HARVARD | BUSINESS | SCHOOL

9-304-090

REV: NOVEMBER 17, 2004

RICHARD M. J. BOHMER

AMY C. EDMONDSON

MICHAEL A. ROBERTO

Columbia's Final Mission

Early Saturday morning, February 1, 2003, after 16 days in space, the seven-member crew of the Space Shuttle Orbiter *Columbia* prepared for reentry into the Earth's atmosphere. At 8:15 a.m. EST Pilot William McCool and Commander Rick Husband executed a series of rolls to slow the orbiter's trajectory, allowing for a landing at Kennedy Space Center (KSC) in Florida. (See **Exhibit 1** for a list of acronyms.) At 8:44 a.m., as the *Columbia* descended into the Earth's atmosphere over the Pacific Ocean, atmospheric gases heated leading edges of the orbiter's wings, as expected, to temperatures estimated at 2,500° Fahrenheit. NASA predicted even higher temperatures as air molecules collided with the craft.

As the orbiter continued eastward, however, the left wing's temperature gauge registered an off-the-charts low reading. Mission Control, based in Houston, Texas, noted other erratic temperature readings, which they communicated to Husband. He responded, "And, uh, Hou . . . " before being cut off. A second communication from the orbiter, at 8:59 a.m., began, "Roger, [cut off in midword] . . . " Mission Control received failed sensor readings from other areas on the shuttle, and then at 9:00 a.m., it lost the *Columbia's* signal.

At 9:12 a.m., a member of the Mission Control team received a phone call from someone who had just watched a televised news report that showed video of the *Columbia* breaking up during reentry. Mission Control began to follow a contingency plan that instructed the team to lock the doors to the room and archive all mission-related data.

In August, the Columbia Accident Investigation Board (CAIB) presented its report on the causes of the accident. A loose piece of insulating foam—approximately 19 inches long by 11 inches wide and weighing 1.7 pounds—had punctured a large hole in the orbiter's left wing shortly after launch. Because of this breach, extremely hot gases penetrated the wing during reentry and destroyed its structural support, ultimately leading to destruction of the wing and breakup of the orbiter. While the CAIB's report detailed the technical causes of the accident, it also documented how managers might have behaved differently in the days leading up to the loss of the *Columbia* and stressed the organizational shortcomings at NASA that contributed to the catastrophe.[1]

Professors Richard M. J. Bohmer, Amy C. Edmondson, and Michael A. Roberto and Research Associates Laura R. Feldman and Erika M. Ferlins prepared this case. This case was developed from published sources and interviews with outside experts. The quotes drawn from those interviews represent the individuals' views and not the view of any agency, institution or collective body. HBS cases are developed solely as the basis for class discussion. Cases are not intended to serve as endorsements, sources of primary data, or illustrations of effective or ineffective management.

Copyright © 2004 President and Fellows of Harvard College. To order copies or request permission to reproduce materials, call 1-800-545-7685, write Harvard Business School Publishing, Boston, MA 02163, or go to http://www.hbsp.harvard.edu. No part of this publication may be reproduced, stored in a retrieval system, used in a spreadsheet, or transmitted in any form or by any means—electronic, mechanical, photocopying, recording, or otherwise—without the permission of Harvard Business School.

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Do Not Copy or Post

National Aeronautics and Space Administration

The Early Years[2]

In 1958 the U.S. Congress and President Eisenhower created the National Aeronautics and Space Administration (NASA) in response to the launch of the satellite *Sputnik* by the Soviet Union the previous year. A 1960 report by the President's Science Advisory Committee stated, "We have been plunged into a race for the conquest of outer space. As a reason for this undertaking some look to the new and exciting scientific discoveries, which are certain to be made. Others feel the challenge to transport man beyond frontiers he scarcely dared dream about until now."[3]

NASA launched several major programs during its first two decades. These initiatives included various aeronautics research projects, scientific probes to the moon and other planets, and the nation's first human space flights, all of which the American public followed with rapture.

Human space flight initiatives The first American traveled into space on May 5, 1961, when Alan Shepard, Jr. rode the *Mercury* capsule on a 15-minute suborbital mission. Over the following five years, additional missions in the Mercury and Gemini capsules tested the ability of humans to survive space flight and practiced space operations such as rendezvous and docking in space.

In 1961, President Kennedy announced that the nation would aim to send astronauts to the moon before the end of the decade. In the 11th mission of Project Apollo on July 20, 1969, astronauts Neil Armstrong and Buzz Aldrin, Jr. became the first human beings to walk on the moon's surface. Armstrong stated, to great acclaim, "That's one small step for man, one giant leap for mankind."

Project Apollo incurred tremendous cost, not only in dollar terms—$25.4 billion—but also in human life: three astronauts died in early 1967 when an Apollo capsule caught fire on the launchpad. In response to this event, Congress recommended that NASA create a senior-level independent safety organization, the Aerospace Safety Advisory Panel, which would focus on human space flight. NASA established additional safety and reliability offices at each of its human space flight centers.

NASA narrowly avoided a second catastrophe during the *Apollo 13* mission in April 1970, when a primary oxygen tank burst while astronauts traveled to the moon. At first, Mission Control staffers believed that they were receiving faulty instrument readings. Soon, however, astronaut James Lovell pronounced, "Houston, we've had a problem." Flight Director Gene Kranz moved quickly to diagnose the situation. He sought frantically for a way to sustain the astronauts in the short term while assembling a team to devise a way to safely return the astronauts to Earth.

Kranz quickly found that the astronauts could move into the attached lunar excursion module. He then assembled a "Tiger Team" consisting of individuals with relevant expertise to focus on the problem.[a] Fortunately, Kranz had developed and trained teams in his organization to deal with various kinds of emergencies through frequent drills and practice sessions. Now, when faced with a real crisis, he pushed this team to think creatively, generate many options, and perform rapid analysis of each alternative. The Tiger Team worked around the clock for three days while oxygen reserves on the capsule slowly depleted. The group's ingenious—and at times remarkably simple—solutions enabled the safe return of the crew. Kranz later stated, "Once you think of surrendering . . .

[a] When an anomalous event occurred on-orbit and reached sufficient criticality or complexity to necessitate additional support, the Mission Evaluation Room (MER) manager designated a Tiger Team to assess the anomaly and plan a course of action. NASA and United Space Alliance engineers would co-chair a Tiger Team, which was composed of any personnel deemed appropriate and reported to shuttle program managers. (Source: CAIB, Vol. 2, Appendix D17.)

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

that is the path you go down. As soon as you start thinking that way, you really have lost . . . the mental sharpness, the mental edge that is going to take this survival situation and bring it to a successful conclusion."[4]

Manned flights to the moon ended soon after the *Apollo 13* incident. After a 1975 mission in which American astronauts met up with a Soviet spacecraft for the first time, NASA endured a six-year hiatus before its next manned space flight.

Organizational Structure

Programs NASA was a complex matrix organization employing over 24,000.[5] In addition to human space flight, NASA programs encompassed deep-space and interplanetary exploration, Earth observation, and aeronautics research. The main human space flight programs were the Space Shuttle Program (described below) and the International Space Station Program.

In 1993, the United States, Russia, Japan, and the European Space Agency, among others, created the International Space Station, intended as a base for further deep-space exploration. The United States and Russia independently launched and joined the first two modules of the station in 1998. Humans had continuously inhabited the Space Station since 2000. Plans called for U.S. additions to the Space Station in early 2004.

Centers NASA was headquartered in Washington, D.C., and by 2003, it maintained over 15 industrial, academic, and field centers across the nation. These centers were dedicated to research, development, testing, and manufacturing of products for the human space flight program. Johnson, Kennedy, and Marshall were the field centers dedicated to launch and management of the Shuttle programs. The Mission Control center and Space Shuttle Program office were located at Johnson Space Center (JSC), in Houston, Texas. Shuttle assembly, launch, and landing occurred at Kennedy Space Center (KSC) on Merritt Island, Florida. Marshall Space Flight Center (MSFC), near Huntsville, Alabama, housed the Space Shuttle Projects Office and was responsible for rocket propulsion efforts, including the Shuttle's External Tank, solid rocket boosters (SRBs), and main engine.

Contractors From its inception, NASA outsourced many aspects of its operations to the private sector. NASA had long-standing relationships with Boeing for design and manufacture of the Orbiter, ATK Thiokol Propulsion (formerly Morton Thiokol) for portions of the Shuttle's SRBs, and Lockheed Martin for design and manufacture of the external fuel tank and special panels on the nose and wings of the orbiter. Boeing and Lockheed Martin formed United Space Alliance to perform the Space Flight Operations Contract of 1996. In essence, United Space Alliance managed relationships with Shuttle contractors so that NASA could focus on research and development.

The Space Shuttle Program[6]

In the early 1970s NASA had devised a plan to construct an outpost to serve as a base for further space exploration, ultimately allowing humans to travel to Mars. The plan required NASA to develop a fleet of vehicles that could transport crew and materials between Earth and the Space Station. Ultimately, neither President Lyndon Johnson nor his successor, Richard Nixon, approved the development of a costly space station. Nevertheless, NASA clung to the concept of a new reusable vehicle for manned space flight. Without a space station, the vehicle needed a new purpose. Facing budget cutbacks, NASA chose to justify the Shuttle on economic grounds. The agency argued that it could employ a reusable vehicle to place satellites into orbit for scientific, commercial, and national security purposes. Sociologist and expert on NASA culture Diane Vaughan described the concept of

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Do Not Copy or Post

a reusable shuttle as a bus, designed to transport "things, objects, and people back and forth into space on a regular basis…. They were really operating an experimental technology, but there was pressure to make it look routine, to attract customers for payloads." When compared to alternative means of transporting satellites into space, a fleet of shuttles offered the promise of substantial cost savings. To justify the massive investment required to develop and build a fleet of shuttles, NASA used a projected rate of 50 flights per year.

