboard tire on the left hand side. The right hand outboard tire (31168 most probable location) does have a circumferential split in the body, while the inboard tire (71814) has no splits. Several brake rotor and stator parts have been recovered along with the upstop pad (8559), the down lock spring bungee housing (16548), and the uplock mechanism drive shaft (41425). This hardware has minimal thermal damage.

The right hand outboard wheel (567) has a melted fracture surface on the inboard side of the wheel and the center portion of the wheel is missing.

The gear retract actuator (27323) is intact and is attached to the upper portion of the landing gear. The gear portion has evidence of high temperature exposure. The down lock brace clevis fitting (45724) that attaches to the upper cylinder was

Item 1805

Item 197

Item 210

Item 2168

Item 567

Item 84265

Item 27323

also recovered with similar thermal damage.

The MLG door retract actuator beam (84265) has some thermal damage as well, however, it is also mostly intact.

Life Support Systems

Environmental Control and Life Support System (ECLSS) – Multiple components of the ECLSS were recovered and identified from the forward, midbody, and aft areas. All items have been exposed to thermal degradation with the majority items identified to the crew module.

In the forward section, the stainless steel cold plates from the water cooling loops, both humidity separators (53764), the avionics bay heat exchangers, the cooling air ducts and miscellaneous water cooling lines were identified. The humidity separators survived with the foam insulation intact, which helped in differentiating them from the SpaceHab humidity separators, which do not have the same foam insulation. Twenty percent of the ECL items had sections of part numbers remaining, but drawing dimensions and/or bolt patterns were used to identify most items. All three fire bottle Halon containers were identified.

In the midbody, items recovered include Freon cooling loop hardware, aluminum cold plates (6800), accumulator parts (2029), and some cooling lines. The Orbiter has five gaseous nitrogen (GN2) tanks, all of which were recovered and identified. Most of the stainless steel vacuum vent and radiator Freon cooling lines were identified.

In the aft, aluminum cold plates were identified either in pieces or in conjunction with avionics boxes. Most of the flash evaporator system was not found. Ammonia tank B was found intact but thermal erosion had removed the insulating paint. Most of the titanium ammonia tank A was recovered as three large items.

Item 53764

Item 6800

Item 2029

Purge, Vent and Drain (PVD) - system employs ducts that are made of composite material, which is susceptible to damage from off-nominal loading. Most duct debris recovered are end pieces or short fragments. A barrier check valve assembly from the area near the crew hatch, assorted tubing from the window cavity conditioning system, the star tracker vent screen, and payload bay vent liner filter frames were also identified.

Item 751

Item 84241

Item 585

Item 74844

Mechanical Systems

The condition of the recovered mechanical system components varied both with respect to the quantity of items per system as well as the degree of degradation. For example, except for the semi-circular housing cover missing from the left hand air data probe (ADP), both the left hand and right hand ADP's were recovered intact, with little significant physical or thermal damage. Likewise, the NLG strut, it's associated axle, and both nose wheel assemblies (NWAs) were recovered as a complete assembly with some physical damage but relatively minor thermal damage. In contrast, nothing has yet been recovered from the -Z star tracker door mechanism.

ADP -Both right hand and left hand ADP's (751) were recovered with little damage except for missing cover on left hand side.

Star Tracker: The -Y star tracker door was recovered with minor physical and thermal damage. Nothing was recovered from the -Z star tracker door.

PLBD - Several bulkhead rollers were recovered such as right hand forward #1, right hand aft #2 and #3 and left hand aft #4. Also recovered were a rotary actuator, one of twelve PLBD drive bellcranks (814), and the right hand forward #2 bulkhead latch bellcrank.

Manipulator Positioning Mechanism (MPM) - An extensive portion of the port sill containing the forward pedestal base and section of the drive shaft was recovered, along with the mid MPM pedestal base, the MPM shoulder base assembly, and the MPM shoulder drive mechanism.

Item 38913

Radiators - Six outboard radiator latch assemblies (428), two inboard radiator latch assemblies, three radiator latch rotary actuators, and one radiator drive rotary actuator were recovered.

ET Doors - The right hand ET door was recovered as a unit (84241). Eight sections representing about 85% of the left hand ET door was also recovered, as were the forward and aft ET door centerline latch mechanisms, and portions of the left hand ET door drive assembly and right hand ET door drive assembly (59003).

Hatches - Hatch interface collars for the A and B hatch (no hatch flown at this location), tunnel adapter C hatch, and tunnel adapter D hatch were all recovered. A hatch (585) was recovered as a unit with some burn through, but all six latches and bellcranks were attached. D hatch (74844) was recovered also, with burn through, and all seventeen latches and most of the drive linkage were intact. Fifteen of eighteen internal/external hatch latches were recovered; latches 1 through 6 and 16 through 18, latches 11 and 12, latches 8 and 9, latch 10, and latch 13. Five latch sections of C hatch were also recovered.

Orbiter Maneuvering Reaction Control and Auxiliary Power Unit Systems

The OMS/reaction control system (RCS) components were damaged more severely than those of the FRCS module. Seventy-five percent of the FRCS internal components were recovered, while 60% of the left pod internal components and 40% of the right pod internal components were recovered. Forty percent of the APU system has been recovered.

OMS/RCS - A significant percentage of FRCS internal components are intact, including the fuel and oxidizer helium tanks, the fuel and oxidizer propellant tanks, all primary thrusters, and both vernier thrusters. Seventy-five percent of the A/C motor valves, various sizes and lengths of stainless steal tubing runs, and several area heater panels were identified. The FRCS components, though damaged, were easily identified. The entire right side of the module was intact with thrusters installed (792).

Recovered aft pod internal components:

- Both OMS helium tanks (38913), intact
- All four RCS helium tanks, intact
- 90% of the left OMS fuel propellant tank
- 5% of the right OMS fuel propellant tank
- 10% of the left OMS oxidizer propellant tank
- 90% of the right OMS oxidizer propellant tank
- 33% of the left RCS fuel propellant tank
- Right RCS fuel propellant tank (53835), intact
- Left RCS oxidizer propellant tank, intact

A significant number of aft pod thrusters were recovered. However, most have no unique characteristics due to heavy thermal erosion and therefore have not been identified to an exact location. Several A/C motor valves and tubing runs were identified, but were too badly damaged to verify the exact location. Very little of the Orbiter maneuvering engine (OME) components were recovered. Two of the items recovered are the right OMS pneumatic pack and the right OMS engine chamber.

Auxilary power unit (APU) – The APU propellant/GN2 tanks from systems 1, 2, and 3 (59623) were recovered. The tanks have moderate damage and all of the diaphragms are torn or detached from their mounting surfaces. One system 3 pump and another undetermined fuel pump were recovered. One APU catch bottle was recovered, while none of the APU assemblies themselves were recovered. A small piece of lubricant oil line tubing with a transducer attached was the only other recovered APU system component.

Item 53835

Payload Mechanical System

Major components - Nine of the ten titanium longeron bridges (266) have been recovered and identified. Damage ranges from mechanical overload fractures, melted holes penetrating thinner flange areas, mounting hole galling, slag, and thermal damage. No damage trends are evident based on the location of this hardware in Orbiter. Eleven of the fourteen sill latches have been recovered, and have heavy damage similar to the longeron bridges. Two of the missing sill latches are secondary latches, and the third missing sill latch is part of the missing longeron bridge. All four of the keel bridges have been recovered, but only three of the keel latches were returned. The missing keel latch is torn off of the bay 3 keel latch.

EVA components - Due to their aluminum or composite construction, and

Item 266

Item 76452

Item 59623

Item 264

the heat encountered, very little of the Orbiter EVA handholds survived, although many smaller handhold support fittings and linkages were found and identified. None of the slidewire linkage structure was recovered. Several port stowage assembly (PSA) tools were recovered. None of the four payload bay cameras were found, and only one camera shelf structure was recovered. Two camera lenses were found.

Payload components - The only recovered sections of the tunnel adapter (264) and forward extension were the main structural rings and small sections of interior panels. The rings are distorted, have slag, and show heavy melting from exposure to intense heat.

Power Reactant Supply and Distribution and Fuel Cells Systems

PRSD System - A hydrogen (H2) T-0 valve and a fuel cell 1 (FC1) reactant valve (16130) were identified, both of which came from H2 manifold 2. The left hand fuel cell oxygen (O2) purge port was identified. Power reactant supply and distribution (PRSD) hydrogen relief 2 port was identified. The PRSD servicing panel (74847) behind door 45 was recovered. A few sections of PRSD plumbing remnants were identified through part marking or unique line insulation. Four Belleville washers, from two O2 tank relief valves, were identified and have minor damage (internal to the relief valve).

PRSD Tanks - All nine PRSD and external duration Orbiter (EDO) tank sets (each containing one O2 and one H2 tank) were recovered except H2 tanks 1 and 4. Tank pressure vessels were recovered with various degrees of damage, some intact and some as fragments. All tanks lost their outer aluminum shell. Many sections of the outer shell trunnion support rings were recovered and were severely degraded.

Several tank quantity probes and heater assemblies were identified. Several tank vacuum-ion pump converters (10257) were recovered, and some of them have thermal damage. The outer metal shell is removed from some of the recovered vacuum-ion pump converters exposing the internal components. One vacuum-ion pump (69490) was recovered with an intact magnet and exposed internal portion of the cathode.

The following is a summary of PRSD tanks recovered:

- O2 tank 1, (1575)
- O2 tank 2, (41040)
- O2 tank 3, (36989)
- O2 tank 4
- O2 tank 5, (2087)
- O2 tank 6 (EDO), (67814)
- O2 tank 7 (EDO), (1122)
- O2 tank 8 (EDO), (43558)
- O2 tank 9 (EDO), (24316)
- H2 tank 2, (1194)

Item 16130

Item 69490

Item 10257

Item 1122

Item 52023

Item 12055

Item 8767

- H2 tank 3, (9279)
- H2 tank 5, (217)
- H2 tank 6 (EDO), (206)
- H2 tank 7 (EDO), (219)
- H2 tank 8 (EDO), (214)
- H2 tank 9 (EDO), (209)

EDO Pallet - All of the PRSD tanks which were mounted to the EDO pallet were recovered and are listed above. The only identified pallet structural components are the port longeron and support, the keel trunnion, and the payload keel. Some of the unidentified plumbing may be from the EDO pallet. A recovered bus current sensor, which was not identified to an exact location, may have also been from the pallet.

Potable & Waste Water Components - Portions of the potable water tanks (52023) and the waste tank (12055) were recovered. Some tank outer skin sections were also recovered. The internal bellows were separated from the outer vessel container. One supply water valve was found but was not identified to an exact location. The waste dump nozzle (8118) was recovered with part of the skin panel.

Fuel Cells - Fuel cell (FC) components were recovered with varying thermal damage. Approximately twenty of 288 internal cell reactant plates (8767) were identified and traced to their original FC. Several plates are nearly intact. Hundreds of small pieces of cell plates were also recovered but could not be identified.

Two hydrogen separator pumps were recovered. The FC1 pump is still attached to the hydrogen condenser housing. All three cell end plates, all three coolant accumulators, and one coolant filter were recovered.

Space Shuttle Main Engines and Main Propulsion Systems

Ten percent of the main propulsion system (MPS) was recovered. The MPS hardware exhibits common characteristics. Items with high ballistic coefficients were able to survive. Also, titanium tanks, which were covered with epoxy-impregnated Kevlar-49 fiber strands, were able to withstand the high temperatures and the off-nominal dynamic forces.

MPS components - The helium supply tanks (49386), which are made from two, forged hemispheres of titanium 6AL-4V alloy and covered with epoxy-impregnated Kevlar-49 fiber strands remained fully intact. The three 17.3 cubic feet and seven 4.7 cubic feet helium supply tanks were recovered and

Item 214

Item 49386

Item 56643

Item 16931

are charred and unraveled. No MPS valves, neither mono-stable nor bi-stable were recovered intact. All four of the fill and drain valve actuators, less the gear racks, were recovered, with the two LO2 valve (16931) visor blades still being attached to the actuators. Prevalve (56643) pieces were limited to housing flanges, anti-slam mechanisms, detent rollers/covers/belleville washers, visor/shaft assemblies, and actuator clutch/bearing assemblies. Mono-stable valve actuator internals such as pinion gears and gear racks along with housing flanges were recovered.

The Orbiter-to-external tank 17-inch disconnect housings (22229) were both recovered, but the associated ancillary tubing, drive arms, flapper valves, and latches are either missing or in various stages of thermal degradation. LH2 4-inch recirculation return system and gaseous oxygen/ gaseous hydrogen (GO2/GH2) 2-inch pressurization disconnect primary and secondary belleville springs along with the 4-inch belleville spring retainer were recovered. Also recovered were one partial 8-inch fill and drain line T-0 disconnect and one 1½-inch liquid oxygen (LO2) bleed T-0 quick disconnects. Small segments of the engine mounted heat shield (EMHS) were recovered ranging from complete cross sections with clips and doubler plates attached to just the inner or outer Inconel 625 sheeting.

Other miscellaneous components identified by MPS are:

- Partial vibration isolators
- Recirculation pump cover plates, rotor, stator, and inducer
- GH2 filter assembly and element (7010)
- LO2 engine cut-off sensor MT2
- LH2 flame arrestor
- 1-inch relief valve SOV bellows/poppet assembly
- Curtain attach plate segments and retainer brackets

Absent from the MPS recovered valves were pneumatic system solenoid valves, check valves, relief mechanisms, and GO2/GH2 Flow Control Valves.

Item 7010

Item 22229

MPS Pressure Carriers - Less than 5% of the MPS system lines/tubing was/were recovered. None of the propellant system vacuum jacketed lines were recovered intact. Small segments of Inconel internal pressure carrier lines and multiple pieces of bellows convolutes (75590) were recovered along with the more robust line flanges, ball strut tie rod assembly (BSTRA) joints and gimbal/gimbar joints. Four LH2 12-inch engine feedline, two LO2 12-inch engine feedline, and two LO2 17-inch BSTRA (1540) joints were recovered.

In addition, three 12-inch feedline gimbal rings (19520) were located and identified. Some of the vacuum jacketed line structural annulus stiffeners, standoff rings, burst disc assemblies, test ports and spacers were also recovered. The small, uninsulated tubing was generally charred beyond recognition and could not, in most cases, be specifically linked to a certain system. A small percentage of MPS pneumatic and GO2/GH2 pressurization tubing was identified by specific fittings, bend configuration, brazes and/or welds.

Item 1540

Item 19520

CONCLUSION

The Columbia search, recovery and reconstruction effort provided evidence critical to the Columbia accident investigation to develop the most probable failure scenario. In general, most recovered debris exhibits a combination of thermal damage and mechanical overload failure. Items with high ballistic coefficients show much greater levels of ablation, while others failed as the result of aerodynamic forces or ground impact. Specifically, the condition of the left hand wing leading edge provides compelling evidence of an initial breach in the transition region that resulted in catastrophic damage.

The transition region of the left hand wing leading edge from RCC panel 7 through panel 11 has unique characteristics compared to the rest of the wing. The upper access panels for RCC panel 8 through panel 11 were not recovered, with the exception of one inboard/interior tile of access panel 8. From the inboard lower rib on panel 8 through panel 10, the absence of all metal hardware (spanner beams, spar fittings, clevis fittings and insulators), with the exception of a single clevis-mounting bolt, suggests that this region experienced temperatures high enough to melt the structural members.

Panel 8 has the heaviest concentration of deposits, followed by panels 7 and 9. The forensic analysis of the deposits on RCC hardware in this area provides key sequencing data. All three panel locations have aluminum, Inconel and Cerachrome deposits. The initial layers of deposits on the interior surface of RCC panels 7 and 9 have aluminum. Panel 8 is free of aluminum deposits in the initial layer, which indicates the spanner beams and insulators melted prior to the wing spar.

The panel 8 outboard rib and panel 9 inboard rib are the only positively identified pieces to have thermal erosion. This erosion is in the downstream direction. Arc jet testing at Johnson Space Center demonstrated that prolonged exposure to plasma is required to obtain thermal erosion of RCC. All the lower access panel 9 tiles have erosion, with the upstream tiles having the most damage. Lower access panel 8 tiles are not eroded.

The missing hardware, analysis of the deposits, damage to the access panel tiles and the directional erosion on the rib pieces bound the breach to panel 8. None of the lower acreage of panel 8 was recovered. The upper portion was recovered and does not have a penetration point, therefore, the initial breach occurred in the lower portion of left hand RCC panel 8.

