



Columbia's Final Flight

Space Shuttle missions are not necessarily launched in the same order they are planned (or “manifested,” as NASA calls the process). A variety of scheduling, funding, technical, and – occasionally – political reasons can cause the shuffling of missions over the course of the two to three years it takes to plan and launch a flight. This explains why the 113th mission of the Space Shuttle Program was called STS-107. It would be the 28th flight of *Columbia*.

While the STS-107 mission will likely be remembered most for the way it ended, there was a great deal more to the dedicated science mission than its tragic conclusion. The planned microgravity research spanned life sciences, physical sciences, space and earth sciences, and education. More than 70 scientists were involved in the research that was conducted by *Columbia*’s seven-member crew over 16 days. This chapter outlines the history of STS-107 from its mission objectives and their rationale through the accident and its initial aftermath. The analysis of the accident’s causes follows in Chapter 3 and subsequent chapters.

2.1 MISSION OBJECTIVES AND THEIR RATIONALES

Throughout the 1990s, NASA flew a number of dedicated science missions, usually aboard *Columbia* because it was equipped for extended-duration missions and was not being used for Shuttle-Mir docking missions or the assembly of the International Space Station. On many of these missions, *Columbia* carried pressurized Spacelab or SPACEHAB modules that extended the habitable experiment space available and were intended as facilities for life sciences and microgravity research.

In June 1997, the Flight Assignment Working Group at Johnson Space Center in Houston designated STS-107, tentatively scheduled for launch in the third quarter of Fiscal Year 2000, a “research module” flight. In July 1997, several committees of the National Academy of Science’s Space Studies Board sent a letter to NASA Administrator Daniel Goldin recommending that NASA dedicate several future Shuttle missions to microgravity and life sciences. The purpose would be to train scientists to take full advantage of the International Space Station’s research capabilities once it became operational, and to reduce the gap between the last planned Shuttle science

mission and the start of science research aboard the Space Station.¹ In March 1998, Goldin announced that STS-107, tentatively scheduled for launch in May 2000, would be a multi-disciplinary science mission modeled after STS-90, the Neurolab mission scheduled later in 1998.² In October 1998, the Veterans Affairs and Housing and Urban Development and Independent Agencies Appropriations Conference Report expressed Congress’ concern about the lack of Shuttle-based science missions in Fiscal Year 1999, and added \$15 million to NASA’s budget for STS-107. The following year the Conference Report reserved \$40 million for a second science mission. NASA cancelled the second science mission in October 2002 and used the money for STS-107.

In addition to a variety of U.S. experiments assigned to STS-107, a joint U.S./Israeli space experiment – the Mediterranean-Israeli Dust Experiment, or MEIDEX – was added to STS-107 to be accompanied by an Israeli astronaut as part of an international cooperative effort aboard the Shuttle similar to those NASA had begun in the early 1980s. *Triana*, a deployable Earth-observing satellite, was also added to the mission to save NASA from having to buy a commercial launch to place the satellite in orbit. Political disagreements between Congress and the White House delayed *Triana*, and the satellite was replaced by the Fast Reaction Experiments Enabling Science, Technology, Applications, and Research (FREESTAR) payload, which was mounted behind the SPACEHAB Research Double Module.³



Figure 2.1-1. Columbia, at the launch pad on January 15, 2003.

Schedule Slippage

STS-107 was finally scheduled for launch on January 11, 2001. After 13 delays over two years, due mainly to other missions taking priority, *Columbia* was launched on January 16, 2003 (see Figure 2.1-1). Delays may take several forms. When any delay is mentioned, most people think of a Space Shuttle sitting on the launch pad waiting for launch. But most delays actually occur long before the Shuttle is configured for a mission. This was the case for STS-107 – of the 13 delays, only a few occurred after the Orbiter was configured for flight; most happened earlier in the planning process. Three specific events caused delays for STS-107:

- **Removal of *Triana*:** This Earth-observing satellite was replaced with the FREESTAR payload.
- **Orbiter Maintenance Down Period:** *Columbia*'s depot-level maintenance took six months longer than originally planned, primarily to correct problems encountered with Kapton wiring (see Chapter 4). This resulted in the STS-109 Hubble Space Telescope service mission be-

ing launched before STS-107 because it was considered more urgent.

- **Flowliner cracks:** About one month before the planned July 19, 2002 launch date for STS-107, concerns about cracks in the Space Shuttle Main Engine propellant system flowliners caused a four-month grounding of the Orbiter fleet. (The flowliner, which is in the main propellant feed lines, mitigates turbulence across the flexible bellows to smooth the flow of propellant into the main engine low-pressure turbopump. It also protects the bellows from flow-induced vibration.) First discovered on *Atlantis*, the cracks were eventually discovered on each Orbiter; they were fixed by welding and polishing. The grounding delayed the exchange of the Expedition 5 International Space Station crew with the Expedition 6 crew, which was scheduled for STS-113. To maintain the International Space Station assembly sequence while minimizing the delay in returning the Expedition 5 crew, both STS-112 and STS-113 were launched before STS-107.

COLUMBIA

Columbia was named after a Boston-based sloop commanded by Captain Robert Gray, who noted while sailing to the Pacific Northwest a flow of muddy water fanning from the shore, and decided to explore what he deemed the "Great River of the West." On May 11, 1792, Gray and his crew maneuvered the *Columbia* past the treacherous sand bar and named the river after his ship. After a week or so of trading with the local tribes, Gray left without investigating where the river led. Instead, Gray led the *Columbia* and its crew on the first U.S. circumnavigation of the globe, carrying otter skins to Canton, China, before returning to Boston in 1793.

In addition to *Columbia* (OV-102), which first flew in 1981, *Challenger* (OV-099) first flew in 1983, *Discovery* (OV-103) in 1984, and *Atlantis* (OV-104) in 1985. *Endeavour* (OV-105), which replaced *Challenger*, first flew in 1992. At the time of the launch of STS-107, *Columbia* was unique since it was the last remaining Orbiter to have an internal airlock on the mid-deck. (All the Orbiters originally had internal airlocks, but all excepting *Columbia* were modified to provide an external docking mechanism for flights to *Mir* and the International Space Station.) Because the airlock was not located in the payload bay, *Columbia* could carry longer payloads such as the *Chandra* space telescope, which used the full length of the payload bay. The internal airlock made the mid-deck more cramped than those of other Orbiters, but this was less of a problem when one of the laboratory modules was installed in the payload bay to provide additional habitable volume.

Columbia had been manufactured to an early structural standard that resulted in the airframe being heavier than the later Orbiters. Coupled with a more-forward center of gravity because of the internal airlock, *Columbia* could not carry as much payload weight into orbit as the other Orbiters. This made *Columbia* less desirable for missions to the International Space Station, although planning was nevertheless underway to modify *Columbia* for an International Space Station flight sometime after STS-107.

The Crew

The STS-107 crew selection process followed standard procedures. The Space Shuttle Program provided the Astronaut Office with mission requirements calling for a crew of seven. There were no special requirements for a rendezvous, extra-vehicular activity (spacewalking), or use of the remote manipulator arm. The Chief of the Astronaut Office announced the crew in July 2000. To maximize the amount of science research that could be performed, the crew formed two teams, Red and Blue, to support around-the-clock operations.

Crew Training

The Columbia Accident Investigation Board thoroughly reviewed all pre-mission training (see Figure 2.1-2) for the STS-107 crew, Houston Mission Controllers, and the Ken-



Figure 2.1-2. Ilan Ramon (left), Laurel Clark, and Michael Anderson during a training exercise at the Johnson Space Center.



Left to right: David Brown, Rick Husband, Laurel Clark, Kalpana Chawla, Michael Anderson, William McCool, Ilan Ramon.

Rick Husband, Commander. Husband, 45, was a Colonel in the U.S. Air Force, a test pilot, and a veteran of STS-96. He received a B.S. in Mechanical Engineering from Texas Tech University and a M.S. in Mechanical Engineering from California State University, Fresno. He was a member of the Red Team, working on experiments including the European Research In Space and Terrestrial Osteoporosis and the Shuttle Ozone Limb Sounding Experiment.

William C. McCool, Pilot. McCool, 41, was a Commander in the U.S. Navy and a test pilot. He received a B.S. in Applied Science from the U.S. Naval Academy, a M.S. in Computer Science from the University of Maryland, and a M.S. in Aeronautical Engineering from the U.S. Naval Postgraduate School. A member of the Blue Team, McCool worked on experiments including the Advanced Respiratory Monitoring System, Biopack, and Mediterranean Israeli Dust Experiment.

Michael P. Anderson, Payload Commander and Mission Specialist. Anderson, 43, was a Lieutenant Colonel in the U.S. Air Force, a former instructor pilot and tactical officer, and a veteran of STS-89. He received a B.S. in Physics/Astronomy from the University of Washington, and a M.S. in Physics from Creighton University. A member of the Blue Team, Anderson worked with experiments including the Advanced Respiratory Monitoring System, Water Mist Fire Suppression, and Structures of Flame Balls at Low Lewis-number.

David M. Brown, Mission Specialist. Brown, 46, was a Captain in the U.S. Navy, a naval aviator, and a naval flight surgeon. He received a B.S. in Biology from the College of William and Mary and a M.D. from Eastern Virginia Medical School. A member

of the Blue Team, Brown worked on the Laminar Soot Processes, Structures of Flame Balls at Low Lewis-number, and Water Mist Fire Suppression experiments.

Kalpana Chawla, Flight Engineer and Mission Specialist. Chawla, 41, was an aerospace engineer, a FAA Certified Flight Instructor, and a veteran of STS-87. She received a B.S. in Aeronautical Engineering from Punjab Engineering College, India, a M.S. in Aerospace Engineering from the University of Texas, Arlington, and a Ph.D. in Aerospace Engineering from the University of Colorado, Boulder. A member of the Red Team, Chawla worked with experiments on Astroculture, Advanced Protein Crystal Facility, Mechanics of Granular Materials, and the Zeolite Crystal Growth Furnace.

Laurel Clark, Mission Specialist. Clark, 41, was a Commander (Captain-Select) in the U.S. Navy and a naval flight surgeon. She received both a B.S. in Zoology and a M.D. from the University of Wisconsin, Madison. A member of the Red Team, Clark worked on experiments including the Closed Equilibrated Biological Aquatic System, Sleep-Wake Actigraphy and Light Exposure During Spaceflight, and the Vapor Compression Distillation Flight Experiment.

Ilan Ramon, Payload Specialist. Ramon, 48, was a Colonel in the Israeli Air Force, a fighter pilot, and Israel's first astronaut. Ramon received a B.S. in Electronics and Computer Engineering from the University of Tel Aviv, Israel. As a member of the Red Team, Ramon was the primary crew member responsible for the Mediterranean Israeli Dust Experiment (MEIDEX). He also worked on the Water Mist Fire Suppression and the Microbial Physiology Flight Experiments Team experiments, among others.

THE CREW



nedy Space Center Launch Control Team. Mission training for the STS-107 crew comprised 4,811 hours, with an additional 3,500 hours of payload-specific training. The Ascent/Entry Flight Control Team began training with the STS-107 crew on October 22, 2002, and participated in 16 integrated ascent or entry simulations. The Orbiter Flight Control team began training with the crew on April 23, 2002, participating in six joint integrated simulations with the crew and payload customers. Seventy-seven Flight Control Room operators were assigned to four shifts for the STS-107 mission. All had prior certifications and had worked missions in the past.

The STS-107 Launch Readiness Review was held on December 18, 2002, at the Kennedy Space Center. Neither NASA nor United Space Alliance noted any training issues for launch controllers. The Mission Operations Directorate noted no crew or flight controller training issues during the January 9, 2003, STS-107 Flight Readiness Review. According to documentation, all personnel were trained and certified, or would be trained and certified before the flight. Appendix D.1 contains a detailed STS-107 Training Report.