In exchange for additional funding from the White House and Congress, NASA agreed to meet challenging Department of Defense specifications. The Department of Defense requirements altered and further complicated the design of the vehicle, as the orbiter incorporated such revolutionary features as delta-shaped wings, engines that used both solid and liquid fuels, and a reusable thermal protection system (TPS) that consisted of tiles designed to protect the shuttle from the heat of reentry into the Earth's atmosphere. Designers intended for these features to minimize the per-flight cost. NASA optimistically predicted that with a $5.15 billion budget, it could build the first reusable spacecraft, a reliable and efficient shuttle that would meet performance requirements and last for 100 missions, at a cost of $7.7 million per mission. CAIB member Sheila Widnall criticized the program as being "badly oversold…. They [NASA] learned a very bad lesson in the sense that every time they over-promised, they got more money."

NASA established the Space Shuttle Program in January 1972.[b] Upon its inception, President Nixon stated that the Shuttle would be "designed to help transform the space frontier of the 1970s into familiar territory, easily accessible for human endeavor in the 1980s and 1990s. This system will center on a space vehicle that can shuttle repeatedly from Earth to orbit and back. It will revolutionize transportation into near space, by routinizing it." (See **Exhibit 2** for an organizational chart of the Space Shuttle Program.)

Development of the Shuttle proved difficult given NASA's tight budget and complex design specifications. Despite these challenges, NASA believed that the Shuttle would be safer than any other spacecraft, and it did not develop an escape system in the orbiter for the crew. The primary components of the spacecraft were the orbiter, the expendable external tank filled with liquid fuel, and two reusable SRBs. (See **Exhibit 3**.) The Shuttle contained 230 miles of wiring and more than 2.5 million parts,[7] including 24,305 TPS tiles applied by hand to the exterior of the orbiter. When assembled for takeoff, the Shuttle stood 184 feet tall and weighed 4.5 million pounds, 90% of which was fuel.[8]

NASA delayed the first Shuttle mission from March 1978 to April 1981 because development of the Shuttle proved to be more complicated than expected. To meet schedule demands during development, NASA transported *Columbia* from its manufacturer in California to KSC in Florida, where engineers completed installation of the TPS tiles. The agency deviated from its previous testing regimens, allowing the newly designed SRBs and external tank to be ground-tested. NASA also used analytic models, rather than an unmanned test flight, to verify the entire system.

NASA launched the *Columbia*, its first Space Shuttle mission, on April 12, 1981. Unlike the later orbiters (*Challenger, Atlantis,* and *Discovery*) that the agency built, *Columbia* lacked the configuration necessary to dock at the International Space Station.[c] Therefore, *Columbia* could carry larger cargoes, such as the equipment required to run experiments for scientific missions.

[b] Space Shuttle missions were labeled with the prefix STS (Space Transport System) before a number indicating the order in which they were planned. Missions were not always launched in the same order that they were planned.

[c] A fifth shuttle, the *Endeavour*, replaced the *Challenger*.

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Following the fourth Shuttle mission, on July 4, 1982, President Ronald Reagan declared, "Beginning with the next flight, the *Columbia* and her sister ships will be fully operational, ready to provide economical and routine access to space for scientific exploration, commercial ventures, and for tasks related to the national security."

Former Shuttle astronaut Dr. James Bagian recalled that during this time, NASA often likened flying the Shuttle to flying a 727 plane to Disney World. However, this assertion quickly became a running joke among astronauts at NASA, due to the difficulties of completing the projected 50 missions in one year. "That was the party line," explained Bagian. "If flying a Shuttle was like flying a 727 to Disney World, there wouldn't be anybody going to Disney World!"

During this period NASA competed aggressively with the European Space Agency, which was developing its own vehicle for delivering commercial payloads to space. To win customers, NASA subsidized the cost of commercial launch contracts quite heavily; in fact, the agency offered its services for $42 million per launch—one-third of actual costs. By 1985, NASA had launched 24 communications satellites. It also launched more missions (nine) in that year alone than it had ever conducted in a calendar year. However, turnaround time between missions rose to 67 days, far more than the 10 days that the agency had anticipated at the start of the Shuttle Program.

The *Challenger* Disaster

On January 28, 1986, the *Challenger* set out on the Space Shuttle Program's 25th mission. On the evening prior to liftoff, officials from NASA and SRB manufacturer Morton Thiokol participated in a teleconference to discuss whether to postpone the shuttle launch. Weather forecasters predicted unusually low temperatures in Florida the next morning, which could arguably affect launch. During the teleconference, Morton Thiokol engineer Roger Boisjoly argued that the shuttle's O-rings might not perform well at low temperatures. The O-rings joined segments of the SRBs and prevented leakage of hot gases during takeoff. Boisjoly contended that the O-rings might not seal the joint properly at temperatures below 40° Fahrenheit.

Although Boisjoly warned of catastrophic consequences, the limited and ambiguous data that he presented in the teleconference did not convince others that the SRBs were unsafe at low temperatures. CAIB member Roger Tetrault compared NASA to the Naval Reactors Program, where "the mantra was always 'prove to me that it's right.'… what we found in NASA was a culture that was more 'prove to me that there's something wrong." In the end, Morton Thiokol management did not recommend against launch. The next morning, 73 seconds after launch, the *Challenger* and its seven crew members (including a civilian elementary school teacher) perished in a burn of hydrogen and oxygen propellants.

The investigation by the Rogers Commission—a task force appointed by President Reagan to examine the accident—identified its technical cause rather quickly. Low temperatures at launch—36° Fahrenheit—caused the rubber O-rings to become rigid and thus fail to seal the joint. Renowned physicist Richard Feynman, participating on the Rogers Commission, illustrated this finding with an elementary experiment. He submerged a piece of O-ring rubber in his glass of ice water and showed that the ring returned to its original shape very slowly after becoming cold, clearly affecting its ability to create a proper seal.[9]

The investigation uncovered long-standing unresolved problems with the rubber O-rings, including leakage and erosion, dating back to 1977. The investigation therefore began to focus on the organizational problems at NASA. The Rogers Commission noted that NASA continued to use O-rings in shuttle flights even after increasing their criticality rating (a rating that indicated the degree

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

of uncertainty involved with the reliability of a component). Although engineers had not resolved the O-ring problem, managers had downgraded its criticality rating in a Flight Readiness Review (FRR) meeting just two weeks prior to the launch of the *Challenger*.[d] "They didn't even define it as a problem," noted *Challenger* expert Diane Vaughan. "It had become for them an acceptable risk, and it was something that was normal, not deviant, to them."

One contributor to the Rogers Commission's report noted that, over the years, NASA had engaged in "a kind of Russian roulette . . . (The Shuttle) flies (with O-ring erosion) and nothing happens. Then it is suggested, therefore, that the risk is no longer so high for the next flights. We can lower our standards a little bit because we got away with it last time . . . You got away with it, but it shouldn't be done over and over again like that."[10]

Foam Strike History[11]

Foam debris strikes caused damage to every mission in the history of the Space Shuttle Program. NASA originally considered foam strikes on ascent particularly dangerous, due to the fragile nature of the TPS. The original design requirements stated that "the Space Shuttle . . . shall be designed to preclude the shedding of . . . debris . . . that would jeopardize the flight crew, vehicle, mission success, or would adversely impact turnaround operations."[12] NASA engineers assumed that only small pieces of debris would strike the Orbiter. Therefore, they designed the TPS, composed of tiles and Reinforced Carbon-Carbon (RCC) panels, to withstand minor impacts. Prior to the final *Columbia* flight, debris had struck but never penetrated the RCC panels.[13]

After the *Columbia*'s 1981 inaugural flight, NASA replaced more than 300 tiles. Foam strikes became a concern during the investigation of the *Challenger* disaster as well. Despite concerns raised by the Rogers Commission regarding NASA's safety procedures and repeated instances of foam separating from the External Tank during ascent, the agency pushed forward with its flight schedule. (See **Exhibit 4** for significant foam-shedding events.) Photographic evidence of foam loss existed for 65 of the 79 missions for which imagery was available.

Over time, as the shuttles continued to land safely, agency engineers and managers began to focus increasingly on the turnaround schedule implications of foam strikes rather than the flight-safety effects. According to CAIB member and top-ranking U.S. Department of Transportation aviation safety expert James Hallock, "[Shedding foam] became sort of expected. Not only was it expected, it eventually became accepted." While originally considered a serious threat, foam loss eventually came to be categorized as an "in-family" event—a problem within NASA's experience base that was not considered a safety-of-flight issue. (See **Exhibit 5** for classification definitions.)

Specifically, foam tended to fall off the left bipod ramp of the External Tank. Ten percent of flights recorded foam loss from this area, while no flights experienced similar issues on the right bipod ramp. NASA never discovered the reason for this discrepancy. In 1990, agency managers classified foam loss as an "in-flight anomaly." This designation meant that NASA should resolve the problem before the next flight or else prove it did not threaten the lives of the crew. Over the years, agency engineers never determined the cause of the foam loss, nor did they discover a means to prevent it.

[d] Flight Readiness Review, or FRR, meetings occurred two weeks prior to launch. Top NASA managers reviewed the certification and verification of the vehicle, flight crew, payloads, and rationales for accepting unresolved risk. Certification of flight readiness was issued at the conclusion of the FRR. (Source: CAIB, Vol. 1, p. 31.)

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Instead, the agency moved incrementally to lessen the severity of its classification of foam losses. In 1992, the Integration Office at JSC terminated the in-flight anomaly status for foam strikes and classified them as an "accepted flight risk." Meanwhile, the External Tank Project at MSFC concluded that debris strikes did not constitute "a safety-of-flight issue."

On October 7, 2002, the *Atlantis* (STS-112) sustained a debris strike 33 seconds after launch. Cameras tracking the launch photographed the debris, but records from the mission management meetings did not indicate discussions concerning the strike. After the orbiter's safe return, inspectors discovered that a sizable piece of foam had fallen off the left bipod ramp. The damage sustained by *Atlantis* was the "most severe of any mission yet flown."[14] Again, the External Tank Project downplayed the significance of the foam strike, categorizing it as an "action" item rather than an "in-flight anomaly"—the more serious classification used in all prior events. This designation still meant that engineers should determine the cause of foam loss and propose corrective action. However, with the agency facing schedule delays for subsequent missions, the Shuttle Program decided to fly two missions, STS-113 (November 23, 2002) and STS-107 (the *Columbia*, to be launched January 16, 2003), without resolution of the foam problem.