The condition of the left hand wing hardware strongly indicates it was exposed to initial heating caused by the breach in the wing leading edge. The erosion pattern on the left hand MLGD perimeter indicates off-nominal port to starboard aerothermal flow. In contrast to the right hand wing, a small percentage of the left hand wing debris was recovered and is dimensionally smaller with greater thermal degradation. Aerodynamic failures were predominant on the right hand wing, as indicated by the condition of the fracture surfaces. In addition, the inner surface of the right hand wing skin has inboard to outboard flow, as evident by erosion of the interior rib surfaces and the evaluation of deposits on the wing leading edge. The leading edge spar pieces have deposit build-up on the inner surface of the spar (wing side) but not the outer surface (RCC side). Forensic analysis detected aluminum in the first layer of slag sampled from the right hand wing RCC panel 8, indicating that melting of the spar occurred concurrent with the melting of the leading edge components.

The elevons and body flap are comprised mostly of honeycomb sandwich panel assemblies that are susceptible to failures due to thermal exposure. The larger recovered body flap items were along the outboard and trailing edges. Slumped tiles on the body flap trailing edge indicates flow in the port to starboard direction. The elevon debris was recovered with a bias to the port side with minimal thermal degradation.

Tile damage to the outboard forward corner of the left hand OMS pod and the disparity of damage between the right and left hand side of three upper vertical tail pieces indicates the tiles were impacted by left wing debris prior to vehicle breakup. Forensic analysis of samples taken from the OMS pod tiles determined the imbedded deposits to be the same materials as the wing leading edge spar fittings and spanner beams.

The small amount of aft fuselage hardware recovered provides some evidence to how it failed. The right hand lower Xo1307 bulkhead has heavier slag on the aft side near the right hand ET attach fitting than the forward side of the bulkhead indicating a flow in the forward direction. The left hand ET attach fitting has significantly more thermal erosion than the right hand fitting. The structure recovered forward of the Xo 1365 bulkhead consists of skin pieces larger than those aft of the bulkhead. The pieces aft of Xo 1365 were exposed to internal heating, which resulted in backside heating tile failures. This indicates that the aft fuselage failed at the Xo1365 spar plane after the initial breakup of the orbiter.

The mid fuselage structure was recovered in decreasing percentage from forward to aft. The primary failure for most of the mid fuselage structure was mechanical overload with subsequent thermal damage. Some mid fuselage items have substantial thermal damage evident by broomstraw fractures. The absence of mid fuselage sidewall skin at both wing interfaces coincides with the absence of internal wing components. A large percentage of the recovered payload bay door debris was broken into relatively small pieces. The payload bay doors, constructed of a lightweight graphite/ epoxy composite, most likely broke up earlier than the rest of the fuselage due to off-nominal loads.

A greater percentage of the forward fuselage structure was recovered than mid or aft fuselage. The recovered forward fuselage structure and TPS items have very little thermal damage when compared to the rest of the vehicle. This suggests that the forward fuselage remained thermally protected for a longer period of time after the initial breach. Separation of the crew module and forward fuselage assembly together from the rest of the vehicle likely occurred at the interface between the Xo576 and Xo582 bulkheads.

The Columbia Debris Assessment Working Group concludes that the initial breach occurred in the lower surface of left hand RCC panel 8. The breach allowed plasma flow into the wing leading edge cavity, which melted the insulation and structural members in the transition region. The upper leading edge access panels were likely lost due to hot gas venting. Shrapnel from the disintegrating left hand wing impacted the vertical tail and left OMS pod. The plasma penetrated the left hand wing with one of the exit points being through the trailing edge. The structural capability of the wing was diminished to the point where it failed aerodynamically allowing the wing tip and elevons to break off. This resulted in vehicle instability thus increasing aerodynamic and thermal loads on the left side of the orbiter, which caused vertical tail and PLBD failure. The vehicle orientation rotated to allow thermal flow to penetrate the left mid and aft fuselage sidewall at the wing footprint. In the right hand wing, the hot gas flow is from the inboard side. Internal thermal loading combined with increased aerodynamic load caused dynamic break up and separation of the upper and lower right hand wing skin panels. The breakup of the remaining fuselage continued from aft to forward until aerodynamic loads caused final disintegration of Columbia.

Samples and Items Analyzed

The M&P Team processed 176 Reconstruction Documentation Sheets (RDS's) for disassembly, identification, NDE, sampling, and analysis of Columbia debris. Each RDS defined specific techniques used to perform Type I (non-destructive) or Type II (destructive) sampling and engineering evaluations of selected debris from RCC pieces, structure, tile, wing leading edge components, and unknown metallic pieces. A summary of the RDS matrix for NDE and Analysis is shown below in Table 9.1.

Initial M&P Engineering Support

The M&P Team supported early assessments of left hand airframe components believed to be possibly associated with the breach and breakup of the Orbiter. The Team also assisted the HFT in selecting Pathfinder debris samples that exhibited similar characteristics like that of damaged components from the left wing. Factual observations of suspect left wing components and tiles including the Midbody Panel, Uplock Roller, Main Landing Gear (MLG) Strut, Tire pieces, A286 Carrier Panel Fasteners, and Left Wing Tiles were recorded into the reconstruction database. Additionally, the Team also recorded extensive photo documentation, radiographic images, and Fact Sheets of debris items in the database, and detailed procedures and sampling techniques were developed to preserve hardware and critical evidence. Much effort was expended into developing the the M&P process and developing the best Type I techniques (CT scan, real time X-ray, etc.) so that limited sampling could be performed.

During the early stages of the investigation, a number of left wing component locations were seriously considered as a possible breach location. Many left wing components exhibited varying degrees of thermal effects, and the M&P Team was tasked to evaluate the significance of the damage and their possible relation to the breakup.

This section reviews the early analyses conducted by the M&P Team prior to the recovery of on-board sensor data. The Team analyzed debris to understand the characteristics of the damage and to qualify early Type I and Type II sampling techniques. Additional knowledge of secondary events that occurred during the breakup was gained from the early analysis. Debris assessments recorded by the M&P Team later appeared to correlate well with the sensor data obtained from Shuttle Modular Auxiliary Data System/ Orbiter Experiments (MADS/OEX) Recorder.

RDS Type	RCC	Structure	Tile	Leading Edge Components	Unknown	Total
Disassembly	2	0	0	0	0	2
NDE	46	6	22	0	0	74
Sampling & Analysis	49	2	14	2	0	67
Failure Analysis	4	8	1	10	0	23
Identification	0	3	0	0	7	10

Table 9.1: Summary of M&P RDS Matrix

MIDBODY PANEL

Unique flow patterns were observed on portions of the left midbody panel (Item

283) tiles, and there was evidence of localized heat erosion at the OML along the panel's edge. The surface of the tiles eroded by the flow patterns was glazed and hardened, and some metallic deposits were observed on the tile surface. The patterns observed in the tile were approximately ninety degrees from the nominal reentry flow pattern. The corners of the tiles near the inboard corner of the gear door were cratered and eroded, however there were no visible deposits on the tiles.

The edge of the panel at the inboard corner was also cratered, and a small hemispherical erosion pattern was observed at the panel's edge. The flow patterns observed in the tile near the forward inboard corner of the panel were approximately ninety degrees from the nominal reentry flow pattern. Additionally, the OML of the panel opposite the midbody panel (forward outboard corner) (Item 24704), and the OML of the saw-tooth doubler (aft inboard corner) (Item 1193) showed very localized heating and erosion at the corners.

MAIN LANDING GEAR DOOR UPLOCK ROLLER

The M&P Team evaluated additional landing gear door and wheel well hardware believed to be relevant to the investigation. One of four left landing gear uplock rollers (Item 9618) was recovered, and several metallic deposits were observed on the frame and roller portions. A thin, uniform, metallic coating was observed on all surfaces of the inner and outer titanium flanges and approximately the lower third of the cylindrical shaft. Additionally, some discoloration/heat tinting was observed on the cylindrical shaft adjacent to the metallic deposits. Analysis of the coating showed large amounts of metallic aluminum with lesser amounts of copper, titanium, manganese, and iron. No surface features or markings could be identified that would aid in identifying the location of the roller within the wheel well.

LANDING GEAR

A portion of a landing gear strut was recovered during search operations and identified by the Mechanical PRT as a left MLG component (Item 1257). The backside and bottom of the cylindrical strut had very localized regions of erosion and burning, and they were heavily coated with metallic slag. The front side (faces forward when deployed) showed no signs of burning or erosion, and some of the chrome plating was still intact. The outboard axle showed uniform thin slag deposits while approximately 3.5 to 4 inches of the inboard axle was heavily eroded.

MAIN LANDING GEAR TIRES

Early visual assessments were also made of thermal effects on two tire pieces (Items 197 & 201) believed to have been installed on the LH MLG. The placement of two balance patches on the internal surface of Item 201 later confirmed it to be the LH MLG Outboard Tire. Physical evidence was not available from the vendor to confirm the location of Item 197, however the fracture surfaces of Item 201 and 197 were visually overlaid and compared. Both tire sections showed significant thermal damage relative to two other unidentified intact tires (Items 2168 & 31168), and their carcasses were heavily deformed. Sections of the rubber and nylon reinforcements in Items 197 and 201 showed signs of high temperature exposure due to their increased hardness and stiffness.

CARRIER PANEL ATTACH FASTENERS

During the debris assessment it was discovered that several steel fasteners that attach the upper and lower aluminum access panels to the wing spar appeared to have brittle fracture characteristics. The aluminum 2024 panels were protected with tile and secured to the RCC spar attach fittings with two A286 stainless steel fasteners. The lower panels had an aluminum 2219 box beam as a spacer between the access panel and the spar fitting.

Nine failed and four unfailed fasteners were delivered to Boeing Huntington Beach for failure analysis. Seven of the nine failed fasteners were determined to be high temperature failures, and the remaining two were lower temperature failures. Of the seven high temperature failures, four were melted at the head end, indicating localized temperatures in excess of 1315°C (2400°F). The remaining three failures exhibited intergranular fractures on a large grained structure, indicating temperatures between 1038°C (1900°F) and 1204°C (2200°F) prior to fracture.

The two lower temperature failures were ductile bending, and the grain sizes of these indicated moderate temperature exposure between 704°C (1300°F) and 927°C (1700°F). Because these were not intergranular fractures, a time of failure could not be correlated to the period of exposure.

FORWARD OUTBOARD LH MLGD CORNER TILE

The LH main landing gear door tile on the forward outboard corner (identified as item 33590, P/N V070-191101-031) demonstrated a similar flow pattern as the left midbody panel (Item 283). Visual evaluation of the OML of the tile revealed apparent thermal flow erosion (melting, flowing and lifting of the RCG coating) of the outboard edge (directly adjacent to the outboard thermal barrier), with the flow direction inboard and slightly forward (Figure 9.1). This flow pattern was oriented approximately ninety degrees from the nominal flow direction expected in this area. In addition, the IML showed similar evidence of thermal flow erosion, but indicated the flow direction to be from inside the forward outboard corner of the main landing gear cavity, outward and forward. X-ray radiography did not detect any notable features aside from the surface features noted above; therefore, no sampling or chemical analysis was performed.

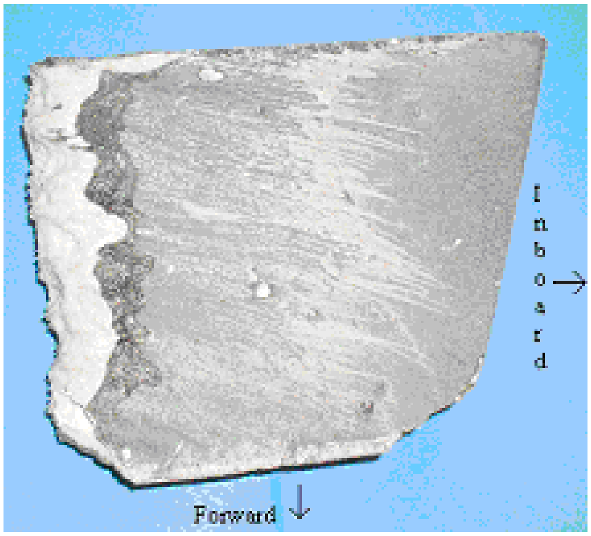


Figure 9.1. Left landing gear door perimeter tile, forward corner, item 33590

LITTLEFIELD TILE

One of the western-most items recovered in the debris field was a tile fragment (Item#14768), commonly referred to as “the Littlefield tile” because it was named after the town in which it was discovered. A high degree of interest was generated in determining where the tile had been located on the vehicle. Although the tile’s surface coating was black in appearance, thickness measurements and a small area of visible white RCG coating beneath the black layer indicated it was most likely from the upper wing or canopy areas. Visual examination alone was not sufficient to determine if the black appearance was paint, which is applied to some of the upper surface tile per drawing, or metallic deposition, which occurred during structural heating/vehicle break-up.

Initial sample analysis on a sample taken from the fragment was inconclusive. Further comparative laboratory analysis with LRSI tile from both painted and unpainted regions of the vehicle indicated the black “coating” was most likely aluminum deposition. In parallel, extrapolation of data obtained through 3-D mapping of the fragment identified three potential LRSI candidate locations, all of which were not painted per drawing, further confirming the hypothesis of the laboratory analyses. Based on the results, a “best fit” candidate location was identified as V070-195003-150/154 (LH/RH), located directly inboard of RCC panels 8 & 9 on the upper wing. Information regarding the analysis was documented in Boeing Report 03-064 and NASA report KSC-MSL-2003-0115.

PATHFINDER DEBRIS ANALYSIS

The M&P Team also assisted the HFT in selecting structural debris that exhibited similar thermal and mechanical damage like that of the left wing areas of interest. Some structural pieces were selected by the HFT to develop a failure analysis process for debris hardware and to obtain exploratory laboratory data. Because of the extreme heating involved with the hardware, the laboratory investigations required exploratory test methods, analyses, and interpretations.

To facilitate and expedite the failure analysis process, six debris items remote from the high interest areas of the left wing were selected as exemplars for failure analysis. A description of the hardware selected for analysis and its analysis location is listed below in Table 9.2

Item	Description	Analysis Location
33767	R/H ET Door Cavity	Boeing – Huntington Beach
24521	R/H Vertical Tail Structure	NASA - JSC
797	R/H Lower Wing Glove Fairing Skin	NASA - Langley
36758	R/H Forward Fuselage Upper Skin Splice	NASA - Langley
37696	Midbody Fuselage / Sidewall	NASA - Langley
41372	R/H Lower Wing Glove Fairing Skin	NASA - Langley

Table 9.2. Pathfinder Parts Selected for Failure Analysis

The Pathfinder 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.

Analysis of Wing Leading Edge Debris and Attach Hardware

The M&P Team's analysis of wing leading edge debris was consistent with assessments made by the HFT regarding Columbia's breakup scenario. The HFT identified potential sites for a breach in the wing leading edge and entry points for plasma flow. Damage patterns observed on select wing leading edge component debris suggested that major thermal events occurred in the left wing leading edge near RCC Panels #8 - 9. These observations were strongly supported by data obtained from the (MADS/OEX) Recorder and physical evidence at the left wing leading edge.

Several left wing leading edge components exhibited unique indications of heat damage relative to other wing leading edge parts, and they were identified by the HFT and CAIB as focus areas for materials analysis. These focus areas included:

- Excessive overheating and slumping of LESS carrier panel tiles
- Eroded and knife-edged RCC rib sections
- Heavy deposits on select pieces of RCC panels

Samples of deposits from these areas were chosen from extensive examinations of radiographic images to minimize the quantity of sampling. Samples of interest were removed from the affected areas where permitted and analyzed by the M&P Team.

RADIOGRAPHY OF CARRIER PANELS AND RCC

Non-destructive Type I sampling included real time radiography of carrier panel tiles and RCC materials. A major objective of this type of sampling was to perform a macro-examination to determine ideal regions to conduct more destructive Type II sampling and limit costly and time consuming analyses requiring special labs. Radiography of tiles and RCC panel pieces showed that x-rays were an excellent method of characterizing the following attributes:

- Location and shape of metallic deposits
- Melt flow patterns on tile
- Imbedded debris not visible on the surface.

The M&P Team used the radiographic data to develop Type II analysis procedures that carefully characterized all important features on critical tile and RCC surfaces.