Orbiter Preparation

Board investigators reviewed *Columbia's* maintenance, or “flow” records, including the recovery from STS-109 and preparation for STS-107, and relevant areas in NASA’s Problem Reporting and Corrective Action database, which contained 16,500 Work Authorization Documents consisting of 600,000 pages and 3.9 million steps. This database maintains critical information on all maintenance and modification work done on the Orbiters (as required by the Orbiter Maintenance Requirements and Specifications Document). It also maintains Corrective Action Reports that document problems discovered and resolved, the Lost/Found item database, and the Launch Readiness Review and Flight Readiness Review documentation (see Chapter 7).

The Board placed emphasis on maintenance done in areas of particular concern to the investigation. Specifically, records for the left main landing gear and door assembly and left wing leading edge were analyzed for any potential contributing factors, but nothing relevant to the cause of the accident was discovered. A review of Thermal Protection System tile maintenance records revealed some “non-conformances” and repairs made after *Columbia's* last flight, but these were eventually dismissed as not relevant to the investigation. Additionally, the Launch Readiness Review and Flight Readiness Review records relating to those systems and the Lost/Found item records were reviewed, and no relevance was found. During the Launch Readiness Review and Flight Readiness Review processes, NASA teams analyzed 18 lost items and deemed them inconsequential. (Although this incident was not considered significant by the Board, a further discussion of foreign object debris may be found in Chapter 4.)

Payload Preparation

The payload bay configuration for STS-107 included the SPACEHAB access tunnel, SPACEHAB Research Double Module (RDM), the FREESTAR payload, the Orbital Ac-

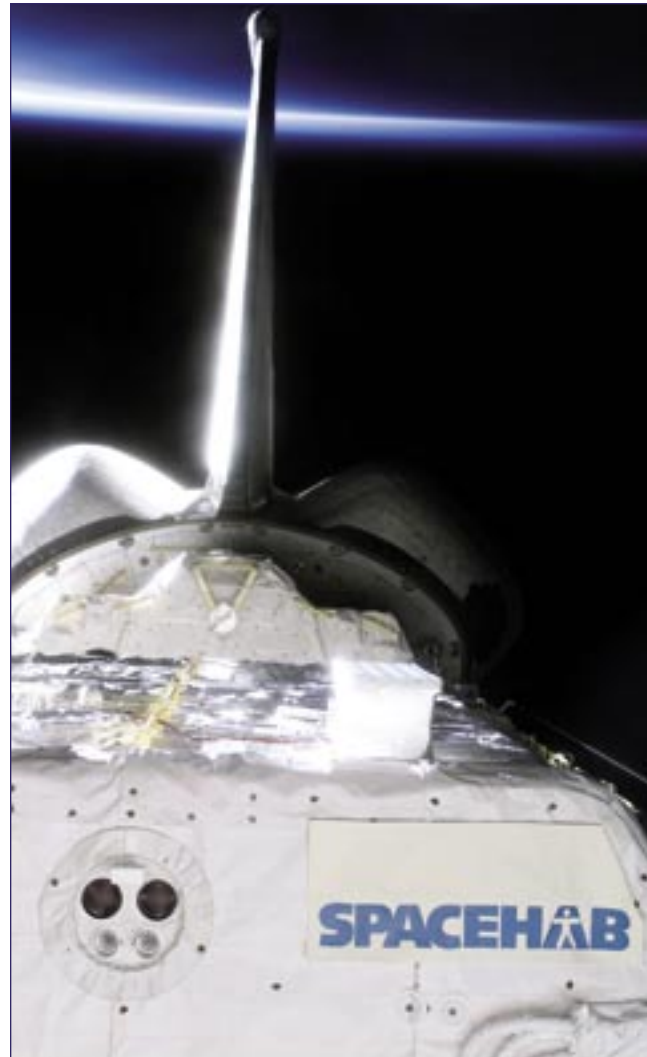


Figure 2.1-3. The SPACEHAB Research Double Module as seen from the aft flight deck windows of Columbia during STS-107. A thin slice of Earth's horizon is visible behind the vertical stabilizer.

celeration Research Experiment, and an Extended Duration Orbiter pallet to accommodate the long flight time needed to conduct all the experiments. Additional experiments were stowed in the Orbiter mid-deck and on the SPACEHAB roof (see Figures 2.1-3 and 2.1-4). The total liftoff payload weight for STS-107 was 24,536 pounds. Details on STS-107 payload preparations and on-orbit operations are in Appendix D.2.

Payload readiness reviews for STS-107 began in May 2002, with no significant abnormalities reported throughout the processing. The final Payload Safety Review Panel meeting prior to the mission was held on January 8, 2003, at the Kennedy Space Center, where the Integrated Safety Assessments conducted for the SPACEHAB and FREESTAR payloads were presented for final approval. All payload physical stresses on the Orbiter were reported within acceptable limits. The Extended Duration Orbiter pallet was loaded into the aft section of the payload bay in High Bay 3 of the Orbiter Processing Facility on April 25, 2002. The SPACEHAB

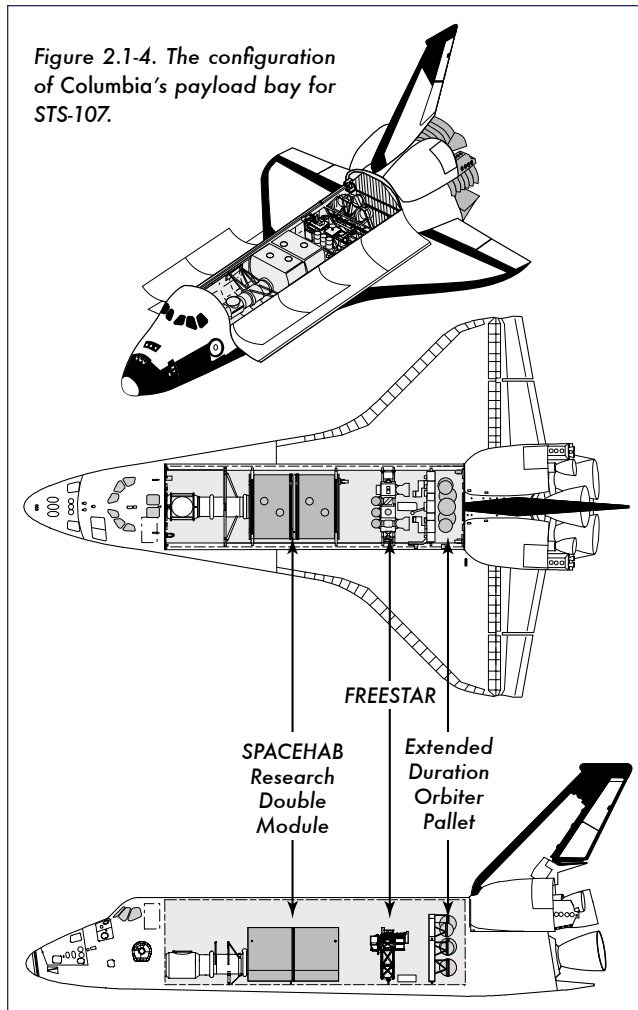


Figure 2.1-4. The configuration of Columbia's payload bay for STS-107.

and FREESTAR payloads were loaded horizontally on March 24, with an Integration Verification Test on June 6. The payload bay doors were closed on October 31 and were not opened prior to launch. (All late stow activities at the launch pad were accomplished in the vertical position using the normal crew entry hatch and SPACEHAB access tunnel.) Rollover of the Orbiter to the Vehicle Assembly Building for mating to the Solid Rocket Boosters and External Tank occurred on November 18. Mating took place two days later, and rollout to Launch Complex 39-A was on December 9.

Unprecedented security precautions were in place at Kennedy Space Center prior to and during the launch of STS-107 because of prevailing national security concerns and the inclusion of an Israeli crew member.

SPACEHAB was powered up at Launch minus 51 (L-51) hours (January 14) to prepare for the late stowing of time-critical experiments. The stowing of material in SPACEHAB once it was positioned vertically took place at L-46 hours and was completed by L-31 hours. Late middeck payload stowage, required for the experiments involving plants and insects, was performed at the launch pad. Flight crew equipment loading started at L-22.5 hours, while middeck experiment loading took place from Launch minus 19 to 16 hours. Fourteen experiments, four of which were powered, were loaded, all without incident.

2.2 FLIGHT PREPARATION

NASA senior management conducts a complex series of reviews and readiness polls to monitor a mission's progress toward flight readiness and eventual launch. Each step requires written certification. At the final review, called the Flight Readiness Review, NASA and its contractors certify that the necessary analyses, verification activities, and data products associated with the endorsement have been accomplished and "indicate a high probability for mission success." The review establishes the rationale for accepting any remaining identifiable risk; by signing the Certificate of Flight Readiness, NASA senior managers agree that they have accomplished all preliminary items and that they agree to accept that risk. The Launch Integration Manager oversees the flight preparation process.

STS-107 Flight Preparation Process

The flight preparation process reviews progress toward flight readiness at various junctures and ensures the organization is ready for the next operational phase. This process includes Project Milestone Reviews, three Program Milestone Reviews, and the Flight Readiness Review, where the Certification of Flight Readiness is endorsed.

The **Launch Readiness Review** is conducted within one month of the launch to certify that Certification of Launch Readiness items from NSTS-08117, Appendices H and Q, Flight Preparation Process Plan, have been reviewed and acted upon. The STS-107 Launch Readiness Review was held at Kennedy Space Center on December 18, 2002. The Kennedy Space Center Director of Shuttle Processing chaired the review and approved continued preparations for a January 16, 2003, launch. Onboard payload and experimental status and late stowage activity were reviewed.

A **Flight Readiness Review**, which is chaired by the Office of Space Flight Associate Administrator, usually occurs about two weeks before launch and provides senior NASA management with a summary of the certification and verification of the Space Shuttle vehicle, flight crew, payloads, and rationales for accepting residual risk. In cases where the Flight Preparation Process has not been successfully completed, Certification of Flight Readiness exceptions will be made, and presented at the Pre-Launch Mission Management Team Review for disposition. The final Flight Readiness Review for STS-107 was held on January 9, 2003, a week prior to launch. Representatives of all organizations except Flight Crew, Ferry Readiness, and Department of Defense Space Shuttle Support made presentations. Safety, Reliability & Quality Assurance summarized the work performed on the Ball Strut Tie Rod Assembly crack, defective booster connector pin, booster separation motor propellant paint chip contamination, and STS-113 Main Engine 1 nozzle leak (see Appendix E.1 for the briefing charts). None of the work performed on these items affected the launch.

Certificate of Flight Readiness: No actions were assigned during the Flight Readiness Review. One exception was included in the Certificate of Flight Readiness pending the completion of testing on the Ball Strut Tie Rod Assembly.

Testing was to be completed on January 15. This exception was to be closed with final flight rationale at the STS-107 Pre-launch Mission Management Team meeting. All principal managers and organizations indicated their readiness to support the mission.

Normally, a Mission Management Team – consisting of managers from Engineering, System Integration, the Space Flight Operations Contract Office, the Shuttle Safety Office, and the Johnson Space Center directors of flight crew operations, mission operations, and space and life sciences – convenes two days before launch and is maintained until the Orbiter safely lands. The Mission Management Team Chair reports directly to the Shuttle Program Manager.

The Mission Management Team resolves outstanding problems outside the responsibility or authority of the Launch and Flight Directors. During pre-launch, the Mission Management Team is chaired by the Launch Integration Manager at Kennedy Space Center, and during flight by the Space Shuttle Program Integration Manager at Johnson Space Center. The guiding document for Mission Management operations is NSTS 07700, Volume VIII.

A Pre-launch Mission Management Team Meeting occurs one or two days before launch to assess any open items or changes since the Flight Readiness Review, provide a GO/NO-GO decision on continuing the countdown, and approve changes to the Launch Commit Criteria. Simultaneously, the Mission Management Team is activated to evaluate the countdown and address any issues remaining from the Flight Readiness Review. STS-107's Pre-launch Mission Management Team meeting, chaired by the Acting Manager of Launch Integration, was held on January 14, some 48 hours prior to launch, at the Kennedy Space Center. In addition to the standard topics, such as weather and range support, the Pre-Launch Mission Management Team was updated on the status of the Ball Strut Tie Rod Assembly testing. The exception would remain open pending the presentation of additional test data at the Delta Pre-Launch Mission Management Team review the next day.