At the October 2002 FRR for STS-113, engineers showed Microsoft *PowerPoint* slides describing the bipod ramp foam loss from *Atlantis'* STS-112 flight. The slides maintained that the probability of foam loss for the upcoming flight was "no higher/no lower than previous flights. The ET [External Tank] is safe to fly with no new concerns (and no added risk)." (See **Exhibit 6** for the slides.) Key Space Shuttle Program managers declared foam strikes an "accepted risk" for STS-113, and fortunately, it sustained minimal damage from foam debris.

The Final *Columbia* Mission

The Columbia's 16-day mission (STS-107) was "dedicated to research in physical, life, and space sciences, conducted in approximately 80 separate experiments, comprised of hundreds of samples and test points."[15] STS-107's scientific plans required the crew to work round-the-clock shifts in two teams. Critics described the mission's scientific experiments as childish and elementary, arguing that STS-107 constituted "a mission to maintain momentum" rather than a flight with a truly valuable and innovative purpose.[16] The crew, radioing from space, described their scientific experiments as "leading-edge."[17]

Launch Day

On Thursday, January 16, 2003, NASA prepared to launch the *Columbia*. Over the past years, people often referred to the *Columbia*, NASA's oldest orbiter, as "the hangar queen" because of the time it spent in repairs between missions.[18] While pilots liked the way the Orbiter performed in space, they found it difficult to launch without problems. Therefore, NASA associated the *Columbia* with the mantra "tough to launch, easy to fly."[19] STS-107 proved to be no exception. On January 16, 81.7 seconds into launch, a chunk of insulating foam fell off the External Fuel Tank and struck the Orbiter's left wing. (See **Exhibit 3** for diagram, **Exhibit 7** for chronology.) The Intercenter Photo Working Group, a team of NASA engineers charged with reviewing liftoff imagery from tracking cameras, did not detect the strike until 9:30 a.m. the next day.[20]

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Flight Day 1

When the Intercenter Photo Working Group identified the strike on the left wing, they found that a restrictive camera angle and a blurry image did not clarify the size, shape, or momentum of the foam or the location of impact. Due to budget cuts over the years, NASA had reduced the camera staff and kept poorly maintained camera lenses. As a result, the five cameras tracking the launch provided neither higher-resolution views nor different angles on the strike; some cameras failed to capture an image at all.[21] While the photographs were unclear, the group did have the distinct impression that the piece of foam was unusually large—larger than any they had seen.

The Intercenter Photo Working Group determined that they needed better imagery to assess potential Shuttle damage accurately. The group's chair contacted Wayne Hale, the Shuttle Program Manager for Launch Integration at KSC, to request imagery of *Columbia*'s left wing on-orbit. The group hoped that NASA could use military spy satellites to capture better images. Hale, who held top-secret clearance and was familiar with the process of requesting military assistance, agreed to look into it, which he did five days later.[22] Hale also informed Ron Dittemore, Space Shuttle Program Manager, and Linda Ham, chair of the Mission Management Team (MMT), of the debris strike.[e]

Meanwhile, the Intercenter Photo Working Group distributed a report, including a digitized clip of the strike, to many others within NASA and its contractors. NASA engineer Rodney Rocha viewed the clip and recalled that he "gasped audibly"[23] due to the debris' size. Boeing began performing an analysis to determine the velocity and angle of and potential damage from the debris strike.

Due to the size of the foam loss, concerned analysts at JSC classified the event as "out of family." In the MER, managers entered in their log that the strike was of "low concern."[24] However, at NASA, when an "out-of-family" event occurred, written guidelines mandated that engineers work with agency contractors to analyze the situation. This group, according to procedure, should have become a Tiger Team, as in the case of *Apollo 13*. In the case of STS-107, Boeing analysts did team up with NASA engineers to evaluate the debris strike, but they were not classified as a Tiger Team. Instead, this ad-hoc group became known as the Debris Assessment Team (DAT). NASA engineer Rocha and United Space Alliance engineering manager Pam Madera chaired the DAT. CAIB member Widnall commented that the DAT's "charter was very vague. It wasn't really clear who they reported to… I think they were probably unsure as to how to make their requests to get additional data." Tetrault also stressed that the DAT "did not report to the Mission Management Team." Moreover, he pointed out that, "When these issues (foam strikes) were discussed, there was never any direct communication between the Debris Assessment Team and the Mission Management Team. It was generally through other parties."

Flight Days 2, 3, and 4

Boeing analysts worked through the weekend to complete their analysis of possible damage to the orbiter. They used a mathematical tool called Crater that employed an algorithm to predict the depth to which debris might penetrate the tiles. Historically, engineers found that Crater predicted more severe damage than what actually occurred. Engineers had never utilized Crater to assess debris impacts while a mission was on-orbit, however, and the estimated size of the debris was 600 times larger than the pieces used to calibrate Crater. Moreover, a Crater-certified engineer at Boeing offices

[e] The MMT "resolved outstanding problems outside of the responsibility or authority of the Launch and Flight Directors." MMT members were managers from Engineering, System Integration, the Space Flight Operations Contract Office, the Shuttle Safety Office, and the JSC directors of flight crew operations, mission operations, and space and life sciences. (Source: CAIB, Vol. 1, p. 32.)

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

DO NOT COPY OR POST

in Texas, who had used the program only twice, performed the analysis for STS-107. The engineer did not consult with more experienced engineers at Boeing's California facility who had used the model on prior occasions.[25]

Crater predicted that the debris created a gaping hole in the Thermal Protection System (TPS) tile. However, the DAT members discounted this conclusion because Crater did not take into account the denser bottom level of the tile, only the more fragile top layer. Widnall described Crater as "not really an analytical model. It was more of a curve fit based on some data, data completely outside the range of the situation, so it really was discounted." The DAT focused their attention on the TPS tiles and not the Reinforced Carbon-Carbon (RCC) panels on the wing's leading edge due to a long-standing belief that foam did not pose a danger to the RCC panels.

Rocha, co-chair of the DAT, e-mailed a JSC manager to determine whether *Columbia*'s crew could perform a space walk to inspect the wing, but he never received an answer.[26] After the disaster, Dittemore told reporters that a space walk was not feasible,[27] but other experts disagreed with his conclusion, though acknowledging the risky nature of the maneuver.

On Flight Day 4, the DAT met informally, and it expanded to include debris, tile, RCC panel, and safety specialists from NASA, Boeing, and United Space Alliance. The team decided that they could not draw firm conclusions without additional imagery.

Flight Day 5

Early in the morning, the DAT briefed MER manager Don McCormack on the results of the Crater analysis while pointing out that they had not completed their analysis. McCormack later relayed this information to the MMT during its second meeting. Space Shuttle procedures directed that the MMT should meet daily during a mission. However, during the 16-day STS-107 mission, the MMT met only five times (Flight Days 1, 5, 8, 11, and 15).

After McCormack briefed the MMT on the debris issue, Ham, the team's chairperson, reminded everyone that foam losses had occurred often on previous flights. She also commented that foam was "not really a factor during the flight because there is not much we can do about it."[28] (See **Exhibit 8** for meeting transcript excerpt.) "The Mission Management Team was run very efficiently," illustrated Vaughan. "There were problems to be considered that were defined as much more serious than foam hitting the Orbiter." Furthermore, Ham inquired about the flight rationale used for STS-113, because it had to address the substantial tile damage discovered upon the completion of the *Atlantis'* STS-112 mission.[29]

Both Ham and Dittemore, the Shuttle Program Manager, attended the meeting in which agency officials concluded that it was safe to fly STS-113 despite the significant foam loss experienced by STS-112. After the MMT meeting on Flight Day 5, Ham revisited the documents presented at that meeting, and she sent an e-mail to Dittemore in which she commented that the flight rationale for STS-113 was "lousy."[30] (See **Exhibit 9** for Flight Day 5 e-mails.) Ham, known for her domineering management style, knew that she was to serve as Launch Integration manager for the next shuttle mission, STS-114. She recognized that she would have to address this flawed past rationale or face a delay of that upcoming mission.

Ham also knew that a delay in STS-114 would jeopardize a major management goal—to launch Node 2 of the International Space Station by February 19, 2004. Management considered that target date critical for two reasons. First, Node 2 would complete the U.S. core of the Space Station. Second,

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

NASA and the Space Station Program had faced increased scrutiny in recent years from the White House Office of Management and Budget.

On the same day as this MMT meeting, engineer Calvin Schomburg distributed an e-mail discounting the risk of damage from the debris. He wrote, "FYI—TPS took a hit—should not be a problem—status by end of week."[31] Schomburg, an engineer closely connected to senior Shuttle Program managers, was considered an expert on TPS. However, he did not have expertise regarding the RCC panels, which the foam may have struck.[32] Following this e-mail, Paul Shack, manager of the Shuttle Engineering office at JSC, informed Rocha that foam loss had been classified as not "a 'Safety-of-Flight' issue" during prior FRRs.[33]

Meanwhile, United Space Alliance manager Bob White, in response to concerns from his employees serving on the DAT, called Lambert Austin in the Space Shuttle Integration Office. White asked Austin how to request imagery of the *Columbia* while it was on-orbit. Austin called the Department of Defense to determine how to obtain such imagery, but he insisted that he was not making a formal request. Austin was not familiar with NASA's imagery request procedures.[34]

That same day, the DAT held its first formal meeting. After agreeing on the need for additional visual data, team members asked Rocha to seek new imagery. The DAT concluded that Rocha should pursue this request through his own engineering division rather than following the Shuttle Program's chain of command (i.e., from Rocha to the MER to the MMT). Rocha e-mailed Shack, his superior, asking if NASA could "petition (beg) for outside agency assistance?"[35] In an attempt to stress the importance of his request, Rocha put this sentence in boldface type. (See **Exhibit 10**.)

Flight Day 6

Wayne Hale responded to the request for imagery placed on Flight Day 1 by calling a Department of Defense representative at KSC. The Defense Department representative was not the designated official for coordinating imagery requests; nevertheless, he began to investigate how to address Hale's inquiry. However, he did not put forth a formal request.