THERMAL EFFECTS OF LESS CARRIER PANEL TILES

Surface Deposits and Slumping

Evidence of overheating and slumping was observed on three LI-2200 Lower Left Carrier Panel 9 tiles adjacent to left hand RCC panel 9. The item numbers of tiles are: 16692 (V070-199716-048), 22571 (V070-199716-052) and 57754 (V070-199716-054). Figure 9.2 shows the simulated configuration of the carrier panel tiles. Depressed/slumped and eroded regions were observed in two of the three tiles (Items 16692, 22571). For

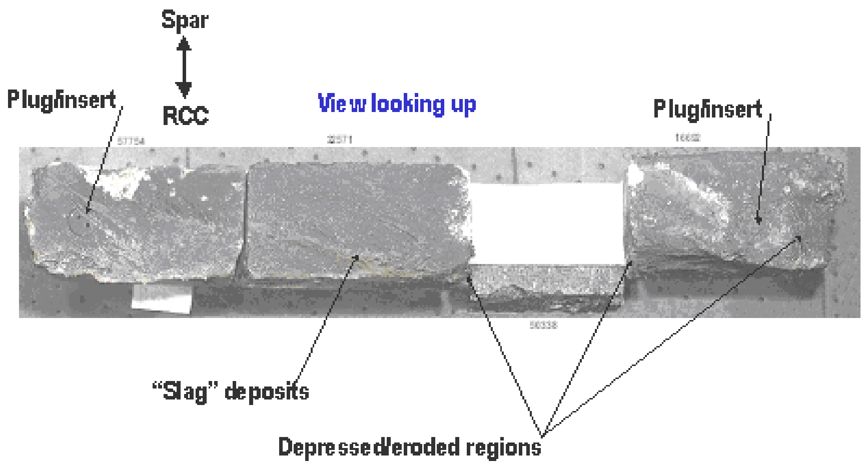
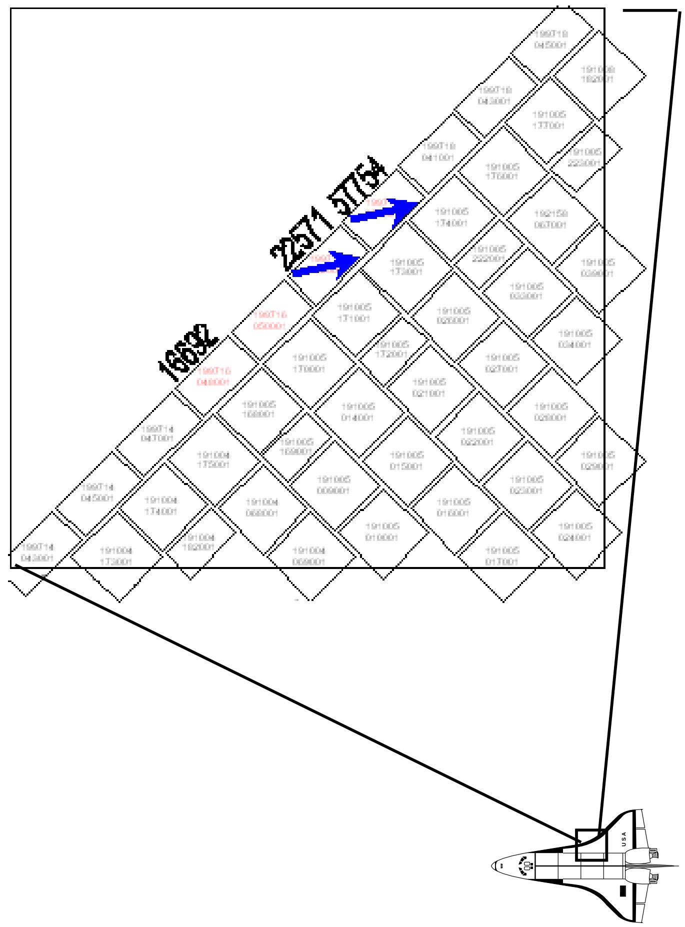


Figure 9.3. Top view of reconstruction lower left LESS Carrier Panel 9.

Figure 9.4. Apparent flow direction of surface deposits on Carrier Panel 9tiles.



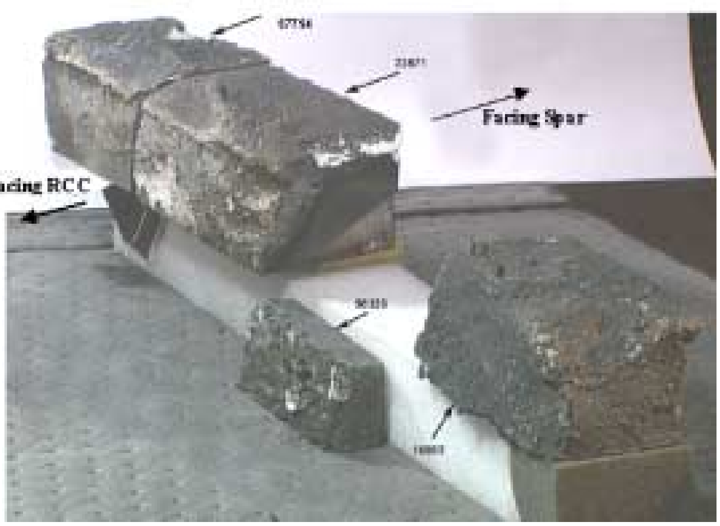


Figure 9.2. Reconstruction of recovered left hand lower LESS Carrier Panel 9 tiles.

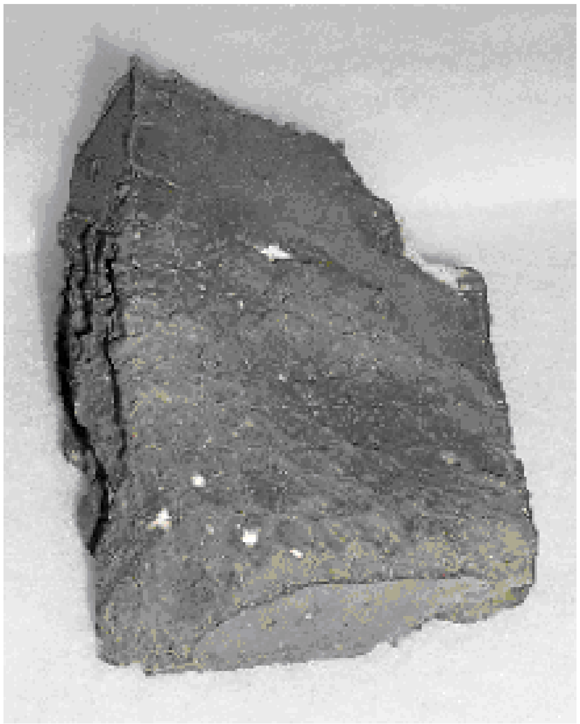


Figure 9.5. Upper left hand LESS Carrier Panel 8 internal tile (Item 50336)

example, the forward-facing sidewalls of Items 16692 and 22571 that nominally seal against the lower RCC panel 9 heel were severely slumped and eroded.

Dark-colored deposits were observed on all three outer mold line (OML) tiles (Items 16692, 22571, 57754). The thickness of the deposits varied across the tile surfaces. In the case of 22571 and 57754, the deposits produced visually apparent flow-like patterns oriented in the aft/outboard direction (Figures 9.3 and 9.4). Visual evaluation showed evidence that in some locations on the tile sidewalls, the deposits had built up over adjacent soft goods. This was supported by the presence of entrapped ceramic fibers in the deposits.

One internal LI-900 tile originally located on Lower Left LESS Carrier Panel 9 was recovered. This tile (Item 50338, V070-194205-004) exhibited a heavily slumped and cratered appearance (Figure 9.2). An additional internal LI-900 tile was recovered from upper Left LESS Carrier Panel 8. This tile exhibited a greenish coloration and heavy slumping (Figure 9.5). The surface deposits on internal tiles 50336 and 50338 were not as thick as those observed on the Lower Left LESS Carrier Panel 9 OML tiles.

X-ray radiography of the carrier panel tiles did not detect any notable features aside from the surface deposits noted above. A typical example is shown in Figure 9.6. Sampling and chemical analysis were therefore initiated for surface deposits only.

Chemical Analysis of Deposits

Samples of the surface deposits were removed and chemical analysis was performed using Scanning Electron Microscopy/Energy Dispersive Spectroscopy (SEM/EDS) and Electron Spectroscopy for Chemical Analysis (ESCA). The results indicated that the elemental components of the deposits were primarily aluminum, nickel, niobium and carbon (references provided in Table 9.3). Although the precise composition of the source alloys/compounds cannot be identified with certainty, the elements found are consistent with the compositions of 2000 series aluminum alloy, Inconel 601, Inconel 718 and Incoflex batting (e.g. Cerachrome). ESCA results indicated that the outermost layer was highly carbonaceous. This indicates that the carbonaceous outer layer was deposited after the metallic layer, which had in some cases fluxed into the RCG coating.

Tile item 57754 remained bonded to a section of underlying carrier panel 9 (Figure 9.7). Tile items 22571, 16692, 50338

Figure 9.6. X-ray radiograph of tile Item 22571; front view (left) and side view (right)

Item #	Date	Title
16692	5/7/03	Boeing NSLD FA Report 03-079, "SEM/EDS Analysis of STS-107 Debris Samples
	N/A	*Xray*
	5/13/03	Boeing HB Case Report 301974, " ESCA of STS-107 Debris Samples"
22571	5/6/03	Boeing NSLD FA Report 03-079, "SEM/EDS Analysis of STS-107 Debris Samples
	N/A	*Xray*
50336	5/6/03	Boeing NSLD FA Report 03-079, "SEM/EDS Analysis of STS-107 Debris Samples
	N/A	*Xray*
	5/13/03	Boeing HB Case Report 301974, "ESCA of STS-107 Debris Samples"
50338	4/18/03	Boeing NSLD FA Report 03-071, "SEM/EDS Analysis of STS-107 Debris Samples"
	N/A	*Xray*
57754	*N/A*	*Xray*

Table 9.3. Index of Laboratory Reports for Tile Sampling/Analysis

and 50336 had all been detached from underlying structure.

Deposits were found on the threaded internal surface of the ceramic insert in tile item 16692. The fused silica plug and lock cord were observed to be intact at the OML end of the insert. This indicated that the deposits were introduced from the IML side of the tile. The elemental composition of the deposits was essentially the same as that of the deposits found on the OML of the tile. The deposits may have occurred after the SIP had been partially eroded away or debonded.

Summary of Thermal Effects

- Tile slumping and surface deposits on the left lower LESS carrier panel tiles are consistent with flow occurring from inside the RCC cavity out through the upper and lower carrier panel locations in that vicinity
- The surface deposits on lower left hand carrier panel 9 tiles are consistent with a flow direction exiting from RCC panel 8.
- The thermal degradation of the internal tiles recovered from upper carrier panel 8 and lower carrier panel 9 suggests that the flow was in excess of 1649°C (3000°F)
- The composition of the tile surface

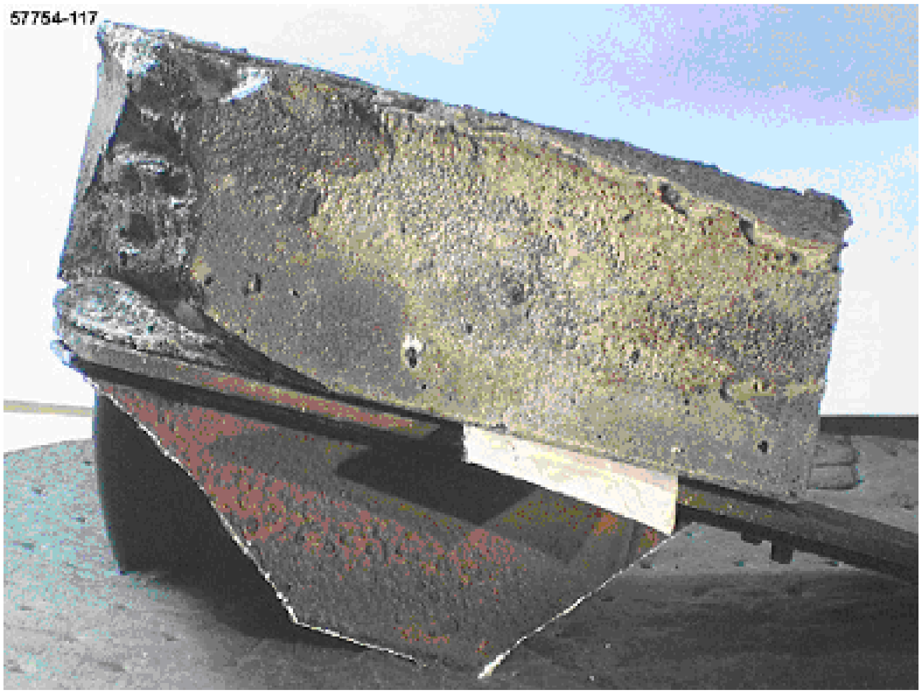


Figure 9.7. Tile Item 57754 bonded to section of carrier panel

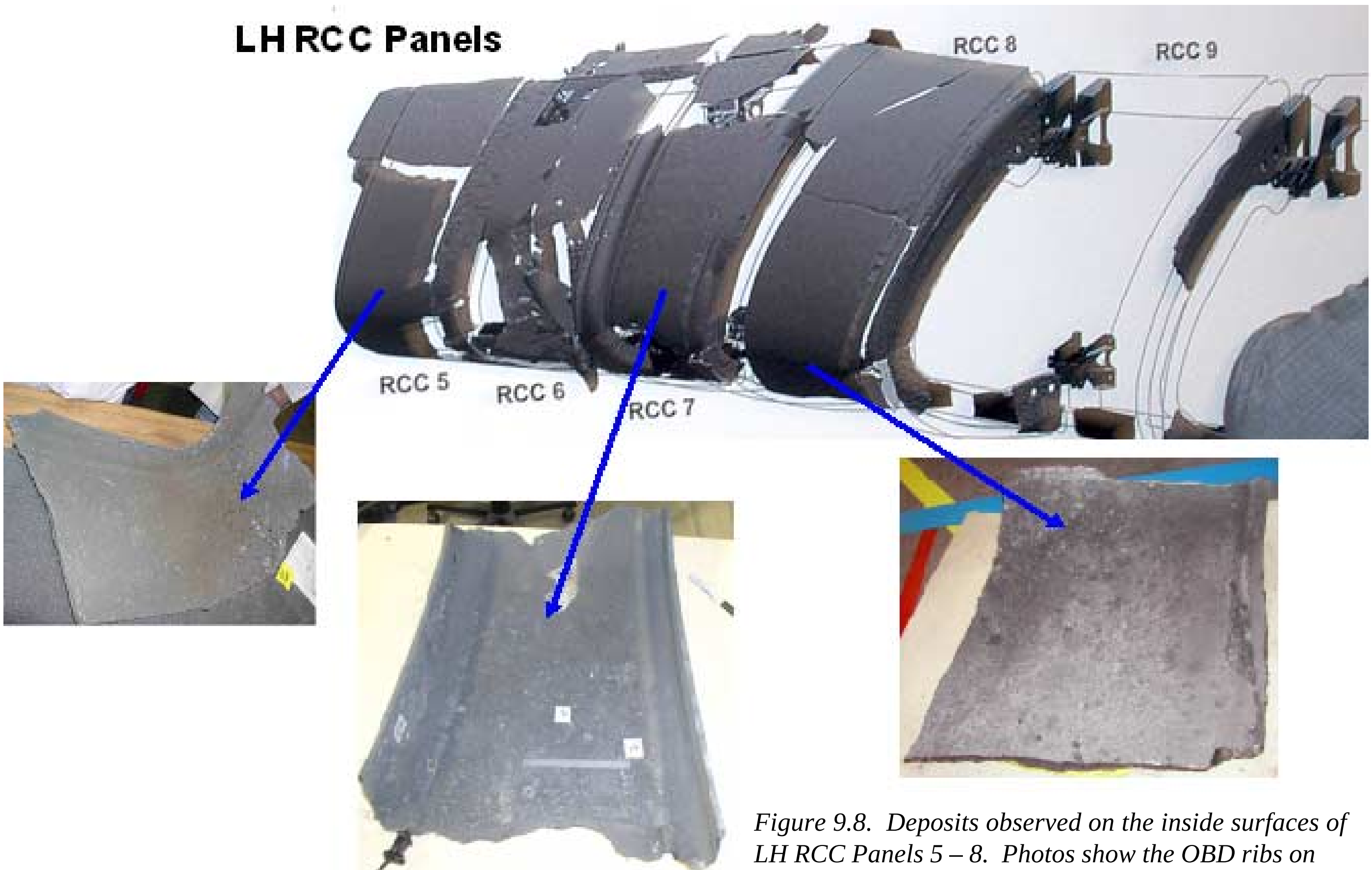


Figure 9.8. Deposits observed on the inside surfaces of LH RCC Panels 5 – 8. Photos show the OBD ribs on the Left and INBD ribs on the Right.

deposits suggests that the flow contained molten/vaporized materials from the LESS internal insulators, attachments, carrier panels, and/or wing spar.

EVALUATION OF DEPOSITS ON RCC PANELS

Visual Assessments of RCC Deposits

Deposits similar to those observed on the LESS carrier panel tiles were also observed on the inner surfaces of several LH RCC panels (Figure 9.8). The deposits resembled solidified metallic slag, and were strongly adhered to the internal surfaces of the panel segments. The quantity and thickness of the deposits also varied according to the RCC panel number.

The M&P Team noted marked differences in the appearance and quantity of deposits between the LH and RH RCC surfaces. Table 9.3 summarizes the visual surface condition observations for left wing RCC panel pieces, ribs and T-seals 1- 12.

Table 9.4 and Figure 9.8 show the relative severity of the left wing leading edge deposits approached a maximum at RCC Panel 8 and decreased on either side. Heavy deposits were also observed on the inner surfaces of the Outboard Ribs of Panels 4, 5, and 7, however very few deposits were observed on the inboard ribs of these panels.