The Delta Pre-Launch Mission Management Team Meeting was also chaired by the Acting Manager of Launch Integration and met at 9:00 a.m. EST on January 15 at the Kennedy Space Center. The major issues addressed concerned the Ball Strut Tie Rod Assembly and potential strontium chromate contamination found during routine inspection of a (non-STS-107) spacesuit on January 14. The contamination concern was addressed and a toxicology analysis determined there was no risk to the STS-107 crew. A poll of the principal managers and organizations indicated all were ready to support STS-107.

A Pre-Tanking Mission Management Team Meeting was also chaired by the Acting Manager of Launch Integration. This meeting was held at 12:10 a.m. on January 16. A problem with the Solid Rocket Booster External Tank Attachment ring was addressed for the first time. Recent mission life capability testing of the material in the ring plates revealed static strength properties below minimum requirements. There were concerns that, assuming worst-case flight

NASA TIMES

Like most engineering or technical operations, NASA generally uses Coordinated Universal Time (UTC, formerly called Greenwich Mean Time) as the standard reference for activities. This is, for convenience, often converted to local time in either Florida or Texas – this report uses Eastern Standard Time (EST) unless otherwise noted. In addition to the normal 24-hour clock, NASA tells time via several other methods, all tied to specific events. The most recognizable of these is “T minus (T–)” time that counts down to every launch in hours, minutes, and seconds. NASA also uses a less precise “L minus” (L–) time that tags events that happens days or weeks prior to launch. Later in this report there are references to “Entry Interface plus (EI+)” time that counts, in seconds, from when an Orbiter begins re-entry. In all cases, if the time is “minus” then the event being counted toward has not happened yet; if the time is “plus” then the event has already occurred.

environments, the ring plate would not meet the safety factor requirement of 1.4 – that is, able to withstand 1.4 times the maximum load expected in operation. Based on analysis of the anticipated flight environment for STS-107, the need to meet the safety factor requirement of 1.4 was waived (see Chapter 10). No Launch Commit Criteria violations were noted, and the STS-107 final countdown began. The loading of propellants into the External Tank was delayed by some 70 minutes, until seven hours and 20 minutes before launch, due to an extended fuel cell calibration, a liquid oxygen replenish valve problem, and a Launch Processing System reconfiguration. The countdown continued normally, and at T–9 minutes the Launch Mission Management Team was polled for a GO/NO-GO launch decision. All members reported GO, and the Acting Manager of Launch Integration gave the final GO launch decision.

Once the Orbiter clears the launch pad, responsibility passes from the Launch Director at the Kennedy Space Center to the Flight Director at Johnson Space Center. During flight, the mission is also evaluated from an engineering perspective in the Mission Evaluation Room, which is managed by Vehicle Engineering Office personnel. Any engineering analysis conducted during a mission is coordinated through and first presented to the Mission Evaluation Room, and is then presented by the Mission Evaluation Room manager to the Mission Management Team.

2.3 LAUNCH SEQUENCE

The STS-107 launch countdown was scheduled to be about 24 hours longer than usual, primarily because of the extra time required to load cryogenics for generating electricity and water into the Extended Duration Orbiter pallet, and for final stowage of plants, insects, and other unique science payloads. SPACEHAB stowage activities were about 90 minutes behind schedule, but the overall launch countdown was back on schedule when the communication system check was completed at L–24 hours.

At 7 hours and 20 minutes prior to the scheduled launch on January 16, 2003, ground crews began filling the External Tank with over 1,500,000 pounds of cryogenic propellants. At about 6:15 a.m., the Final Inspection Team began its visual and photographic check of the launch pad and vehicle. Frost had been noted during earlier inspections, but it had dissipated by 7:15 a.m., when the Ice Team completed its inspection.

Heavy rain had fallen on Kennedy Space Center while the Shuttle stack was on the pad. The launch-day weather was 65 degrees Fahrenheit with 68 percent relative humidity, dew point 59 degrees, calm winds, scattered clouds at 4,000 feet, and visibility of seven statute miles. The forecast weather for Kennedy Space Center and the Transoceanic Abort Landing sites in Spain and Morocco was within launch criteria limits.

At about 7:30 a.m. the crew was driven from their quarters in the Kennedy Space Center Industrial Area to Launch Complex 39-A. Commander Rick Husband was the first crew member to enter *Columbia*, at the 195-foot level of the launch tower at 7:53 a.m. Mission Specialist Kalpana Chawla was the last to enter, at 8:45 a.m. The hatch was closed and locked at 9:17 a.m.

The countdown clock executed the planned hold at the T-20 minute-mark at 10:10 a.m. The primary ascent computer software was switched over to the launch-ready configuration, communications checks were completed with all crew members, and all non-essential personnel were cleared from the launch area at 10:16 a.m. Fifteen minutes later the countdown clock came out of the planned hold at the T-9 minutes, and at 10:35 a.m., the GO was given for Auxiliary Power Unit start. STS-107 began at 10:39 a.m. with ignition of the Solid Rocket Boosters (see Figure 2.3-1).

Wind Shear

Before a launch, balloons are released to determine the direction and speed of the winds up to 50,000 to 60,000 feet. Various Doppler sounders are also used to get a wind profile, which, for STS-107, was unremarkable and relatively constant at the lower altitudes.

Columbia encountered a wind shear about 57 seconds after launch during the period of maximum dynamic pressure (max-q). As the Shuttle passed through 32,000 feet, it experienced a rapid change in the out-of-plane wind speed of minus 37.7 feet per second over a 1,200-foot altitude range. Immediately after the vehicle flew through this altitude range, its sideslip (beta) angle began to increase in the negative direction, reaching a value of minus 1.75 degrees at 60 seconds.

A negative beta angle means that the wind vector was on the left side of the vehicle, pushing the nose to the right and increasing the aerodynamic force on the External Tank bipod strut attachment. Several studies have indicated that the aerodynamic loads on the External Tank forward attach bipod, and also the interacting aerodynamic loads between the External Tank and the Orbiter, were larger than normal but within design limits.

Predicted and Actual I-Loads

On launch day, the General-Purpose Computers on the Orbiter are updated with information based on the latest observations of weather and the physical properties of the vehicle. These "I-loads" are initializing data sets that contain elements specific to each mission, such as measured winds, atmospheric data, and Shuttle configuration. The I-loads output target angle of attack, angle of sideslip, and dynamic pressure



Figure 2.3-1. The launch of Columbia on STS-107.

as a function of Mach number to ensure that the structural loads the Shuttle experiences during ascent are acceptable.

After the accident, investigators analyzed *Columbia*'s ascent loads using a reconstruction of the ascent trajectory. The wing loads measurement used a flexible body structural loads assessment that was validated by data from the Modular Auxiliary Data System recorder, which was recovered from the accident debris. The wing loads assessment included crosswind effects, angle of attack (alpha) effects, angle of sideslip (beta) effects, normal acceleration (g), and dynamic pressure (q) that could produce stresses and strains on the Orbiter's wings during ascent. This assessment showed that all Orbiter wing loads were approximately 70 percent of their design limit or less throughout the ascent, including the previously mentioned wind shear.

The wind shear at 57 seconds after launch and the Shuttle stack's reaction to it appears to have initiated a very low frequency oscillation, caused by liquid oxygen sloshing inside the External Tank,⁴ that peaked in amplitude 75 seconds after launch and continued through Solid Rocket Booster separation at 127 seconds after launch. A small oscillation is not unusual during ascent, but on STS-107 the amplitude was larger than normal and lasted longer. Less severe wind shears at 95 and 105 seconds after launch contributed to the continuing oscillation.

An analysis of the External Tank/Orbiter interface loads, using simulated wind shear, crosswind, beta effects, and liquid oxygen slosh effects, showed that the loads on the External Tank forward attachment were only 70 percent of the design certification limit. The External Tank slosh study confirmed that the flight control system provided adequate stability throughout ascent.

The aerodynamic loads on the External Tank forward attach bipod were analyzed using a Computational Fluid Dynamics simulation, that yielded axial, side-force, and radial loads, and indicated that the external air loads were well below the design limit during the period of maximum dynamic pressure and also when the bipod foam separated.

Nozzle Deflections

Both Solid Rocket Boosters and each of the Space Shuttle Main Engines have exhaust nozzles that deflect ("gimbal") in response to flight control system commands. Review of the STS-107 ascent data revealed that the Solid Rocket Booster and Space Shuttle Main Engine nozzle positions twice exceeded deflections seen on previous flights by a factor of 1.24 to 1.33 and 1.06, respectively. The center and right main engine yaw deflections first exceeded those on previous flights during the period of maximum dynamic pressure, immediately following the wind shear. The deflections were the flight control system's reaction to the wind shear, and the motion of the nozzles was well within the design margins of the flight control system.

Approximately 115 seconds after launch, as booster thrust diminished, the Solid Rocket Booster and Space Shuttle Main Engine exhaust nozzle pitch and yaw deflections ex-

ceeded those seen previously by a factor of 1.4 and 1.06 to 1.6, respectively. These deflections were caused by lower than expected Reusable Solid Rocket Motor performance, indicated by a low burn rate; a thrust mismatch between the left and right boosters caused by lower-than-normal thrust on the right Solid Rocket Booster; a small built-in adjustment that favored the left Solid Rocket Booster pitch actuator; and flight control trim characteristics unique to the Performance Enhancements flight profile for STS-107.⁵

The Solid Rocket Booster burn rate is temperature-dependent, and behaved as predicted for the launch day weather conditions. No two boosters burn exactly the same, and a minor thrust mismatch has been experienced on almost every Space Shuttle mission. The booster thrust mismatch on STS-107 was well within the design margin of the flight control system.

Debris Strike

Post-launch photographic analysis showed that one large piece and at least two smaller pieces of insulating foam separated from the External Tank left bipod (-Y) ramp area at 81.7 seconds after launch. Later analysis showed that the larger piece struck *Columbia* on the underside of the left wing, around Reinforced Carbon-Carbon (RCC) panels 5 through 9, at 81.9 seconds after launch (see Figure 2.3-2). Further photographic analysis conducted the day after launch revealed that the large foam piece was approximately 21 to 27 inches long and 12 to 18 inches wide, tumbling at a minimum of 18 times per second, and moving at a relative velocity to the Shuttle Stack of 625 to 840 feet per second (416 to 573 miles per hour) at the time of impact.

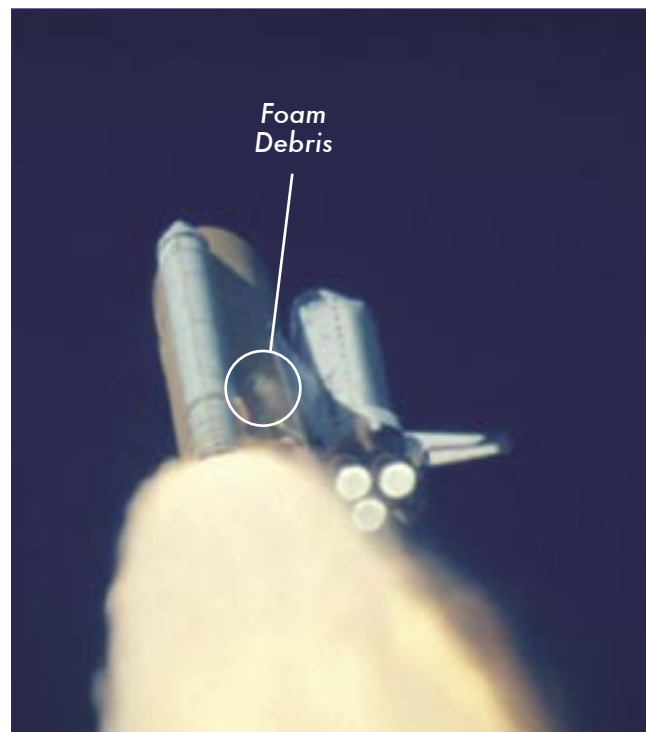


Figure 2.3-2. A shower of foam debris after the impact on *Columbia*'s left wing. The event was not observed in real time.