Around this time, Austin called Ham to inform her of the inquiries being made regarding assistance from the Department of Defense. Ninety minutes later, NASA cancelled the informal requests for imagery. According to the CAIB, Ham ordered the requests cancelled because she could not find out exactly who needed imagery. She called the members of the MMT, who each stated that they had not requested imagery, were not aware of an "official" request, and did not see a "requirement" for imagery.[36] Notably, Ham did not contact the DAT directly to determine if its members wanted additional imagery. Vaughan commented that, "The MMT was supposed to operate in a decentralized way. That's not what happened. It was a very centralized operation with all the information flowing to the manager. It was very rule-oriented, very protocol-oriented." According to Vaughan, that emphasis on procedure explains why management became so concerned when individuals "didn't follow the right route when they requested the engineering images."

After canceling the request, Ham e-mailed JSC engineers to confirm that foam did not pose a "safety-of-flight" issue. Their responses indicated that uncertainties still existed, particularly regarding the sensitivity of the RCC panels. (See **Exhibit 11**.) However, no action was taken to obtain further imagery. Later, Shack informed Rocha that management had chosen not to pursue images. Rocha was astounded. He called Shack to discover management's reasoning, only to hear Shack's reply: "I'm not going to be a Chicken Little on this."[37]

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

The CAIB also reported that Ham expressed concern to others that the time spent maneuvering the *Columbia* for valuable imagery of the left wing would unduly impact the mission schedule.[38] One employee recalled, "Linda Ham said it was no longer being pursued since even if we saw something, we couldn't do anything about it. The Program didn't want to spend the resources."[39]

On that same day, the DAT conducted its second official meeting. All members learned that Shuttle Program managers had decided against seeking additional imagery. Though the DAT believed that better imagery was critical to its analysis, members could not cite a "mandatory" requirement for new photographs.[40] As such, they adjourned the meeting without agreeing to further pursue imagery requests.

An angry Rocha later wrote a scathing e-mail, saying, "In my humble technical opinion, this is the wrong (and bordering on irresponsible) answer . . . not to request additional imaging help from any outside source. I must emphasize (again) that severe enough damage . . . could potentially present grave hazards."[41] (See **Exhibit 12** for full e-mail.) However, Rocha did not send the e-mail to his superiors or to Shuttle Program managers. Instead, he simply showed it to his colleagues. He later explained, "engineers were often told not to send messages much higher than their own rung in the ladder."[42] Former NASA engineer Torarie Durden described the culture at NASA as "extremely bureaucratic" and "hard to navigate," and therefore, "as an engineer, it was often extremely difficult to speak up or go against the norm." Moreover, Durden pointed out that it was difficult to challenge the conventional wisdom without a great deal of scientific evidence:

> "As an engineer, you are accustomed to the scientific method of problem-solving where you create a hypothesis, you do experiments, you get data, and you prove or disprove your hypotheses. But, at NASA, the burden of proof, especially for factual data, is leaps and bounds beyond anything I have ever seen. It was hard to create the number of experiments needed to create the data to prove your point."

Flight Day 7

In a final effort, one of Rocha's colleagues mentioned the DAT co-leader's concerns to Leroy Cain, the STS-107 Flight Director. Cain spoke with an MMT member and then distributed an e-mail stating that he considered the issue "dead."[43]

During that afternoon, Rocha encountered Schomburg in the hallway. The two began heatedly discussing the need for imagery. Schomburg insisted that foam strikes had occurred many times without catastrophic consequences. Rocha countered that there was still a possibility of damage severe enough to cause burn-through during reentry. He recalled that the disagreement closed with Schomburg's remark, "Well, if it's that bad, there's not a damn thing we can do about it!"[44]

Later that evening, Mission Control personnel determined that they should alert Commander Husband and Pilot McCool to the foam strike. Their e-mail to the astronauts stated that it was "not even worth mentioning" if not for the fact that they did not want the astronauts to be "surprised by it in a question from a reporter."[45] The e-mail concluded that NASA had "seen this phenomenon on several other flights, and there is absolutely no concern for entry."[46]

Also on Flight Day 7, the NASA liaison responsible for communicating all requests to the Department of Defense e-mailed military officials in Colorado, who had begun to process the now-defunct imagery requests. The e-mail reminded the military officials that all requests had to follow the proper channels. If they did not, unofficial requests could "slip through the system and spin the community up about potential problems that have not been fully vetted through the proper

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

channels."[47] To avoid unnecessary confusion, NASA called for a confirmation of all requests prior to any resource allocation. (See **Exhibit 13** for full e-mail.)

Flight Day 8

On January 24, Boeing and United Space Alliance managers presented the DAT's findings to MER manager McCormack. Engineers filled the briefing room and even spilled out into the hallway. The presentation detailed the team's methodology, five impact scenarios based on Crater, and predicted threat to the *Columbia* for reentry. The analysis focused on impact to the tiles but not to the RCC panels. The team had one scenario left to run, but it believed the results would not drastically differ from the first five. While the DAT felt convinced its analysis was thorough and complete—given the limited information at its disposal—it emphasized that questions and uncertainty remained. For example, they were not entirely sure where the debris hit the Orbiter or at what speed the impact took place. Still, the presentation concluded that no safety-of-flight issue existed.[48]

One hour later, McCormack relayed the team's findings to the MMT. He mentioned that uncertainties existed and that the team had one scenario left to run. However, he explained that the engineers had concluded that the debris did not constitute a safety-of-flight issue. McCormack told Ham and the MMT that the Orbiter would probably suffer significant tile damage. Ham emphasized that tile damage constituted a turnaround issue—the Orbiter would need repairs, which would impact the next mission schedule. She repeatedly told the team that no catastrophic damage would occur. (For the meeting transcript excerpts, see **Exhibit 14**.)

Rocha, who was listening to the meeting, later told McCormack he did not think the level of uncertainty surrounding the DAT's conclusions had been communicated clearly. He also wished that McCormack had stressed that the analysis of one scenario remained incomplete. McCormack agreed to correct any misperceptions, which he did at the January 27 MMT meeting. On Flight Day 11, McCormack informed the MMT that the DAT's analysis had been ongoing but was now complete. He confirmed that the DAT concluded that the strike did not constitute a safety-of-flight issue.[49]

Two days later, on Sunday, January 26, Rocha sent an e-mail to his managers and the DAT commending the team members for their work. He felt that they had briefed the MER thoroughly, and they had successfully communicated their concerns as much as possible. There were no more mentions of the foam strike until February 1, when the *Columbia* broke up during reentry on Flight Day 16.

The *Columbia*'s Tragic End

The *Columbia* broke apart only minutes away from its landing site in Florida. NASA later housed the wreckage—all 83,900 pieces of it—in a 50,000-square-foot hangar.[50] In a press conference just days after the disaster, Dittemore refused to believe that the foam caused the tragedy: "It does not make sense to us that a piece of debris could be the root cause for the loss of *Columbia* and her crew. There has got to be another reason."[51] NASA chief Sean O'Keefe downplayed the concerns of those he described as "foamologists."[52]

Despite operating in what one expert described as "a risky business," NASA had functioned for 17 years and 89 flights without misfortune following the *Challenger* disaster.[53] After the *Challenger* accident, President Reagan told the nation, "I know it's hard to understand, but sometimes painful things like this happen. It's all part of taking a chance and expanding man's horizons. . . ."[54] Reagan

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

also remarked, "We've grown used to the idea of space, and perhaps we forget that we've only just begun."[55]

The CAIB concurred that space travel involved "high inherent risk,"[56] yet it stressed that the *Columbia* tragedy was not inevitable. During seven months of investigation, the 13-member board, supported by 120 staff and over 400 NASA engineers, examined 30,000 documents and interviewed over 200 engineers, managers, and experts.[57] The CAIB found two experiments—one conducted by CAIB member Hallock, the other by NASA's own engineers and managers—to be particularly enlightening.

A renowned physicist, Hallock sought to understand what it would take to break an RCC panel. Through a series of simple experiments, employing a box of No. 2 pencils, a postal scale, and the 25-year-old NASA panel specifications, Hallock made his surprising discovery. According to NASA's old design documents, the RCC panels should be able to endure an impact equal to the kinetic energy of 0.006 foot-pounds. Hallock asked himself how far he would have to drop a No. 2 pencil to generate the same level of kinetic energy. He explained what he found: "The answer is that a No. 2 pencil dropped from about 6 inches equals the kinetic energy number they had." [58]

Once manufactured, the panels proved to be stronger than NASA's antiquated specifications. Therefore, Hallock's experiment, while astounding, did not convince NASA officials that foam debris could puncture the RCC panels. Admiral Gehman, CAIB chairman, decided a reenactment of the foam strike would constitute a more compelling piece of evidence. NASA resisted because the test would entail the use of their last spare RCC Panel Eight, a $700,000 custom-made orbiter component.[59] Despite NASA's fervent opposition, the Board used a compressed-nitrogen gun, typically used in aircraft bird-strike certification tests, to fire a series of foam shots at multiple panels.[60] The simulations resulted in little damage to the panels until the last shot—at 500 miles per hour and a 25° angle at Panel Eight, the conservative estimate of the strike on the *Columbia*—which punctured a hole in the panel large enough to accommodate a human head.[61]

CAIB Report Findings

The CAIB also investigated the possibility of a rescue or a repair attempt during the *Columbia* mission. The Board concluded that a repair attempt would entail "high risk," but it decided that a rescue mission would have been "challenging but feasible."[62] If NASA had recognized the severity of the foam strike by Flight Day 7, engineers determined that the *Columbia* could have remained in space for an additional 30 days. Meanwhile, ground crews could have worked around-the-clock to launch *Atlantis* so that it could rendezvous with *Columbia* in space and bring the astronauts safely home.[63] However, the slightest error would result in the loss of two shuttles instead of one. This theory was highly contentious, and top NASA administrators refused to acknowledge the plausibility of a rescue attempt.