Very few deposits were observed on RCC Panels past Panel 12, and there was more evidence of mechanical damage than thermal effects on the remaining panels outboard of Panel 12. Although the

RCC Panel	No. of Parts Assessed	Observations
1	3	Good Condition; No Deposits
2	5	Good Condition; No Deposits
3	5	Light Deposits – gray, red discolorations (2 of 5)
4	5	Light Deposits (3 of 5); Slag on IML of OBD rib on T-Seal facing 5
5	9	Light Deposits (4) ; Medium Deposits(1); Slag on IML of OBD rib on T-Seal facing 6
6	0 (Missing)	
7	3	Heavy (1); Very Heavy (1); Heavy slag on IML of OBD rib; No deposits on inner surface of INBD rib
8	**5**	**Medium (T-seal); Very Heavy (3); Heavy (1)**
9	3	Heavy (3)
10	3	Light – Heavy (1); Medium (3)
11	1	Light
12	1	No Deposits

Table 9.4. Left wing RCC panel deposits

quantity of deposits was considerably greater on the LH leading edge panels than the RH panel sections, Medium grade deposits were also observed on an upper panel portion and outboard rib section of RH RCC Panel 8.

Metallurgical Analysis of RCC Deposits

The relative differences observed between the amount of slag deposits on the LH and RH RCC panels prompted a metallurgical analysis. The analysis included the following: (A) review of the chemistry of high temperature reactions associated with the wing materials, (B) non-destructive radiography of the RCC panel surfaces, and (C) a metallurgical evaluation of samples removed from the RCC panels. Cross sections of deposits from LH and RH RCC panels were analyzed to identify and characterize their composition, composition gradients, and any layering effects on the inner surfaces.

The high level objectives of the analysis were the following:

- Can evidence of plasma flow direction and thermal damage be correlated withs lag deposition?
- Can the sequence of deposition be identified and correlated with relative altitude/time and temperature?
- Do slag deposits reveal information about the location of a breach in the wing leading edge?

Initial Phase I samples were analyzed to validate process flows within the labs and analytical techniques that would be used to meet the high level objectives. Later in the investigation, visual assessments made by the HFT and data from the MADS/OEX Recorder narrowed the analytical focus to LH RCC Panels 5 – 10, precipitating Phase II & III sampling and analysis of wing leading edge materials. Some RH RCC panel segments were also analyzed for comparison with LH RCC deposits. Details of each phase of RCC sampling and the analytical techniques used to characterize the samples are described in Appendix A.

(A) Chemistry of Reactions

Prior to the metallurgical analysis of debris samples from the RCC panel surfaces, experts from NASA-WSTF and Glenn Research Center (GRC) reviewed the chemistry of high temperature reactions associated with wing leading edge materials. Atmospheric conditions expected during reentry and during Orbiter breakup were reviewed, and high temperature reactions associated with the Aluminum spar material were discussed. Key points determined from the discussions were as follows:

- The atmosphere during peak heating

was significantly less dense than sea level conditions but still contained elemental nitrogen and oxygen

- High temperature compounds may have formed from the reaction of aluminum spar materials in the upper atmosphere (GRC Report CT-050103-1O).
- Aluminum oxide (Al_2O_3) was the most stable oxide formed
  - Other oxides (AlO, Al_2O, etc.) may form at high temperatures and lower partial pressures of oxygen
  - Upon lowering of the temperature, in presence of abundant oxygen, oxides immediately convert to Al_2O_3
  - Nitrides are only stable if the temperature is immediately quenched to less than 1200°C (2192°F) (not expected)

Based on the expected air reaction products with Al, it was hypothesized that Al_2O_3 was the primary oxide compound formed. Therefore, Al_2O_3 was chosen as one of the trend marker for the chemical analysis of debris, and the amount of Al_2O_3 formed would also depend on the time that Al metal was exposed to air at high temperature.

Identification of the compound Mullite (crystalline $2Al_2O_3$ +$1SiO_2$) from preliminary x-ray diffraction of a sample containing Cerachrome prompted the M&P Team to study high temperature transformations. In laboratory experiments at GRC, Cerachrome formed Mullite at around 1100°C (2012°F) and Cristobalite at 1300°C (2372°F). With higher temperature, their amounts increased. Cerachrome melted between temperatures of 1800-1900°C (3272-3452°F). These results were summarized in GRC reports CT-051203-7C, -7D.

The identification of nickel-aluminides in preliminary x-ray diffraction experiments also prompted some studies of mixing effects between Ni and Al at high temperature. High purity Ni and Al pellets were exposed to temperatures from 1100-1500°C (2012-2732°F) in a vacuum furnace. Various forms of stable nickel-aluminides were formed (identified by x-ray diffraction) and summarized in GRC report CT-051203-6C, -6D. In the presence of air, despite molten aluminum, no nickel aluminides were formed until Ni melted. The formation of aluminum oxide appears to have prevented formation of the aluminides.

(B) Radiography of RCC Panels

The M&P Team collaborated with Langley Research Center for the use of real time radiography to assist in destructively sampling and evaluating RCC deposits. Large density differences between the deposits of LH and RH RCC panels were detected, and possible deposition patterns on the RCC panels were interpreted from the images. The initial radiographic images of calibration samples clearly identified locations, shapes, sizes, and distributions of deposits on the RCC panels having large density differences. Details of the measurement method and the images obtained were described in a NASA LARC Report.

Key findings from the radiography of both calibration and RCC panel samples were:

- The inverse radiographic response of heavier materials compared well with that of an IN718 standard
- Darker areas in the inverse radiographic images compared with the Inconel standard
- Aluminum and Cerachrome gave a similar radiographic response despite their diverse material characteristics
- Four types of deposit patterns were identified from LH RCC Panel 8 (Fig. 9.9)
  - Uniform thickness
  - Spheroids
  - Tear-shaped
  - Globular-shaped
- Other RCC panels imaged had Uniform thickness deposits

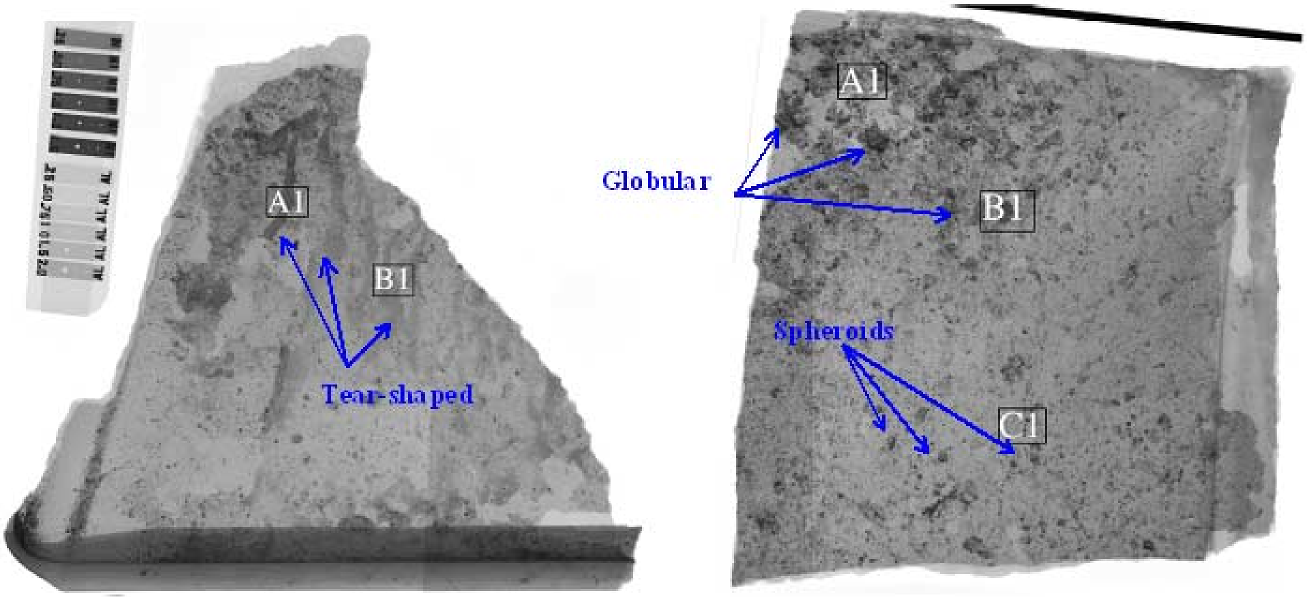


Figure 9.9. Types of deposition patterns observed on radiographic images of LH RCC Panel 8 pieces.

(C) Metallurgical Evaluation of RCC Deposits

Interpretation Criteria

Due to the presence of different materials in the wing leading edge, it was also expected that other high temperature reactions would take place resulting in formation of many other products. Therefore, prior to rigorous analysis, some criteria for the interpretation of results from chemical analyses of the deposits were established from preliminary microprobe analyses. Examples of those criteria are summarized below. They are all listed in report MSFC-ED33-2003-066.

1. Alloys containing high amounts of Ni and Fe such as A286, IN718, IN625, and IN601 could be identified and distinguished based on a Ni/Fe ratio and the presence of secondary elements such as Mo, Nb, Co, and Ti
2. Aluminum 2024 wing spar material could be identified from the presence of Cu with Al and Cu with Al_2O_3.
3. Cerachrome could be identified by the presence of Cr within a mixture of Al_2O_3 and SiO_2.
5. The presence of a pure metal, such as Iron that is surrounded by Al_2O_3, with no other elements nearby, is indicative of a thermite reaction
6. SiO_2 from tile may be identified by physical nature and the absence of other accompanying elements and compounds. However, SiO_2 may also form from the erosion and oxidation of SiC in RCC.

Guided by radiography, samples of deposits from LH RCC Panels 4-5, 7-9, and RH RCC Panel 8 were removed and analyzed using SEM/EDS, microprobe, and x-ray diffraction. A description of the techniques used for all phases of the analysis is provided in Appendix A, and the results are summarized in Reports: MSFC-ED33-2003: 067 - 098 and GRC reports CT-050903-4: C-D, and CT-060203-9: C-D.

Key findings from each metallurgical analysis were as follows:

<u>LH RCC Panel 4:</u>

1. Aluminum was detected in all layers of the deposits on the RCC Panels (Figure 9.10)

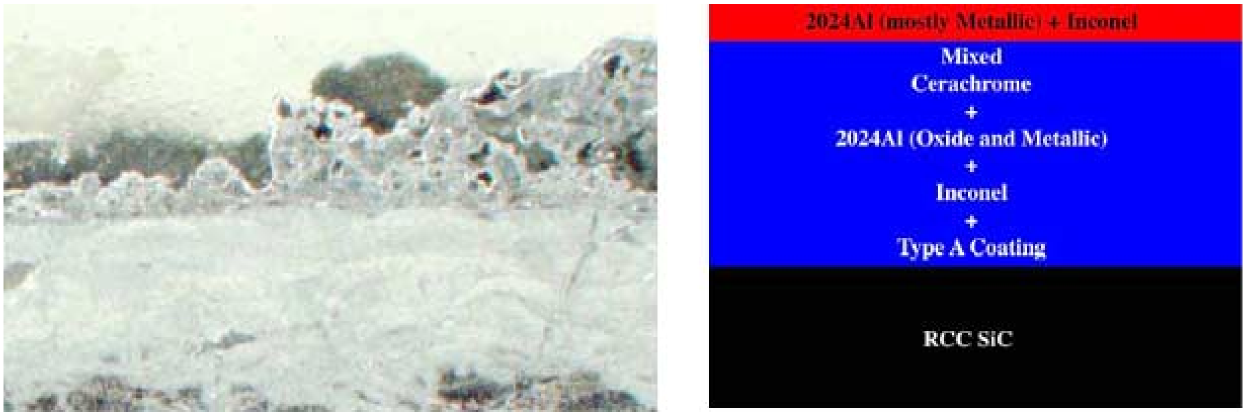


Figure 9.10. Cross-section of LH Panel 4 Lower Inboard (Item 80632)

2. Aluminum was not detected in the first deposited layer on the RCC Rib (Figure 9.11). This is unlike the observations of LH RCC panel 8 and is similar to LH RCC panels 5 & 7.

<u>LH RCC Panel 5:</u>

1. Aluminum was detected in all layers on the RCC Panels (similar to Panel 4)
2. Aluminum was detected in the first deposited layer, which is similar to LH RCC panels 4 & 7 but unlike LH RCC panel 8
3. Deposits on the RCC panels were uniform and thinner than those on LH RCC panel 8

<u>LH RCC Panel 7:</u>

1. Aluminum was detected in the first deposited layer, which is similar to LH RCC panels 4 & 5 but unlike LH RCC panel 8 (Figure 9.12)
2. Deposit thickness was thinner than that of LH RCC panel 8

<u>LH RCC Panel 8:</u>

1. Samples contained large amounts of molten Cerachrome mixed with metallic deposits of Inconel 718 and Inconel 601 (Figure 9.13)
   - Initially believed to be molten aluminum due to low density radiographic indications
   - Deposition temperatures exceeded 1760°C (3200°F), which is the melting point of Cerachrome)
2. Samples contained large spheroids of both Inconel 601 and 718
   - Consistent with melting of RCC

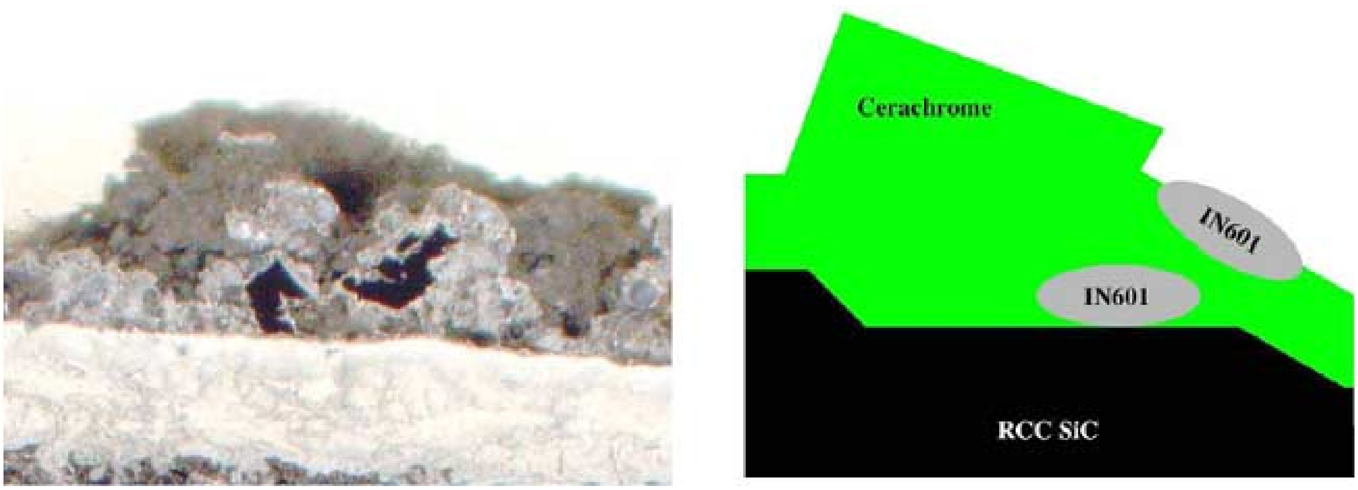


Figure 9.11. Cross-section of RCC Panel 4 Lower Inboard Rib (Item 80632)

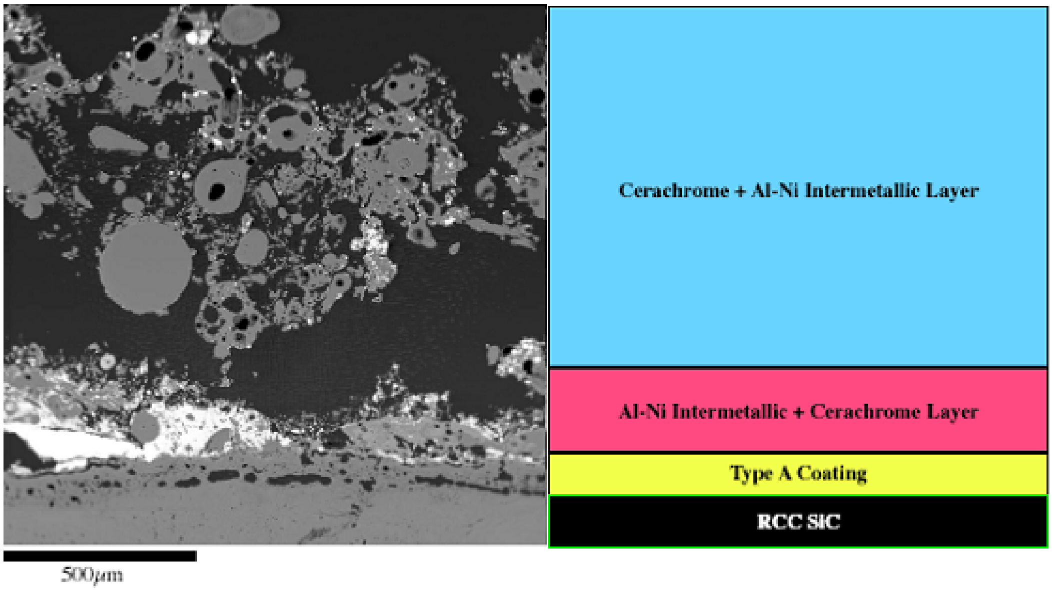


Figure 9.12. Cross-section of LH Panel 7 Upper (Item 31985)

spanner beam, insulator foils, and other RCC fitting materials

3. The first deposited layer contained both Cerachrome and Inconel but not aluminum
4. The final deposited layers contained heavy amounts of aluminum
   - Elemental composition was consistent with Al 2024 alloy
   - Aluminum was in either metallic or oxidized form
5. Deposits on the OML apex of Item 2200's fracture surface were molten Cerachrome with significant porosity, and some sodium and minor amounts of copper were observed
   - Indicates that the deposited Cerachrome was mixed in with Type