Arrival on Orbit

Two minutes and seven seconds after launch, the Solid Rocket Boosters separated from the External Tank. They made a normal splashdown in the Atlantic Ocean and were subsequently recovered and returned to the Kennedy Space Center for inspection and refurbishment. Approximately eight and a half minutes after launch, the Space Shuttle Main Engines shut down normally, followed by the separation of the External Tank. At 11:20 a.m., a two-minute burn of the Orbital Maneuvering System engines began to position *Columbia* in its proper orbit, inclined 39 degrees to the equator and approximately 175 miles above Earth.

2.4 ON-ORBIT EVENTS

By 11:39 a.m. EST, one hour after launch, *Columbia* was in orbit and crew members entered the “post-insertion timeline.” The crew immediately began to configure onboard systems for their 16-day stay in space.

Flight Day 1, Thursday, January 16

The payload bay doors were opened at 12:36 p.m. and the radiator was deployed for cooling. Crew members activated the Extended Duration Orbiter pallet (containing extra propellants for power and water production) and FREESTAR, and they began to set up the SPACEHAB module (see Figure 2.4-1). The crew then ran two experiments with the Advanced Respiratory Monitoring System stationary bicycle in SPACEHAB.

The crew also set up the Bioreactor Demonstration System, Space Technology and Research Students Bootes, Osteoporosis Experiment in Orbit, Closed Equilibrated Biological Aquatic System, Miniature Satellite Threat Reporting System, and Biopack, and performed Low Power Transceiver communication tests.

Flight Day 2, Friday, January 17

The Ozone Limb Sounding Experiment 2 began measuring the ozone layer, while the Mediterranean Israeli Dust Experiment (MEIDEX) was set to measure atmospheric aerosols over the Mediterranean Sea and the Sahara Desert. The Critical Viscosity of Xenon 2 experiment began studying the fluid properties of Xenon.

The crew activated the SPACEHAB Centralized Experiment Water Loop in preparation for the Combustion Module 2 and Vapor Compression Distillation Flight Experiment and also activated the Facility for Absorption and Surface Tension, Zeolite Crystal Growth, Astroculture, Mechanics of Granular Materials, Combined Two Phase Loop Experiment, European Research In Space and Terrestrial Osteoporosis, Biological Research in Canisters, centrifuge configurations, Enhanced Orbiter Refrigerator/Freezer Operations, and Microbial Physiological Flight Experiment.

Not known to Mission Control, the *Columbia* crew, or anyone else, between 10:30 and 11:00 a.m. on Flight Day 2, an object drifted away from the Orbiter. This object, which subsequent

analysis suggests may have been related to the debris strike, had a departure velocity between 0.7 and 3.4 miles per hour, remained in a degraded orbit for approximately two and a half days, and re-entered the atmosphere between 8:45 and 11:45 p.m. on January 19. This object was discovered after the accident when Air Force Space Command reviewed its radar tracking data. (See Chapter 3 for additional discussion.)

Flight Day 3, Saturday, January 18

The crew conducted its first on-orbit press conference. Because of heavy cloud cover over the Middle East, MEIDEX objectives could not be accomplished. Crew members began an experiment to track metabolic changes in their calcium levels. The crew resolved a discrepancy in the SPACEHAB Video Switching Unit, provided body fluid samples for the Physiology and Biochemistry experiment, and activated the Vapor Compression Distillation Flight Experiment.

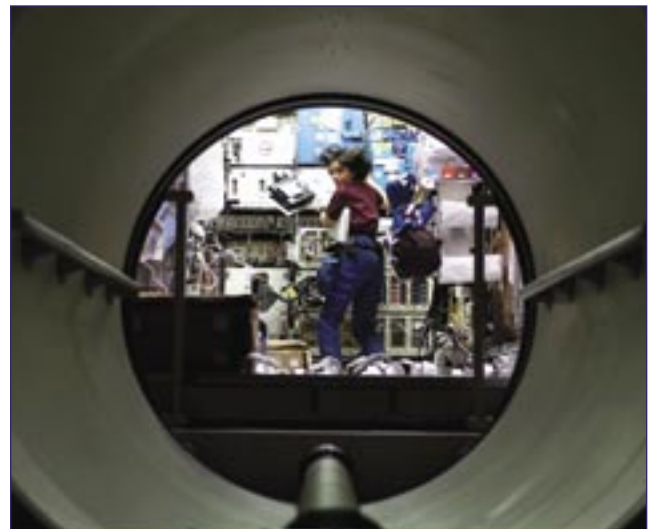


Figure 2.4-1. The tunnel linking the SPACEHAB module to the Columbia crew compartment provides a view of Kalpana Chawla working in SPACEHAB.

Flight Day 4, Sunday, January 19

Husband, Chawla, Clark, and Ramon completed the first experiments with the Combustion Module 2 in SPACEHAB, which were the Laminar Soot Processes, Water Mist Fire suppression, and Structure of Flame Balls at Low Lewis number. The latter studied combustion at the limits of flammability, producing the weakest flame ever to burn: each flame produced one watt of thermal power (a birthday-cake candle, by comparison, produces 50 watts).

Experiments on the human body’s response to microgravity continued, with a focus on protein manufacturing, bone and calcium production, renal stone formation, and saliva and urine changes due to viruses. Brown captured the first ever images of upper-atmosphere “sprites” and “elves,” which are produced by intense cloud-to-ground electromagnetic impulses radiated by heavy lightning discharges and are associated with storms near the Earth’s surface.

The crew reported about a cup of water under the SPACEHAB module sub-floor and significant amounts clinging to the Water Separator Assembly and Aft Power Distribution Unit. The water was mopped up and Mission Control switched power from Rotary Separator 1 to 2.

Flight Day 5, Monday, January 20

Mission Control saw indications of an electrical short on Rotary Separator 2 in SPACEHAB; the separator was powered down and isolated from the electrical bus. To reduce condensation with both Rotary Separators off, the crew had to reduce the flow in one of *Columbia*'s Freon loops to SPACEHAB in order to keep the water temperature above the dew point and prevent condensation from forming in the Condensing Heat Exchanger. However, warmer water could lead to higher SPACEHAB cabin temperatures; fortunately, the crew was able to keep SPACEHAB temperatures acceptable and avoid condensation in the heat exchanger.

Flight Day 6, Tuesday, January 21

The temperature in the SPACEHAB module reached 81 degrees Fahrenheit. The crew reset the temperature to acceptable levels, and Mission Control developed a contingency plan to re-establish SPACEHAB humidity and temperature control if further degradation occurred. The Miniature Satellite Threat Reporting System, which detects ground-based radio frequency sources, experienced minor command and telemetry problems.

Flight Day 7, Wednesday, January 22

Both teams took a half day off. MEIDEX tracked thunderstorms over central Africa and captured images of four sprites and two elves as well as two rare images of meteoroids entering Earth's atmosphere. Payload experiments continued in SPACEHAB, with no further temperature complications.

Flight Day 8, Thursday, January 23

Eleven educational events were completed using the low-power transceiver to transfer data files to and from schools in Maryland and Massachusetts. The Mechanics of Granular Materials experiment completed the sixth of nine tests. Biopack shut down, and attempts to recycle the power were unsuccessful; ground teams began developing a repair plan.

Mission Control e-mailed Husband and McCool that post-launch photo analysis showed foam from the External Tank had struck the Orbiter's left wing during ascent. Mission Control relayed that there was "no concern for RCC or tile damage" and because the phenomenon had been seen before, there was "absolutely no concern for entry." Mission Control also e-mailed a short video clip of the debris strike, which Husband forwarded to the rest of the crew.

Flight Day 9, Friday, January 24

Crew members conducted the mission's longest combustion test. Spiral moss growth experiments continued, as well as Astroculture experiments that harvested samples of oils from

roses and rice flowers. Experiments in the combustion chamber continued. Although the temperature in SPACEHAB was maintained, Mission Control estimated that about a half-gallon of water was unaccounted for, and began planning in-flight maintenance for the Water Separator Assembly.



David Brown stabilizes a digital video camera prior to a press conference in the SPACEHAB Research Double Module aboard Columbia during STS-107.

Flight Day 10, Saturday, January 25

Experiments with bone cells, prostate cancer, bacteria growth, thermal heating, and surface tension continued. MEIDEX captured images of plumes of dust off the coasts of Nigeria, Mauritania, and Mali. Images of sprites were captured over storms in Perth, Australia. Biopack power could not be restored, so all subsequent Biopack sampling was performed at ambient temperatures.

Flight Day 11, Sunday, January 26

Vapor Compression Distillation Flight Experiment operations were complete; SPACEHAB temperature was allowed to drop to 73 degrees Fahrenheit. Scientists received the first live Xybian digital downlink images from MEIDEX and confirmed significant dust in the Middle East. The STARS experiment hatched a fish in the aquatic habitat and a silk moth from its cocoon.

Flight Day 12, Monday, January 27

Combustion and granular materials experiments concluded. The combustion module was configured for the Water Mist experiment, which developed a leak. The Microbial Physiol-

ogy Flight Experiment expended its final set of samples in yeast and bacteria growth. The crew made a joint observation using MEIDEX and the Ozone Limb Sounding Experiment. MEIDEX captured images of dust over the Atlantic Ocean for the first time.

Flight Day 13, Tuesday, January 28

The crew took another half day off. The Bioreactor experiment produced a bone and prostate cancer tumor tissue sample the size of a golf ball, the largest ever grown in space. The crew, along with ground support personnel, observed a moment of silence to honor the memory of the men and women of *Apollo 1* and *Challenger*. MEIDEX was prepared to monitor smoke trails from research aircraft and bonfires in Brazil. Water Mist runs began after the leak was stopped.

Flight Day 14, Wednesday, January 29

Ramon reported a giant dust storm over the Atlantic Ocean that provided three days of MEIDEX observations. Ground teams confirmed predicted weather and climate effects and found a huge smoke plume in a large cumulus cloud over the Amazon jungle. BIOTUBE experiment ground teams reported growth rates and root curvatures in plant and flax roots different from anything seen in normal gravity on Earth. The crew received procedures from Mission Control for vacuum cleanup and taping of the Water Separator Assembly prior to re-entry. Temperatures in two Biopack culture chambers were too high for normal cell growth, so several Biopack experiments were terminated.

Flight Day 15, Thursday, January 30

Final samples and readings were taken for the Physiology and Biochemistry team experiments. Husband, McCool, and Chawla ran landing simulations on the computer training system. Husband found no excess water in the SPACEHAB sub-floor, but as a precaution, he covered several holes in the Water Separator Assembly.

Flight Day 16, Friday, January 31

The Water Mist Experiment concluded and the combustion module was closed. MEIDEX made final observations of dust concentrations, sprites, and elves. Husband, McCool, and Chawla completed their second computer-based landing simulation. A flight control system checkout was performed satisfactorily using Auxiliary Power Unit 1, with a run time of 5 minutes, 27 seconds.

After the flight control system checkout, a Reaction Control System “hot-fire” was performed during which all thrusters were fired for at least 240 milliseconds. The Ku-band antenna and the radiator on the left payload bay door were stowed.

Flight Day 17, Saturday, February 1

All onboard experiments were concluded and stowed, and payload doors and covers were closed. Preparations were completed for de-orbit, re-entry, and landing at the Kennedy



Rick Husband works with the Biological Research in Canister experiment on Columbia's mid-deck.

Space Center. Suit checks confirmed that proper pressure would be maintained during re-entry and landing. The payload bay doors were closed. Husband and McCool configured the onboard computers with the re-entry software, and placed *Columbia* in the proper attitude for the de-orbit burn.

2.5 DEBRIS STRIKE ANALYSIS AND REQUESTS FOR IMAGERY

As is done after every launch, within two hours of the lift-off the Intercenter Photo Working Group examined video from tracking cameras. An initial review did not reveal any unusual events. The next day, when the Intercenter Photo Working Group personnel received much higher resolution film that had been processed overnight, they noticed a debris strike at 81.9 seconds after launch.

