CHAPTER 6

Decision Making at NASA

The dwindling post-Cold War Shuttle budget that launched NASA leadership on a crusade for efficiency in the decade before *Columbia*'s final flight powerfully shaped the environment in which Shuttle managers worked. The increased organizational complexity, transitioning authority structures, and ambiguous working relationships that defined the restructured Space Shuttle Program in the 1990s created turbulence that repeatedly influenced decisions made before and during STS-107.

This chapter connects Chapter 5's analysis of NASA's broader policy environment to a focused scrutiny of Space Shuttle Program decisions that led to the STS-107 accident. Section 6.1 illustrates how foam debris losses that violated design requirements came to be defined by NASA management as an acceptable aspect of Shuttle missions, one that posed merely a maintenance "turnaround" problem rather than a safety-of-flight concern. Section 6.2 shows how, at a pivotal juncture just months before the *Columbia* accident, the management goal of completing Node 2 of the International Space Station on time encouraged Shuttle managers to continue flying, even after a significant bipod-foam debris strike on STS-112. Section 6.3 notes the decisions made during STS-107 in response to the bipod foam strike, and reveals how engineers' concerns about risk and safety were competing with – and were defeated by – management's belief that foam could not hurt the Orbiter, as well as the need to keep on schedule. In relating a rescue and repair scenario that might have enabled the crew's safe return, Section 6.4 grapples with yet another latent assumption held by Shuttle managers during and after STS-107: that even if the foam strike had been discovered, nothing could have been done.

6.1 A HISTORY OF FOAM ANOMALIES

The shedding of External Tank foam – the physical cause of the *Columbia* accident – had a long history. Damage caused by debris has occurred on every Space Shuttle flight, and most missions have had insulating foam shed during ascent. This raises an obvious question: Why did NASA continue flying the Shuttle with a known problem that violated design requirements? It would seem that the longer the Shuttle Program allowed debris to continue striking the Orbiters, the more opportunity existed to detect the serious threat it posed. But this is not what happened. Although engineers have made numerous changes in foam design and application in the 25 years that the External Tank has been in production, the problem of foam-shedding has not been solved, nor has the Orbiter's ability to tolerate impacts from foam or other debris been significantly improved.

The Need for Foam Insulation

The External Tank contains liquid oxygen and hydrogen propellants stored at minus 297 and minus 423 degrees Fahrenheit. Were the super-cold External Tank not sufficiently insulated from the warm air, its liquid propellants would boil, and atmospheric nitrogen and water vapor would condense and form thick layers of ice on its surface. Upon launch, the ice could break off and damage the Orbiter. (See Chapter 3.)

To prevent this from happening, large areas of the External Tank are machine-sprayed with one or two inches of foam, while specific fixtures, such as the bipod ramps, are hand-sculpted with thicker coats. Most of these insulating materials fall into a general category of "foam," and are outwardly similar to hardware store-sprayable foam insulation. The problem is that foam does not always stay where the External Tank manufacturer Lockheed Martin installs it. During flight, popcorn- to briefcase-size chunks detach from the External Tank.

Original Design Requirements

Early in the Space Shuttle Program, foam loss was considered a dangerous problem. Design engineers were extremely concerned about potential damage to the Orbiter and its fragile Thermal Protection System, parts of which are so vulnerable to impacts that lightly pressing a thumbnail into them leaves a mark. Because of these concerns, the baseline design requirements in the Shuttle's "Flight and Ground System Specification-Book 1, Requirements," precluded foam-shedding by the External Tank. Specifically:

> ***3.2.1.2.14 Debris Prevention:*** *The Space Shuttle System, including the ground systems, shall be designed to preclude the shedding of ice and/or other debris from the Shuttle elements during prelaunch and flight operations that would jeopardize the flight crew, vehicle, mission success, or would adversely impact turnaround operations.*[1]

> ***3.2.1.1.17 External Tank Debris Limits:*** *No debris shall emanate from the critical zone of the External Tank on the launch pad or during ascent except for such material which may result from normal thermal protection system recession due to ascent heating.*[2]

The assumption that only tiny pieces of debris would strike the Orbiter was also built into original design requirements, which specified that the Thermal Protection System (the tiles and Reinforced Carbon-Carbon, or RCC, panels) would be built to withstand impacts with a kinetic energy less than 0.006 foot-pounds. Such a small tolerance leaves the Orbiter vulnerable to strikes from birds, ice, launch pad debris, and pieces of foam.

Despite the design requirement that the External Tank shed no debris, and that the Orbiter not be subjected to any significant debris hits, *Columbia* sustained damage from debris strikes on its inaugural 1981 flight. More than 300 tiles had to be replaced.[3] Engineers stated that had they known in advance that the External Tank "was going to produce the debris shower that occurred" during launch, "they would have had a difficult time clearing *Columbia* for flight."[4]

Discussion of Foam Strikes Prior to the Rogers Commission

Foam strikes were a topic of management concern at the time of the *Challenger* accident. In fact, during the Rogers Commission accident investigation, Shuttle Program Manager Arnold Aldrich cited a contractor's concerns about foam shedding to illustrate how well the Shuttle Program manages risk:

> *On a series of four or five external tanks, the thermal insulation around the inner tank … had large divots of insulation coming off and impacting the Orbiter. We found significant amount of damage to one Orbiter after a flight and … on the subsequent flight we had a camera in the equivalent of the wheel well, which took a picture of the tank after separation, and we determined that this was in fact the cause of the damage. At that time, we wanted to be able to proceed with the launch program if it was acceptable … so we undertook discussions of what would be acceptable in terms of potential field repairs, and during those discussions, Rockwell was very conservative because, rightly, damage to the Orbiter TPS [Thermal Protection System] is damage to the Orbiter system, and it has a very stringent environment to experience during the re-entry phase.*

Aldrich described the pieces of foam as "… half a foot square or a foot by half a foot, and some of them much smaller and localized to a specific area, but fairly high up on the tank. So they had a good shot at the Orbiter underbelly, and this is where we had the damage."[5]

Continuing Foam Loss

Despite the high level of concern after STS-1 and through the *Challenger* accident, foam continued to separate from the External Tank. Photographic evidence of foam shedding exists for 65 of the 79 missions for which imagery is available. Of the 34 missions for which there are no imagery, 8 missions where foam loss is not seen in the imagery, and 6 missions where imagery is inconclusive, foam loss can be inferred from the number of divots on the Orbiter's lower surfaces. Over the life of the Space Shuttle Program, Orbiters have returned with an average of 143 divots in the upper and lower surfaces of the Thermal Protection System tiles, with 31 divots averaging over an inch in one dimension.[6] (The Orbiters' lower surfaces have an average of 101 hits, 23 of which are larger than an inch in diameter.) Though the Orbiter is also struck by ice and pieces of launch-pad hardware during launch, by micrometeoroids and orbital debris in space, and by runway debris during landing, the Board concludes that foam is likely responsible for most debris hits.

With each successful landing, it appears that NASA engineers and managers increasingly regarded the foam-shedding as inevitable, and as either unlikely to jeopardize safety or simply an acceptable risk. The distinction between foam loss and debris events also appears to have become blurred. NASA and contractor personnel came to view foam strikes not as a safety of flight issue, but rather a simple maintenance, or "turnaround" issue. In Flight Readiness Review documentation, Mission Management Team minutes, In-Flight Anomaly disposition reports, and elsewhere, what was originally considered a serious threat to the Orbiter

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.[8]

Out of Family: Operation or performance outside the expected performance range for a given parameter or which has not previously been experienced.[9]

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 reoccur. 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.

Flight	STS-7	STS-32R	STS-50	STS-52	STS-62	STS-112	STS-107
ET #	06	25	45	55	62	115	93
ET Type	SWT	LWT	LWT	LWT	LWT	SLWT	LWT
Orbiter	*Challenger*	*Columbia*	*Columbia*	*Columbia*	*Columbia*	*Atlantis*	*Columbia*
Inclination	28.45 deg	28.45 deg	28.45 deg	28.45 deg	39.0 deg	51.6 deg	39.0 deg
Launch Date	06/18/83	01/09/90	06/25/92	10/22/92	03/04/94	10/07/02	01/16/03
Launch Time (Local)	07:33:00 AM EDT	07:35:00 AM EST	12:12:23 PM EDT	1:09:39 PM EDT	08:53:00 AM EST	3:46:00 PM EDT	10:39:00 AM EDT

Figure 6.1-1. There have been seven known cases where the left External Tank bipod ramp foam has come off in flight.

came to be treated as "in-family,"[7] a reportable problem that was within the known experience base, was believed to be understood, and was not regarded as a safety-of-flight issue.

Bipod Ramp Foam Loss Events

Chunks of foam from the External Tank's forward bipod attachment, which connects the Orbiter to the External Tank, are some of the largest pieces of debris that have struck the Orbiter. To place the foam loss from STS-107 in a broader context, the Board examined every known instance of foam-shedding from this area. Foam loss from the left bipod ramp (called the –Y ramp in NASA parlance) has been confirmed by imagery on 7 of the 113 missions flown. However, only on 72 of these missions was available imagery of sufficient quality to determine left bipod ramp foam loss. Therefore, foam loss from the left bipod area occurred on approximately 10 percent of flights (seven events out of 72 imaged flights). On the 66 flights that imagery was available for the right bipod area, foam loss was never observed. NASA could not explain why only the left bipod experienced foam loss. (See Figure 6.1-1.)

The first known bipod ramp foam loss occurred during STS-7, *Challenger*'s second mission (see Figure 6.1-2). Images taken after External Tank separation revealed that a 19- by 12-inch piece of the left bipod ramp was missing, and that the External Tank had some 25 shallow divots in the foam just forward of the bipod struts and another 40 divots in the foam covering the lower External Tank. After the mission was completed, the Program Requirements Control Board cited the foam loss as an In-Flight Anomaly. Citing an event as an In-Flight Anomaly means that before the next launch, a specific NASA organization must resolve the problem or prove that it does not threaten the safety of the vehicle or crew.[11]

At the Flight Readiness Review for the next mission, Orbiter Project management reported that, based on the completion of repairs to the Orbiter Thermal Protection System, the bipod ramp foam loss In-Flight Anomaly was resolved, or "closed." However, although the closure documents detailed the repairs made to the Orbiter, neither the Certificate of Flight Readiness documentation nor the Flight Readiness Review documentation referenced correcting the *cause* of the damage – the shedding of foam.