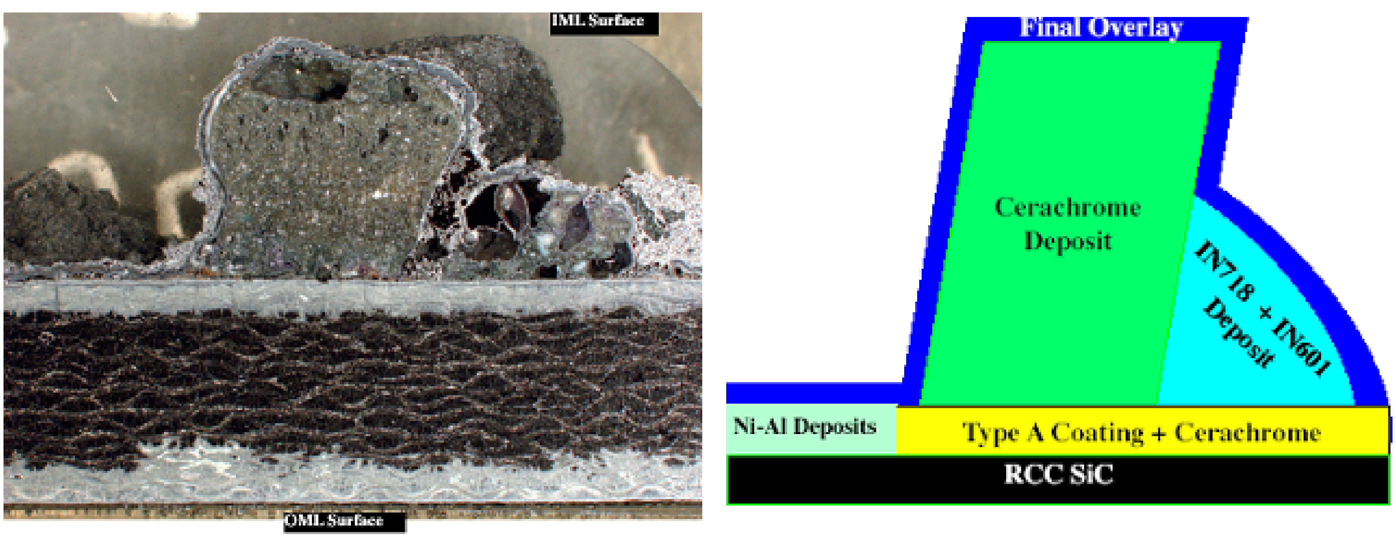


Figure 9.13. Cross-section of LH Panel 8 Upper (Item 43709)

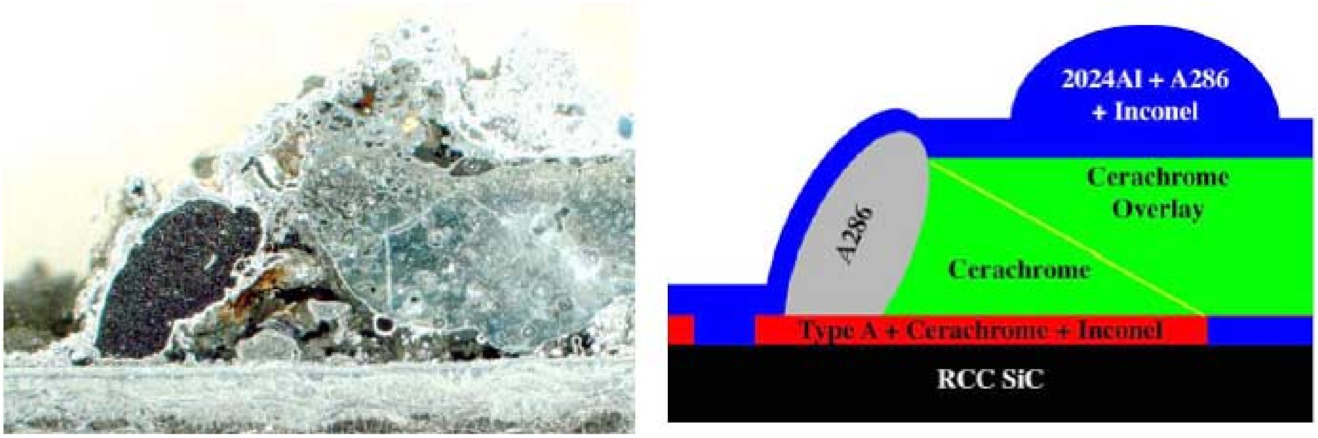


Figure 9.14. Cross section of LH Panel 8 Upper (Item 18477). The sample was removed near the inside of the panel's heel.

A coating and Al 2024 spar material

- No metallic components were detected, suggesting it either evaporated or flowed away with the plasma

6. A286 alloy was only detected in samples from Item 18477 at a location close to the spar fitting (Figure 9.14)
   - A286 was not detected in the first layers of the deposit
   - A286 was mixed with molten Cerachrome and coated with aluminum deposits
7. Heavy erosion was detected on Item 24724, LH RCC Panel 8 outboard heel rib, on the OML side (Figure 9.15)
   - The silicon carbide layer on the OML of the RCC was missing
   - Silicon carbide on the IML was partially missing in some locations
   - Where SiC remained on the IML, it was infiltrated by IN718 and then overlaid by aluminum.
   - The exposed carbon on the OML was also infiltrated by IN718 and overlaid by aluminum

<u>LH RCC Panel 9:</u>

Although very small pieces of RCC Panel 9 were identified, the deposits on LH RCC Panel 9 parts 7025, 29741, and

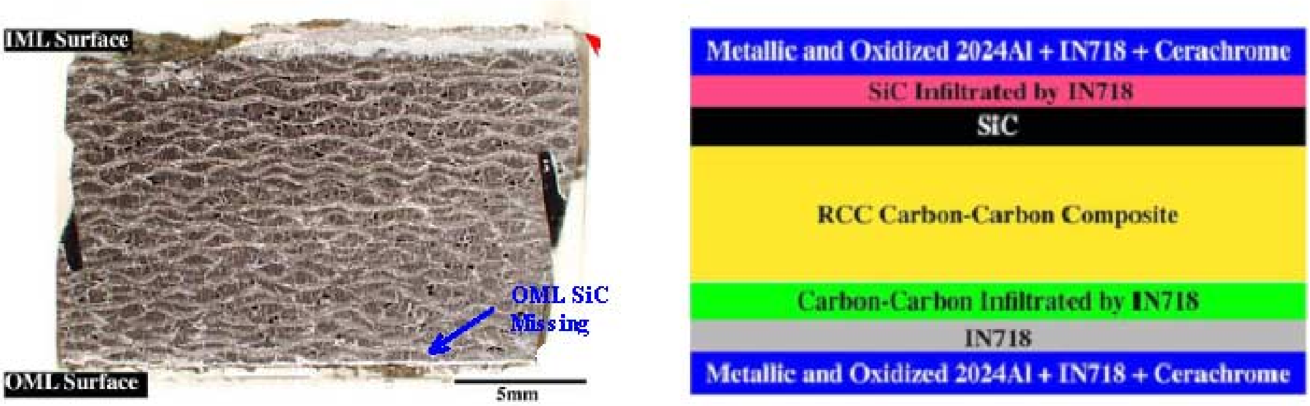


Figure 9.15. Cross section of Panel 8 Outboard Rib (Item 24724)

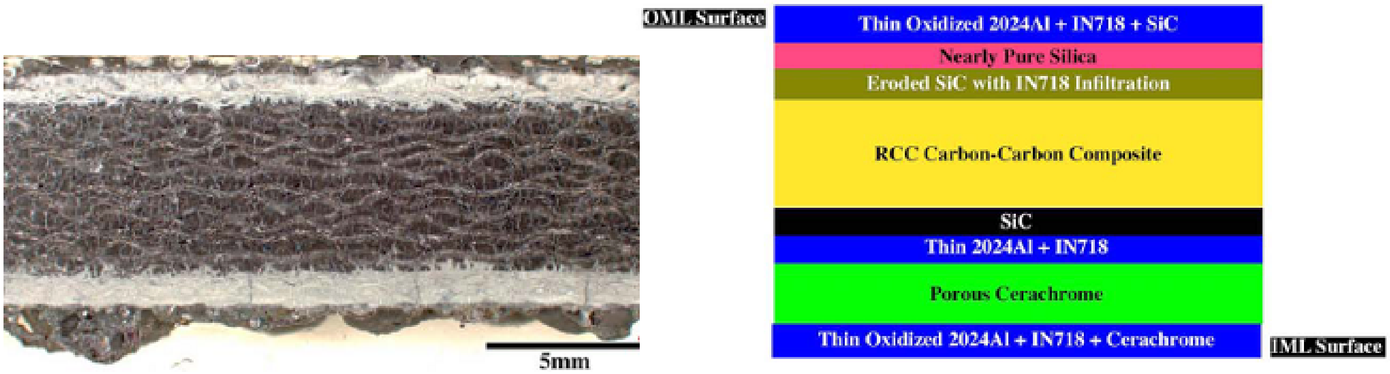


Figure 9.16. Cross section of Panel 9 Upper Rib (Item 7025)

38223 suggested the following:

1. Aluminum was detected in the first deposited layer
   - The amount of initially deposited aluminum was less than that of LH RCC 5, 7 and RH RCC 8
   - Elemental composition was consistent with Al 2024 alloy
2. Aluminum deposits on the outer layers of the samples were thinner and more oxidized than that of LH RCC 8 deposits
3. No erosion was detected on the IML of Items 29741 and 38223
   - Erosion only detected on the OML of Item 7025 (Panel 9 Inboard Rib) (Figure 9.16)
4. Smaller quantities of molten Cerachrome were detected in the deposits relative to LH RCC Panel 8
   - Cerachrome was porous and contained less amounts of aluminum
   - Outer layers had less amounts of aluminum as a top layer
5. Samples contained spheroids of A286, IN718, and IN625 alloys (Figures 9.17-9.18)
   - A286 alloy was not detected in the first layers
6. There were less deposits on the IML of the Outboard Rib (Item 29741) than that of the IML of RCC Panel 8 (Item 61143)

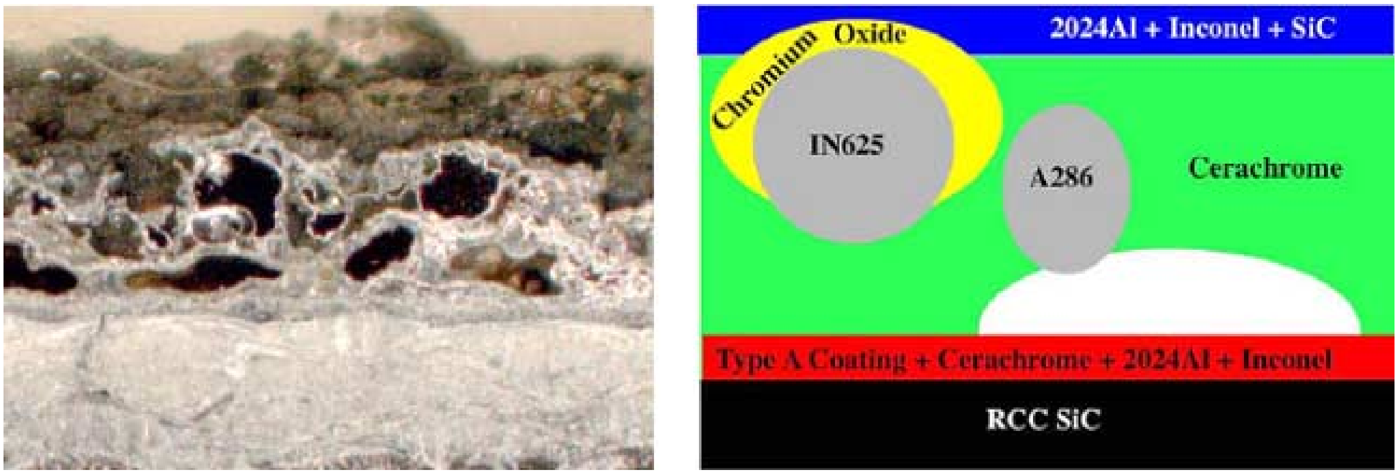


Figure 9.17. Cross section of Panel 9 Upper Outboard (Item 38223)

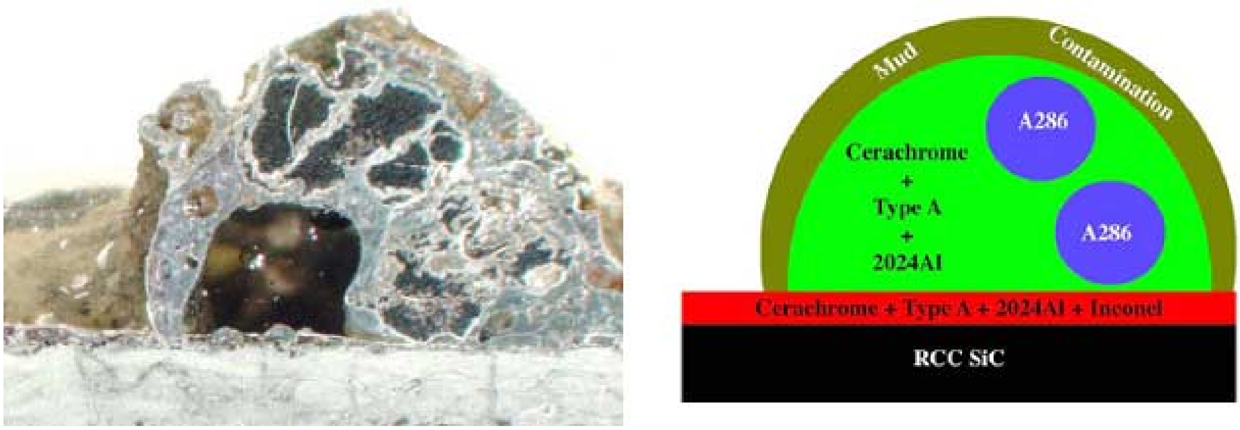


Figure 9.18. Cross section of Panel 9 Rib (Item 29741)

<u>RH RCC Panel 8:</u>

1. Samples from Item 16523 and 1419 contained mixtures of aluminum alloy, Inconel 718, and Cerachrome
   - Deposits were more uniform and thinner than LH RCC deposits; no concentrated regions of melting detected
   - Aluminum was found in all deposited layers.
   - Leading edge RCC surfaces contained very little deposits; fracture surfaces were not eroded

SUMMARY OF RCC ANALYSIS

- LH RCC Panel 8 surfaces contained larger quantities of IN718 and Cerachrome deposits when compared to other LH and RH RCC panels.
- A286 alloy, used mainly in the spar attachment fittings, was only detected on RCC Panel 8, upper, near the spar attach fitting location, while IN718, used in side spanner supports, was found in almost all samples.
- Most of the initial deposits on LH RCC panel 8 were composed of IN718, IN601, and Cerachrome.
- Metallic aluminum and aluminum oxide mixed with Cerachrome were detected in most of the first deposited layers of the other remaining RCC panels.
- The deposit analysis could not provide exact duration time but did shed some light on possible plasma flow directions.

SUMMARY AND CONCLUSIONS

Results obtained from the materials analyses of Columbia debris were consistent with the visual assessments and interpretations presented by the Reconstruction Team. Analytical data collected by the M&P Team showed that a significant thermal event occurred at the left wing leading edge in the proximity of LH RCC Panels 8-9, and a correlation was formed between the deposits and overheating in these areas to the wing leading edge components. Additionally, the finding of molten Cerachrome deposits showed that temperatures in excess of 1649°C (3200°F) were present which could severely slump and erode support structure, tiles, and lead to eroded RCC panel materials.