A large object from the left bipod area of the External Tank struck the Orbiter, apparently impacting the underside of the left wing near RCC panels 5 through 9. The object's large size and the apparent momentum transfer concerned Intercenter Photo Working Group personnel, who were worried that *Columbia* had sustained damage not detectable in the limited number of views their tracking cameras captured. This concern led the Intercenter Photo Working Group Chair to request, in anticipation of analysts' needs, that a high-resolution image of the Orbiter on-orbit be obtained by the Department of Defense. By the Board's count, this would be the first of three distinct requests to image *Columbia* on-orbit. The exact chain of events and circumstances surrounding the movement of each of these requests through Shuttle Program Management, as well as the ultimate denial of these requests, is a topic of Chapter 6.

After discovering the strike, the Intercenter Photo Working Group prepared a report with a video clip of the impact and sent it to the Mission Management Team, the Mission Evaluation Room, and engineers at United Space Alliance and Boeing. In accordance with NASA guidelines, these contractor and NASA engineers began an assessment of potential impact damage to *Columbia*'s left wing, and soon formed a Debris Assessment Team to conduct a formal review.

The first formal Debris Assessment Team meeting was held on January 21, five days into the mission. It ended with the highest-ranking NASA engineer on the team agreeing to bring the team's request for imaging of the wing on-orbit, which would provide better information on which to base their analysis, to the Johnson Space Center Engineering Management Directorate, with the expectation the request would go forward to Space Shuttle Program managers. Debris Assessment Team members subsequently learned that these managers declined to image *Columbia*.

Without on-orbit pictures of *Columbia*, the Debris Assessment Team was restricted to using a mathematical modeling tool called Crater to assess damage, although it had not been designed with this type of impact in mind. Team members concluded over the next six days that some localized heating damage would most likely occur during re-entry, but they could not definitively state that structural damage would result. On January 24, the Debris Assessment Team made a presentation of these results to the Mission Evaluation Room, whose manager gave a verbal summary (with no data) of that presentation to the Mission Management Team the same day. The Mission Management Team declared the debris strike a "turnaround" issue and did not pursue a request for imagery.

Even after the Debris Assessment Team's conclusion had been reported to the Mission Management Team, engineers throughout NASA and Mission Control continued to exchange e-mails and discuss possible damage. These messages and discussions were generally sent only to people within the senders' area of expertise and level of seniority.



William McCool talks to Mission Control from the aft flight deck of Columbia during STS-107.

2.6 DE-ORBIT BURN AND RE-ENTRY EVENTS

At 2:30 a.m. EST on February 1, 2003, the Entry Flight Control Team began duty in the Mission Control Center. The Flight Control Team was not working any issues or problems related to the planned de-orbit and re-entry of *Columbia*. In particular, the team indicated no concerns about the debris impact to the left wing during ascent, and treated the re-entry like any other.

The team worked through the de-orbit preparation checklist and re-entry checklist procedures. Weather forecasters, with the help of pilots in the Shuttle Training Aircraft, evaluated landing site weather conditions at the Kennedy Space Center. At the time of the de-orbit decision, about 20 minutes before the initiation of the de-orbit burn, all weather observations and forecasts were within guidelines set by the flight rules, and all systems were normal.

Shortly after 8:00 a.m., the Mission Control Center Entry Flight Director polled the Mission Control room for a GO/NO-GO decision for the de-orbit burn, and at 8:10 a.m., the Capsule Communicator notified the crew they were GO for de-orbit burn.

As the Orbiter flew upside down and tail-first over the Indian Ocean at an altitude of 175 statute miles, Commander Husband and Pilot McCool executed the de-orbit burn at 8:15:30 a.m. using *Columbia*'s two Orbital Maneuvering System engines. The de-orbit maneuver was performed on the 255th orbit, and the 2-minute, 38-second burn slowed the Orbiter from 17,500 mph to begin its re-entry into the atmosphere. During the de-orbit burn, the crew felt about 10 percent of the effects of gravity. There were no problems during the burn, after which Husband maneuvered *Columbia* into a right-side-up, forward-facing position, with the Orbiter's nose pitched up.

Entry Interface, arbitrarily defined as the point at which the Orbiter enters the discernible atmosphere at 400,000 feet, occurred at 8:44:09 a.m. (Entry Interface plus 000 seconds, written EI+000) over the Pacific Ocean. As *Columbia* descended from space into the atmosphere, the heat produced by air molecules colliding with the Orbiter typically caused wing leading-edge temperatures to rise steadily, reaching an estimated 2,500 degrees Fahrenheit during the next six minutes. As superheated air molecules discharged light, astronauts on the flight deck saw bright flashes envelop the Orbiter, a normal phenomenon.

At 8:48:39 a.m. (EI+270), a sensor on the left wing leading edge spar showed strains higher than those seen on previous *Columbia* re-entries. This was recorded only on the Modular Auxiliary Data System, and was not telemetered to ground controllers or displayed to the crew (see Figure 2.6-1).

At 8:49:32 a.m. (EI+323), traveling at approximately Mach 24.5, *Columbia* executed a roll to the right, beginning a pre-planned banking turn to manage lift, and therefore limit the Orbiter's rate of descent and heating.

At 8:50:53 a.m. (EI+404), traveling at Mach 24.1 and at approximately 243,000 feet, *Columbia* entered a 10-minute period of peak heating, during which the thermal stresses were at their maximum. By 8:52:00 a.m. (EI+471), nearly eight minutes after entering the atmosphere and some 300 miles west of the California coastline, the wing leading-edge temperatures usually reached 2,650 degrees Fahrenheit. *Columbia* crossed the California coast west of Sacramento at 8:53:26 a.m. (EI+557). Traveling at Mach 23 and 231,600 feet, the Orbiter's wing leading edge typically reached more than an estimated 2,800 degrees Fahrenheit.



Columbia streaking over the Very Large Array radio telescope in Socorro, New Mexico.

Now crossing California, the Orbiter appeared to observers on the ground as a bright spot of light moving rapidly across the sky. Signs of debris being shed were sighted at 8:53:46 a.m. (EI+577), when the superheated air surrounding the Orbiter suddenly brightened, causing a noticeable streak in the Orbiter's luminescent trail. Observers witnessed another four similar events during the following 23 seconds, and a bright flash just seconds after *Columbia* crossed from California into Nevada airspace at 8:54:25 a.m. (EI+614), when the Orbiter was traveling at Mach 22.5 and 227,400 feet. Witnesses observed another 18 similar events in the next four minutes as *Columbia* streaked over Utah, Arizona, New Mexico, and Texas.

In Mission Control, re-entry appeared normal until 8:54:24 a.m. (EI+613), when the Maintenance, Mechanical, and Crew Systems (MMACS) officer informed the Flight Director that four hydraulic sensors in the left wing were indicating "off-scale low," a reading that falls below the minimum capability of the sensor. As the seconds passed, the Entry Team continued to discuss the four failed indicators.

At 8:55:00 a.m. (EI+651), nearly 11 minutes after *Columbia* had re-entered the atmosphere, wing leading edge temperatures normally reached nearly 3,000 degrees Fahrenheit. At 8:55:32 a.m. (EI+683), *Columbia* crossed from Nevada into Utah while traveling at Mach 21.8 and 223,400 ft. Twenty seconds later, the Orbiter crossed from Utah into Arizona.

At 8:56:30 a.m. (EI+741), *Columbia* initiated a roll reversal, turning from right to left over Arizona. Traveling at Mach 20.9 and 219,000 feet, *Columbia* crossed the Arizona-New Mexico state line at 8:56:45 (EI+756), and passed just north of Albuquerque at 8:57:24 (EI+795).

Around 8:58:00 a.m. (EI+831), wing leading edge temperatures typically decreased to 2,880 degrees Fahrenheit. At 8:58:20 a.m. (EI+851), traveling at 209,800 feet and Mach 19.5, *Columbia* crossed from New Mexico into Texas, and about this time shed a Thermal Protection System tile, which was the most westerly piece of debris that has been recovered.

Searchers found the tile in a field in Littlefield, Texas, just northwest of Lubbock. At 8:59:15 a.m. (EI+906), MMACS informed the Flight Director that pressure readings had been lost on both left main landing gear tires. The Flight Director then told the Capsule Communicator (CAPCOM) to let the crew know that Mission Control saw the messages and was evaluating the indications, and added that the Flight Control Team did not understand the crew's last transmission.

At 8:59:32 a.m. (EI+923), a broken response from the mission commander was recorded: "Roger, [cut off in mid-word] ..." It was the last communication from the crew and the last telemetry signal received in Mission Control. Videos made by observers on the ground at 9:00:18 a.m. (EI+969) revealed that the Orbiter was disintegrating.

2.7 EVENTS IMMEDIATELY FOLLOWING THE ACCIDENT

A series of events occurred immediately after the accident that would set the stage for the subsequent investigation.

NASA Emergency Response

Shortly after the scheduled landing time of 9:16 a.m. EST, NASA declared a "Shuttle Contingency" and executed the Contingency Action Plan that had been established after the *Challenger* accident. As part of that plan, NASA Administrator Sean O'Keefe activated the International Space Station and Space Shuttle Mishap Interagency Investigation Board at 10:30 a.m. and named Admiral Harold W. Gehman Jr., U.S. Navy, retired, as its chair.

Senior members of the NASA leadership met as part of the Headquarters Contingency Action Team and quickly notified astronaut families, the President, and members of Congress. President Bush telephoned Israeli Prime Minister Ariel Sharon to inform him of the loss of *Columbia* crew member Ilan Ramon, Israel's first astronaut. Several hours later, President Bush addressed the nation, saying, "The *Columbia* is lost. There are no survivors."



The Orbiter has a large glowing field surrounding it in this view taken from Mesquite, Texas, looking south.



Taken at the same time as the photo at left, but from Hewitt, Texas, looking north.

