Shuttle Columbia Accident Investigation – Final findings

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Some seven month after the loss of Space Shuttle Columbia on 01 February 2003 at around 14:00 UTC (GMT) – 16 minutes prior to a scheduled landing at the Kennedy Space Center –, the root cause of the accident has been identified as insulating foam breaking away from the external tank's left bipod ramp structure at 82 seconds after lift-off. A sizable chunk of foam debris hit the vulnerable lower side of the left wing near one of the U-shaped leading edge panels, punching a larger hole in this vital heat protection element. The crew of seven astronauts on mission STS-107 died when – as a consequence of the foam shedding during ascent – the doomed orbiter disintegrated during re-entry over central Texas.

A seven month long accident investigation was undertaken by the Columbia Accident Investigation Board's (CAIB) 13 principal members, more than 120 investigators, and 400 NASA and contractor employees. The final findings have been published by the CAIB on 26 August 2003 [3].

Summary of near-term recommendations issued by the CAIB

The Columbia Accident Investigation Board in its Report Volume 1 [3] makes 29 recommendations addressing near-term return-to-flight (RTF) issues, mid-term requirements for a reshuffling of NASA, and a long-term reorientation in US space policy.
The following 15 recommendations with a RTF objective – cited from the CAIB report [3] indicating the number in () – relate to the thermal protection system, imaging, bolt catchers, closeouts, foreign object debris, scheduling, training, organization and closeout photos (drawing system):

- "Initiate an aggressive program to eliminate all External Tank Thermal Protection System debris-shedding at the source with particular emphasis on the region where the bipod struts attach to the External Tank." (R3.2-1)
- "Develop and implement a comprehensive inspection plan to determine the structural integrity of all Reinforced Carbon-Carbon system components. This inspection plan should take advantage of advanced non-destructive inspection technology." (R3.3-1)
- "Initiate a program designed to increase the Orbiter's ability to sustain minor debris damage by measures such as improved impact-resistant Reinforced Carbon-Carbon and acreage tiles. This program should determine the actual impact resistance of current materials and the effect of likely debris strikes." (R3.3-2)
- "Upgrade the imaging system to be capable of providing a minimum of three useful views of the Space Shuttle from liftoff to at least Solid Rocket Booster separation, along any expected ascent azimuth. The operational status of these assets should be included in the Launch Commit Criteria for future launches. Consider using ships or aircraft to provide additional views of the Shuttle during ascent." (R3.4-1)
- "Provide a capability to obtain and downlink high-resolution images of the External Tank after it separates." (R3.4-2)
- "Provide a capability to obtain and downlink high-resolution images of the underside of the Orbiter wing leading edge and forward section of both wings' Thermal Protection System." (R3.4-3)
- "Test and qualify the flight hardware bolt catchers." (R4.2-1)
- "Require that at least two employees attend all final closeouts and intertank area hand-spraying procedures." (R4.2-3)
- "Kennedy Space Center Quality Assurance and United Space Alliance must return to the straightforward, industry-standard definition of 'Foreign Object Debris' and eliminate any alternate or statistically deceptive definitions like 'processing debris'." (R4.2-5)
- "Adopt and maintain a Shuttle flight schedule that is consistent with available resources. Although schedule deadlines are an important management tool, those deadlines must be regularly evaluated to ensure that any additional risk incurred to meet the schedule is recognized, understood, and acceptable." (R6.2-1)
- "Implement an expanded training program in which the Mission Management Team faces potential crew and vehicle safety contingencies beyond launch and ascent. These contingencies should involve potential loss of Shuttle or crew, contain numerous uncertainties and unknowns, and require the Mission Management Team to assemble and interact with support organizations across NASA/Contractor lines and in various locations." (R6.3-1)

- "Modify the Memorandum of Agreement with the National Imagery and Mapping Agency to make the imaging of each Shuttle flight while on orbit a standard requirement." (R6.3-2)
- "For missions to the International Space Station, develop a practicable capability to inspect and effect emergency repairs to the widest possible range of damage to the Thermal Protection System, including both tile and Reinforced Carbon-Carbon, taking advantage of the additional capabilities available when near to or docked at the International Space Station.
  For non-Station missions, develop a comprehensive autonomous (independent of Station) inspection and repair capability to cover the widest possible range of damage scenarios.
  Accomplish an on-orbit Thermal Protection System inspection, using appropriate assets and capabilities, early in all missions.
  The ultimate objective should be a fully autonomous capability for all missions to address the possibility that an International Space Station mission fails to achieve the correct orbit, fails to dock successfully, or is damaged during or after undocking." (R6.4-1)
- "Prepare a detailed plan for defining, establishing, transitioning, and implementing an independent Technical Engineering Authority, independent safety program, and a reorganized Space Shuttle Integration Office as described in R7.5-1, R7.5- 2, and R7.5-3. In addition, NASA should submit annual reports to Congress, as part of the budget review process, on its implementation activities." (R9.1-1)
- "Develop an interim program of closeout photographs for all critical sub-systems that differ from engineering drawings. Digitize the closeout photograph system so that images are immediately available for on-orbit troubleshooting." (R10.3-1)

Rescue scenarios for STS-107

The possibilities for rescue or on orbit repair have been studied by a NASA team on request by the CAIB. The two considered options were based on the assumption that the severity of Columbia's wing damage could have been determined on flight day five through imaging from Earth or a spacewalk by the Columbia crew. Based on consultations with flight surgeons, an extension of the STS-107 mission until flight day 30 (15 February 2003) was deemed possible through limiting of crew activity.