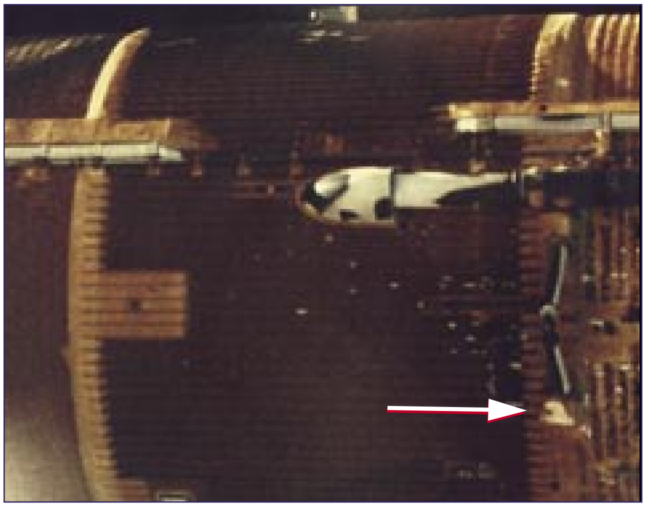


Figure 6.1-2. The first known instance of bipod ramp shedding occurred on STS-7 which was launched on June 18, 1983.

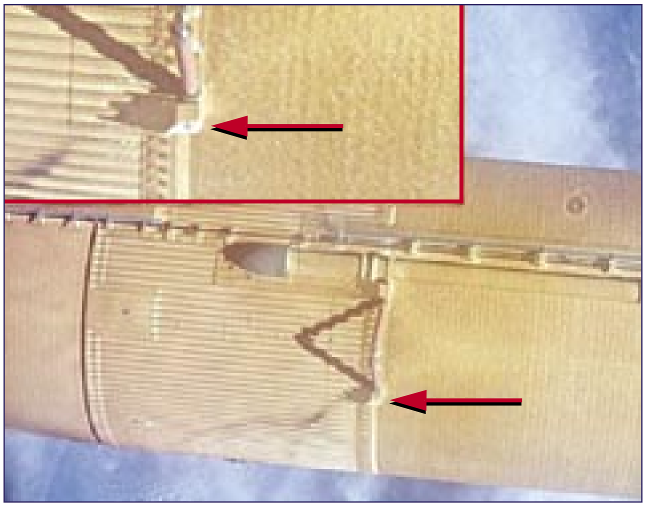


Figure 6.1-3. Only three months before the final launch of Columbia, the bipod ramp foam had come off during STS-112.

Umbilical Cameras and the Statistics of Bipod Ramp Loss

Over the course of the 113 Space Shuttle missions, the left bipod ramp has shed significant pieces of foam at least seven times. (Foam-shedding from the right bipod ramp has never been confirmed. The right bipod ramp may be less subject to foam shedding because it is partially shielded from aerodynamic forces by the External Tank's liquid oxygen line.) The fact that five of these left bipod shedding events occurred on missions flown by *Columbia* sparked considerable Board debate. Although initially this appeared to be a improbable coincidence that would have caused the Board to fault NASA for improper trend analysis and lack of engineering curiosity, on closer inspection, the Board concluded that this "coincidence" is probably the result of a bias in the sample of known bipod foam-shedding. Before the *Challenger* accident, only *Challenger* and *Columbia* carried umbilical well cameras that imaged the External Tank after separation, so there are more images of *Columbia* than of the other Orbiters.[10]

The bipod was imaged 26 of 28 of *Columbia*'s missions; in contrast, *Challenger* had 7 of 10, *Discovery* had only 14 of 30, *Atlantis* only 14 of 26, and *Endeavour* 12 of 19.

The second bipod ramp foam loss occurred during STS-32R, *Columbia*'s ninth flight, on January 9, 1990. A post-mission review of STS-32R photography revealed five divots in the intertank foam ranging from 6 to 28 inches in diameter, the largest of which extended into the left bipod ramp foam. A post-mission inspection of the lower surface of the Orbiter revealed 111 hits, 13 of which were one inch or greater in one dimension. An In-Flight Anomaly assigned to the External Tank Project was closed out at the Flight Readiness Review for the next mission, STS-36, on the basis that there may have been local voids in the foam bipod ramp where it attached to the metal skin of the External Tank. To address the foam loss, NASA engineers poked small "vent holes" through the intertank foam to allow trapped gases to escape voids in the foam where they otherwise might build up pressure and cause the foam to pop off. However, NASA is still studying this hypothesized mechanism of foam loss. Experiments conducted under the Board's purview indicate that other mechanisms may be at work. (See "Foam Fracture Under Hydrostatic Pressure" in Chapter 3.) As discussed in Chapter 3, the Board notes that the persistent uncertainty about the causes of foam loss and potential Orbiter damage results from a lack of thorough hazard analysis and engineering attention.

The third bipod foam loss occurred on June 25, 1992, during the launch of *Columbia* on STS-50, when an approximately 26- by 10-inch piece separated from the left bipod ramp area. Post-mission inspection revealed a 9-inch by 4.5-inch by 0.5-inch divot in the tile, the largest area of tile damage in Shuttle history. The External Tank Project at Marshall Space Flight Center and the Integration Office at Johnson Space Center cited separate In-Flight Anomalies. The Integration Office closed out its In-Flight Anomaly two days before the next flight, STS-46, by deeming damage to the Thermal Protection System an "accepted flight risk."[12] In Integration Hazard Report 37, the Integration Office noted that the impact damage was shallow, the tile loss was not a result of excessive aerodynamic loads, and the External Tank Thermal Protection System failure was the result of "inadequate venting."[13] The External Tank Project closed out its In-Flight Anomaly with the rationale that foam loss during ascent was "not considered a flight or safety issue."[14] Note the difference in how the each program addressed the foam-shedding problem: While the Integration Office deemed it an "accepted risk," the External Tank Project considered it "not a safety-of-flight issue." Hazard Report 37 would figure in the STS-113 Flight Readiness Review, where the crucial decision was made to continue flying with the foam-loss problem. This inconsistency would reappear 10 years later, after bipod foam-shedding during STS-112.

The fourth and fifth bipod ramp foam loss events went undetected until the Board directed NASA to review all available imagery for other instances of bipod foam-shedding. This review of imagery from tracking cameras, the umbilical well camera, and video and still images from flight crew hand held cameras revealed bipod foam loss on STS-52 and STS-62, both of which were flown by *Columbia*. STS-52, launched on October 22, 1992, lost an 8- by 4-inch corner of the left bipod ramp as well as portions of foam covering the left jackpad, a piece of External Tank hardware that facilitates the Orbiter attachment process. The STS-52 post-mission inspection noted a higher-than-average 290 hits on upper and lower Thermal Protection System tiles, 16 of which were greater than one inch in one dimension. External Tank separation videos of STS-62, launched on March 4, 1994, revealed that a 1- by 3-inch piece of foam in the rear face of the left bipod ramp was missing, as were small pieces of foam around the bipod ramp. Because these incidents of missing bipod foam were not detected until after the STS-107 accident, no In-Flight Anomalies had been written. The Board concludes that NASA's failure to identify these bipod foam losses at the time they occurred means the agency must examine the adequacy of its film review, post-flight inspection, and Program Requirements Control Board processes.

The sixth and final bipod ramp event before STS-107 occurred during STS-112 on October 7, 2002 (see Figure 6.1-3). At 33 seconds after launch, when *Atlantis* was at 12,500 feet and traveling at Mach 0.75, ground cameras observed an object traveling from the External Tank that subsequently impacted the Solid Rocket Booster/External Tank Attachment ring (see Figure 6.1-4). After impact, the debris broke into multiple pieces that fell along the Solid Rocket Booster exhaust plume.[15] Post-mission inspection of the Solid Rocket Booster confirmed damage to foam on the forward face of the External Tank Attachment ring. The impact was approximately 4 inches wide and 3 inches deep. Post-External Tank separation photography by the crew showed that a 4- by 5- by 12-inch (240 cubic-inch) corner section of the left bipod ramp was missing, which exposed the super lightweight ablator coating on the bipod housing. This missing chunk of foam was believed to be the debris that impacted the External Tank Attachment ring during ascent. The post-launch review of photos and video identified these debris events, but the Mission Evaluation Room logs and Mission Management Team minutes do not reflect any discussions of them.

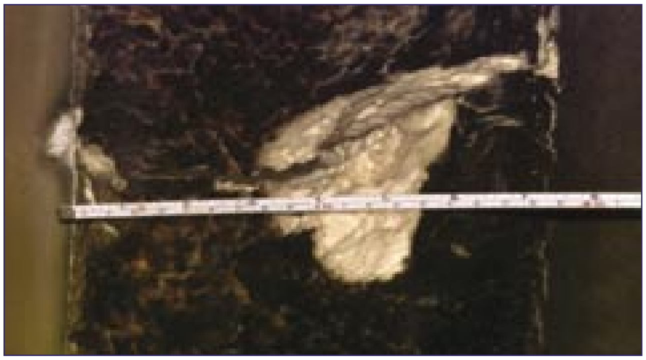


Figure 6.1-4. On STS-112, the foam impacted the External Tank Attach ring on the Solid Rocket Booster, causing this tear in the insulation on the ring.