The Board concluded that "the physical cause of the loss of *Columbia* and its crew was a breach in the Thermal Protection System on the leading edge of the left wing, caused by a piece of insulating foam. . . ."[64] The report went on to criticize NASA for its organizational weaknesses, stating, "In this Board's opinion, unless the technical, organizational, and cultural recommendations . . . are implemented, little will have been accomplished to lessen the chance that another accident will follow."[65]

The Board also concluded that organizational communication barriers stifled the flow of critical information, such as Rocha's concerns and requests for imagery. Dittemore disagreed, saying that NASA encouraged people to speak freely and openly. He added that if people such as Rocha had

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

concerns during STS-107, "they weren't brought to my attention."[66] Ham also noted that she "was never alerted to the concerns that were expressed by the engineers working the issue, neither . . . the potential severity of the damage, nor the fact that they wanted the on-orbit image."[67] Flight Director Leroy Cain reproached the engineers: "You are duty bound as a member of this team to voice your concerns, in particular as they relate to safety of flight. You wouldn't have to holler. You stand up and say, 'here's my concern, and this is why I'm uncomfortable.'"[68] Hearing these comments, Rocha lamented, "I couldn't do it [speak up more forcefully] . . . I'm too low down . . . and she's [Ham] way up here."[69]

In the aftermath of the accident and the investigation report, many people debated the issue of who should be held accountable for the failures that occurred at NASA. Some argued that NASA's issues were systemic. Vaughan argued, "This was no personality problem. This was a structural and a cultural problem. And if you just change the cast of characters, the next person who comes in is going to be met with the same structure, the same culture, and they're going to be impelled to act in the same way." In his testimony to Congress, Admiral Gehman concurred, "There's no one person responsible here. There are a whole lot of people responsible. We believe that this is a systemic problem. If you just change the people or change the names of the committees, it won't do any good." Those comments prompted a stern reply from Senator John McCain, who exclaimed that it was "infuriating that no one is responsible. Those decisions weren't made by machines. Someone is responsible."

Despite contentious disagreements on these issues, O'Keefe accepted the Board's report, saying NASA would "comply with the recommendations to the best of our ability."[70] Both the CAIB and NASA concurred that space exploration should continue. Reflecting on the loss of the *Columbia*, President Bush told the country, "In an age when space flight has come to seem as almost routine, it is easy to overlook the dangers. . . . The cause in which [the *Columbia* astronauts] died will continue. Mankind is led into the darkness beyond our world by the inspiration of discovery and the longing to understand. Our journey into space will go on."[71]

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Exhibit 1 Acronyms

CAIB—Columbia Accident Investigation Board

DAT—Debris Assessment Team

FRR—Flight Readiness Review

JSC—Johnson Space Center, Houston, Texas

KSC—Kennedy Space Center, Merritt Island, Florida

MER—Mission Evaluation Room

MMT—Mission Management Team

MSFC—Marshall Space Flight Center, Huntsville, Alabama

NASA—National Aeronautics and Space Administration

RCC—Reinforced Carbon-Carbon

SRB—Solid Rocket Booster

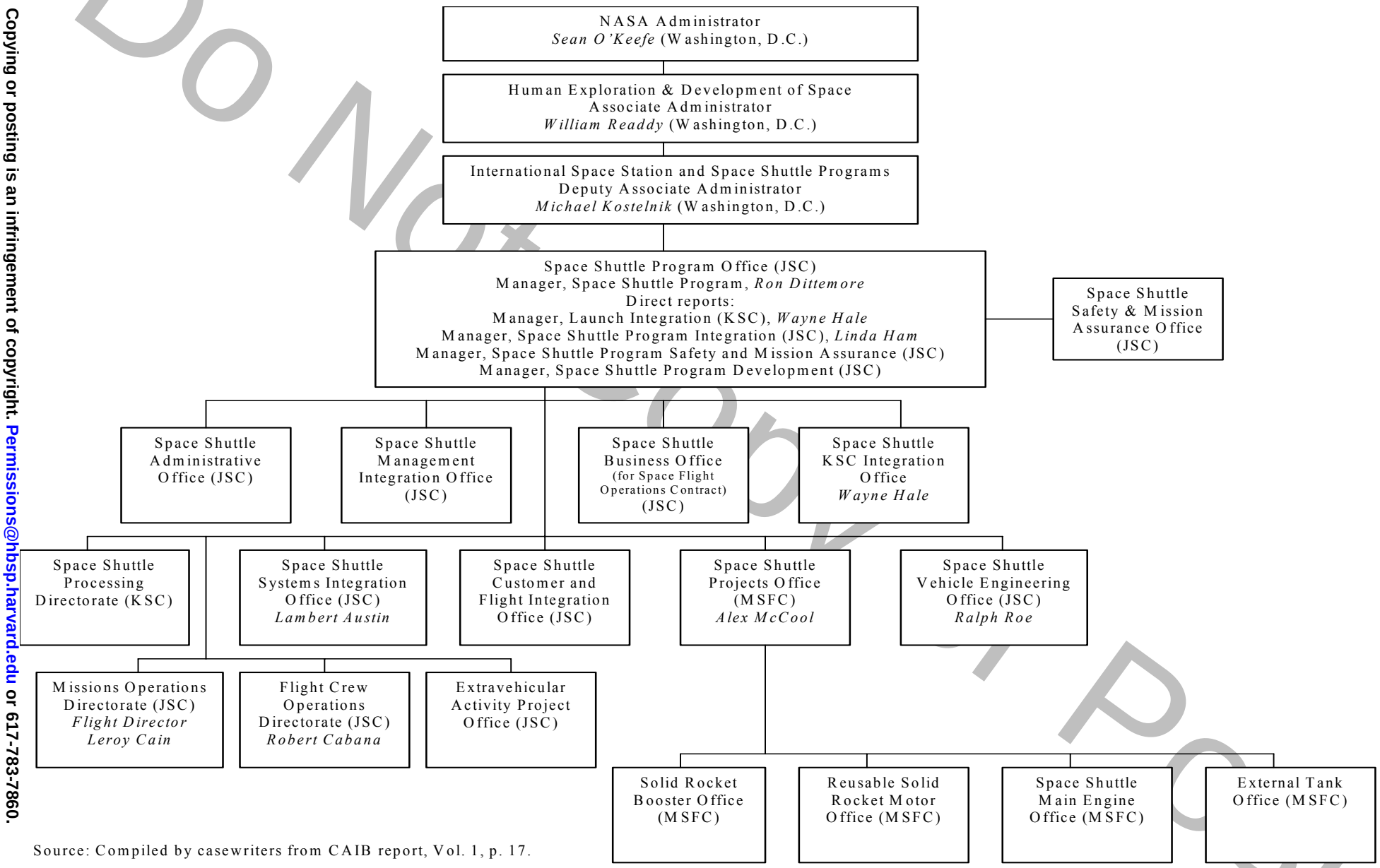
TPS—Thermal Protection System

Source: Casewriters.

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Exhibit 2 The Space Shuttle Program

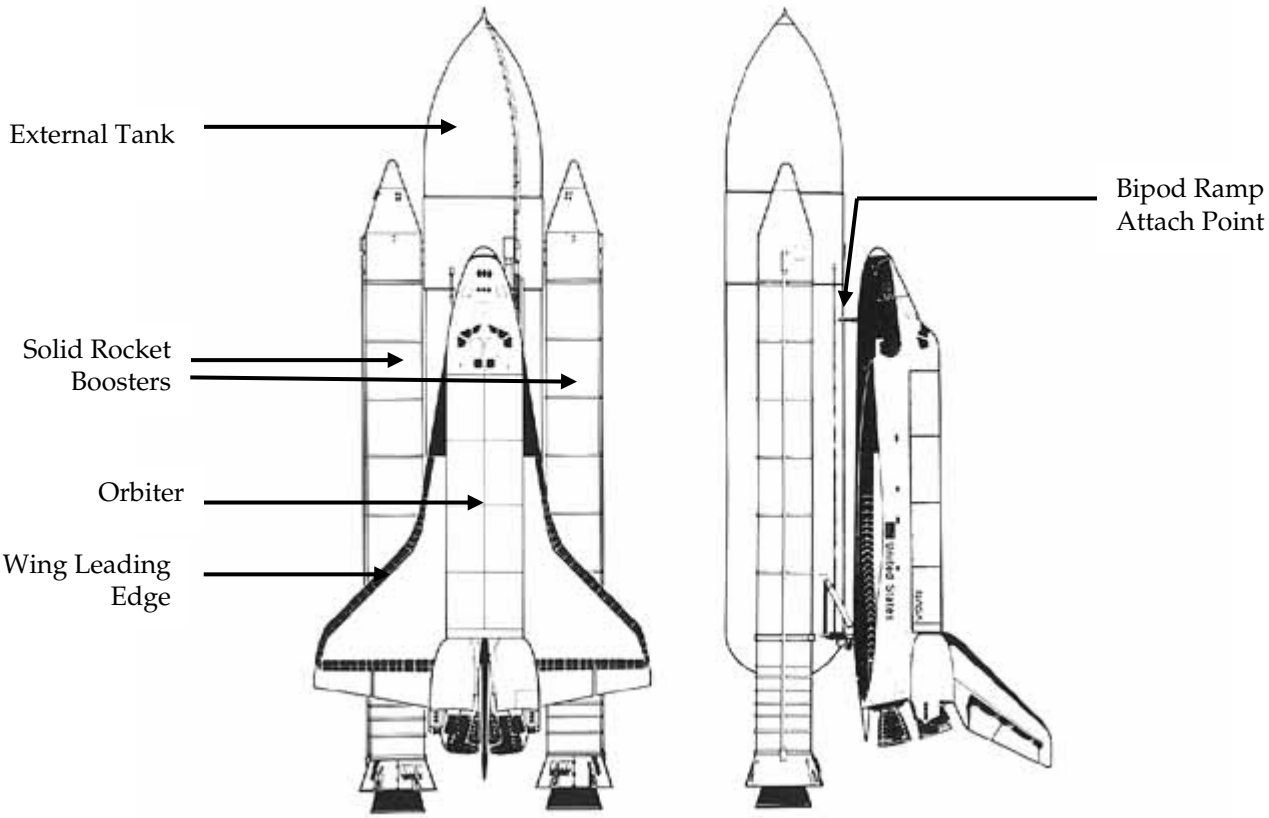


Source: Compiled by casewriters from CAIB report, Vol. 1, p. 17.

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Do Not Copy or Post

Exhibit 3 The Space Shuttle



Artist's drawing depicts the Shuttle stacked for launch in view from the dorsal side of the Orbiter (left) and from the left side of the stack.