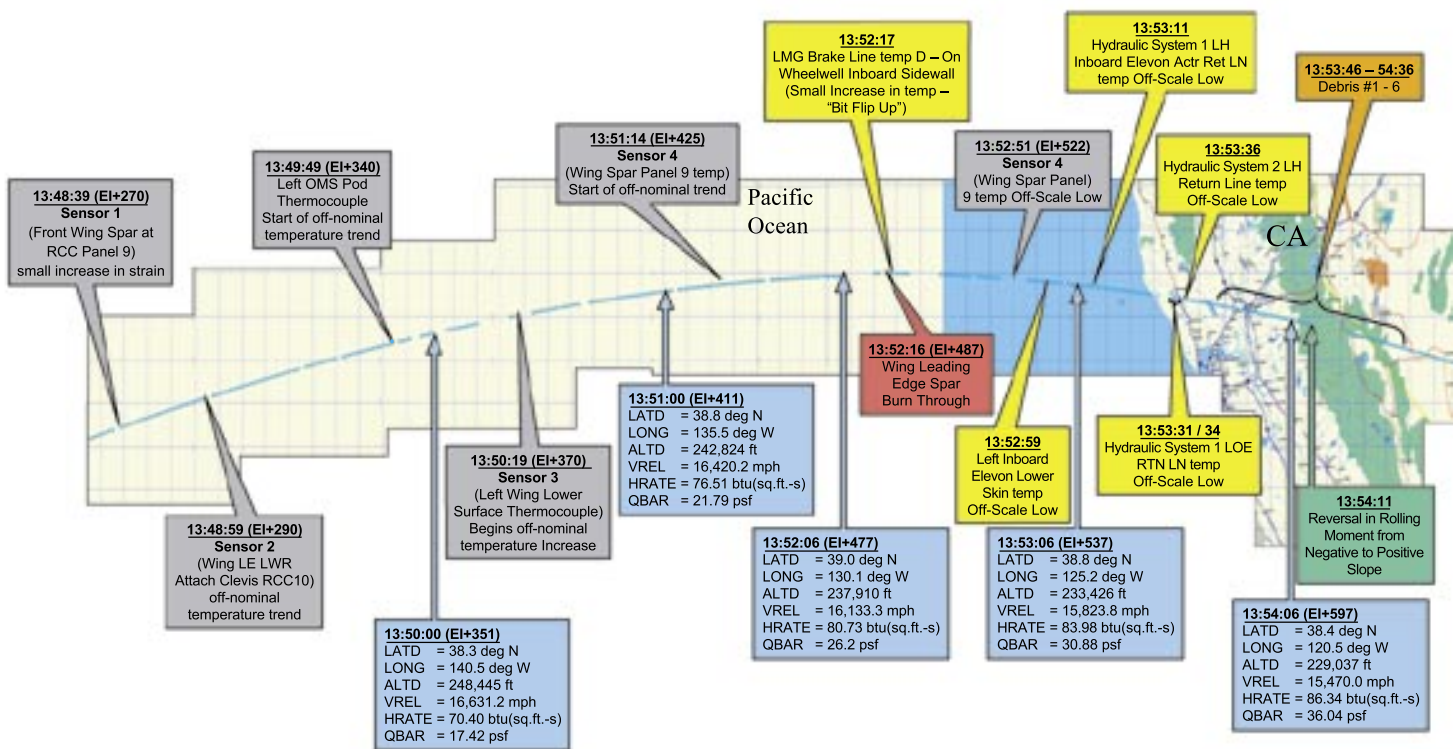


Figure 2.6-1. This simplified timeline shows the re-entry path of Columbia on February 1, 2003. The information presented here is a composite of sensor data telemetered to the ground combined with data from the Modular Auxiliary Data System recorder recovered after the accident. Note that the first off-nominal reading was a small increase in a strain gauge at the front wing spar behind RCC panel 9-left. The chart is color-coded: blue boxes contain position, attitude, and velocity information; orange boxes indicate when debris was shed from the Orbiter; green boxes are significant aerodynamic control events; gray boxes contain sensor information from the Modular Auxiliary Data System; and yellow boxes contain telemetered sensor information. The red boxes indicate other significant events.

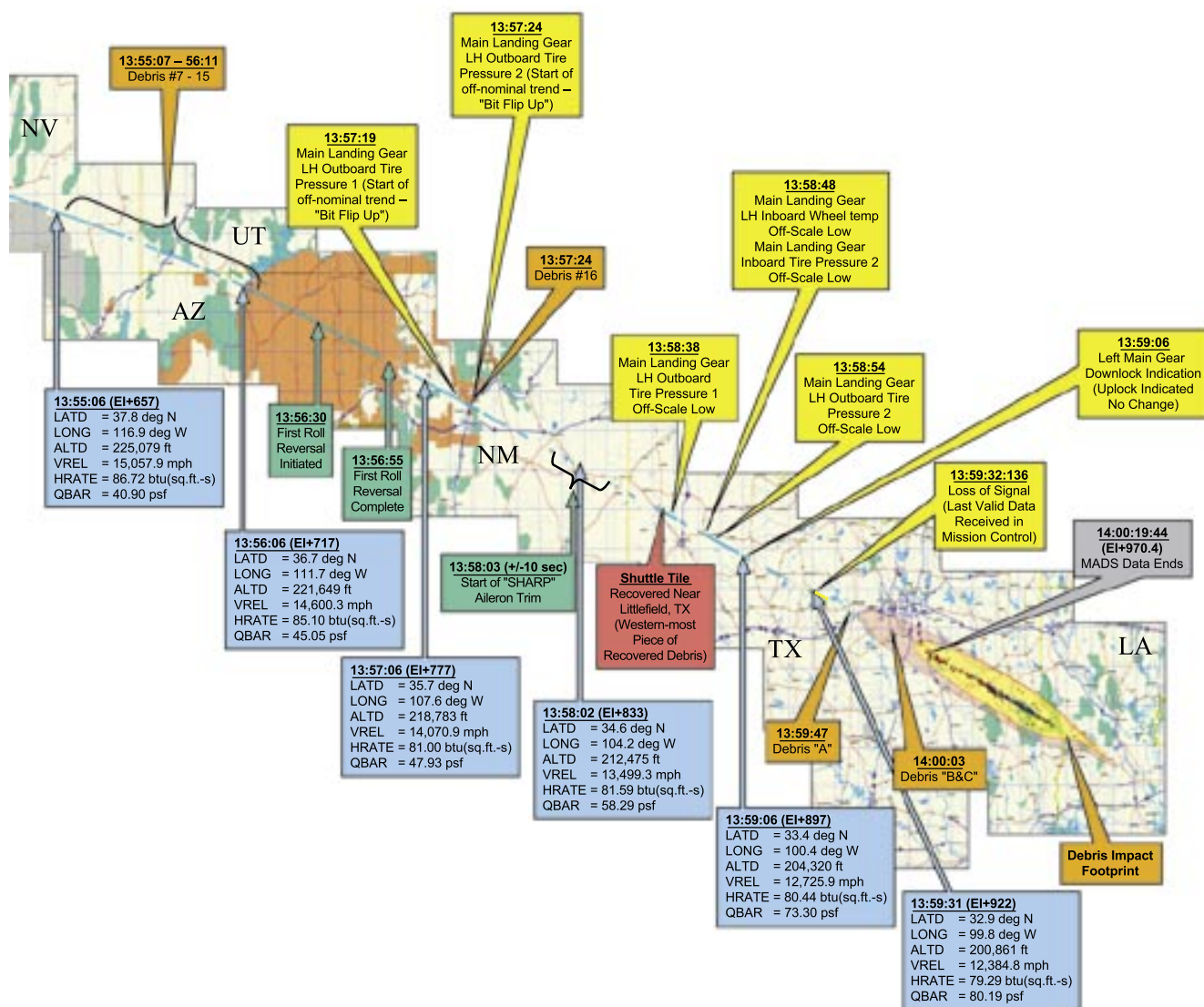


This view was taken from Dallas. (Robert McCullough/© 2003 The Dallas Morning News)



This video was captured by a Danish crew operating an AH-64 Apache helicopter near Fort Hood, Texas.

STS-107 Re-entry Trajectory and Timeline (First Off-Nominal Event to Loss of Signal)



MISSION CONTROL CENTER COMMUNICATIONS



At 8:49 a.m. Eastern Standard Time (EI+289), the Orbiter's flight control system began steering a precise course, or drag profile, with the initial roll command occurring about 30 seconds later. At 8:49:38 a.m., the Mission Control Guidance and Procedures officer called the Flight Director and indicated that the "closed-loop" guidance system had been initiated.

The Maintenance, Mechanical, and Crew Systems (MMACS) of the Flight Director (Flight) had the following exchange beginning at 8:54:24 a.m. (EI+613).

MMACS: "Flight – MMACS."
Flight: "Go ahead, MMACS."
MMACS: "FYI, I've just lost four separate temperature transducers on the left side of the vehicle, hydraulic return temperatures. Two of them on system one and one in each of systems two and three."
Flight: "Four hyd [hydraulic] return temps?"
MMACS: "To the left outboard and left inboard elevon."
Flight: "Okay, is there anything common to them? DSC [discrete signal conditioner] or MDM [multiplexer-demultiplexer] or anything? I mean, you're telling me you lost them all at exactly the same time?"
MMACS: "No, not exactly. They were within probably four or five seconds of each other."
Flight: "Okay, where are those, where is that instrumentation located?"
MMACS: "All four of them are located in the aft part of the left wing, right in front of the elevons, elevon actuators. And there is no commonality."
Flight: "No commonality."

At 8:56:02 a.m. (EI+713), the conversation between the Flight Director and the MMACS officer continues:

Flight: "MMACS, tell me again which systems they're for."
MMACS: "That's all three hydraulic systems. It's ... two of them are to the left outboard elevon and two of them to the left inboard."
Flight: "Okay, I got you."

The Flight Director then continues to discuss indications with other Mission Control Center personnel, including the Guidance, Navigation, and Control officer (GNC).

Flight: "GNC – Flight."
GNC: "Flight – GNC."
Flight: "Everything look good to you, control and rates and everything is nominal, right?"
GNC: "Control's been stable through the rolls that we've done so far, flight. We have good trims. I don't see anything out of the ordinary."
Flight: "Okay. And MMACS, Flight?"
MMACS: "Flight – MMACS."
Flight: "All other indications for your hydraulic system indications are good."
MMACS: "They're all good. We've had good quantities all the way across."
Flight: "And the other temps are normal?"
MMACS: "The other temps are normal, yes sir."
Flight: "And when you say you lost these, are you saying that they went to zero?" [Time: 8:57:59 a.m., EI+830]
"Or, off-scale low?"
MMACS: "All four of them are off-scale low. And they were all staggered. They were, like I said, within several seconds of each other."
Flight: "Okay."

At 8:58:00 a.m. (EI+831), Columbia crossed the New Mexico-Texas state line. Within the minute, a broken call came on the air-to-ground voice loop from Columbia's commander, "And, uh, Hou ...". This was followed by a call from MMACS about failed tire pressure sensors at 8:59:15 a.m. (EI+906).

MMACS: "Flight – MMACS."
Flight: "Go."
MMACS: "We just lost tire pressure on the left outboard and left inboard, both tires."

[continued on next page]

The Flight Director then told the Capsule Communicator (CAPCOM) to let the crew know that Mission Control saw the messages and that the Flight Control Team was evaluating the indications and did not copy their last transmission.

CAPCOM: "And Columbia, Houston, we see your tire pressure messages and we did not copy your last call."

Flight: "Is it instrumentation, MMACS? Gotta be ..."

MMACS: "Flight – MMACS, those are also off-scale low."

At 8:59:32 a.m. (EI+923), Columbia was approaching Dallas, Texas, at 200,700 feet and Mach 18.1. At the same time, another broken call, the final call from Columbia's commander, came on the air-to-ground voice loop:

Commander: "Roger, [cut off in mid-word] ..."

This call may have been about the backup flight system tire pressure fault-summary messages annunciated to the crew onboard, and seen in the telemetry by Mission Control personnel. An extended loss of signal began at 08:59:32.136 a.m. (EI+923). This was the last valid data accepted by the Mission Control computer stream, and no further real-time data updates occurred in Mission Control. This coincided with the approximate time when the Flight Control Team would expect a short-duration loss of signal during antenna switching, as the onboard communication system automatically reconfigured from the west Tracking and Data Relay System satellite to either the east satellite or to the ground station at Kennedy Space Center. The following exchange then took place on the Flight Director loop with the Instrumentation and Communication Office (INCO):

INCO: "Flight – INCO."

Flight: "Go."

INCO: "Just taking a few hits here. We're right up on top of the tail. Not too bad."

The Flight Director then resumes discussion with the MMACS officer at 9:00:18 a.m. (EI+969).

Flight: "MMACS – Flight."

MMACS: "Flight – MMACS."

Flight: "And there's no commonality between all these tire pressure instrumentations and the hydraulic return instrumentations."

MMACS: "No sir, there's not. We've also lost the nose gear down talkback and the right main gear down talkback."

Flight: "Nose gear and right main gear down talkbacks?"

MMACS: "Yes sir."

At 9:00:18 a.m. (EI+969), the postflight video and imagery analyses indicate that a catastrophic event occurred. Bright flashes suddenly enveloped the Orbiter, followed by a dramatic change in the trail of superheated air. This is considered the most likely time of the main breakup of Columbia. Because the loss of signal had occurred 46 seconds earlier, Mission Control had no insight into this event. Mission Control continued to work the loss-of-signal problem to regain communication with Columbia:

INCO: "Flight – INCO, I didn't expect, uh, this bad of a hit on comm [communications]."

Flight: "GC [Ground Control officer] how far are we from UHF? Is that two-minute clock good?"

GC: "Affirmative, Flight."

GNC: "Flight – GNC."

Flight: "Go."

GNC: "If we have any reason to suspect any sort of controllability issue, I would keep the control cards handy on page 4-dash-13."

Flight: "Copy."