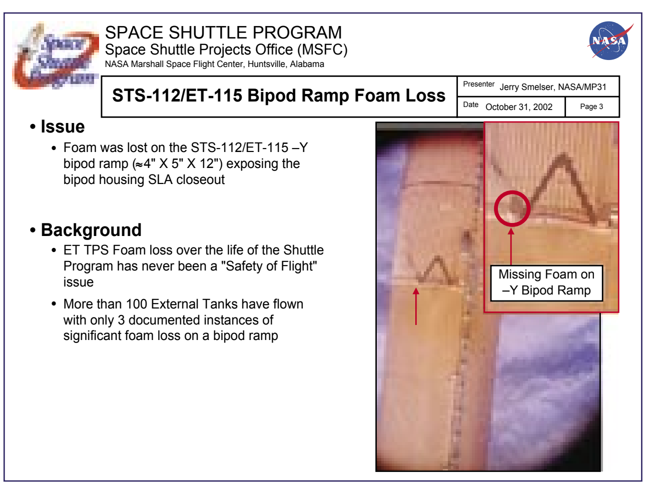
STS-113 Flight Readiness Review: A Pivotal Decision

Because the bipod ramp shedding on STS-112 was significant, both in size and in the damage it caused, and because it occurred only two flights before STS-107, the Board investigated NASA's rationale to continue flying. This decision made by the Program Requirements Control Board at the STS-113 Flight Readiness Review is among those most directly linked to the STS-107 accident. Had the foam loss during STS-112 been classified as a more serious threat, managers might have responded differently when they heard about the foam strike on STS-107. Alternately, in the face of the increased risk, STS-107 might not have flown at all. However, at STS-113's Flight Readiness Review, managers formally accepted a flight rationale that stated it was safe to fly with foam losses. This decision enabled, and perhaps even encouraged, Mission Management Team members to use similar reasoning when evaluating whether the foam strike on STS-107 posed a safety-of-flight issue.

At the Program Requirements Control Board meeting following the return of STS-112, the Intercenter Photo Working Group recommended that the loss of bipod foam be classified as an In-Flight Anomaly. In a meeting chaired by Shuttle Program Manager Ron Dittemore and attended by many of the managers who would be actively involved with STS-107, including Linda Ham, the Program Requirements Control Board ultimately decided against such classification. Instead, after discussions with the Integration Office and the External Tank Project, the Program Requirements Control Board Chairman assigned an "action" to the External Tank Project to determine the root cause of the foam loss and to propose corrective action. This was inconsistent with previous practice, in which all other known bipod foam-shedding was designated as In-Flight Anomalies. The Program Requirements Control Board initially set December 5, 2002, as the date to report back on this action, even though STS-113 was scheduled to launch on November 10. The due date subsequently slipped until after the planned launch and return of STS-107. The Space Shuttle Program decided to fly not one but two missions before resolving the STS-112 foam loss.

The Board wondered why NASA would treat the STS-112 foam loss differently than all others. What drove managers to reject the recommendation that the foam loss be deemed an In-Flight Anomaly? Why did they take the unprecedented step of scheduling not one but eventually two missions to fly before the External Tank Project was to report back on foam losses? It seems that Shuttle managers had become conditioned over time to not regard foam loss or debris as a safety-of-flight concern. As will be discussed in Section 6.2, the need to adhere to the Node 2 launch schedule also appears to have influenced their decision. Had the STS-113 mission been delayed beyond early December 2002, the Expedition 5 crew on board the Space Station would have exceeded its 180-day on-orbit limit, and the Node 2 launch date, a major management goal, would not be met.

Even though the results of the External Tank Project engineering analysis were not due until after STS-113, the foam-shedding was reported, or "briefed," at STS-113's Flight Readiness Review on October 31, 2002, a meeting that Dittemore and Ham attended. Two slides from this brief (Figure 6.1-5) explain the disposition of bipod ramp foam loss on STS-112.



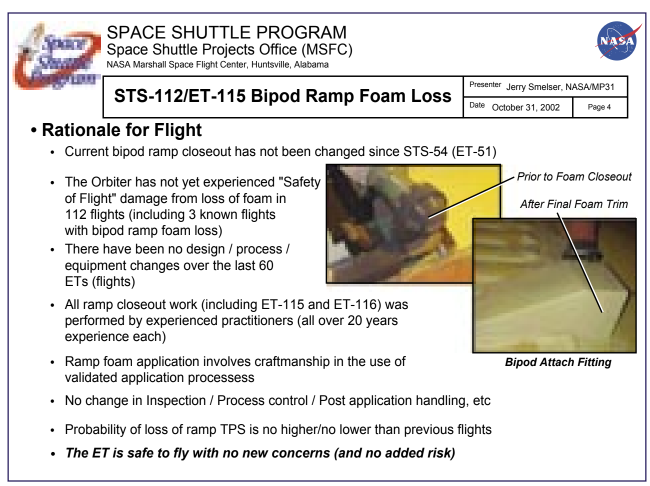


Figure 6.1-5. These two briefing slides are from the STS-113 Flight Readiness Review. The first and third bullets on the right-hand slide are incorrect since the design of the bipod ramp had changed several times since the flights listed on the slide.

This rationale is seriously flawed. The first and third statements listed under "Rationale for Flight" are incorrect. Contrary to the chart, which was presented by Jerry Smelser, the Program Manager for the External Tank Project, the bipod ramp design *had* changed, as of External Tank-76. This casts doubt on the implied argument that because the design had *not* changed, future bipod foam events were unlikely to occur. Although the other points may be factually correct, they provide an exceptionally weak rationale for safe flight. The fact that ramp closeout work was "performed by experienced practitioners" or that "application involves craftsmanship in the use of validated application processes" in no way decreases the chances of recurrent foam loss. The statement that the "probability of loss of ramp Thermal Protection System is no higher/no lower than previous flights" could be just as accurately stated "the probability of bipod foam loss on the next flight is just as high as it was on previous flights." With no engineering analysis, Shuttle managers used past success as a justification for future flights, and made no change to the External Tank configurations planned for STS-113, and, subsequently, for STS-107.

Along with this chart, the NASA Headquarters Safety Office presented a report that estimated a 99 percent probability of foam not being shed from the same area, even though no corrective action had been taken following the STS-112 foam-shedding.[16] The ostensible justification for the 99 percent figure was a calculation of the actual rate of bipod loss over 61 flights. This calculation was a sleight-of-hand effort to make the probability of bipod foam loss appear low rather than a serious grappling with the probability of bipod ramp foam separating. For one thing, the calculation equates the probability of left and right bipod loss, when right bipod loss has never been observed, and the amount of imagery available for left and right bipod events differs. The calculation also miscounts the actual number of bipod ramp losses in two ways. First, by restricting the sample size to flights between STS-112 and the last known bipod ramp loss, it excludes known bipod ramp losses from STS-7, STS-32R, and STS-50. Second, by failing to project the statistical rate of bipod loss across the many missions for which no bipod imagery is available, the calculation assumes a "what you don't see won't hurt you" mentality when in fact the reverse is true. When the statistical rate of bipod foam loss is projected across missions for which imagery is not available, and the sample size is extended to include every mission from STS-1 on, the probability of bipod loss increases dramatically. The Board's review after STS-107, which included the discovery of two additional bipod ramp losses that NASA had not previously noted, concluded that bipod foam loss occurred on approximately 10 percent of all missions.

During the brief at STS-113's Flight Readiness Review, the Associate Administrator for Safety and Mission Assurance scrutinized the Integration Hazard Report 37 conclusion that debris-shedding was an accepted risk, as well as the External Tank Project's rationale for flight. After conferring, STS-113 Flight Readiness Review participants ultimately agreed that foam shedding should be characterized as an "accepted risk" rather than a "not a safety-of-flight" issue. Space Shuttle Program management accepted this rationale, and STS-113's Certificate of Flight Readiness was signed.

The decision made at the STS-113 Flight Readiness Review seemingly acknowledged that the foam posed a threat to the Orbiter, although the continuing disagreement over whether foam was "not a safety of flight issue" versus an "accepted risk" demonstrates how the two terms became blurred over time, clouding the precise conditions under which an increase in risk would be permitted by Shuttle Program management. In retrospect, the bipod foam that caused a 4- by 3-inch gouge in the foam on one of *Atlantis*' Solid Rocket Boosters – just months before STS-107 – was a "strong signal" of potential future damage that Shuttle engineers ignored. Despite the significant bipod foam loss on STS-112, Shuttle Program engineers made no External Tank configuration changes, no moves to reduce the risk of bipod ramp shedding or potential damage to the Orbiter on either of the next two flights, STS-113 and STS-107, and did not update Integrated Hazard Report 37. The Board notes that although there is a process for conducting hazard analyses when the system is designed and a process for re-evaluating them when a design is changed or the component is replaced, no process addresses the need to update a hazard analysis when anomalies occur. A stronger Integration Office would likely have insisted that Integrated Hazard Analysis 37 be updated. In the course of that update, engineers would be forced to consider the cause of foam-shedding and the effects of shedding on other Shuttle elements, including the Orbiter Thermal Protection System.

STS-113 launched at night, and although it is occasionally possible to image the Orbiter from light given off by the Solid Rocket Motor plume, in this instance no imagery was obtained and it is possible that foam could have been shed.

The acceptance of the rationale to fly cleared the way for *Columbia*'s launch and provided a method for Mission managers to classify the STS-107 foam strike as a maintenance and turnaround concern rather than a safety-of-flight issue. It is significant that in retrospect, several NASA managers identified their acceptance of this flight rationale as a serious error.

The foam-loss issue was considered so insignificant by some Shuttle Program engineers and managers that the STS-107 Flight Readiness Review documents include no discussion of the still-unresolved STS-112 foam loss. According to Program rules, this discussion was not a requirement because the STS-112 incident was only identified as an "action," not an In-Flight Anomaly. However, because the action was still open, and the date of its resolution had slipped, the Board believes that Shuttle Program managers should have addressed it. Had the foam issue been discussed in STS-107 pre-launch meetings, Mission managers may have been more sensitive to the foam-shedding, and may have taken more aggressive steps to determine the extent of the damage.

The seventh and final known bipod ramp foam loss occurred on January 16, 2003, during the launch of *Columbia* on STS-107. After the *Columbia* bipod loss, the Program Requirements Control Board deemed the foam loss an In-Flight Anomaly to be dealt with by the External Tank Project.

Other Foam/Debris Events

To better understand how NASA's treatment of debris strikes evolved over time, the Board investigated missions where debris was shed from locations other than the External Tank bipod ramp. The number of debris strikes to the Orbiters' lower surface Thermal Protection System that resulted in tile damage greater than one inch in diameter is shown in Figure 6.1-6.[17] The number of debris strikes may be small, but a single strike could damage several tiles (see Figure 6.1-7).