Source: Report to the President by the Presidential Commission on the Space Shuttle Challenger Accident, Vol. 1, Ch. 1. (Washington, D.C.: Government Printing Office, 1986).

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Exhibit 4 Significant Foam-Shedding Events

Orbiter	Mission	Date	Comments
Columbia	STS-1	April 1981	300 tiles replaced
Challenger	STS-7	June 1983	First known left bipod ramp foam-shedding event
Atlantis	STS-27R	December 1988	Debris knocks off tile; structural damage; near burn-through results
Columbia	STS-32R	January 1990	Second known left bipod ramp foam event
Columbia	STS-35	December 1990	NASA calls foam debris "safety-of-flight issue"
Discovery	STS-42	January 1992	First mission after which the next mission (STS-45) launched without debris in-flight anomaly resolution
Atlantis	STS-45	March 1992	Damage to RCC panel unexplained anomaly, "most likely orbital debris"
Columbia	STS-50	June 1992	Third known bipod ramp foam event. Classified an "accepted risk."
Columbia	STS-52	October 1992	Fourth (undetected) bipod ramp foam loss
Discovery	STS-56	April 1993	Large area of tile damage. Considered "in-family."
Columbia	STS-62	October 1994	Fifth (undetected) bipod ramp foam loss
Columbia	STS-87	November 1997	Damage to TPS results in NASA conducting 9 flight tests to resolve foam shedding. Foam fix ineffective. In-flight anomaly closed, deemed "accepted risk."
Atlantis	STS-112	October 2002	Sixth known left bipod ramp foam loss. First time major debris strike not assigned an "in-flight anomaly." Assigned an action. Not closed out until after STS-113 and STS-107.
Columbia	STS-107	January 2003	Seventh known bipod ramp foam loss event

Source: Adapted from CAIB report, p. 128; and NASA Web site, www.nasa.gov/missions/timeline, accessed March 3, 2004.

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Exhibit 5 Foam Strike Classification Definitions

In Family: A reportable problem that was previously experienced, analyzed, and understood. Out-of-limits performance or discrepancies that have been previously experienced may be considered as in family when specifically approved by the Space Shuttle Program or design project.

Out of Family: Operation or performance outside the expected performance range for a given parameter or that has not previously been experienced.

Accepted Risk: The threat associated with a specific circumstance is known and understood, cannot be completely eliminated, and the circumstance(s) producing that threat is considered unlikely to recur. Hence, the circumstance is fully known and is considered a tolerable threat to the conduct of a shuttle mission.

No Safety-of-Flight Issue: The threat associated with a specific circumstance is known and understood and does not pose a threat to the crew and/or vehicle.

Source: CAIB, Vol. 1, p. 122.

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

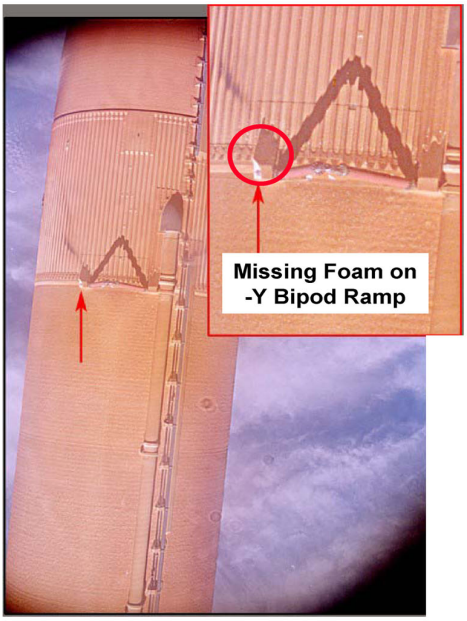
Exhibit 6 Flight Readiness Review Slides

SPACE SHUTTLE PROGRAM
Space Shuttle Projects Office (MSFC)
NASA Marshall Space Flight Center, Huntsville, Alabama

STS-112/ET-115 Bipod Ramp Foam Loss

Presenter: Jerry Smelser, NASA/MP31
Date: October 31, 2002 Page: 3

- **Issue**
  - Foam was lost on the STS-112/ET-115 -Y bipod ramp (≈ 4" X 5" X 12") exposing the bipod housing SLA closeout
- **Background**
  - ET TPS Foam loss over the life of the Shuttle Program has never been a "Safety of Flight" issue
  - More than 100 External Tanks have flown with only 3 documented instances of significant foam loss on a bipod ramp



Do Not Copy Post

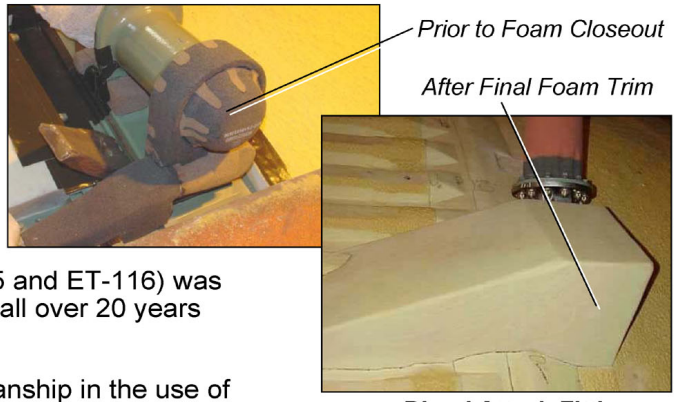
Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Exhibit 6 (continued)

SPACE SHUTTLE PROGRAM
Space Shuttle Projects Office (MSFC)
NASA Marshall Space Flight Center, Huntsville, Alabama

STS-112/ET-115 Bipod Ramp Foam Loss	Presenter Jerry Smelser, NASA/MP31
	Date October 31, 2002 Page 4

- **Rationale for Flight**
  - Current bipod ramp closeout has not been changed since STS-54 (ET-51)
  - The Orbiter has not experienced "Safety of Flight" damage from loss of foam in 112 flights (including 3 known flights with bipod ramp foam loss)
  - There have been no design / process / equipment changes over the the last 60 ETs (flights)
  - All ramp closeout work (including ET-115 and ET-116) was performed by experienced practitioners (all over 20 years experience each)
  - Ramp foam application involves craftsmanship in the use of validated application processes
  - No change in Inspection / Process control / Post application handling, etc
  - Probability of loss of ramp TPS is no higher/no lower than previous flights
  - ***The ET is safe to fly with no new concerns (and no added risk)***



Bipod Attach Fitting

Source: Johnson Space Center Web site, http://www.jsc.nasa.gov/news/columbia/frr/sts-113/08_et.pdf, accessed March 3, 2004.

Note: ET represents External Tank.

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Exhibit 7 Chronology

Columbia's 16 Days of Flight

Flight Day 1—Thursday 1/16

- Launch. 81.7 seconds later, foam fell from External Tank and struck left wing.

Flight Day 2—Friday 1/17

- 9:30 a.m., images of shuttle launch revealed foam strike.
- Intercenter Photo Working Group requested images from Wayne Hale, who had top-secret clearance and knew request procedures.
- Hale informed Linda Ham and Ron Dittemore.
- Engineers and managers (37 specialists from NASA and its contractors) began to form Debris Assessment Team (DAT).
- Boeing began its analysis.
- Mission Evaluation Room log entry read that foam strike was "low concern."

Flight Day 3—Saturday 1/18 through Flight Day 5—Monday 1/20

- Boeing began preliminary damage assessment, using mathematical model Crater.
- Because Crater predicted damage deeper than the tile thickness and did not take into account the tile's lower layer, DAT discounted the possibility of burn-through.
- Rodney Rocha e-mailed shuttle engineering office manager Paul Shack, asking if the astronauts could look at the impact area. Never received an answer.
- DAT met informally, emerged with goal of obtaining images of shuttle on orbit.

Flight Day 6—Tuesday 1/21

- DAT briefed MER manager McCormack on Crater results.
- McCormack relayed information in first MMT meeting.
- TPS expert Calvin Schomberg sent e-mail saying foam strike should not be a problem.
- United Space Alliance manager Bob White reacted to concerns from his employees on the DAT and called Lambert Austin at JSC. Austin informally asked Defense Department representative about imaging possibilities.
- DAT first formal meeting, nominated co-chairman Rocha to pursue imagery requests.
- Rocha e-mailed manager Paul Shack, asking in bold if they could beg for outside agency assistance.

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Exhibit 7 (continued)

Flight Day 7—Wednesday 1/22

- Hale responded to Flight Day 2 requests and called Department of Defense, which made an informal inquiry into imagery possibilities.
- Austin called Ham to inform her of his and Hale's requests to the Defense Department.
- Ham found no official requests for shuttle images, could not confirm why they were formally required, so all requests for imaging were cancelled.
- Ham e-mailed managers to clarify that foam was not a safety-of-flight issue.
- Paul Shack e-mailed Rocha that management cancelled requests.
- Rocha drafted an e-mail categorizing management's decision as wrong and bordering on irresponsible, but he did not send it.
- DAT learned that mission management canceled imaging requests and could not identify a "mandatory" need that would reverse management's decision.

Flight Day 8—Thursday 1/23

- Cain heard of DAT's concerns and sought the counsel of an MMT member. Sent an e-mail saying he considered the issue dead.
- Rocha encountered Schomburg, and they had a heated debate over the potential for danger, which ended when Schomburg said, "Well, if it's that bad, there's not a damn thing we can do about it!"
- NASA e-mailed STS-107 crew to notify them of strike.
- NASA liaison e-mailed USSTRATCOM, directing that all requests be sent through proper channels and confirmed before resources were spent.

Flight Day 9—Friday 1/24

- DAT presented findings to McCormack. Presented data on five scenarios of possible damage, emphasizing uncertainties with information they had and that their analysis was not yet complete.
- McCormack relayed DAT findings to MMT. All members advised no safety-of-flight issue.
- Rocha concerned that MMT did not realize DAT's analysis was not quite complete. McCormack clarified any misunderstandings at MMT meeting on 1/27.

Flight Day 17—Saturday 2/1

- Shuttle broke apart during reentry.

Source: Created by casewriters from "Decision Making at NASA," CAIB Report, Vol. 1, Ch. 6.

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Exhibit 8 MMT Meeting Transcript Excerpt

Flight Day 6—January 21, 2003

Ham: Alright, I know you guys are looking at debris.