Analysis of lower and upper carrier panel tiles showed leading edge material-containing deposits on the outside surfaces, suggesting flow of plasma from the inside of the RCC panel to the outside.

Referring to Figure 9.19 and data collected from the analysis of both carrier panel tiles and RCC materials, several conclusions can be made regarding the observed thermal effects:

- The composition of deposits near LH Panels 8-9 and the deposition patterns revealed from radiography suggested that flow occurred from inside the RCC cavity out through the upper and lower carrier panel locations.

- The presence of Inconel 601 and 718 deposits as first layers on the surface of LH Panel 8 suggested that plasma entered through a breach on the lower side of the panel.
- Initial materials possibly exposed to the plasma were the insulators (Inconel 601, Cerachrome), spanner beams (Inconel 718); the A286 fittings were not exposed
- Evidence of plasma flow and deposits near the carrier panel tile vents were consistent with the deposits observed on the upper tile surfaces
- Evidence of molten Cerachrome within the RCC deposits suggested that temperatures were in excess of 1649°C (3000°F) that melted all leading edge materials except RCC
- Melting of the wing spar section was a secondary event due to the lack of aluminum detected at the RCC surface and protection of the spar by insulator materials

The integrated failure analysis of wing leading edge debris and deposits strongly supported the hypothesis of a breach that occurred at LH RCC Panel 8, however there was insufficient evidence to preclude additional damage near the T-Seal 8 or RCC Panel 9.

Due to the absence of wing leading edge debris adjacent to LH RCC Panels 8-9, the duration of exposure and direction of plasma flow could not be determined. Additionally, sufficient material evidence near LH RCC Panels 8-9 was not available to correlate the configuration and geometry of the breach to the observed thermal effects.

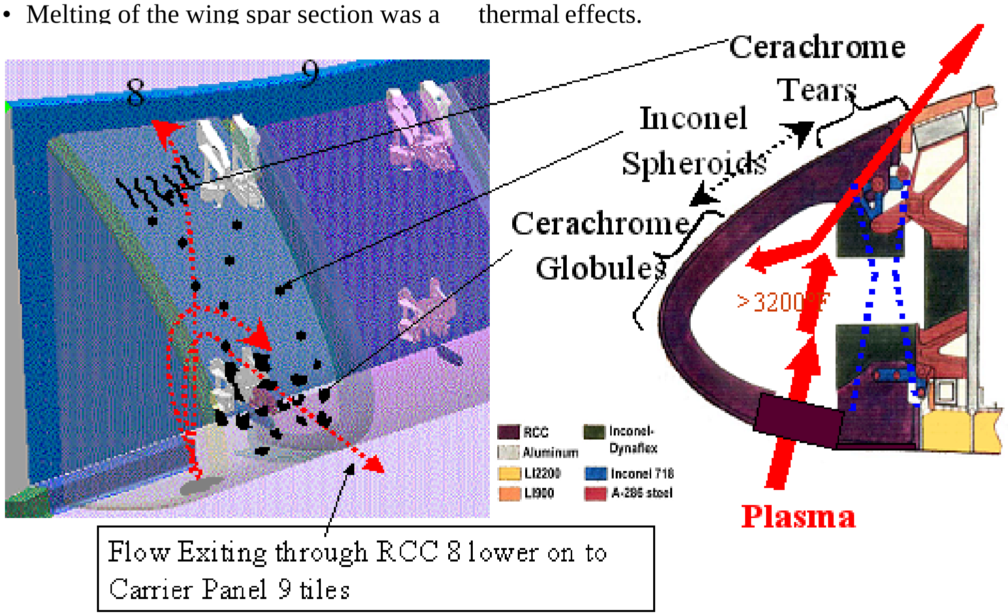


Figure 9.19. Schematic of deposition patterns analyzed near LH RCC Panels 8-9

Organization and Communication

...Build a well-defined, co-located, and focused team...

The success of the reconstruction effort was attributable to a well defined, co-located, and focused team of knowledgeable people with a common mission. The team, with no regards to company affiliations, was willing to cross functional lines and overcome any obstacle encountered. This cohesive attitude, along with the persistence to prevail even when facing an overwhelming task under unpleasant circumstances, allowed this initiative to exceed expectations.

This broad and diverse team of experts gathered from essentially every NASA Center and Shuttle prime contractor. In addition, resident experts assigned by the CAIB and NTSB were co-located at the Columbia hangar. As a direct result of this resident support, the reconstruction team was able to address the needs of all the various investigative bodies directly.

...Write flexible contingency plans...

Initially, the organization of the recovery and reconstruction effort was based upon KSC's salvage plan. The good intentions of this approach cannot be overlooked and adaptation of these plans to the specifics of the situation is the key to success. Using plans in contingency situations as guidelines and not as specific situational mapping and implementation tools is appropriate.

...Clearly define and empower the chain of command...

By necessity, NASA is a very process oriented organization in order to accomplish the complex mission of human space flight. This procedural hierarchy actually hindered the investigation in some instances. A prime example encountered during the early phases of debris receiving was when on-site personnel made a recommendation regarding whether it was acceptable to wash mud off of the debris or disassemble a part to aid in identification. There were multiple management forums that had to render a decision before work could proceed. This slowed the pace of debris processing. More autonomy and approval authority should be given to the on-site team, which was specifically staffed with appropriate expertise to make these types of on site decisions.

The reconstruction team reported to both the MIT Chair and the OVEWG Chair. Both recognized the need for the preservation of evidence and both took leadership roles in reconstruction. However, the relationship between these two entities was not well defined. The impact of this to the Reconstruction Team was conflicting requirements and priorities. It remained unclear to some as to who was ultimately in charge of the reconstruction activity at the Program level. Therefore, the role of reconstruction engineering and their chain of command remained fuzzy for the duration of the effort.

There was also strain induced in the M&P PRT due to multiple and often times conflicting priorities levied on the team by differing CAIB teams, OVEWG, and the HFT. Requests for sampling and failure analysis should go through one individual to prioritize multiple or conflicting requests for analysis and information.

...Promote trust and a free flow of information...

There is a lesson to learn in the evolution of the team from independent elements to a synergistic unit. The initial charge to the CAIB was for an independent investigation. However, a teaming approach from the start would have been more effective. Though the reconstruction participants eventually melded into a team, early on in the investigation the information flow to and from CAIB was very slow. The duality of the investigation by the CAIB and NASA during the first few weeks caused some tension and competition for resources.

There appeared to be a fear of giving raw data to on-site CAIB personnel before

NASA had a chance to review and validate it. Part of the reservations exhibited by the NASA team was due to the legitimate fear that the data would be released prematurely or misinterpreted by the CAIB. Communications improved when the CAIB personnel were permitted to share any factual reports with NASA. Once the teams began two-way sharing of data and analyses, real investigation and technical exchange of ideas could occur.

The ability of the Reconstruction Team Chair to communicate directly with the CAIB Chair for certain issues and the ability to work particularly sensitive issues outside the normal, public forums was valuable. These specific issues were associated with flight crew, security, and those of a time critical nature.

...Create a "badge less" environment...

The Reconstruction Team had many unique characteristics that distinguished it from a classic organization, but the single most significant trait was its "badge less" operation. While there was a team structure, the corporate or governmental affiliation of its members and leaders was largely inconsequential. This altruistic attitude, along with a common purpose, contributed more to team success than anything else. It was apparent which teams adopted this attitude and those whose members looked to the organizational charts or contractual hierarchy. The experience of the Reconstruction Team bears out a lesson that has been timelessly learned and taught in every class on successful management: The best teams are those with a truly common purpose and membership dedicated to that purpose and no other.

Facilities and Infrastructure

...Select a site with broad and available infrastructure...

The decision to reconstruct the Orbiter at KSC was the correct one. As a reconstruction site, KSC was ideal because the other Orbiters were within close proximity, the hangar space was available, and technicians and engineers that worked with the hardware during day-to-day processing were available to provide their expertise.

The KSC engineering team was able to provide technical expertise while examining the recovered vehicle hardware. The technical experts in particular systems efficiently identified and performed assessments on the debris, as well as educated the multiple investigation team members on the fundamentals of their systems.

Having the other Orbiters in close proximity to the reconstruction site allowed for first hand comparisons of the debris with the flight vehicles. This aided in the overall debris identification process.

One of the other benefits of KSC reconstruction was the availability of the KSC infrastructure. KSC is home to three world-class material science laboratories that were available to perform the majority of the forensic analysis of the debris. The availability of KSC's prototype lab and resident carpentry shop filled an unexpected need for the construction of jigs, fixtures, and enclosures for the debris. KSC was also able to provide other resources used during vehicle processing; namely Safety, Environmental Health, security services, photographic support, heavy equipment, office space, and Information Technology (IT) support.

...Overestimate information technology requirements...

IT support in particular was critical to communications among and between investigative entities. Both NASA and USA were able to make their service contractors and network infrastructure available to support the investigation.

Satisfying the IT requirements necessary for the reconstruction effort proved to be more difficult than originally anticipated, as computers were extensively used in all areas of the effort. The entire process of tracking, identification, assessment, and analysis of debris was performed and documented electronically. Based on the multitude of tasks being performed electronically, and the volume of data being developed and exchanged, it quickly became apparent that the initial set of requirements would not be sufficient. Upgraded computer systems and increased network bandwidth resolved the issues. Computer resources were essentially tripled to support the investigation.

With a team as broad and diverse as the Reconstruction Team, the IT team faced challenges associated with connecting users from various contractors, agencies, and geographic locations, while maintaining security. In order to overcome this issue, trust agreements were negotiated between centers to allow users to access any computer regardless of their domain. However, one integrated network for information exchange that all teams, and sub-teams could access would have eased communications.

The size of the Columbia hangar (50,000 square feet) limited the mobility of engineers, technicians, and handlers working to identify and locate debris via networked desktop computers. To optimize productivity, the IT team implemented a wireless network with wireless laptop computers. Even though it took many weeks to get the wireless network approved and implemented, it was an extremely effective tool. It provided hangar personnel the mobility to move about the grid while performing their assessments with all the available identification resources at their fingertips.

Tools and Techniques

...Provide high-fidelity identification tools in a timely manner...

Reference material to aid in debris identification was essential to successful reconstruction. The dependency on these reference tools was apparent when the initial effort to identify flight crew equipment debris was delayed by the unavailability of a quality library of digital photos. Bench review and other photos tended to show items all together in their packed and stowed configuration, as opposed to individual photos of equipment. Eventually a library of CDs and hard copy drawings of these items was built up, but in many cases no photos existed at all. The effort to identify orbiter structure was much easier because the SDS and KSC closeout photos were readily available.

Initially, the payload reconstruction team did not have access to the available payload photos and drawings. While payload developers provided extensive information to the Program Payload Integration Office within days of the accident, that information was not transferred to the reconstruction team until a month and a half later. The lack of this information delayed the identification and assessment of the debris.

...Create a powerful yet flexible database...

The CRDS was an immensely powerful and useful tool to organize and track items throughout the reconstruction process. The programmers are commended for such a rapid and successful deployment. The CRDS was routinely enhanced to meet changing requirements. The ability to see the photos and reports associated with a piece of debris and the ability to search and export results was very helpful.

The CRDS Team was very receptive to the user's needs by continually addressing issues and by adding new functionality to the system. Enhancements were made throughout the entire life of the reconstruction project, and were normally incorporated within a day or two of the request. The team stayed in constant communications with the user community to ensure any issues that arose were addressed as quickly as possible. The team also consistently supported the user community by providing custom reports for data not readily available from the standard query reports provided via the web page.

However, as helpful as the database was, it was only as good as the data being entered into it. A standard vocabulary list and structured description fields could have been created and applied to every debris item. These key words and descriptions would have aided in database searches. In addition, the initial field identifications were only valuable until a more exact identification could be made. Once made, the initial field identification should have been overwritten with the correct assessment.

...Consider innovative technologies...

The potential of 3-D scanning was demonstrated in the scope of the virtual 3D reconstruction product. This pathfinder project demonstrated the concept of virtually reconstructing large sections of a vehicle without requiring a large amount of floor space to do it. The team was able to successfully visualize in 3D most of the left wing, left WLE panels 1 through 22, several pieces of the left mid-fuselage sidewall, the left OMS pod leading edge and the vertical stabilizer leading edge. Virtual reconstruction was also able to identify six significant debris items: The "Littlefield Tile" and five RCC pieces. Another feature was the ability to reproduce a scanned item in a plastic form. Virtual reconstruction was successful in all of these regards, though its practical application to this investigation was limited.

Texture mapping proved to be very labor intensive. The workload depended heavily on the complexity of the surface shapes of the debris item. Familiarity with the tasks greatly affected the production rate. An outside company had to be hired to produce the majority of the texture-mapped files due to the backlog of work and the available schedule.

Two-way data transfer was a significant obstacle to completing virtual reconstruction due to large file sizes and network bandwidth limitations. Most file transfers were accomplished by hand carried or shipped CD ROM. These files had to be transferred back to KSC for implementation in the visualization applications then stored for back-up and archiving purposes. Eventually the facility network capabilities were enhanced and electronic transfer became possible between two different on-site facilities at KSC only. However, secure cross-country data transfer of large data files from KSC was never consistently accomplished during reconstruction.

The Reconstruction Team recognizes the two tremendous potentials for 3-D scanning. The first potential is reverse engineering to identify parts. The second one gives people who cannot travel to see the items in person the ability to visualize debris (in either individual items or in a reconstructed section). The 3-D scanning effort realized the first potential to some extent and the second one late in the investigation. If 3-D scanning can be made cost effective and quickly provide those two things, then the true potential can be realized.

...Let the debris tell its story...

Immediately following the accident, it appeared that the investigation would have to depend solely on analytical methods and most probable scenarios. The assumption was that a significant amount of debris would not be recovered. This initial assumption was due to the altitude of the breakup, reentry heating, and the magnitude of the debris field. However, after one of the most extensive ground searches in history, 38 percent of the orbiter was recovered. In fact, many critical pieces were recovered, identified, and became compelling evidence. Facts began to emerge from the debris regarding the initiation point, damage progression, and severity. This evidence was used to refute or confirm scenarios developed by other branches of the investigation. In the end, the reconstructed debris provided tangible evidence about the initial breach to the orbiter, and proved to be a significant factor in understanding the failure.

As hardware began to arrive at KSC and identification was underway, a process was developed to assess debris items and provide some level of documentation (fact sheet) on their condition. Fact sheets are a fairly standard tool in aircraft accident investigations and are normally just quick notes and sketches of individual items. Investigators use the fact sheets as the basis for their final reports. However, for this accident, fact sheets very quickly mushroomed into an unmanageable task when the Technical Integration Team/OVEWG required briefings and top quality, exacting reports complete with color photos on every item that was of interest. This left no time for individual evaluation of the mass majority of items. As a result the investigation began to outpace the team's ability to prepare fact sheets. The technique was therefore suspended in lieu of broader sub-system or zonal reports. The final report had to be generated without the benefit of a large number of fact sheets as back-up material. Fact sheets would have continued to serve their purpose if an appropriate statusing tool was made available to facilitate technical information exchange among teams.

...Address the medium for technical information exchange...

Most of the system components on the orbiter were identified per drawing with decals, metal tags, or ink stamped over coated surfaces. This made identification very difficult unless the appropriate area on the item was shielded from aerodynamic and thermal effects. Items that had etched part numbers usually required only minimal cleaning to raise the number and were therefore much easier to identify. With respect to TPS, today's convention is to print part numbers on the OML only. Most tile part numbers on the OML were ablated and unreadable. However, many recovered Columbia tiles were identified by the stamped part numbers on the IML; a technique used in the past for array SIP bonds. This duplicate part marking of tile was useful in the identification process.

...Develop survivable part marking...

Search and Recovery Coordination

Communications between the recovery and reconstruction teams was imperative to operations. Initially, during the planning phase of reconstruction as processes were being established, the recovery team provided insight into the condition and hazard level of debris to be shipped to KSC. The day-to-day operations of the two efforts required a constant exchange of information concerning truck delivery schedules, hazardous debris handling, sensitive shipments, fast track items, and equipment exchanges.

...Foster communication between recovery and reconstruction...

During the continuing debris collection effort, a search coordination function was established to serve as a liaison between the two teams. This function was the conduit for sharing debris identification data with the field recovery teams in an effort to direct search patterns for critical debris. The search coordinators actually rotated assignments between recovery and reconstruction for continuity throughout the process. By coupling the engineering expertise at KSC with the search recovery forces that established air and ground search priorities, emphasis could be placed on recovering much more critical left wing debris and recording devices. It was through these efforts that the OEX recorder was found.

The communication exchange had to continue for the extended collection effort even after the main thrust of recovery was completed. Communications on the transition of authority and coordination of continuing small shipments had to be established.