One debris strike in particular foreshadows the STS-107 event. When *Atlantis* was launched on STS-27R on December 2, 1988, the largest debris event up to that time significantly damaged the Orbiter. Post-launch analysis of tracking camera imagery by the Intercenter Photo Working Group identified a large piece of debris that struck the Thermal Protection System tile at approximately 85 seconds into the flight. On Flight Day Two, Mission Control asked the flight crew to inspect *Atlantis* with a camera mounted on the remote manipulator arm, a robotic device that was not installed on *Columbia* for STS-107. Mission Commander R.L. "Hoot" Gibson later stated that *Atlantis* "looked like it had been blasted by a shotgun."[18] Concerned that the Orbiter's Thermal Protection System had been breached, Gibson ordered that the video be transferred to Mission Control so that NASA engineers could evaluate the damage.

When *Atlantis* landed, engineers were surprised by the extent of the damage. Post-mission inspections deemed it "the most severe of any mission yet flown."[19] The Orbiter had 707 dings, 298 of which were greater than an inch in one dimension. Damage was concentrated outboard of a line right of the bipod attachment to the liquid oxygen umbilical line. Even more worrisome, the debris had knocked off a tile, exposing the Orbiter's skin to the heat of re-entry. Post-flight analysis concluded that structural damage was confined to the exposed cavity left by the missing tile, which happened to be at the location of a thick aluminum plate covering an L-band navigation antenna. Were it not for the thick aluminum plate, Gibson stated during a presentation to the Board that a burn-through may have occurred.[20]

The Board notes the distinctly different ways in which the STS-27R and STS-107 debris strike events were treated. After the discovery of the debris strike on Flight Day Two of STS-27R, the crew was immediately directed to inspect the vehicle. More severe thermal damage – perhaps even a burn-through – may have occurred were it not for the aluminum plate at the site of the tile loss. Fourteen years later, when a debris strike was discovered on Flight Day Two of STS-107, Shuttle Program management declined to have the crew inspect the Orbiter for damage, declined to request on-orbit imaging, and ultimately discounted the possibility of a burn-through. In retrospect, the debris strike on STS-27R is a "strong signal" of the threat debris posed that should have been considered by Shuttle management when STS-107 suffered a similar debris strike. The Board views the failure to do so as an illustration of the lack of institutional memory in the Space Shuttle Program that supports the Board's claim, discussed in Chapter 7, that NASA is not functioning as a learning organization.

After the STS-27R damage was evaluated during a post-flight inspection, the Program Requirements Control Board assigned In-Flight Anomalies to the Orbiter and Solid Rocket Booster Projects. Marshall Sprayable Ablator (MSA-1) material found embedded in an insulation blanket on the right Orbital Maneuvering System pod confirmed that the ablator on the right Solid Rocket Booster nose cap was the most likely source of debris.[21] Because an improved ablator material (MSA-2) would now be used on the Solid Rocket Booster nose cap, the issue was considered "closed" by the time of the next mission's Flight Readiness Review. The Orbiter Thermal Protection System review team concurred with the use of the improved ablator without reservation.

An STS-27R investigation team notation mirrors a Columbia Accident Investigation Board finding. The STS-27R investigation noted: "it is observed that program emphasis

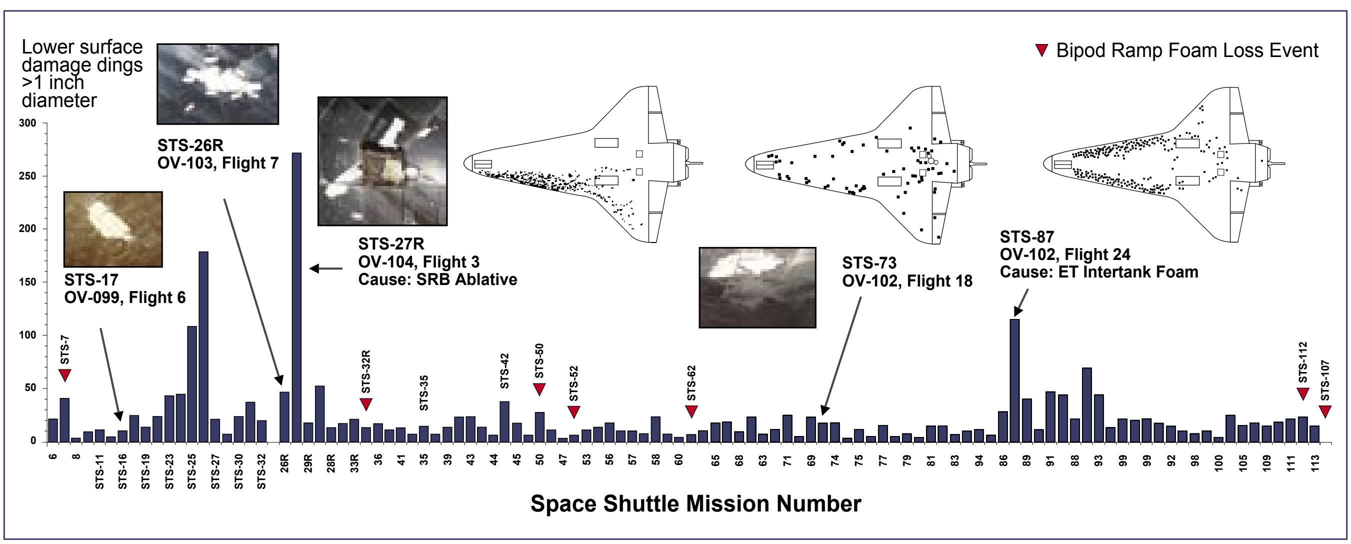


Figure 6.1-6. This chart shows the number of dings greater than one inch in diameter on the lower surface of the Orbiter after each mission from STS-6 through STS-113. Flights where the bipod ramp foam is known to have come off are marked with a red triangle.

MISSION	*DATE*	*COMMENTS*
STS-1	April 12, 1981	Lots of debris damage. 300 tiles replaced.
STS-7	June 18, 1983	First known left bipod ramp foam shedding event.
STS-27R	December 2, 1988	Debris knocks off tile; structural damage and near burn through results.
STS-32R	January 9, 1990	Second known left bipod ramp foam event.
STS-35	December 2, 1990	First time NASA calls foam debris "safety of flight issue," and "re-use or turn-around issue."
STS-42	January 22, 1992	First mission after which the next mission (STS-45) launched without debris In-Flight Anomaly closure/resolution.
STS-45	March 24, 1992	Damage to wing RCC Panel 10-right. Unexplained Anomaly, "most likely orbital debris."
STS-50	June 25, 1992	Third known bipod ramp foam event. Hazard Report 37: an "accepted risk."
STS-52	October 22, 1992	Undetected bipod ramp foam loss (Fourth bipod event).
STS-56	April 8, 1993	Acreage tile damage (large area). Called "within experience base" and considered "in family."
STS-62	October 4, 1994	Undetected bipod ramp foam loss (Fifth bipod event).
STS-87	November 19, 1997	Damage to Orbiter Thermal Protection System spurs NASA to begin 9 flight tests to resolve foam-shedding. Foam fix ineffective. In-Flight Anomaly eventually closed after STS-101 as "accepted risk."
STS-112	October 7, 2002	Sixth known left bipod ramp foam loss. First time major debris event not assigned an In-Flight Anomaly. External Tank Project was assigned an Action. Not closed out until after STS-113 and STS-107.
STS-107	January 16, 2003	*Columbia* launch. Seventh known left bipod ramp foam loss event.

Figure 6.1-7. The Board identified 14 flights that had significant Thermal Protection System damage or major foam loss. Two of the bipod foam loss events had not been detected by NASA prior to the Columbia Accident Investigation Board requesting a review of all launch images.

and *attention to tile damage assessments varies with severity* and that detailed records could be augmented to ease trend maintenance" (emphasis added).[22] In other words, Space Shuttle Program personnel knew that the monitoring of tile damage was inadequate and that clear trends could be more readily identified if monitoring was improved, but no such improvements were made. The Board also noted that an STS-27R investigation team recommendation correlated to the *Columbia* accident 14 years later: "It is recommended that the program actively solicit design improvements directed toward eliminating debris sources or minimizing damage potential."[23]

Another instance of non-bipod foam damage occurred on STS-35. Post-flight inspections of *Columbia* after STS-35 in December 1990, showed a higher-than-average amount of damage on the Orbiter's lower surface. A review of External Tank separation film revealed approximately 10 areas of missing foam on the flange connecting the liquid hydrogen tank to the intertank. An In-Flight Anomaly was assigned to the External Tank Project, which closed it by stating that there was no increase in Orbiter Thermal Protection System damage and that it was "not a safety-of-flight concern."[24] The Board notes that it was in a discussion at the STS-36 Flight Readiness Review that NASA first identified this problem as a turnaround issue.[25] Per established procedures, NASA was still designating foam-loss events as In-Flight Anomalies and continued to make various corrective actions, such as drilling more vent holes and improving the foam application process.

Discovery was launched on STS-42 on January 22, 1992. A total of 159 hits on the Orbiter Thermal Protection System were noted after landing. Two 8- to 12-inch-diameter divots in the External Tank intertank area were noted during post-External Tank separation photo evaluation, and these pieces of foam were identified as the most probable sources of the damage. The External Tank Project was assigned an

In-Flight Anomaly, and the incident was later described as an unexplained or isolated event. However, at later Flight Readiness Reviews, the Marshall Space Flight Center briefed this as being "not a safety-of-flight" concern.[26] The next flight, STS-45, would be the first mission launched before the foam-loss In-Flight Anomaly was closed.

On March 24, 1992, *Atlantis* was launched on STS-45. Post-mission inspection revealed exposed substrate on the upper surface of right wing leading edge Reinforced Carbon-Carbon (RCC) panel 10 caused by two gouges, one 1.9 inches by 1.6 inches and the other 0.4 inches by 1 inch.[27] Before the next flight, an In-Flight Anomaly assigned to the Orbiter Project was closed as "unexplained," but "most likely orbital debris."[28] Despite this closure, the Safety and Mission Assurance Office expressed concern as late as the pre-launch Mission Management Team meeting two days before the launch of STS-49. Nevertheless, the mission was cleared for launch. Later laboratory tests identified pieces of man-made debris lodged in the RCC, including stainless steel, aluminum, and titanium, but no conclusion was made about the source of the debris. (The Board notes that this indicates there were transport mechanisms available to determine the path the debris took to impact the wing leading edge. See Section 3.4.)