At 9:02:21 a.m. (EI+1092, or 18 minutes-plus), the Mission Control Center commentator reported, "Fourteen minutes to touchdown for Columbia at the Kennedy Space Center. Flight controllers are continuing to stand by to regain communications with the spacecraft."

Flight: "INCO, we were rolled left last data we had and you were expecting a little bit of ratty comm [communications], but not this long?"

INCO: "That's correct, Flight. I expected it to be a little intermittent. And this is pretty solid right here."

Flight: "No onboard system config [configuration] changes right before we lost data?"

INCO: "That is correct, Flight. All looked good."

Flight: "Still on string two and everything looked good?"

INCO: "String two looking good."

The Ground Control officer then told the Flight Director that the Orbiter was within two minutes of acquiring the Kennedy Space Center ground station for communications, "Two minutes to MILA." The Flight Director told the CAPCOM to try another communications check with Columbia, including one on the UHF system (via MILA, the Kennedy Space Center tracking station):

CAPCOM: "Columbia, Houston, comm [communications] check."

CAPCOM: "Columbia, Houston, UHF comm [communications] check."

At 9:03:45 a.m. (EI+1176, or 19 minutes-plus), the Mission Control Center commentator reported, "CAPCOM Charlie Hobaugh calling Columbia on a UHF frequency as it approaches the Merritt Island (MILA) tracking station in Florida. Twelve-and-a-half minutes to touchdown, according to clocks in Mission Control."

MMACS: "Flight – MMACS."

Flight: "MMACS?"

MMACS: "On the tire pressures, we did see them go erratic for a little bit before they went away, so I do believe it's instrumentation."

Flight: "Okay."

The Flight Control Team still had no indications of any serious problems onboard the Orbiter. In Mission Control, there was no way to know the exact cause of the failed sensor measurements, and while there was concern for the extended loss of signal, the recourse was to continue to try to regain communications and in the meantime determine if the other systems, based on the last valid data, continued to appear as expected. The Flight Director told the CAPCOM to continue to try to raise Columbia via UHF:

CAPCOM: "Columbia, Houston, UHF comm [communications] check."

CAPCOM: "Columbia, Houston, UHF comm [communications] check."

GC: "Flight – GC."

Flight: "Go."

GC: "MILA not reporting any RF [radio frequency] at this time."

[continued on next page]

[continued from previous page]

INCO: "Flight – INCO, SPC [stored program command] just should have taken us to STDN low." *[STDN is the Space Tracking and Data Network, or ground station communication mode]*

Flight: "Okay."

Flight: "FDO, when are you expecting tracking?" *"[FDO is the Flight Dynamics Officer in the Mission Control Center]"*

FDO: "One minute ago, Flight."

GC: "And Flight – GC, no C-band yet."

Flight: "Copy."

CAPCOM: "Columbia, Houston, UHF comm [communications] check."

INCO: "Flight – INCO."

Flight: "Go."

INCO: "I could swap strings in the blind."

Flight: "Okay, command us over."

INCO: "In work, Flight."

At 09:08:25 a.m. (EI+1456, or 24 minutes-plus), the Instrumentation and Communications Officer reported, "Flight – INCO, I've commanded string one in the blind," which indicated that the officer had executed a command sequence to Columbia to force the onboard S-band communications system to the backup string of avionics to try to regain communication, per the Flight Director's direction in the previous call.

GC: "And Flight – GC."

Flight: "Go."

GC: "MILA's taking one of their antennas off into a search mode [to try to find Columbia]."

Flight: "Copy. FDO – Flight?"

FDO: "Go ahead, Flight."

Flight: "Did we get, have we gotten any tracking data?"

FDO: "We got a blip of tracking data, it was a bad data point, Flight. We do not believe that was the Orbiter *[referring to an errant blip on the large front screen in the Mission Control, where Orbiter tracking data is displayed.]* We're entering a search pattern with our C-bands at this time. We do not have any valid data at this time."

By this time, 9:09:29 a.m. (EI+1520), Columbia's speed would have dropped to Mach 2.5 for a standard approach to the Kennedy Space Center.

Flight: "OK. Any other trackers that we can go to?"

FDO: "Let me start talking, Flight, to my navigator."

At 9:12:39 a.m. (E+1710, or 28 minutes-plus), Columbia should have been banking on the heading alignment cone to line up on Runway 33. At about this time, a member of the Mission Control team received a call on his cell phone from someone who had just seen live television coverage of Columbia breaking up during re-entry. The Mission Control team member walked to the Flight Director's console and told him the Orbiter had disintegrated.

Flight: "GC, – Flight. GC – Flight?"

GC: "Flight – GC."

Flight: "Lock the doors."

Having confirmed the loss of Columbia, the Entry Flight Director directed the Flight Control Team to begin contingency procedures.

In order to preserve all material relating to STS-107 as evidence for the accident investigation, NASA officials impounded data, software, hardware, and facilities at NASA and contractor sites in accordance with the pre-existing mishap response plan.

At the Johnson Space Center, the door to Mission Control was locked while personnel at the flight control consoles archived all original mission data. At the Kennedy Space Center, mission facilities and related hardware, including Launch Complex 39-A, were put under guard or stored in secure warehouses. Officials took similar actions at other key Shuttle facilities, including the Marshall Space Flight Center and the Michoud Assembly Facility.

Within minutes of the accident, the NASA Mishap Investigation Team was activated to coordinate debris recovery efforts with local, state, and federal agencies. The team initially operated out of Barksdale Air Force Base in Louisiana and soon after in Lufkin, Texas, and Carswell Field in Fort Worth, Texas.

Debris Search and Recovery

On the morning of February 1, a crackling boom that signaled the breakup of *Columbia* startled residents of East Texas. The long, low-pitched rumble heard just before 8:00 a.m. Central Standard Time (CST) was generated by pieces of debris streaking into the upper atmosphere at nearly 12,000 miles per hour. Within minutes, that debris fell to the ground. Cattle stampeded in Eastern Nacogdoches County. A fisherman on Toledo Bend reservoir saw a piece splash down in the water, while a woman driving near Lufkin almost lost control of her car when debris smacked her windshield. As 911 dispatchers across Texas were flooded with calls reporting sonic booms and smoking debris, emergency personnel soon realized that residents were encountering the remnants of the Orbiter that NASA had reported missing minutes before.

The emergency response that began shortly after 8:00 a.m. CST Saturday morning grew into a massive effort to decontaminate and recover debris strewn over an area that in Texas alone exceeded 2,000 square miles (see Figure 2.7-1). Local fire and police departments called in all personnel, who began responding to debris reports that by late afternoon were phoned in at a rate of 18 per minute.

Within hours of the accident, President Bush declared East Texas a federal disaster area, enabling the dispatch of emergency response teams from the Federal Emergency Management Agency and Environmental Protection Agency. As the day wore on, county constables, volunteers on horseback, and local citizens headed into pine forests and bushy thickets in search of debris and crew remains, while National Guard units mobilized to assist local law-enforcement guard debris sites. Researchers from Stephen F. Austin University sent seven teams into the field with Global Positioning System units to mark the exact location of debris. The researchers and later searchers then used this data to update debris distribution on detailed Geographic Information System maps.

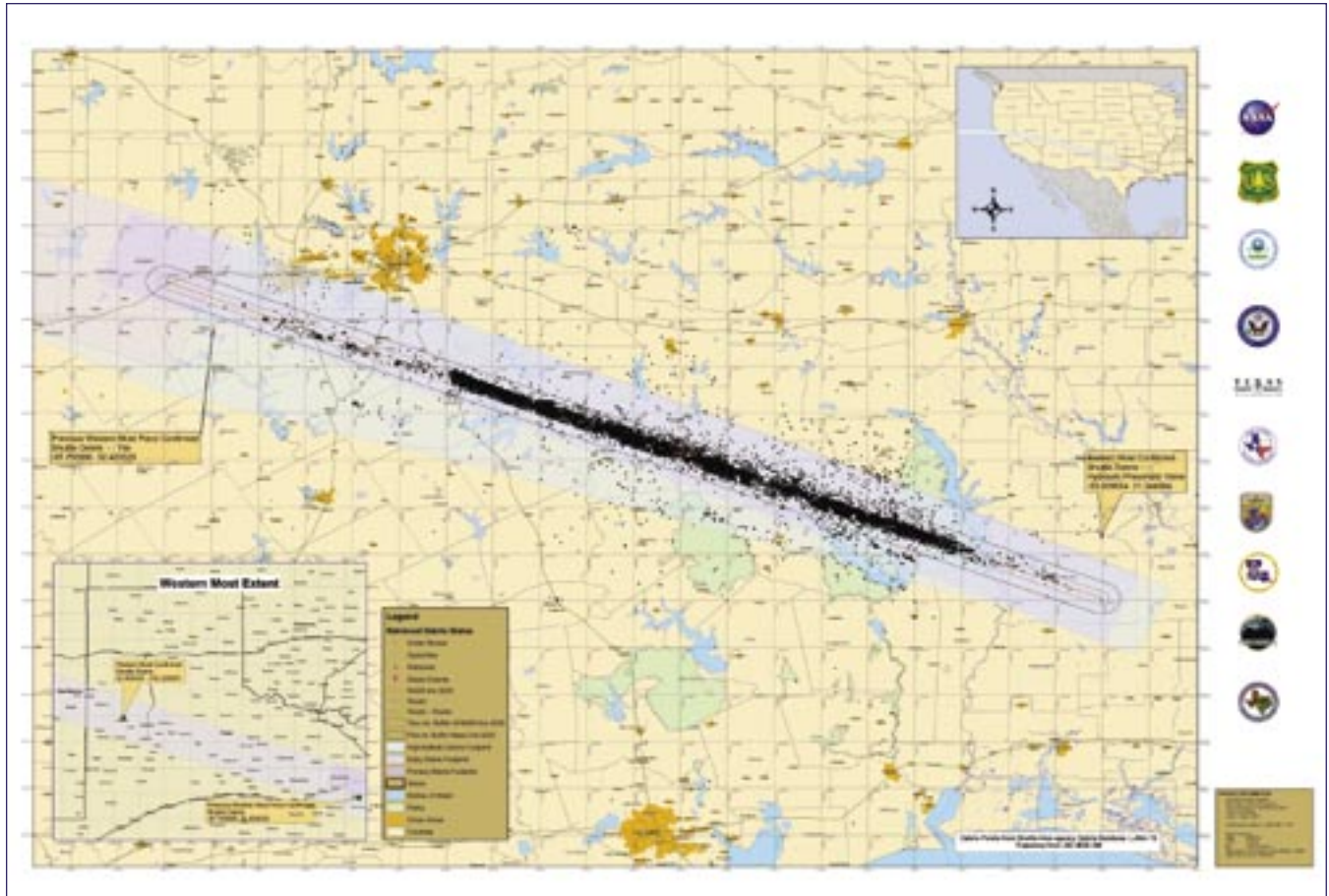


Figure 2.7-1. The debris field in East Texas spread over 2,000 square miles, and eventually over 700,000 acres were searched.

Public Safety Concerns

From the start, NASA officials sought to make the public aware of the hazards posed by certain pieces of debris, as well as the importance of turning over all debris to the authorities. *Columbia* carried highly toxic propellants that maneuvered the Orbiter in space and during early stages of re-entry. These propellants and other gases and liquids were stored in pressurized tanks and cylinders that posed a danger to people who might approach Orbiter debris. The propellants, monomethyl hydrazine and nitrogen tetroxide, as well as concentrated ammonia used in the Orbiter's cooling systems, can severely burn the lungs and exposed skin when encountered in vapor form. Other materials used in the Orbiter, such as beryllium, are also toxic. The Orbiter also contains various pyrotechnic devices that eject or release items such as the Ku-Band antenna, landing gear doors, and hatches in an emergency. These pyrotechnic devices and their triggers, which are designed to withstand high heat and therefore may have survived re-entry, posed a danger to people and livestock. They had to be removed by personnel trained in ordnance disposal.