On orbit repair of Columbia's damaged left wing would have involved:
- a spacewalk of two astronauts to fill an assumed 15 cm (6 in) hole in an RCC panel with heavy metal material and titanium pieces;
- fitting of a water-filled bag, that would have frozen in orbit, helping to restore the wing leading edge geometry, limiting aerodynamic forces and resulting heating for a modified re-entry; and
- crew bailout after the shuttle passing the re-entry.

The CAIB report [3] states that "The repair option, while logistically viable using existing materials onboard Columbia, relied on so many uncertainties that NASA rated this option 'high risk'." (F6.4-1)

Rescue of the STS-107 crew with shuttle Atlantis would have required:
- accelerated processing of shuttle Atlantis (on Columbia's flight day five it was 40 days from its scheduled STS-114 launch on 1 March 2003);
- to ready Atlantis for a launch by 10 February with a five day launch window until 15 February;
- to launch the second shuttle with a crew of four (commander, pilot, and two astronauts trained for spacewalks) for rendezvous with Columbia with the two vehicles manoeuvring to face each other with their payload bay doors open;
- to transfer astronauts via spacewalks using ropes; and
- Atlantis to return with four astronauts on the flight deck and seven on the mid-deck.

The abandoned Columbia would have been configured to either reaching a higher orbit to leave open the chance for later repair, or would have been forced into a de-orbit to ditch in the Pacific Ocean.
The CAIB report [3] concludes that "If Program managers were able to unequivocally determine before Flight Day Seven that there was potentially catastrophic damage to the left wing, accelerated processing of Atlantis might have provided a window in which Atlantis could rendezvous with Columbia before Columbia's limited consumables ran out." (F6.4-2)

Summary of accident data and latest findings in the investigation

- Nominal Entry Interface (EI) point was at 13:44:09 UTC northwest of Hawaii over the Pacific. Altitude 120.399 km (395,010 ft) at Mach 24.56.
- First unusual readings of four sensors, all either inside or outside the left wing leading edge spar, were recorded at 13:48:39 UTC by the Modular Auxiliary Data System (MADS). However, these readings were not transmitted by telemetry to ground controllers or displayed to the shuttle crew.
- Shuttle entered the region of maximum heating at 13:50:53 UTC. Altitude was 74.081 km (243,048 ft) at Mach 24.12. This period of peak heating typically lasts some 10 minutes, and puts the highest thermal stresses on the vehicle's thermal protection system (TPS).
- Sudden temperature spikes began at 13:51:09 UTC, according to readings from the recovered OEX (Orbiter Experiment Support System) flight data recorder, confirming pre-existing damage to the orbiter.
- Earliest known off-nominal external event during re-entry, which had been confirmed by telemetry, occurred at 13:51:19 UTC, or more than eight minutes before loss of signal while approaching the California coastline north of San Francisco (73.513 km / 241,186 ft at Mach 23.97).
- Aerodynamic roll and yaw forces began to differ from those on previous flights at about 13:52:29 UTC.
- At 13:53:24 UTC, Columbia crossed the California borderline.
- First of 16 early debris separations observed at 13:53:46 UTC over California.
- Temperatures in the left wheel well began to rise sharply at 13:54:10 UTC.
- Re-entry appeared normal until 13:54:24 UTC, when Mission Control detected the first anomalous readings for four hydraulic sensors in the left wing.
- Around 13:54:33 UTC, the first of several bright flashes in the orbiter's contrails were observed.
- At 13:58:20 UTC, travelling at 63.947 km (209,800 ft) and Mach 19.5, Columbia crossed from New Mexico into Texas. About this time a ceramic TPS tile, which was the most westerly piece of debris that has been recovered, was shed from the orbiter.
- At 13:59:06 UTC, the left main landing gear downlock position indicator reported that the gear was now down and locked.
- Loss of Signal (LOS) in Mission Control Center, Houston occurred at 13:59:32.136 UTC. Altitude 61.173 km (200,700 ft) at Mach 18.1 near Dallas, Texas.
- First large piece of debris ("A") departed from the shuttle at 14:00:02 UTC. Two more large debris chunks ("B"&"C") broke off 15 and 16 seconds, respectively, later.
- Loss of vehicle control occurred at 14:00:19.44 UTC. At this time the MADS stopped recording.
- Orbiter main body break-up occurred at 14:00:21 UTC, some 32 seconds before the shuttle would have passed the peak heating portion of the re-entry.
- No earlier than approximately at 14:12:30 UTC – some 12 minutes after Columbia disintegrated – the Mission Control team received an outside call via mobile phone informing about television coverage of the shuttle's crash.
- A Crew Survivability Working Group, formed by NASA on request by the CAIB, calculated that the destruction of the crew module happened over a 24 second period between 14:00:57 UTC and 14:01:21 UTC at an altitude between 42.273 km and 32.151 km (138,690 ft to 105,483 ft).
- More than 84,000 pieces of confirmed shuttle items (over 38,510 kg / 84,900 lbs) have been recovered in total, amounting to 38% of the craft's dry weight. The bulk of debris has been found from central Texas to western Louisiana, while parts began shedding of the vehicle as early as over California. No confirmed piece of debris has been found west of Littlefield, Texas or farther east than Fort Polk, Louisiana, though investigators had hoped to collect clues in California, Nevada, Arizona or New Mexico.
- In excess of 25,000 recovery team members have searched around 2,850 km² (over 704,000 acres) by foot. Ground and air personnel have searched in total some 9,300 km² (more than 2.3 million acres). The main debris search corridor was a 16 km by 386 km (10 mi by 240 mi) strip, extending from Ellis County, Texas to Toledo Bend Reservoir on the Texas/Louisiana border. Search operations in Texas, Louisiana, California and New Mexico have been concluded by end-May. However, searches continued in Nevada and Utah for some time.