The Program Requirements Control Board also assigned the External Tank Project an In-Flight Anomaly after foam loss on STS-56 (*Discovery*) and STS-58 (*Columbia*), both of which were launched in 1993. These missions demonstrate the increasingly casual ways in which debris impacts were dispositioned by Shuttle Program managers. After post-flight analysis determined that on both missions the foam had come from the intertank and bipod jackpad areas, the rationale for closing the In-Flight Anomalies included notations that the External Tank foam debris was "in-family," or within the experience base.[29]

During the launch of STS-87 (*Columbia*) on November 19, 1997, a debris event focused NASA's attention on debris-shedding and damage to the Orbiter. Post-External Tank separation photography revealed a significant loss of material from both thrust panels, which are fastened to the Solid Rocket Booster forward attachment points on the intertank structure. Post-landing inspection of the Orbiter noted 308 hits, with 244 on the lower surface and 109 larger than an inch. The foam loss from the External Tank thrust panels was suspected as the most probable cause of the Orbiter Thermal Protection System damage. Based on data from post-flight inspection reports, as well as comparisons with statistics from 71 similarly configured flights, the total number of damage sites, and the number of damage sites one inch or larger, were considered "out-of-family."[30] An investigation was conducted to determine the cause of the material loss and the actions required to prevent a recurrence.

The foam loss problem on STS-87 was described as "popcorning" because of the numerous popcorn-size foam particles that came off the thrust panels. Popcorning has always occurred, but it began earlier than usual in the launch of STS-87. The cause of the earlier-than-normal popcorning (but not the fundamental cause of popcorning) was traced back to a change in foam-blowing agents that caused pressure buildups and stress concentrations within the foam. In an effort to reduce its use of chlorofluorocarbons (CFCs), NASA had switched from a CFC-11 (chlorofluorocarbon) blowing agent to an HCFC-141b blowing agent beginning with External Tank-85, which was assigned to STS-84. (The change in blowing agent affected only mechanically applied foam. Foam that is hand sprayed, such as on the bipod ramp, is still applied using CFC-11.)

The Program Requirements Control Board issued a Directive and the External Tank Project was assigned an In-Flight Anomaly to address the intertank thrust panel foam loss. Over the course of nine missions, the External Tank Project first reduced the thickness of the foam on the thrust panels to minimize the amount of foam that could be shed; and, due to a misunderstanding of what caused foam loss at that time, put vent holes in the thrust panel foam to relieve trapped gas pressure.

The In-Flight Anomaly remained open during these changes, and foam shedding occurred on the nine missions that tested the corrective actions. Following STS-101, the 10th mission after STS-87, the Program Requirements Control Board concluded that foam-shedding from the thrust panel had been reduced to an "acceptable level" by sanding and venting, and the In-Flight Anomaly was closed.[31] The Orbiter Project, External Tank Project, and Space Shuttle Program management all accepted this rationale without question. The Board notes that these interventions merely reduced foam-shedding to previously experienced levels, which have remained relatively constant over the Shuttle's lifetime.

Making the Orbiter More Resistant To Debris Strikes

If foam shedding could not be prevented entirely, what did NASA do to make the Thermal Protection System more resistant to debris strikes? A 1990 study by Dr. Elisabeth Paté-Cornell and Paul Fishback attempted to quantify the risk of a Thermal Protection System failure using probabilistic analysis.[32] The data they used included (1) the probability that a tile would become debonded by either debris strikes or a poor bond, (2) the probability of then losing adjacent tiles, (3) depending on the final size of the failed area, the probability of burn-through, and (4) the probability of failure of a critical sub-system if burn-through occurs. The study concluded that the probability of losing an Orbiter on any given mission due to a failure of Thermal Protection System tiles was approximately one in 1,000. Debris-related problems accounted for approximately 40 percent of the probability, while 60 percent was attributable to tile debonding caused by other factors. An estimated 85 percent of the risk could be attributed to 15 percent of the "acreage," or larger areas of tile, meaning that the loss of any one of a relatively small number of tiles pose a relatively large amount of risk to the Orbiter. In other words, not all tiles are equal – losing certain tiles is more dangerous. While the actual risk may be different than that computed in the 1990 study due to the limited amount of data and the underlying simplified assumptions, this type of analysis offers insight that enables management to concentrate their resources on protecting the Orbiters' critical areas.

Two years after the conclusion of that study, NASA wrote to Paté-Cornell and Fishback describing the importance of their work, and stated that it was developing a long-term effort to use probabilistic risk assessment and related disciplines to improve programmatic decisions.[33] Though NASA has taken some measures to invest in probabilistic risk assessment as a tool, it is the Board's view that NASA has not fully exploited the insights that Paté-Cornell's and Fishback's work offered.[34]

Impact Resistant Tile

NASA also evaluated the possibility of increasing Thermal Protection System tile resistance to debris hits, lowering the possibility of tile debonding, and reducing tile production and maintenance costs.[35] Indeed, tiles with a "tough" coating are currently used on the Orbiters. This coating, known as Toughened Uni-piece Fibrous Insulation (TUFI), was patented in 1992 and developed for use on high-temperature rigid insulation.[36] TUFI is used on a tile material known as Alumina Enhanced Thermal Barrier (AETB), and has a debris impact resistance that is greater than the current acreage tile's resistance by a factor of approximately 6-20.[37] At least 772 of these advanced tiles have been installed on the Orbiters' base heat shields and upper body flaps.[38] However, due to its higher thermal conductivity, TUFI-coated AETB cannot be used as a replacement for the larger areas of tile coverage. (Boeing, Lockheed Martin and NASA are developing a lightweight, impact-resistant, low-conductivity tile.[39]) Because the impact requirements for these next-generation tiles do not appear to be based on resistance to specific (and probable) damage sources, it is the Board's view that certification of the new tile will not adequately address the threat posed by debris.

Conclusion

Despite original design requirements that the External Tank not shed debris, and the corresponding design requirement that the Orbiter not receive debris hits exceeding a trivial amount of force, debris has impacted the Shuttle on each flight. Over the course of 113 missions, foam-shedding and other debris impacts came to be regarded more as a turnaround or maintenance issue, and less as a hazard to the vehicle and crew.

Assessments of foam-shedding and strikes were not thoroughly substantiated by engineering analysis, and the process for closing In-Flight Anomalies is not well-documented and appears to vary. Shuttle Program managers appear to have confused the notion of foam posing an "accepted risk" with foam not being a "safety-of-flight issue." At times, the pressure to meet the flight schedule appeared to cut short engineering efforts to resolve the foam-shedding problem.

NASA's lack of understanding of foam properties and behavior must also be questioned. Although tests were conducted to develop and qualify foam for use on the External Tank, it appears there were large gaps in NASA's knowledge about this complex and variable material. Recent testing conducted at Marshall Space Flight Center and under the auspices of the Board indicate that mechanisms previously considered a prime source of foam loss, cryopumping and cryoingestion, are not feasible in the conditions experienced during tanking, launch, and ascent. Also, dissections of foam bipod ramps on External Tanks yet to be launched reveal subsurface flaws and defects that only now are being discovered and identified as contributing to the loss of foam from the bipod ramps.

While NASA properly designated key debris events as In-Flight Anomalies in the past, more recent events indicate that NASA engineers and management did not appreciate the scope, or lack of scope, of the Hazard Reports involving foam shedding.[40] Ultimately, NASA's hazard analyses, which were based on reducing or eliminating foam-shedding, were not succeeding. Shuttle Program management made no adjustments to the analyses to recognize this fact. The acceptance of events that are not supposed to happen has been described by sociologist Diane Vaughan as the "normalization of deviance."[41] The history of foam-problem decisions shows how NASA first began and then continued flying with foam losses, so that flying with these deviations from design specifications was viewed as normal and acceptable. Dr. Richard Feynman, a member of the Presidential Commission on the Space Shuttle Challenger Accident, discusses this phenomena in the context of the *Challenger* accident. The parallels are striking:

> *The phenomenon of accepting … flight seals that had shown erosion and blow-by in previous flights is very clear. The Challenger flight is an excellent example. There are several references to flights that had gone before. The acceptance and success of these flights is taken as evidence of safety. But erosions and blow-by are not what the design expected. They are warnings that something is wrong … The O-rings of the Solid Rocket Boosters were not designed to erode. Erosion was a clue that something was wrong. Erosion was not something from which safety can be inferred … If a reasonable launch schedule is to be maintained, engineering often cannot be done fast enough to keep up with the expectations of originally conservative certification criteria designed to guarantee a very safe vehicle. In these situations, subtly, and often with apparently logical arguments, the criteria are altered so that flights may still be certified in time. They therefore fly in a relatively unsafe condition, with a chance of failure of the order of a percent (it is difficult to be more accurate).*[42]

Findings

F6.1–1 NASA has not followed its own rules and requirements on foam-shedding. Although the agency continuously worked on the foam-shedding problem, the debris impact requirements have not been met on any mission.

F6.1–2 Foam-shedding, which had initially raised serious safety concerns, evolved into "in-family" or "no safety-of-flight" events or were deemed an "accepted risk."

F6.1–3 Five of the seven bipod ramp events occurred on missions flown by *Columbia*, a seemingly high number. This observation is likely due to

Columbia having been equipped with umbilical cameras earlier than other Orbiters.

F6.1–4 There is lack of effective processes for feedback or integration among project elements in the resolution of In-Flight Anomalies.

F6.1–5 Foam bipod debris-shedding incidents on STS-52 and STS-62 were undetected at the time they occurred, and were not discovered until the Board directed NASA to examine External Tank separation images more closely.

F6.1–6 Foam bipod debris-shedding events were classified as In-Flight Anomalies up until STS-112, which was the first known bipod foam-shedding event not classified as an In-Flight Anomaly.

F6.1–7 The STS-112 assignment for the External Tank Project to "identify the cause and corrective action of the bipod ramp foam loss event" was not due until after the planned launch of STS-113, and then slipped to after the launch of STS-107.

F6.1–8 No External Tank configuration changes were made after the bipod foam loss on STS-112.

F6.1–9 Although it is sometimes possible to obtain imagery of night launches because of light provided by the Solid Rocket Motor plume, no imagery was obtained for STS-113.

F6.1–10 NASA failed to adequately perform trend analysis on foam losses. This greatly hampered the agency's ability to make informed decisions about foam losses.