In light of these and other hazards, NASA officials worked with local media and law enforcement to ensure that no one on the ground would be injured. To determine that Orbiter debris did not threaten air quality or drinking water, the Envi-

ronmental Protection Agency activated Emergency Response and Removal Service contractors, who surveyed the area.

Land Search

The tremendous efforts mounted by the National Guard, Texas Department of Public Safety, and emergency personnel from local towns and communities were soon overwhelmed by the expanding bounds of the debris field, the densest region of which ran from just south of Fort Worth, Texas, to Fort Polk, Louisiana. Faced with a debris field several orders of magnitude larger than any previous accident site, NASA and Federal Emergency Management Agency officials activated Forest Service wildland firefighters to serve as the primary search teams. As NASA identified the areas to be searched, personnel and equipment were furnished by the Forest Service.

Within two weeks, the number of ground searchers exceeded 3,000. Within a month, more than 4,000 searchers were flown in from around the country to base camps in Corsicana, Palestine, Nacogdoches, and Hemphill, Texas. These searchers, drawn from across the United States and Puerto Rico, worked 12 hours per day on 14-, 21-, or 30-day rotations and were accompanied by Global Positioning System-equipped NASA and Environmental Protection Agency personnel trained to handle and identify debris.

Based on sophisticated mapping of debris trajectories gathered from telemetry, radar, photographs, video, and meteorological data, as well as reports from the general public, teams were dispatched to walk precise grids of East Texas pine brush and thicket (see Figure 2.7-2). In lines 10 feet apart, a distance calculated to provide a 75 percent probability of detecting a six-inch-square object, wildland firefighters scoured snake-infested swamps, mud-filled creek beds, and brush so thick that one team advanced only a few hundred feet in an entire morning. These 20-person ground teams systematically covered an area two miles to either side of the Orbiter's ground track. Initial efforts concentrated on the search for human remains and the debris corridor between Corsicana, Texas, and Fort Polk. Searchers gave highest priority to a list of some 20 "hot items" that potentially contained crucial information, including the Orbiter's General Purpose Computers, film, cameras, and the Modular Auxiliary Data System recorder. Once the wildland firefighters entered the field, recovery rates exceeded 1,000 pieces of debris per day.



Figure 2.7-2. Searching for debris was a laborious task that used thousands of people walking over hundreds of acres of Texas and Louisiana.

After searchers spotted a piece of debris and determined it was not hazardous, its location was recorded with a Global Positioning System unit and photographed. The debris was then tagged and taken to one of four collection centers at Corsicana, Palestine, Nacogdoches, and Hemphill, Texas. There, engineers made a preliminary identification, entered the find into a database, and then shipped the debris to Kennedy Space Center, where it was further analyzed in a hangar dedicated to the debris reconstruction.

Air Search

Air crews used 37 helicopters and seven fixed-wing aircraft to augment ground searchers by searching for debris farther out from the Orbiter's ground track, from two miles from the centerline to five miles on either side. Initially, these crews used advanced remote sensing technologies, including two satellite platforms, hyper-spectral and forward-looking infrared scanners, forest penetration radars, and imagery from Lockheed U-2 reconnaissance aircraft. Because of the densi-



Figure 2.7-3. Tragically, a helicopter crash during the debris search claimed the lives of Jules "Buzz" Mier (in black coat) and Charles Krennek (yellow coat).

ty of the East Texas vegetation, the small sizes of the debris, and the inability of sensors to differentiate Orbiter material from other objects, these devices proved of little value. As a result, the detection work fell to spotter teams who visually scanned the terrain. Air search coordinators apportioned grids to allow a 50 percent probability of detection for a one-foot-square object. Civil Air Patrol volunteers and others in powered parachutes, a type of ultralight aircraft, also participated in the search, but were less successful than helicopter and fixed-wing air crews in retrieving debris. During the air search, a Bell 407 helicopter crashed in Angelina National Forest in San Augustine County after a mechanical failure. The accident took the lives of Jules F. "Buzz" Mier Jr., a contract pilot, and Charles Krennek, a Texas Forest Service employee, and injured three others (see Figure 2.7-3).

Water Search

The United States Navy Supervisor of Salvage organized eight dive teams to search Lake Nacogdoches and Toledo Bend Reservoir, two bodies of water in dense debris fields. Sonar mapping of more than 31 square miles of lake bottom identified more than 3,100 targets in Toledo Bend and 326 targets in Lake Nacogdoches. Divers explored each target, but in murky water with visibility of only a few inches, underwater forests, and other submerged hazards, they recovered only one object in Toledo Bend and none in Lake Nacogdoches. The 60 divers came from the Navy, Coast Guard, Environmental Protection Agency, Texas Forest Service, Texas Department of Public Safety, Houston and Galveston police and fire departments, and Jasper County Sheriff's Department.

Search Beyond Texas and Louisiana

As thousands of personnel combed the Orbiter's ground track in Texas and Louisiana, other civic and community groups searched areas farther west. Environmental organizations and local law enforcement walked three counties of California coastline where oceanographic data indicated a high

probability of debris washing ashore. Prison inmates scoured sections of the Nevada desert. Civil Air Patrol units and other volunteers searched thousands of acres in New Mexico, by air and on foot. Though these searchers failed to find any debris, they provided a valuable service by closing out potential debris sites, including nine areas in Texas, New Mexico, Nevada, and Utah identified by the National Transportation Safety Board as likely to contain debris. NASA's Mishap Investigation Team addressed each of the 1,459 debris reports it received. So eager was the general public to turn in pieces of potential debris that NASA received reports from 37 U.S. states that *Columbia's* re-entry ground track did not cross, as well as from Canada, Jamaica, and the Bahamas.

Property Damage

No one was injured and little property damage resulted from the tens of thousands of pieces of falling debris (see Chapter 10). A reimbursement program administered by NASA distributed approximately \$50,000 to property owners who made claims resulting from falling debris or collateral damage from the search efforts. There were, however, a few close calls that emphasize the importance of selecting the ground track that re-entering Orbiters follow. A 600-pound piece of a main engine dug a six-foot-wide hole in the Fort Polk golf course, while an 800-pound main engine piece, which hit the ground at an estimated 1,400 miles per hour, dug an even larger hole nearby. Disaster was narrowly averted outside Nacogdoches when a piece of debris landed between two highly explosive natural gas tanks set just feet apart.

Debris Amnesty

The response of the public in reporting and turning in debris was outstanding. To reinforce the message that Orbiter debris was government property as well as essential evidence of the accident's cause, NASA and local media officials repeatedly urged local residents to report all debris immediately. For those who might have been keeping debris as souvenirs, NASA offered an amnesty that ran for several days. In the end, only a handful of people were prosecuted for theft of debris.

Final Totals

More than 25,000 people from 270 organizations took part in debris recovery operations. All told, searchers expended over 1.5 million hours covering more than 2.3 million acres, an area approaching the size of Connecticut. Over 700,000 acres were searched by foot, and searchers found over 84,000 individual pieces of Orbiter debris weighing more than 84,900 pounds, representing 38 percent of the Orbiter's dry weight. Though significant evidence from radar returns and video recordings indicate debris shedding across California, Nevada, and New Mexico, the most westerly piece of confirmed debris (at the time this report was published) was the tile found in a field in Littleton, Texas. Heavier objects with higher ballistic coefficients, a measure of how far objects will travel in the air, landed toward the end of the debris trail in western Louisiana. The most easterly debris pieces, including the Space Shuttle Main Engine turbopumps, were found in Fort Polk, Louisiana.

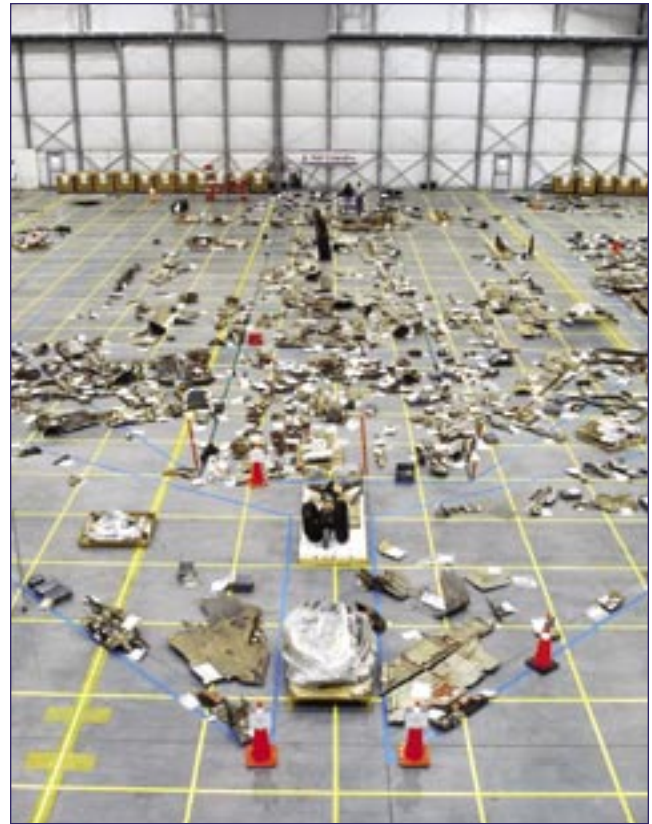


Figure 2.7-4. Recovered debris was returned to the Kennedy Space Center where it was laid out in a large hangar. The tape on the floor helped workers place each piece near where it had been on the Orbiter.

The Federal Emergency Management Agency, which directed the overall effort, expended more than \$305 million to fund the search. This cost does not include what NASA spent on aircraft support or the wages of hundreds of civil servants employed at the recovery area and in analysis roles at NASA centers.

The Importance of Debris

The debris collected (see Figure 2.7-4) by searchers aided the investigation in significant ways. Among the most important finds was the Modular Auxiliary Data System recorder that captured data from hundreds of sensors that was not telemetered to Mission Control. Data from these 800 sensors, recorded on 9,400 feet of magnetic tape, provided investigators with millions of data points, including temperature sensor readings from *Columbia's* left wing leading edge. The data also helped fill a 30-second gap in telemetered data and provided an additional 14 seconds of data after the telemetry loss of signal.

Recovered debris allowed investigators to build a three-dimensional reconstruction of *Columbia's* left wing leading edge, which was the basis for understanding the order in which the left wing structure came apart, and led investigators to determine that heat first entered the wing in the location where photo analysis indicated the foam had struck.

ENDNOTES FOR CHAPTER 2

The citations that contain a reference to "CAIB document" with CAB or CTF followed by seven to eleven digits, such as CAB001-0010, refer to a document in the Columbia Accident Investigation Board database maintained by the Department of Justice and archived at the National Archives.

¹ The primary source document for this process is NSTS 08117, Requirements and Procedures for Certification and Flight Readiness. CAIB document CTF017-03960413.

² Statement of Daniel S. Goldin, Administrator, National Aeronautics and Space Administration, before the Subcommittee on VA-HUD-Independent Agencies, Committee on Appropriations, House of Representatives, March 31, 1998. CAIB document CAB048-04000418.

³ Roberta L. Gross, Inspector General, NASA, to Daniel S. Goldin, Administrator, NASA, "Assessment of the Triana Mission, G-99-013, Final Report," September 10, 1999. See in particular footnote 3, concerning Triana and the requirements of the Commercial Space Act, and Appendix C, "Accounting for Shuttle Costs." CAIB document CAB048-02680269.

⁴ Although there is more volume of liquid hydrogen in the External Tank, liquid hydrogen is very light and its slosh effects are minimal and are generally ignored. At launch, the External Tank contains approximately 1.4 million pounds (140,000 gallons) of liquid oxygen, but only 230,000 pounds (385,000 gallons) of liquid hydrogen.

⁵ The Performance Enhancements (PE) flight profile flown by STS-107 is a combination of flight software and trajectory design changes that were introduced in late 1997 for STS-85. These changes to the ascent flight profile allow the Shuttle to carry some 1,600 pounds of additional payload on International Space Station assembly missions. Although developed to meet the Space Station payload lift requirement, a modified PE profile has been used for all Shuttle missions since it was introduced.