- The Federal Emergency Management Agency (FEMA), which coordinated the overall effort, spent more than $305 million to fund the search, not counting NASA expenditures on aircraft support or the wages of search personnel and analysis team members.
- Three chunks of foam insulation from Columbia's external tank came off 81.9 seconds into the lift-off on 16 January 2003, hitting the orbiter's left wing leading edge at a speed of approximately 850 km/h (528 mph). Originally assessed as being too lightweight to impose substantial damage to ceramic tiles or leading edge reinforced carbon-carbon (RCC) panels, the main piece of foam debris has been calculated to be 19,700 cm^3 (1200 cu in) large and 0.75 kg (1.67 lb) heavy. The foam shedding now is considered being the initiating event which led to the destruction of the orbiter.
- One or multiple breaches to the left wing leading edge occurred in the vicinity of the lower half of RCC panel 8. Superheated gases penetrated the leading edge insulation and progressively destroyed the aluminium wing structure, which has a melting point of 650°C (1200°F). The extremely hot air entered the shuttle's left main landing gear compartment where it exceeded 1,650°C (3,000°F). Two vents in corners of the landing gear door then allowed hot gas to spray out, leaving molten aluminium on the orbiter's underside as confirmed by collected debris.
  The unusual heat-up of the wing box subsequently led to loss of structural integrity until increasing aerodynamic forces caused loss of control, failure of the wing, and break-up of the Orbiter.
- A shuttle flight data recorder (Orbiter Experiment Support System recorder – OEX) that had been found outside Hemphill, Texas on 19 March proved to be one of the most significant debris finds.
- The mystery object, observed by US Air Force radars and designated 2003-003B, separating from the shuttle on the second day in orbit, closely matches the radar cross-section and area-to-mass measurements of an RCC panel fragment.
- The roughness characteristics of Columbia's left wing have been of some concern to experts since the late 1980s. Higher wing roughness can contribute to early transition from laminar to more thermally stressful turbulent aerodynamic flow during re-entry, thus exposing the vehicle to an exceptionally hot flight profile. In particular, early boundary layer transition (BLT) added to the suspected wing damage could have posed a fatal combination.

Space Shuttle basics & Columbia facts

- Orbiter Columbia (OV-102), the oldest vehicle in the shuttle fleet, was on its 28th mission including the maiden flight on 12 April 1981. Overall, it was the 113th mission of a US space shuttle. The three remaining shuttles Discovery, Atlantis and Endeavour have logged 30, 26 and 19 flights, respectively. Challenger was lost on its 10th flight on 28 January 1986.
- Columbia was the last shuttle not refitted with a docking adapter for rendezvous with the International Space Station (ISS), and actually never visited the former Mir space station. However, it was the second orbiter to be upgraded with a modern MEDS "glass" cockpit.
  Due to its internal air lock, Columbia offered more usable load bay length and was thus best suited for accommodating large payloads, such as the Chandra observation telescope and other outsized scientific equipment.
- Temperatures during the hot phase of re-entry typically reach 1,100-1,650°C (2,000-3,000°F) when the shuttle plunges into the denser layers of atmosphere at a speed of some 28,150 km/h (17,500 mph).
- During the Challenger investigation about 55% of the orbiter itself (some 15 t) was recovered, including most of the crew compartment and all three intact main engines (SSME's). Space Shuttle Challenger exploded 73 seconds into flight STS 51-L on 28 January 1986 due to a leak in faulty O-ring seals of Challenger’s right solid-fuel booster, triggered by extremely low temperatures on launch day. All seven crew members were killed in the accident.

The STS-107 crew

The crew on shuttle Columbia's last flight consisted of Rick D. Husband (Commander), William C. McCool (Pilot), Michael P. Anderson (Payload Commander), David M. Brown (Mission Specialist), Kalpana Chawla (Mission Specialist), Laurel Blair Clark (Mission Specialist) and the first Israeli astronaut Ilan Ramon (Payload Specialist).

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