F6.1–11 Despite the constant shedding of foam, the Shuttle Program did little to harden the Orbiter against foam impacts through upgrades to the Thermal Protection System. Without impact resistance and strength requirements that are calibrated to the energy of debris likely to impact the Orbiter, certification of new Thermal Protection System tile will not adequately address the threat posed by debris.

Recommendations:

- None

6.2 Schedule Pressure

Countdown to Space Station "Core Complete:" A Workforce Under Pressure

During the course of this investigation, the Board received several unsolicited comments from NASA personnel regarding pressure to meet a schedule. These comments all concerned a date, more than a year after the launch of *Columbia*, that seemed etched in stone: February 19, 2004, the scheduled launch date of STS-120. This flight was a milestone in the minds of NASA management since it would carry a section of the International Space Station called "Node 2." This would configure the International Space Station to its "U.S. Core Complete" status.

At first glance, the Core Complete configuration date seemed noteworthy but unrelated to the *Columbia* accident. However, as the investigation continued, it became apparent that the complexity and political mandates surrounding the International Space Station Program, as well as Shuttle Program management's responses to them, resulted in pressure to meet an increasingly ambitious launch schedule.

In mid-2001, NASA adopted plans to make the over-budget and behind-schedule International Space Station credible to the White House and Congress. The Space Station Program and NASA were on probation, and had to prove they could meet schedules and budgets. The plan to regain credibility focused on the February 19, 2004, date for the launch of Node 2 and the resultant Core Complete status. If this goal was not met, NASA would risk losing support from the White House and Congress for subsequent Space Station growth.

By the late summer of 2002, a variety of problems caused Space Station assembly work and Shuttle flights to slip beyond their target dates. With the Node 2 launch endpoint fixed, these delays caused the schedule to become ever more compressed.

Meeting U.S. Core Complete by February 19, 2004, would require preparing and launching 10 flights in less than 16 months. With the focus on retaining support for the Space Station program, little attention was paid to the effects the aggressive Node 2 launch date would have on the Shuttle Program. After years of downsizing and budget cuts (Chapter 5), this mandate and events in the months leading up to STS-107 introduced elements of risk to the Program. *Columbia* and the STS-107 crew, who had seen numerous launch slips due to missions that were deemed higher priorities, were further affected by the mandatory Core Complete date. The high-pressure environments created by NASA Headquarters unquestionably affected *Columbia*, even though it was not flying to the International Space Station.

February 19, 2004 – "A Line in the Sand"

Schedules are essential tools that help large organizations effectively manage their resources. Aggressive schedules by themselves are often a sign of a healthy institution. However, other institutional goals, such as safety, sometimes compete with schedules, so the effects of schedule pressure in an organization must be carefully monitored. The Board posed the question: Was there undue pressure to nail the Node 2 launch date to the February 19, 2004, signpost? The management and workforce of the Shuttle and Space Station programs each answered the question differently. Various members of NASA upper management gave a definite "no." In contrast, the workforce within both programs thought there was considerable management focus on Node 2 and resulting pressure to hold firm to that launch date, and individuals were becoming concerned that safety might be compromised. The weight of evidence supports the workforce view.

Employees attributed the Node 2 launch date to the new Administrator, Sean O'Keefe, who was appointed to execute a Space Station management plan he had proposed as Deputy Director of the White House Office of Management and Budget. They understood the scrutiny that NASA, the new Administrator, and the Space Station Program were under, but now it seemed to some that budget and schedule were of paramount concern. As one employee reflected:

> *I guess my frustration was … I know the importance of showing that you … manage your budget and that's an important impression to make to Congress so you can continue the future of the agency, but to a lot of people, February 19th just seemed like an arbitrary date … It doesn't make sense to me why at all costs we were marching to this date.*

The importance of this date was stressed from the very top. The Space Shuttle and Space Station Program Managers briefed the new NASA Administrator monthly on the status of their programs, and a significant part of those briefings was the days of margin remaining in the schedule to the launch of Node 2 – still well over a year away. The Node 2 schedule margin typically accounted for more than half of the briefing slides.

Figure 6.2-1 is one of the charts presented by the Shuttle Program Manager to the NASA Administrator in December 2002. The chart shows how the days of margin in the existing schedule were being managed to meet the requirement of a Node 2 launch on the prescribed date. The triangles are events that affected the schedule (such as the slip of a Russian Soyuz flight). The squares indicate action taken by management to regain the lost time (such as authorizing work over the 2002 winter holidays).

Figure 6.2-2 shows a slide from the International Space Station Program Manager's portion of the briefing. It indicates that International Space Station Program management was also taking actions to regain margin. Over the months, the extent of some testing at Kennedy was reduced, the number of tasks done in parallel was increased, and a third shift of workers would be added in 2003 to accomplish the processing. These charts illustrate that both the Space Shuttle and Space Station Programs were being managed to a particular launch date – February 19, 2004. Days of margin in that schedule were one of the principle metrics by which both programs came to be judged.

NASA Headquarters stressed the importance of this date in other ways. A screen saver (see Figure 6.2-3) was mailed to managers in NASA's human spaceflight program that depicted a clock counting down to February 19, 2004 – U.S. Core Complete.

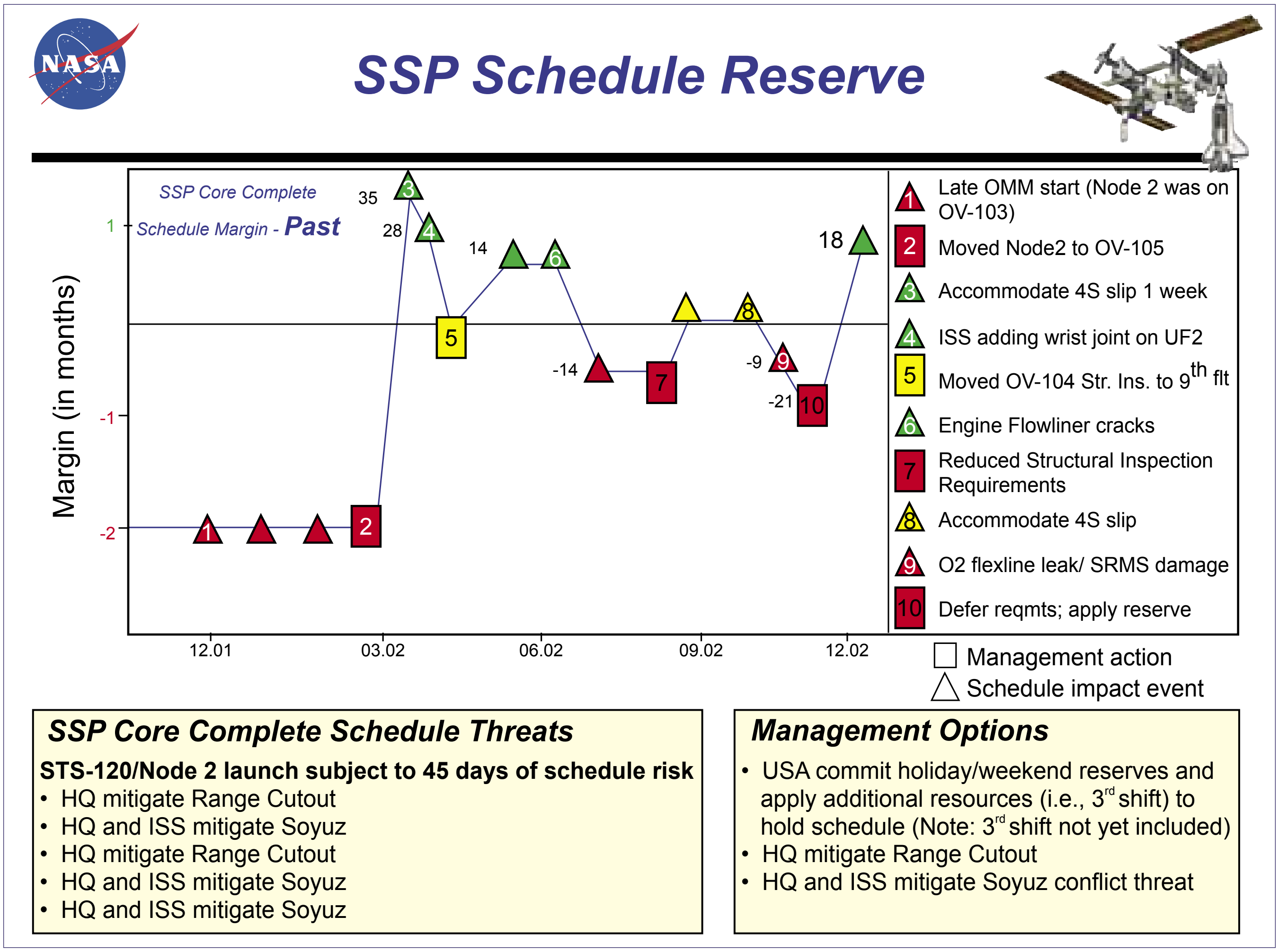


Figure 6.2-1. This chart was presented by the Space Shuttle Program Manager to the NASA Administrator in December 2002. It illustrates how the schedule was being managed to meet the Node 2 launch date of February 19, 2004.

While employees found this amusing because they saw it as a date that could not be met, it also reinforced the message that NASA Headquarters was focused on and promoting the achievement of that date. This schedule was on the minds of the Shuttle managers in the months leading up to STS-107.

The Background: Schedule Complexity and Compression

In 2001, the International Space Station Cost and Management Evaluation Task Force report recommended, as a cost-saving measure, a limit of four Shuttle flights to the International Space Station per year. To meet this requirement, managers began adjusting the Shuttle and Station manifests to "get back in the budget box." They rearranged Station assembly sequences, moving some elements forward and taking others out. When all was said and done, the launch of STS-120, which would carry Node 2 to the International Space Station, fell on February 19, 2004.

The Core Complete date simply emerged from this planning effort in 2001. By all accounts, it was a realistic and achievable date when first approved. At the time there was more concern that four Shuttle flights a year would limit the capability to carry supplies to and from the Space Station, to rotate its crew, and to transport remaining Space Station segments and equipment. Still, managers felt it was a rea-

Figure 6.2-3. NASA Headquarters distributed to NASA employees this computer screensaver counting down to February 19, 2004.