McCormack: Yeah, uh, as everyone knows we took a hit on the, somewhere on the left wing leading edge. And uh, the photo guys are completed, I think, pretty much, their work, although I know, I'm sure they're still reviewing their stuff. And they have given us, you know, approximate size for the debris and approximate area for where it came from and approximately where it hit. Uh, so we are, you know, talking about doing some sort of "parametric" type analyses, uh, and also we're talking about looking at what you can do, uh, in the event we really have some damage there but . . .

Ham: Hey, just a comment, I was just thinking that our flight rationale at the FRR from tank and orbiter from STS-112 was that this . . . I'm not sure if the area is exactly the same where the foam came from that, but the material properties and density of the foam wouldn't do any damage. So we ought to pull that along with 87 data where we had some damage, pull this data from 112 or whatever flight it was and make sure that you know . . . I hope we had good flight rationale then . . .

McCormack: Yeah, we'll look at that. You mention 87, you know we saw some fairly significant damage area between RCC panels and 8 and 9 and main landing gear door down at the bottom on STS-87. We did some analyses prior to the STS-89 so uh . . .

Ham: And really, I don't think there is much we can do, so you know it's not really a factor during flight because there isn't much we can do about it. But what I'm really interested in is making sure our flight rationale two flights ago was good. Maybe this is foam from a different area, I'm not sure, and it may not be just . . . ? Can't maybe correlate it, but maybe try and see, maybe what we have.

McCormack: Okay . . .

Ham: Okay, Vanessa.

Source: NASA Web site, http://www.nasa.gov/pdf/47228main_mmt_030124.pdf, accessed March 3, 2004.

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Exhibit 9 E-mails from January 21, 2003—Flight Day 6

----Original Message----
From: DITTEMORE, RONALD D. (JSC-MA) (NASA)
Sent: Wednesday, January 22, 2003 9:14 AM
To: HAM, LINDA J. (JSC-MA2) (NASA)
Subject: RE: ET Briefing - STS-112 Foam Loss

You remember the briefing! Jerry did it and had to go out and say that the hazard report had not changed and that the risk had not changed...But it is worth looking at again.

----Original Message----
From: HAM, LINDA J. (JSC-MA2) (NASA)
Sent: Tuesday, January 21, 2003 11:14 AM
To: DITTEMORE, RONALD D. (JSC-MA) (NASA)
Subject: FW: ET Briefing - STS-112 Foam Loss

You probably can't open the attachment. But, the ET rationale for flight for the STS-112 loss of foam was lousy. Rationale states we haven't changed anything, we haven't experienced any 'safety of flight' damage in 112 flights, risk of loss of bi-pod ramp TPS is same as previous flghts...So ET is safe to fly with no added risk

Rationale was lousy then and still is....

----Original Message----
From: MCCORMACK, DONALD L. (DON) (JSC-MV6) (NASA)
Sent: Tuesday, January 21, 2003 9:45 AM
To: HAM, LINDA J. (JSC-MA2) (NASA)
Subject: FW: ET Briefing - STS-112 Foam Loss
Importance: High

FYI - it kinda says that it will probably be all right

[ORR=Operational Readiness Review, VAB=Vehicle Assembly Building, IFA=In-Flight Anomaly, TPS=Thermal Protection System, ET=External Tank]

Source: CAIB report, Vol. 1, pp. 147–148.

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Exhibit 10 Email from Rodney Rocha—Flight Day 6

-----Original Message-----
From: ROCHA, ALAN R. (RODNEY) (JSC-ES2) (NASA)
Sent: Tuesday, January 21, 2003 4:41 PM
To: SHACK, PAUL E. (JSC-EA42) (NASA); HAMILTON, DAVID A. (DAVE) (JSC-EA) (NASA); MILLER, GLENN J. (JSC-EA) (NASA)
Cc: SERIALE-GRUSH, JOYCE M. (JSC-EA) (NASA); ROGERS, JOSEPH E. (JOE) (JSC-ES2) (NASA); GALBREATH, GREGORY F. (GREG) (JSC-ES2) (NASA)
Subject: STS-107 Wing Debris Impact, Request for Outside Photo-Imaging Help

Paul and Dave,
The meeting participants (Boeing, USA, NASA ES2 and ES3, KSC) all agreed we will always have big uncertainties in any transport/trajectory analyses and applicability/extrapolation of the old Arc-Jet test data until we get definitive, better, clearer photos of the wing and body underside. Without better images it will be very difficult to even bound the problem and initialize thermal, trajectory, and structural analyses. Their answers may have a wide spread ranging from acceptable to not-acceptable to horrible, and no way to reduce uncertainty. Thus, giving MOD options for entry will be very difficult.

Can we petition (beg) for outside agency assistance? We are asking for Frank Benz with Ralph Roe or Ron Dittemore to ask for such. Some of the old timers here remember we got such help in the early 1980's when we had missing tile concerns.

Despite some nay-sayers, there are some options for the team to talk about: On-orbit thermal conditioning for the major structure (but is in contradiction with tire pressure temp. cold limits), limiting high cross-range de-orbit entries, constraining right or left had turns during the Heading Alignment Circle (only if there is struc. damage to the RCC panels to the extent it affects flight control.

Rodney Rocha
Structural Engineering Division (ES-SED)
- ES Div. Chief Engineer (Space Shuttle DCE)
- Chair, Space Shuttle Loads & Dynamics Panel

Mail Code ES2

[USA=United Space Alliance, NASA ES2, ES3=separate divisions of the Johnson Space Center Engineering Directorate, KSC=Kennedy Space Center, MOD=Missions Operations Directorate, or Mission Control]

Source: CAIB report, Vol. 1, pp. 147–151.

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Exhibit 11 E-mails from Flight Day 7

-----Original Message---
From: HAM, LINDA J. (JSC-MA2) (NASA)
Sent: Wednesday, January 22, 2003 9:33 AM
To: AUSTIN, LAMBERT D. (JSC-MS) (NASA); ROE, RALPH R. (JSC-MV) (NASA)
Subject: ET Foam Loss

Can we say that for any ET foam lost, no 'safety of flight' damage can occur to the Orbiter because of the density?

[ET=External Tank]

-----Original Message-----
From: ROE, RALPH R. (JSC-MV) (NASA)
Sent: Wednesday, January 22, 2003 9:38 AM
To: SCHOMBURG, CALVIN (JSC-EA) (NASA)
Subject: FW: ET Foam Loss

Calvin,

I wouldn't think we could make such a generic statement but can we bound it some how by size or acreage?

[Acreage=larger areas of foam coverage]

-----Original Message-----
From: DITTEMORE, RONALD D. (JSC-MA) (NASA)
Sent: Wednesday, January 22, 2003 10:15 AM
To: HAM, LINDA J. (JSC-MA2) (NASA)
Subject: RE: ET Briefing - STS-112 Foam Loss

Another thought, we need to make sure that the density of the ET foam cannot damage the tile to where it is an impact to the orbiter...Lambert and Ralph need to get some folks working with ET.

Do Not Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Exhibit 11 (continued)

-----Original Message-----
From: SCHOMBURG, CALVIN (JSC-EA) (NASA)
Sent: Wednesday, January 22, 2003 10:53 AM
To: ROE, RALPH R. (JSC-MV) (NASA)
Subject: RE: ET Foam Loss

No-the amount of damage ET foam can cause to the TPS material-tiles is based on the amount of impact energy-the size of the piece and its velocity(from just after pad clear until about 120 seconds-after that it will not hit or it will not enough energy to cause any damage)-it is a pure kinetic problem-there is a size that can cause enough damage to a tile that enough of the material is lost that we could burn a hole through the skin and have a bad day-(loss of vehicle and crew -about 200-400 tile locations(out of the 23,000 on the lower surface)-the foam usually fails in small popcorn pieces-that is why it is vented-to make small hits-the two or three times we have been hit with a piece as large as the one this flight-we got a gouge about 8-10 inches long about 2 inches wide and 3/4 to an 1 inch deep across two or three tiles. That is what I expect this time-nothing worst. If that is all we get we have have no problem-will have to replace a couple of tiles but nothing else.

[ET=External Tank, TPS=Thermal Protection System]

-----Original Message-----
From: AUSTIN, LAMBERT D. (JSC-MS) (NASA)
Sent: Wednesday, January 22, 2003 3:22 PM
To: HAM, LINDA J. (JSC-MA2) (NASA)
Cc: WALLACE, RODNEY O. (ROD) (JSC-MS2) (NASA); NOAH, DONALD S. (DON) (JSC-MS) (NASA)
Subject: RE: ET Foam Loss

NO. I will cover some of the pertinent rationale....there could be more if I spent more time thinking about it. Recall this issue has been discussed from time to time since the inception of the basic "no debris" requirement in Vol. X and at each review the SSP has concluded that it is not possible to PRECLUDE a potential catastrophic event as a result of debris impact damage to the flight elements. As regards the Orbiter, both windows and tiles are areas of concern.

You can talk to Cal Schomberg and he will verify the many times we have covered this in SSP reviews. While there is much tolerance to window and tile damage, ET foam loss can result in impact damage that under subsequent entry environments can lead to loss of structural integrity of the Orbiter area impacted or a penetration in a critical function area that results in loss of that function. My recollection of the most critical Orbiter bottom acreage areas are the wing spar, main landing gear door seal and RCC panels...of course Cal can give you a much better rundown.

We can and have generated parametric impact zone characterizations for many areas of the Orbiter for a few of our more typical ET foam loss areas. Of course, the impact/damage significance is always a function of debris size and density, impact velocity, and impact angle--these latter 2 being a function of the flight time at which the ET foam becomes debris. For STS-107 specifically, we have generated this info and provided it to Orbiter. Of course, even this is based on the ASSUMPTION that the location and size of the debris is the same as occurred on STS-112----this cannot be verified until we receive the on-board ET separation photo evidence post Orbiter landing. We are requesting that this be expedited. I have the STS-107 Orbiter impact map based on the assumptions noted herein being sent down to you. Rod is in a review with Orbiter on this info right now.

[SSP=Space Shuttle Program, ET=External Tank]

Source: CAIB report, Vol. 1, pp. 154–156.