The process of labeling items in the field as "Fast Track" to increase their priority and speed their identification because of their suspected criticality was useful in

...Prioritize recovered debris carefully...

assisting grid search priorities. However, it was only useful when it was used for a limited number of items. Fast track was to be an exception process. It lost its significance when the majority of parts received were labeled as such, therefore overwhelming the identification pipeline. The recovery forces must have clear guidelines on what to identify as fast track.

Other factors contributed to the success and limitations of the fast track process. Changes in the process were not always communicated immediately between the collection sites, Barksdale, and KSC. Notification of process evolution or changes must be provided to all teams so that a consistent process with consistent tags. Physically attaching visual identifiers to the debris, and then packing all items together on the delivery trucks worked well. Ensure individual items are labeled “Fast Track” in lieu of just labeling the box containing multiple items. As items within these boxes were removed for processing, they were separated and lost their fast track designation.

...Standardize data entry forms for field items...

Accuracy of data entry is the key to database success and is important at all levels of the process, from the initial formation of the record in the field through engineering assessments and storage at the reconstruction site. Consistent data format, particularly GPS coordinates, is vital to a search and recovery effort.

Field recovery teams adopted a variety of formats when entering GPS location data for each recovered piece of debris. This inconsistency was the source of data entry errors as the information was transferred to the EPA and CRDS databases. The actual field data proved to be the best method to resolve latitude/longitude miscompares between in the EPA/Weston database and the CRDS. The further removed the data was from the point of origin the more suspect it became. Field data must always remain with the item or should be properly placed in a library.

The other source of data discrepancy was in the EPA number. CRDS provided a link to the SIDDS via the EPA Field ID number. Due to inconsistent formats and typos of the EPA Field ID, this link was often broken. If the link was broken, CRDS did not have access to critical latitude/longitude information needed for the investigation. CRDS was modified to aid data entry personnel by providing a drop down list of valid EPA Field ID numbers. Although this helped, it did not completely alleviate the problem. There were still multiple items with the same EPA Field ID number and the data entry personnel had to make a ‘best effort’ choice on which one to select. In some cases, items found outside of Texas did not have an EPA Field ID so the link between CRDS and SIDDS did not exist.

...Consider science recovery from the start...

The initial focus, plans, and implementation of the investigation were geared towards Columbia debris recovery and reconstruction. Though STS-107 was a science mission, there were no initial plans or consideration given to implement the return of payload debris to payload investigators for the purpose of science recovery. Although researchers eventually were given access to their science, recognition and a higher priority for the possibility of science recovery may have yielded faster results and possibly even more science recovery opportunities.

Early on, the SSP Payload Integration Office attempted to insulate the reconstruction effort from an onslaught of payload developers to avoid impeding investigation progress. In the end, payload developers that did participate in the reconstruction proved effective in identifying payload components and science recovery. In hindsight, earlier controlled and locally managed developer access to the debris would have expedited payload identification and science recovery.

Because of biological material presence, several science items were held at JSC for up to two months without identification or tracking, and therefore their recovery remained unknown. Once these items were shipped from JSC to KSC, they were immediately identified, and in the case of Biological Research in Canisters (BRIC), some science was recovered.

In addition to delays due to traceability issues, the debris release process delayed possible science recovery. The TAR process and approval loop was laborious and not geared to expedite the rapid return of payload debris to the payload developer. To overcome this delay, a generic TAR was proposed, drafted, and initiated to accommodate the return and science recovery for payloads.

Supporting Processes

...Emphasize security controls...

The entire security process was well organized. The Action Center worked well for badging, especially requiring another photo identification to be exchanged for the temporary hangar badge. Personnel manning the guard gate did a good job of controlling hangar access and of checking for cameras and other items entering the hangar. They also did a good job looking for items leaving the hangar. Finally, the access control monitor process for logging visitors in and out of the hangar and ensuring no debris was removed without proper paperwork worked well.

...Generate a realistic safety plan...

One safety issue that was never adequately resolved was the monitoring of personnel and air within the hangar for hazardous particulates generated from the collection and handling of debris. Safety and Health representatives imposed requirements for daily personnel and area air monitoring of operations inside the Columbia hangar. The original plan was designed around the potential for worst-case friable materials and by-products because of the unknown condition of the debris arriving from the field collection sites.

The Reconstruction Team established an air-monitoring program to gain baseline data on air quality in the hangar. Once some baseline monitoring was performed and the results of the samples showed that particulate counts remained at ambient levels, the Reconstruction Team requested that the Safety and Health organization revisit the plan to see if some of the more stringent requirements for personnel monitoring could be lifted.

Although a revised sampling plan was eventually put in place, there was a great deal of debate within the Safety and Health organization with no clear ruling authority among parties involved to make the appropriate revisions. There remained some confusion over the requirements and the team never did come to consensus on the plan. It is recommended that any future Safety Plan that is geared to address the worst-case scenario also have provisions to allow for modification of the requirements to fit the needs of the operations when warranted.

Debris Handling and Management

...Plan, execute, and adapt the process flow...

The process flow of debris through the hangar was excellent. From unloading off the truck, safety checks, logging in and photographing the debris, assessing the debris, and finally placing it on the grid, the process worked extremely well. The process was robust enough to handle over 83,900 pieces during the three months of debris collection.

Identification of the debris was a meticulous, often tedious and time-consuming process. Material handlers and technicians were brought into the identification process to help reduce the engineering workload. With their specific hands-on vehicle experience, they proved very effective at providing initial assessments and placement of debris.

Other methods used to adapt to the increasing backlog of items in engineering assessment included splitting the process flow so that the identification area was duplicated on the west side of the hangar and all non-airframe debris was routed to the west identification area. This cleared the way for priority processing of airframe and TPS debris.

Based on requirements for safe handling of MMVF, several encapsulation techniques were proposed and tested early in the debris receiving effort. During the course of this testing, protective sealants were sprayed on some recovered debris. This approach was quickly altered to not compromise evidence. This encapsulation technique had the potential for contaminating the surface of debris that would need to be analyzed for chemical composition later in the investigation. The primary and most effective means of encapsulating friable items was by wrapping them in plastic wrap.

General debris cleaning guidelines and guidelines for the handling of friable material should be established in GO0014 – Space Shuttle Salvage Operation Plan. Perhaps the cleaning policy that was finally adopted for the Columbia reconstruction can be made the standard. This would reduce the excessive time required to get approval for cleaning procedures.

...Keep photographs to a minimum, but take the right photographs...

To keep from accumulating a large volume of extraneous photographs, the NTSB cautioned the Reconstruction Team to minimize the number of photographs taken. However, many photos were missing scales/rulers and a significant percentage of the time only one side of the object was photographed. To be more useful items, should be photographed in perspective view, out of bags, with registration marks, preferably in an area with proper lighting, and background. Furthermore, at a minimum, both top and bottom views of a part should be photographed as well as other unique features.

...Adopt a flexible approach to fit the phases of reconstruction...

The approach adopted for Columbia reconstruction called for a 2-D grid of the OML of the vehicle. This approach allowed engineers to view the debris close-up, and made the debris accessible for sampling and forensic analysis. The 2-D grid approach was extremely successful and appropriate up to the point where determining the orientation of the many pieces of debris on the grid became difficult for investigators, especially in the leading edge area of the wings. Therefore, the LH and RH wing grids were modified to highlight the leading edge components. Eventually, critical sections of the LH wing were reconstructed in 3-D using uniquely designed fixtures. The RH wing was reconstructed in 3-D on the floor without the use of fixtures. While not as glamorous, this technique was also useful as a visualization aid, though it hindered viewing the backside of the assembled debris.

The use of 3-D fixtures to integrate debris of the left wing leading edge subsystem in a see-through lexan cover was an excellent idea that quickly led to an improved forensic understanding of the debris evidence. In addition, the development of tables to elevate, and accurately place recovered left wing tiles aided in the evaluation of plasma flow and associated damage to tiles, also enhancing the forensic analysis of the debris. The approach to adapt the reconstruction techniques to accommodate the shape, size, and characteristics of the debris allowed the team to extract the greatest amount of information from the recovered debris.

As population of the grid increased, it became more difficult for some to visualize the debris in its 2-D layout. At this point, members of the CAIB proposed major alterations to the grid. Keeping to the approach to evolve the grid slowly as we gained a better understanding of the debris and not make midstream wholesale changes to the layout saved time, energy, money, and shortened the time required to identify a likely failure mode and cause.

The originally selected 2-D layout was not without its limitations however. First, due to the limits on space, the wing lower surfaces were not placed contiguous with the mating mid-body and aft fuselages. Secondly, the mid-body sidewalls were positioned adjacent to the mid-body lower surface, which further complicated the reconstruction effort. Additionally, this placed the left hand wing at the complete opposite side of the hangar from the right wing, thereby eliminating any potential for easy comparison between the two. It would have been easier to place right wing RCC parts if the right wing and left wing RCC parts were in closer proximity to the unidentified RCC parts racks and RCC identification area. However, several subsequent evaluations of the grid layout failed to produce a better design that could eliminate all the deficiencies without creating other problems.

...Streamline the paper process...

No paper process is without flaws or limitations. The Columbia investigation and the reconstruction effort in particular generated large volumes of paperwork to assure proper tracking and investigation integrity. The reconstruction documentation process was established with the best intentions, but did not result in as streamlined a process as planned or desired. The process turned out to be burdensome, requiring unique procedures (RDS) for the analysis of each component. Each RDS required multiple reviews and signatures before implementation. Generically grouped procedures, or "Bucket RDS's", could have been used for non-destructive, generic failure analyses.

The overarching investigation documentation process - involving Test Approval Requests (TAR) and Hardware Release Requests (HRR) - was usually the cause for delays in accomplishing tasks that had some urgency. Delays of several days were not uncommon throughout the investigation. The Reconstruction Team acknowledges the responsibility of the CAIB to oversee the reconstruction and suggests that more local authority by CAIB resident members would have greatly increased the speed of many test and analysis efforts.

...Develop a standard for handling crew sensitive debris...

The overall handling and management of crew module related debris and items of personnel or sensitive nature was exceptional and accommodated the appropriate level of discretion to protect the interests of NASA and the families. At the outset of the reconstruction, the team developed guidelines for dealing with crew module related debris and items of a personal or sensitive nature. The team used its best judgment in establishing the processes and protocols in the absence of prescribed standards. The team's recommendation is to craft a NASA standard for future investigations dealing with legal status and handling of crew personal effects, handling of sensitive items like crew helmets, physical access to the crew module related debris, and accessibility of data records and photographs. Discussed below are some of the issues encountered during the effort.

It was decided early on that the crew module debris would be reconstructed separate from the rest of the Orbiter behind closed doors and by a select group of people. Most of the investigators examining the general Orbiter structure were not allowed access to the crew module area and those working on the crew module did not spend much time working with the rest of the vehicle. Understandably, there were some sensitivity issues that had to be taken into consideration when dealing with the human aspect of space flight, but it was very difficult to determine failure scenarios when only looking at a fraction of the debris for the forward section of the vehicle. Strictly from an investigative perspective, it was burdensome having the interior crew module structure segregated from the rest of the structure and only observable to a select few.

Initially, the CAIB and MRT/NAIT provided little direction concerning the level of investigation to be performed on the crew module. Much later in the overall investigation, NASA chartered an official crew module investigation without disclosing the initiative to Reconstruction Team management. Up until this point, the Reconstruction Team had begun a “grass roots” investigation, adopting the processes, knowledge, and techniques of the broader reconstruction effort. An earlier understanding of the crew module reconstruction initiative could have facilitated the investigation.

A critical issue to the crew module team became the wide access to the database enjoyed by NASA employees and contractors. This access was useful because it enhanced the identification and investigation process, but it also created the potential for inappropriate levels of information to be available to people without a need to know.

In order to address this concern, there were a few database features provided. First, a secure text field called “Crew Module Description” was provided. Also, all pictures of items inside the crew module were put into a secure bin called “Crew Module Photos”. Approximately 30 people, including the crew module team and the crew module investigation team, were allowed access to both the text field and the photos. Although this did limit the ability of engineers at JSC to evaluate hardware from a distance, the benefits far outweighed the disadvantages. There were always a few people with access at JSC who could access the pictures if needed, and pictures were emailed when needed for identification. Personal items photographs were not entered into the database at all; they were stored on a secure JSC server.

Definitions

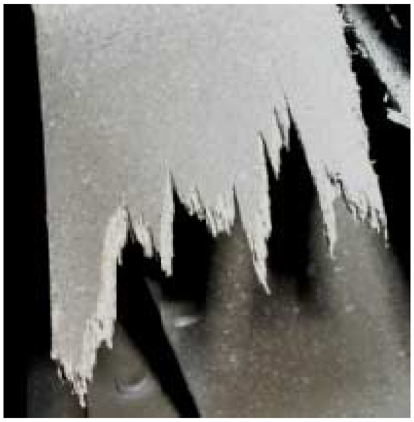
Ablation – Melting of material due to heat and airflow generated by atmospheric friction during re-entry.

Backside Heating - Separation of tile from structure that occurs at the primer interface due to internal vehicle heating. Item 57481 shown

Backside Heating

Ballistic Coefficient - Ratio of mass to surface area that governs the re-entry trajectory, velocity and heating of an object.

Broomstraw - Type of aluminum alloy fracture due to a high temperature failure of the material where there is incipient melting along the grain boundaries. At high temperatures very little applied stress is needed to fracture the material. Item 105 shown.



Broomstraw

Erosion - Gradual loss of material by aerodynamic abrasion.

Friable - Material that can be easily broken down into small particles or powder.

Glassification - Melting of the base silica material of a tile forming glass when subjected to temperatures over 3000 degrees Fahrenheit. The RCG must be damaged or missing for this to occure.

Glassification

Ground Impact Damage – 1. Damaged surface of tile where the exposed silica is soft and has no glassification, normally associated with ground impact.
2. Deformation of non-TPS components associated with ground impact.

Inner Mold Line – 1. The bottom surface of TPS that is bonded to the structure.
2. Internal structural surface that comprises the outer shell of the vehicle.

In-Plane TPS Fracture

In-Plane TPS Fracture - Tile fracture

Overload Fracture

Primer-to-Primer Failure

Sawtooth Fracture

Slumping

occurring about 0.10 inches above the IML just above the densified portion of the tile. Also known as densification layer failure.

Liquification - Melting and separation of RCG from the tile base material that pools onto the OML .
(See glassification image item 33590)

Outer Mold Line –
1 The TPS outer surface exposed to the airflow
2. The structure surface in which TPS is bonded.
3. Structure with TPS bonded which makes up the outer shell of the vehicle.

Overload Fracture - Failure when the applied stress exceeds the material allowable, typically in ductile materials, with a fracture face on a 45-degree shear plane and associated with crisp (unablated) fracture surfaces, tearing of machined stringers, or skin fracture along fastener rows. Item 2436 shown.

Primer-to-Primer Failure - Separation between two coats of epoxy primer, normally associated with back side heating. Item 283 shown.

Sawtooth Fracture – Fracture characterized by a saw blade appearance. May or may not be associated with a fastener row. Item 52981 shown.

Slag - Deposits of molten material present on the debris

Slumping - Melting of the RCG coating combined with substrate collapse when the tile is subjected to temperatures above 3100 degrees fahrenheit. Item 76761 shown.

RCC Sampling

PHASE I SAMPLING

Phase I sampling involved the extraction of only Type I samples to preserve critical hardware and establish trend markers through various analytical techniques. This activity served as a benchmark for identifying techniques that could be used to obtain meaningful results for future sampling and analysis.

A total of 8 RCC pieces were sampled and 53 samples were taken. They are summarized in Table I.

Analytical Techniques – Phase I

The analysis techniques and the information it would provide are summarized below. Alternative techniques where feasible are also identified.

1. Optical photography of top and bottom surfaces of the sample. Purpose of this technique was to document unique features of the sample.
2. Scanning Electron Microscopy/Energy Dispersive Spectroscopy (SEM/EDS) of top and bottom surface of deposit. Initial elemental analysis on top and bottom surface may suggest layering through thickness based on the differences in the analysis. This technique uses electrons for imaging and resultant x-rays for chemical analysis. The beam penetrates to shallow depths on the surface. It is well known that an EDS spectrum is sensitive to many external parameters and quantitative reproducibility is not the greatest asset. The method is more efficient in identifying the elements present and their ranges of composition in categories of “major”, “minor”, and “trace”. However, quantification of the spectra was the
3. only way of representing and effectively communicating the data to a larger audience. It was accepted that the Analysis results in only semi-quantitative elemental composition of the area analyzed.
4. Electron Spectroscopy for Chemical Analysis (ESCA) or X-ray Photo-electron spectroscopy (XPS). The purpose of this technique is to identify compounds on the surface. This technique essentially establishes the shift in elemental binding energy. Upon

Item #	RDS #	Sample ID	Part	Current Location
2200	2200-3	A1-A3, B1,B2,D1	RCC	Left Panel 8 Upper
18477	18477-1	A1-A3, B1, C1, C2, D1, E1-E4	RCC	Left Panel 8
1419	1419-1	A1-A4	RCC	Right Panel 8
16523	16523-1	A1-A4	RCC	Right Panel 8
24732	24732-1	A1-A5	RCC	Left Panel 5
853	853-1	A1,A2,B1,C1,D1-D3, E1-E3, F1	Fitting	Left Upper Spar Attach Fitting Panel 3
24543	24543-1	A1-A5	LESS Carrier Panel	Lower Left #2
24086	24086-1	A1-A4	LESS Carrier Panel	Lower Left #1

Appendix B Table 1 - Phase I Sampling Matrix comparing this shift with known compounds, compound identification can be made. In this technique the beam only penetrates the first few layers of atoms on the surface. It is not a through-thickness technique. An alternative technique is powder X-ray diffraction where crystalline compounds can be identified directly. Moreover, XRD is a bulk technique that is destructive to the sample.