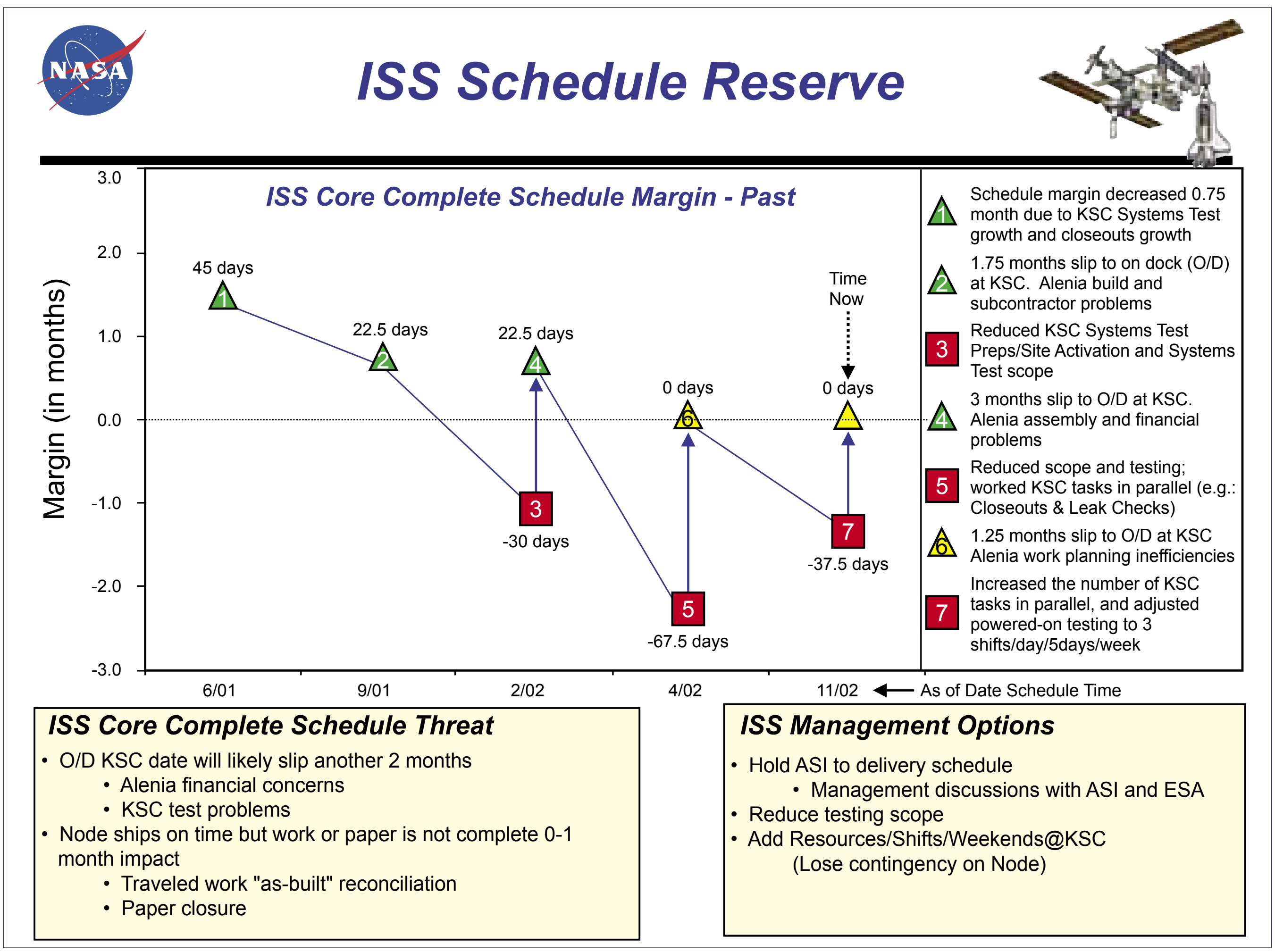


Figure 6.2-2. At the same December 2002 meeting, the International Space Station Program Manager presented this slide, showing the actions being taken to regain margin in the schedule. Note that the yellow triangles reflect zero days remaining margin.

sonable goal and assumed that if circumstances warranted a slip of that date, it would be granted.

Shuttle and Station managers worked diligently to meet the schedule. Events gradually ate away at the schedule margin. Unlike the "old days" before the Station, the Station/Shuttle partnership created problems that had a ripple effect on both programs' manifests. As one employee described it, "the serial nature" of having to fly Space Station assembly missions in a specific order made staying on schedule more challenging. Before the Space Station, if a Shuttle flight had to slip, it would; other missions that had originally followed it would be launched in the meantime. Missions could be flown in any sequence. Now the manifests were a delicate balancing act. Missions had to be flown in a certain order and were constrained by the availability of the launch site, the Russian Soyuz and Progress schedules, and a myriad of other processes. As a result, employees stated they were now experiencing a new kind of pressure. Any necessary change they made on one mission was now impacting future launch dates. They had a sense of being "under the gun."

Shuttle and Station program personnel ended up with manifests that one employee described as "changing, changing, changing" all the time. One of the biggest issues they faced entering 2002 was "up mass," the amount of cargo the Shuttle can carry to the Station. Up mass was not a new problem, but when the Shuttle flight rate was reduced to four per year, up mass became critical. Working groups were actively evaluating options in the summer of 2002 and bartering to get each flight to function as expected.

Sometimes the up mass being traded was actual Space Station crew members. A crew rotation planned for STS-118 was moved to a later flight because STS-118 was needed for other cargo. This resulted in an increase of crew duration on the Space Station, which was creeping past the 180-day limit agreed to by the astronaut office, flight surgeons, and Space Station international partners. A space station worker described how this one change created many other problems, and added: *"… we had a train wreck coming …"* Future on-orbit crew time was being projected at 205 days or longer to maintain the assembly sequence and meet the schedule.

By July 2002, the Shuttle and Space Station Programs were facing a schedule with very little margin. Two setbacks occurred when technical problems were found during routine maintenance on *Discovery*. STS-107 was four weeks away from launch at the time, but the problems grounded the entire Shuttle fleet. The longer the fleet was grounded, the more schedule margin was lost, which further compounded the complexity of the intertwined Shuttle and Station schedules. As one worker described the situation:

> *… a one-week hit on a particular launch can start a steam roll effect including all [the] constraints and by the time you get out of here, that one-week slip has turned into a couple of months.*

In August 2002, the Shuttle Program realized it would be unable to meet the Space Station schedule with the available Shuttles. *Columbia* had never been outfitted to make a Space Station flight, so the other three Orbiters flew the Station missions. But *Discovery* was in its Orbiter Maintenance Down Period, and would not be available for another 17 months. All Space Station flights until then would have to be made by *Atlantis* and *Endeavour*. As managers looked ahead to 2003, they saw that after STS-107, these two Orbiters would have to alternate flying five consecutive missions, STS-114 through STS-118. To alleviate this pressure, and regain schedule margin, Shuttle Program managers elected to modify *Columbia* to enable it to fly Space Station missions. Those modifications were to take place immediately after STS-107 so that *Columbia* would be ready to fly its first Space Station mission eight months later. This decision put *Columbia* directly in the path of Core Complete.

As the autumn of 2002 began, both the Space Shuttle and Space Station Programs began to use what some employees termed "tricks" to regain schedule margin. Employees expressed concern that their ability to gain schedule margin using existing measures was waning.

In September 2002, it was clear to Space Shuttle and Space Station Program managers that they were not going to meet the schedule as it was laid out. The two Programs proposed a new set of launch dates, documented in an e-mail (right) that included moving STS-120, the Node 2 flight, to mid-March 2004. (Note that the first paragraph ends with *"… the 10A* [U.S. Core Complete, Node 2] *launch remains 2/19/04."*)

These launch date changes made it possible to meet the early part of the schedule, but compressed the late 2003/early 2004 schedule even further. This did not make sense to many in the program. One described the system as at *"an uncomfortable point,"* noted having to go to great lengths to reduce vehicle-processing time at Kennedy, and added:

> *… I don't know what Congress communicated to O'Keefe. I don't really understand the criticality of February 19th, that if we didn't make that date, did that mean the end of NASA? I don't know … I would like to think that the technical issues and safely resolving the technical issues can take priority over any budget issue or scheduling issue.*

When the Shuttle fleet was cleared to return to flight, attention turned to STS-112, STS-113, and STS-107, set for October, November, and January. Workers were uncomfortable with the rapid sequence of flights.

> *The thing that was beginning to concern me … is I wasn't convinced that people were being given enough time to work the problems correctly.*

The problems that had grounded the fleet had been handled well, but the program nevertheless lost the rest of its margin. As the pressure to keep to the Node 2 schedule continued, some were concerned that this might influence the future handling of problems. One worker expressed the concern:

> *… and I have to think that subconsciously that even though you don't want it to affect decision-making, it probably does.*

-----Original Message-----
From: THOMAS, DAWN A. (JSC-OC) (NASA)
Sent: Friday, September 20, 2002 7:10 PM
To: 'Flowers, David'; 'Horvath, Greg'; 'O'Fallon, Lee'; 'Van Scyoc, Neal'; 'Gouti, Tom'; 'Hagen, Ray'; 'Kennedy, John'; 'Thornburg, Richard'; 'Gari, Judy'; 'Dodds, Joel'; 'Janes, Lou Ann'; 'Breen, Brian'; 'Deheck-Stokes, Kristina'; 'Narita, Kaneaki (NASDA)'; 'Patrick, Penny O'; 'Michael Rasmussen (E-mail)'; DL FPWG; 'Hughes, Michael G'; 'Bennett, Patty'; 'Masazumi, Miyake'; 'Mayumi Matsuura'; NORIEGA, CARLOS I. (JSC-CB) (NASA); BARCLAY, DINA E. (JSC-DX) (NASA); MEARS, AARON (JSC-XA) (HS); BROWN, WILLIAM C. (JSC-DT) (NASA); DUMESNIL, DEANNA T. (JSC-OC) (USA); MOORE, NATHAN (JSC-REMOTE); MONTALBANO, JOEL R. (JSC-DA8) (NASA); MOORE, PATRICIA (PATTI) (JSC-DA8) (NASA); SANCHEZ, HUMBERTO (JSC-DA8) (NASA)
Subject: FPWG status - 9/20/02 OA/MA mgrs mtg results

The ISS and SSP Program Managers have agreed to proceed with the crew rotation change and the following date changes: 12A launch to 5/23/03, 12A.1 launch to 7/24/03, 13A launch to 10/2/03, and 13A.1 launch to NET 11/13/03. Please note that 10A launch remains 2/19/04.