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Exhibit 12 Rodney Rocha's E-mail

"In my humble technical opinion, this is the wrong (and bordering on irresponsible) answer from the SSP and Orbiter not to request additional imaging help from any outside source. I must emphasize (again) that severe enough damage (3 or 4 multiple tiles knocked out down to the densification layer) combined with the heating and resulting damage to the underlying structure at the most critical location (viz., MLG door/wheels/tires/hydraulics or the X1191 spar cap) could present potentially grave hazards. The engineering team will admit it might not achieve definitive high confidence answers without additional images, but, without action to request help to clarify the damage visually, we will guarantee it will not. Can we talk to Frank Benz before Friday's MMT? Remember the NASA safety posters everywhere around stating, 'If it's not safe, say so'? Yes, it's that serious." [SSP=Space Shuttle Program, MLG=Main Landing Gear, MMT=Mission Management Team]

Source: CAIB report, Vol. 1, p. 157.

Exhibit 13 E-mail from NASA Liaison to USSTRATCOM

"Let me assure you that, as of yesterday afternoon, the Shuttle was in excellent shape, mission objectives were being performed, and that there were no major debris system problems identified. The request that you received was based on a piece of debris, most likely ice or insulation from the ET, that came off shortly after launch and hit the underside of the vehicle. Even though this is not a common occurrence it is something that has happened before and is not considered to be a major problem. The one problem that this has identified is the need for some additional coordination within NASA to assure that when a request is made it is done through the official channels. The NASA/ USSTRAT (USSPACE) MOA identifies the need for this type of support and that it will be provided by USSTRAT. Procedures have been long established that identifies the Flight Dynamics Officer (for the Shuttle) and the Trajectory Operations Officer (for the International Space Station) as the POCs to work these issues with the personnel in Cheyenne Mountain. One of the primary purposes for this chain is to make sure that requests like this one does not slip through the system and spin the community up about potential problems that have not been fully vetted through the proper channels. Two things that you can help us with is to make sure that future requests of this sort are confirmed through the proper channels. For the Shuttle it is via CMOC to the Flight Dynamics Officer. For the International Space Station it is via CMOC to the Trajectory Operations Officer. The second request is that no resources are spent unless the request has been confirmed. These requests are not meant to diminish the responsibilities of the DDMS office or to change any previous agreements but to eliminate the confusion that can be caused by a lack of proper coordination." [ET=External Tank,

Source: CAIB report, Vol. 1, p. 159.

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Exhibit 14 MMT Meeting Transcript Excerpt from Flight Day 9— January 24, 2003

McCormack: And the other item, Linda, that we are looking at is um, you know we took the inputs that we got from the system integration guys on um, on um the debris.

Ham: Before we go on . . . (discussed other mission subjects). Okay, go ahead Don.

McCormack: Okay, and also we uh received, uh received the data from the systems integration guys of the potential ranges of sizes and impact angles and where it might of hit and the guys have gone off and done an analysis. They've used, uh, they've used a tool they refer to as "Crater," which is their official evaluation tool to determine the potential size of the damage, um . . . They went off and done all that work and they've done thermal analysis of the areas of where there may be damaged tiles, uh . . . The analysis is not complete, there is one case yet they wish to run, but were just kind of jumping to the conclusion of all, that, um, they do show obviously there's a potential for significant tile damage here, but, but they do not indicate that, the thermal analysis does not indicate that there is a potential for a burn-through. There could be localized heating damage, um, obviously there is a lot of uncertainty in all this, in terms of the size of the debris and where it hit and the angle of incidence, and uh, it's difficult.

Ham: No burn-through means no catastrophic damage, and localized heating damage would mean a tile replacement?

McCormack: It would mean possible impact to turnaround repairs and that sort of thing but we do not see any kind of safety-of-flight issue here yet in anything we've looked at.

Ham: No safety-of-flight and no issue for this mission, nothing we're going to do different, there may be a turnaround?

McCormack: Right, right, it could potentially hit the RCC and we don't indicate, other than possible coating damage or something, we don't see any issue if it hit the RCC so . . . Although we could again, although we could have some significant tile damage, we don't see a safety-of-flight issue.

Ham: What do you mean by that?

McCormack: Well it could be down to the uh, we could lose an entire tile, I mean, and then the ramp into and out of that, it could be a significant area of tile damage down to the SIP [strain isolation panel] . . . perhaps um, it could be a significant piece missing, but um . . .

Ham: Would be a turnaround issue only?

McCormack: Right.

Ham: We've seen pieces of this size before, haven't we?

(Can't hear the speaker. Someone tells Ham they can't hear the speaker.)

Ham: He was just reiterating, it was Calvin [Schomburg], that he does not believe that there is any uh burn through so no safety of flight kind of issue, it's more of a turnaround issue, similar to what we have had on other flights. That's it? All right, any questions on that? Okay, Vanessa?

Source: NASA Web site, http://www.nasa.gov/pdf/47229main_mmt_030127.pdf, accessed March 3, 2004.

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

Endnotes

[1] "Columbia's Final Flight," The Columbia Accident Investigation Board (CAIB) report, August 26, 2003, Washington, D.C., Vol. 1, Ch. 2.

[2] NASA History Fact Sheet, available at www.hq.nasa.gov/office/pao/History/factsheet.htm, accessed February 24, 2004.

[3] "Report of the Ad Hoc Panel on Man-in-Space," the President's Science Advisory Committee, December 16, 1960, NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C., available at www.hq.nasa.gov/office/pao/History/report60.html, accessed March 9, 2004.

[4] Michael Useem, *The Leadership Moment* (New York: Times Books, 2000), p. 82.

[5] NASA Web site, http://www.hq.nasa.gov/office/pao/facts/HTML/FS-002-HQ.html, accessed February 26, 2004.

[6] "The Evolution of the Space Shuttle Program," CAIB, Vol. 1, Ch. 1.

[7] Robert Lee Hotz, "Decoding Columbia: A detective story," *Los Angeles Times*, December 21, 2003.

[8] William Langewiesche, "Columbia's Last Flight," *The Atlantic Monthly*, November 2003, p. 68.

[9] Michael Isikoff, "Low Temperatures on Booster Probed – Commission Physicist Visits Cape Canaveral for Inquiry," *The Washington Post*, February 18, 1986.

[10] "Report to the Presidential Commission on the Space Shuttle Challenger Accident" (Washington, D.C.: Government Printing Office, 1986), Vol. II, Appendix F.

[11] "Decision Making at NASA," CAIB, Vol. 1, Ch. 6.

[12] CAIB, Vol. 1, p. 122.

[13] Ibid., p. 56.

[14] Ibid., p. 127.

[15] NASA Web site, http://www.nasa.gov/columbia/mission/index.html, accessed February 23, 2004.

[16] Robert Lee Hotz, "Butterfly on a Bullet: Swallowing the Fire: Columbia's Final Voyage," *Los Angeles Times*, December 26, 2003.

[17] Langewiesche.

[18] Warren E. Leary, "'Easy to Fly' Reputation, but Shuttle has its Quirks," *The New York Times*, February 3, 2003.

[19] Ibid.

[20] CAIB, Vol. 1, p. 140.

[21] Ibid.

[22] Ibid.

[23] ABC News, Primetime Live video, "Final Mission," 2003.

[24] CAIB, Vol. 1, p. 142.

[25] Ibid., p. 145.

[26] Ibid.

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

[27] Excerpts from NASA news conference at Johnson Space Center, *The New York Times*, February 2, 2003.

[28] NASA Web site, http://www.nasa.gov/pdf/47227main_mmt_030121.pdf, accessed February 25, 2004.

[29] CAIB, Vol. 1, p. 124.

[30] Ibid., p. 148.

[31] Ibid., p. 149.

[32] Ibid., p. 148.

[33] Ibid., p. 149.

[34] Ibid., p. 150.

[35] Ibid., p. 152.

[36] Ibid., p. 153.

[37] James Glanz and John Schwartz, "Dogged Engineer's Effort to Assess Shuttle Damage," *The New York Times*, September 26, 2003.

[38] CAIB, Vol. 1, p. 153.

[39] Ibid., p. 154.

[40] Ibid., p. 157.

[41] Ibid.

[42] Glanz and Schwartz.

[43] CAIB, Vol. 1, p. 158.

[44] Glanz and Schwartz.

[45] CAIB, Vol. 1, p. 159.

[46] Ibid.

[47] Ibid.

[48] Ibid., p. 161.

[49] NASA Web site, http://www.nasa.gov/pdf/47229main_mmt_030127.pdf, accessed February 27, 2004.

[50] Robert Lee Hotz, "Butterfly on a Bullet."

[51] Matthew L. Wald and John Schwartz, "Alerts Lacking, Shuttle Manager Said," *The New York Times*, July 23, 2003.

[52] Langewiesche.

[53] James Glanz, "Space Flight's Dangers Are Raised By Speed," *The New York Times*, February 2, 2003.

[54] Todd S. Purdum, "Another Blow and More Loss for an Already Anxious Nation," *The New York Times*, February 2, 2003.

[55] Ibid.

[56] CAIB, Vol. 1, p. 9.

[57] Ibid.

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.

[58] Hotz, "Decoding Columbia: A detective story."

[59] Langewiesche.

[60] Ibid.

[61] Ibid.

[62] CAIB, Vol. 1, pp. 173–174.

[63] Langewiesche.

[64] CAIB, Vol. 1, p. 9.

[65] Ibid., p. 6

[66] John Broder, "Debris is Now Leading Suspect in Shuttle Catastrophe," *The New York Times*, February 4, 2003.

[67] Wald and Schwartz, "Alerts Lacking."`

[68] "Television Review; Unheeded Concerns and the Columbia Disaster," *The New York Times*, July 7, 2003.

[69] ABC News, "Final Mission."

[70] John Schwartz and Matthew L. Wald, "Report on Loss of Shuttle Focuses on NASA Blunders and Issues Somber Warning," *The New York Times*, August 27, 2003.

[71] "Bush Remarks on Shuttle: 'Destruction and Tragedy,'" *The New York Times*, February 2, 2003.

Do Not Copy or Post

Copying or posting is an infringement of copyright. Permissions@hbsp.harvard.edu or 617-783-7860.