4. Fourier Transformation Infra-red (FTIR) Spectroscopy was identified as a technique for analysis of organic deposits. This technique was not required in any analysis.
5. Destructive cross sectioning combined with SEM/EDS dot maps can help identify layering of compounds through thickness. However, this technique is also subject to the limitations of SEM/EDS. It was known that microprobe analysis provides more accurate local compositions and could be effectively used in combination with SEM/EDS to determine distribution of material in the cross-section. The limitations of microprobe analysis are that it requires a polished sample, the analysis is more accurate at higher magnifications, and is not the best tool for imaging. None of the local labs had an operational microprobe. Therefore, as the analysis approached this step, a decision was made to send it to another NASA lab that had the right facility.
5. Another destructive technique was the bulk chemical analysis of samples. All other techniques listed above are surface analysis techniques. This technique was considered as a last technique because in its destructive nature, it consumed the sample. A significant limitation of this technique for the application is that the slag deposit could not be standardized. It was also important prior to using these techniques to find out what elements and compounds are present by above analysis. Thus, this technique was the last resort.

Phase I Results

1. SEM/EDS analysis of metallic slag provided information on the types of elements present, including oxygen. Their semi-quantitative analysis suggested the levels of each element present. It was immediately clear that there were differences between the top and bottom surfaces of the slag suggesting cross-sections to obtain through-thickness information. It was also clear that the elements identified in the slag were consistent with the elements present in leading edge materials. However, due to limitations of the information this technique provides, it was recommended not to carry forward in Phase II analysis. KSC reports that summarize Phase I results are KSC-MSL-2003-0137, KSC-MSL-2003-0143, KSC-MSL-2003-0144, KSC-MSL-2003-0145, KSC-MSL-2003-0148, KSC-MSL-2003-0149, KSC-MSL-2003-0150, KSC-MSL-2003-0167.
2. ESCA analysis suggested the presence of compounds. In addition to metallic elements, compounds identified were oxides such as Al_2O_3, Fe_2O_3, Cr_2O_3, and Ni-Aluminides. No nitrides were identified. Once again the results are summarized in individual reports and are consistent with leading edge materials and their possible reaction products. For verification of results, parts of the samples were sent to GRC for reproduction where a powder diffractometer was utilized as an alternative technique. ESCA results at GRC matched in principle with results obtained at KSC. However, the powder diffraction method was more successful in identifying bulk crystalline compounds. It identified the presence of crystalline mullite, Ni-aluminides and other compounds. It was decided that powder diffraction technique was more powerful and sensitive and will be

utilized for the phase II analysis. ESCA was chosen not to be utilized for phase II analysis. KSC reports that summarize phase I results are KSC-MSL-2003-0137, KSC-MSL-2003-0143, KSC-MSL-2003-0144, KSC-MSL-2003-0145, KSC-MSL-2003-0148, KSC-MSL-2003-0149, KSC-MSL-2003-0150, KSC-MSL-2003-0167.

3. The FTIR technique was not utilized because no organic compounds appeared to be present.
4. Cross-sectioning and dot mapping of elements clearly showed distribution and layering of elements (and possibly compounds). However, the technique lacked the detail that would be necessary to identify the source of the deposits and exact content of layering. Accurate compositional analysis by microprobe was required. Several cross-ectioned and mounted samples were sent to NASA MSFC and NASA GRC for microprobe analysis. The results were conclusive and solidified the position that cross sectioning with SEM/EDS dot maps, followed by point microprobe analysis will provide the best content and layering information. The interpretative findings from GRC analysis were very similar to those at MSFC despite different samples. This further attested to the reproducibility aspect of the technique. The relevant reports that summarize Phase I results are KSC-MSL-2003-0137, KSC-MSL-2003-0143, KSC-MSL-2003-0144, KSC-MSL-2003-0145, KSC-MSL-2003-0148, KSC-MSL-2003-0149, KSC-MSL-2003-0150, KSC-MSL-2003-0167, MSFC-ED33-2003-063, MSFC-ED33-2003-064, GRC (CT-050103-2C, -2D, CT-050903-3C, 3D, CT-051203-5C, -5D).
5. No bulk chemical analysis was done because of technical hurdles of standardizing the sample and the ability to get point information from the above techniques.

Standards Verification of Techniques Selected

An important aspect of using an analysis technique is its verification by known standards. This underscores the emphasis on accurate interpretation due to confidence in results. Once it was decided that electron microprobe analysis would be used for more accurate local compositional analysis, selected standards were purchased and the equipment calibrated. Metallic analyses were compared against pure metal and IN718 standards. A 100-point average statistical method was used for calibration. Oxide analysis was compared with mainly oxide standards. The analysis indicates that the results varied from standards from 0.5% to 25% depending on the amount of element present. For greater than 1% by weight element composition in standard, the analysis error was maximum of 5%. For less than 1% by weight element composition in standard, the analysis error could be as high as 25%. The variations in oxide standards and analysis results were in similar ranges. The details are presented in MSFC-ED33-2003-065 and GRC reports CT-051203-8C, -8D.

PHASE II SAMPLING PLAN

Phase II sampling plan was generated based on the success of radiography in identifying “heavy material”. The decision was made to sample with RCC intact. It was also agreed that two samples in close proximity could be taken for X-ray diffraction and cross sectioning. This will help save time.

The sampling procedure that worked successfully was a diamond cutter wheel on a Dremel tool. The Dremel tool operated at 20,000 rpm and took about 15 minutes of cutting per sample. There was minimal heating of the part, and the part was warm to the touch after cutting. A vacuum was operated to collect the dust generated. A1"X1.25" sample was taken and a 0.25"

Part #	RDS #	Sample ID	Part	Deposit Features
55083	55083-2	A1, A2, B1, B2, C1, C2	LH RCC #5 upper	Uniform deposit with some small globular nature at the apex of the panel. Sample A was taken in region of globular deposit. Other samples were taken in areas of thin sketchy deposits.
31985	31985-2	A1, A2, B1, B2, C1, C2	LH RCC #7 Upper panel	Sample A and B were taken from the panel with more uniform deposit. Sample C was taken from the inboard rib with thicker deposit indicating some directionality to the deposit.
2200	2200-6	A1, A2, B1, B2, C1, C2	LH RCC #8, Upper panel	Samples A and B were taken from the apex area which show globular deposits. Sample C was taken in location having spheroids as seen in the radiograph.
18477	18477-5	A1, A2, B1, B2	LH RCC #8, Upper panel	Sample A was taken in region of uniform deposit not having any other unique features. Sample B was taken in a region with more spheroids in an effort to take more specimens with spheroids
43709	43709-2	A1, A2, B1, B2	LH RCC #8, Upper panel	Sample A was taken in a very thick “Tear” region. Sample B was taken in a thin “Tear” region.
61143	61143-2	A1, A2	LH RCC #8 Upper Rib	Deposits exist on inbd and otbd side. Both surfaces will be analyzed. The deposit shows uniform nature and spheroid features.
1419	1419-3	A1, A2, B1, B2	RH RCC #8 Upper Rib	Uniform deposit. No special feature to deposit identified in radiographs.
16523	16523-4	A1, A2	RH RCC #8 Upper panel	Uniform deposit. No special feature to deposit identified in radiographs.

Appendix B Table 2 - Phase II Sampling Matrix

X 0.25" piece was cut for x-ray diffraction. The samples were photographed at every step and documented in the reconstruction database. They were boxed in a petri dish and held down with Kapton tape for transportation. They were also radiographed post-cutting. These radiographs were used as a guide to decide where exactly to take the cross-section.

Table 2 details the number of samples taken. Sample “1” will be cross-sectioned and sample “2” will be x-ray diffraction tested.

PHASE III SAMPLING PLAN:

Based on the additional questions, additional parts were sampled. Their samples taken are described in Table 3 below.

Part #	RDS #	Sample ID	Part	Comments
2200	2200-XY	A1	LH RCC #8 Apex	Bluish green deposit on the outer surface of the apex.
18477	18477-XY	A1,A2	LH RCC #8 Upper panel	Sample is being taken close to spar fitting attachment location. Objective is to look for A286.
24724	24724-XY	A1, A2, B1	LH RCC #8, Lower heel	Sample A was taken to find evidence of A286 and study the RCC degradation. Sample B is flaked off deposit from rib surface.
7025	7025-XY	A1, A2	LH RCC #9, Upper inbd rib	The rib has deposits on inside and outside surfaces and is located on previously un-analyzed RCC 9. The sample shows some spheroids.
29741	29741-XY	A1, A2	LH RCC #9, Upper obd rib	Sampling of RCC Panel 9 for slag content and layering.
38223	38223-XY	A1, A2, B1, B2	LH RCC #9 Upper panel	Sampling of RCC Panel 9 for slag content and layering.
80632	80632-XY	A1, A2, B1, B2	LH RCC #4 Upper	Sampling of RCC Panel 4 for slag content and layering. Compare analysis with LH RCC Panels 5,7.
1860	1860-XY	A1, A2	Unknown	Sample has spheroids and hole in RCC through which material is seen coming out. Can slag sampling help locate it to LH RCC 9.

Appendix B Table 3 - Phase III Sampling Matrix

APPENDIX C

Acronyms

ACGIH	American Conference of Governmental Industrial Hygienists
ACM	Access Control Monitor
ADP	Air Data Probe
AMEC	Advanced Master Events Controller
APU	Auxiliary Power Unit
ARC	Ames Research Center
ASA	Aero-surface Amplifier
ATOS	Advanced Topometric Optical Scanner
ATVC	Ascent Thrust Vector Control
AWCS	Automated Work Control System
BAFB	Barksdale Air Force Base
BRIC	Biological Research in Canisters
BSTRA	Ball Strut Tie Rod Assembly
CAD	Computer Aided Drafting
CAIB	Columbia Accident Investigation Board
CBX-2	Critical Viscosity of Xenon
CCCD	Crew Compartment Configuration Drawing
CCTV	Closed Circuit Television
CM	Combustion Module
CRDS	Columbia Reconstruction Data System
CRO	Columbia Recovery Office
CT	Computed Tomography
CTF	Columbia Task Force
CVAS	Configuration Verification Accounting System
DAWG	Debris Assessment Working Group
DBA	Database Administrator
DHCP	Dynamic Host Configuration Protocol
EA	Electronic Assembly
ECLSS	Environmental Controls and Life Support Systems

EDO	Extended Duration Orbiter
EMS	Experiment Module
EMU	Extravehicular Mobility Unit
EPA	Environmental Protection Agency
ESCA	Electron Spectroscopy for Chemical Analysis
ET	External Tank
EVA	Extravehicular Activity
FC	Fuel Cell
FCOD	Flight Crew Operations Directorate
FCPA	Fluid Control and Pump Assembly
FCS	Flight Crew Systems
FDEP	Florida Department of Environment Protection
FDF	Flight Data File
FDM	Frequency Division Multiplexer
FIB	Fibrous Insulation Blanket
FRCS	Forward Reaction Control System
FREESTAR	Fast Reaction Experiment Enabling Science, Technology, Applications and Research
FRSI	Felt Reusable Surface Insulation
FTE	Full Time Equivalent
FTIR	Fourier Transform Infrared Spectroscopy
GAS	Get-Away Special
GFE	Government Furnished Equipment
GH2	Gaseous Hydrogen
GIS	Geographical Information Systems
GN2	Gaseous Nitrogen
GNC	Guidance, Navigation and Controls
GO2	Gaseous Oxygen
GPC	General Purpose Computer
GPS	Global Positioning Satellite
GRC	Glenn Research Center

GSFC	Goddard Space Flight Center
HEPA	High Efficiency Particle Air (filter)
HFT	Hardware Forensics Team
HMIS	Hazardous Material Inventory System
HRSI	High Temperature Reusable Surface Insulation
HUDE	Heads Up Display Electronics
HYD	Hydraulics
IML	Inner Mold Line
IP	Internet Protocol
IPA	Isopropyl Alcohol
IRF	Item Release Form
IT	Information Technology
JSC	Johnson Space Center
KSC	Kennedy Space Center
LACB	Landing Aids Control Building
LAN	Local Area Network
LaRC	Langley Research Center
LESS	Leading Edge Sub-System
LH	Left Hand
LH2	Liquid Hydrogen
LO2	Liquid Oxygen
LRSI	Low Temperature Reusable Surface Installation
M&P	Materials and Processes
MAC	Machine Address Code
MADS	Measurement and Acquisition Data Systems
MAR	Middeck Access Rack
MDM	Multiplexer De-Mulitiplexer
MESS	Large Stowage Rack
MIT	Mishap Investigation Team
MLG	Main Landing Gear
MLGD	Main Landing Gear Door

MMT	Mission Management Team
MMVF	Man Made Vitreous Fibers
MPM	Manipulator Positioning Mechanism
MPS	Main Propulsion System
MRT	Mishap Response Team
MSFC	Marshall Space Flight Center
NAIT	NASA Accident Investigation Team
NASA	National Aeronautics and Space Administration
NDE	Non-Destructive Evaluation
NHA	Next Higher Assembly
NSLD	NASA Shuttle Logistics Depot
NTSB	National Transportation Safety Board
NWA	Nose Wheel Assembly
OCN	Order Control Number
ODIN	Outsourcing Desktop Initiative
OEL	Orbiter Electrical
OEX	Orbiter Experiment Recorder
OFK	Official Flight Kit
OML	Outer Mold Line
OMS	Orbital Maneuvering System
OPF	Orbiter Processing Facility
ORB	Orbiter
OSHA	Occupational Safety and Health
OVEWG	Orbiter Vehicle Engineering Working Group
PAO	Public Affairs Office
PCM	Pulse Code Multiplexer
PCPA	Pressure Control and Pump Assembly
PDA	Personal Digital Assistant
PEL	Permissible Exposure Limit
PGSC	Payload and General Support Computers
PIM	Payload Integration Management

PLBD	Payload Bay Door
PPE	Personal Protective Equipment
PPK	Personal Preference Kit
PRSD	Power Reactant Storage and Distribution
PRT	Prevention/Resolution Team
PSA	Port Stowage Assembly
PVD	Purge, Vent and Drain Systems
QA	Quality Assurance
QC	Quality Control
RCC	Reinforced Carbon Carbon
RCG	Reaction Cured Glass
RCS	Reaction Control System
RDM	Responsible Data Manager
RDM	Research Double Module
RDS	Reconstruction Documentation Sheet
RH	Right Hand
RLV	Reusable Launch Vehicle
RMT	Recovery Management Team
RRT	Rapid Response Team
RSB	Rudder Speed Brake
RTV	Room Temperature Vulcanizing
SAM	Sub-system Area Manager
SDS	Shuttle Drawing System
SEG	Similar Exposure Group
SFOC	Space Flight Operations Contract
SGS	Space Gateway Services
SIDDS	Shuttle Interagency Debris Database System
SILTS	Shuttle Infra-red Leeside Temperature Sensor
SIMS	Still Image Management System
SIP	Strain Isolation Pad

SLF	Shuttle Landing Facility
SOFBALL	Structure of Flame Balls at Low Lewis-Number
SPA	Signal Processing Assembly
SQL	Structured Query Language
SRF	Sample Release Form
SRIL	Significant Recovered Items List
SSME	Space Shuttle Main Engine
SSP	Space Shuttle Program
STS	Space Transportation System
TAR	Test Approval Request
TCS	Thermal Control System
TIPS	Thermal Information Processing System
TLV	Threshold Limit Value
TPS	Thermal Protection System
TPSF	Thermal Protection System Facility
TVC	Toxic Vapor Check
TWA	Time Weighted Average
USA	United Space Alliance
VAB	Vehicle Assembly Building
VCD	Vapor condensation Distillation
VITO	Vehicle Integration Test Office
VPN	Virtual Private Network
VRML	Virtual Reality Modeling Language
WDS	Wavelength Dispersive Spectroscopy
WLE	Wing Leading Edge
XPS	X-Ray Photoelectron Spectroscopy
XRD	X-ray Diffraction
ZCG	Zeolite Crystal Growth

Great hearts, hands, and minds devoted their talents to this reconstruction in honor of Columbia, her crew, and their loved ones.