The ISS SSCN that requests evaluation of these changes will be released Monday morning after the NASA/Russian bilateral Requirements and Increment Planning videocon. It will contain the following:

- Increments 8 and 9 redefinition - this includes baseline of ULF2 into the tactical timeframe as the new return flight for Expedition 9
- Crew size changes for 7S, 13A.1, 15A, and 10A
- Shuttle date changes as listed above
- Russian date changes for CY2003 that were removed from SSCN 6872 (11P launch/10P undock and subsequent)
- CY2004 Russian data if available Monday morning
- Duration changes for 12A and 15A
- Docking altitude update for 10A, along with "NET" TBR closure.

The evaluation due date is 10/2/02. Board/meeting dates are as follows: MIOCB status - 10/3/02; comment dispositioning - 10/3/02 FPWG (meeting date/time under review); OA/MA Program Managers status - 10/4/02; SSPCB and JPRCB - 10/8/02; MMIOCB status (under review) and SSCB - 10/10/02.

The 13A.1 date is indicated as "NET" (No Earlier Than) since SSP ability to meet that launch date is under review due to the processing flow requirements.

There is no longer a backup option to move ULF2 to OV-105: due to vehicle processing requirements, there is no launch opportunity on OV-105 past May 2004 until after OMM.

The Program Managers have asked for preparation of a backup plan in case of a schedule slip of ULF2. In order to accomplish this, the projected ISS upmass capability shortfall will be calculated as if ULF2 launch were 10/7/04, and a recommendation made for addressing the resulting shortfall and increment durations. Some methods to be assessed: manifest restructuring, fallback moves of rotation flight launch dates, LON (Launch on Need) flight on 4/29/04.

[ISS=International Space Station, SSP=Space Shuttle Program, NET=no earlier than, SSCN=Space Station Change Notice, CY=Calendar Year, TBR=To Be Revised (or Reviewed), MIOCB=Mission Integration and Operations Control Board, FPWG=Flight Planning Working Group, OA/MA=Space Station Office Symbol/Shuttle Program Office Symbol, SSPCB=Space Station Program Control Board, JPRCB=Space Shuttle/Space Station Joint Program Requirements Control Board, MMIOCB=Multi-Lateral Mission Integration and Operations Control Board, SSCB=Space Station Control Board, ULF2=U.S. Logistics Flight 2, OMM=Orbiter Major Modification, OV-105=Endeavour]

This was the environment for October and November of 2002. During this time, a bipod foam event occurred on STS-112. For the first time in the history of the Shuttle Program, the Program Requirements Control Board chose to classify that bipod foam loss as an "action" rather than a more serious In-Flight Anomaly. At the STS-113 Flight Readiness Review, managers accepted with little question the rationale that it was safe to fly with the known foam problem.

The Operations Tempo Following STS-107

After STS-107, the tempo was only going to increase. The vehicle processing schedules, training schedules, and mission control flight staffing assignments were all overburdened.

The vehicle-processing schedule for flights from February 2003, through February 2004, was optimistic. The schedule could not be met with only two shifts of workers per day. In late 2002, NASA Headquarters approved plans to hire a third shift. There were four Shuttle launches to the Space Station scheduled in the five months from October 2003, through the launch of Node 2 in February 2004. To put this in perspective, the launch rate in 1985, for which NASA was criticized by the Rogers Commission, was nine flights in 12 months – and that was accomplished with four Orbiters and a manifest that was not complicated by Space Station assembly.

Endeavour was the Orbiter on the critical path. Figure 6.2-4 shows the schedule margin for STS-115, STS-117, and STS-120 (Node 2). To preserve the margin going into 2003, the vehicle processing team would be required to work the late 2002-early 2003 winter holidays. The third shift of workers at Kennedy would be available in March 2003, and would buy eight more days of margin for STS-117 and STS-120. The workforce would likely have to work on the 2003 winter holidays to meet the Node 2 date.

Figure 6.2-5 shows the margin for each vehicle (*Discovery,* OV-103, was in extended maintenance). The large boxes indicate the "margin to critical path" (to Node 2 launch date). The three smaller boxes underneath indicate (from left to right) vehicle processing margin, holiday margin, and Dryden margin. The vehicle processing margin indicates how many days there are in addition to the days required for that mission's vehicle processing. *Endeavour* (OV-105) had zero days of margin for the processing flows for STS-115, STS-117, and STS-120. The holiday margin is the number of days that could be gained by working holidays. The Dryden margin is the six days that are always reserved to accommodate an Orbiter landing at Edwards Air Force Base in California and having to be ferried to Kennedy. If the Orbiter landed at Kennedy, those six days would automatically be regained. Note that the Dryden margin had already been surrendered in the STS-114 and STS-115 schedules. If bad weather at Kennedy forced those two flights to land at Edwards, the schedule would be directly affected.

The clear message in these charts is that any technical problem that resulted in a slip to one launch would now directly affect the Node 2 launch.

The lack of housing for the Orbiters was becoming a factor as well. Prior to launch, an Orbiter can be placed in an Orbiter Processing Facility, the Vehicle Assembly Building, or on one of the two Shuttle launch pads. Maintenance and

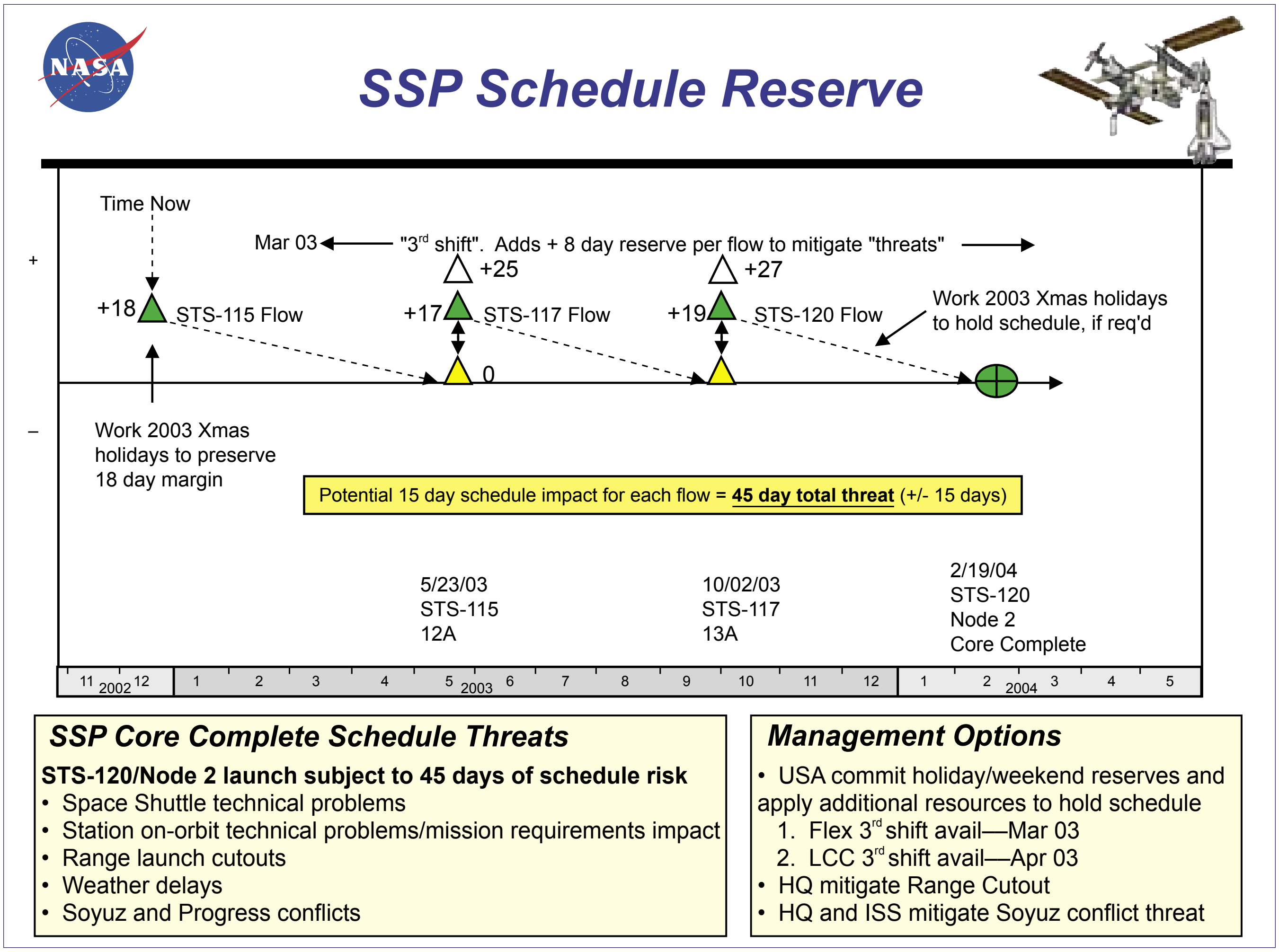


Figure 6.2-4. By late 2002, the vehicle processing team at the Kennedy Space Center would be required to work through the winter holidays, and a third shift was being hired in order to meet the February 19, 2004, schedule for U.S. Core Complete.

refurbishment is performed in the three Orbiter Processing Facilities at Kennedy. One was occupied by *Discovery* during its scheduled extended maintenance. This left two to serve the other three Orbiters over the next several months. The 2003 schedule indicated plans to move *Columbia* (after its return from STS-107) from an Orbiter Processing Facility to the Vehicle Assembly Building and back several times in order to make room for *Atlantis* (OV-104) and *Endeavour* (OV-105) and prepare them for missions. Moving an Orbiter is tedious, time-consuming, carefully orchestrated work. Each move introduces an opportunity for problems. Those 2003 moves were often slated to occur without a day of margin between them – another indication of the additional risks that managers were willing to incur to meet the schedule.

The effect of the compressed schedule was also evident in the Mission Operations Directorate. The plans for flight controller staffing of Mission Control showed that of the seven flight controllers who lacked current certifications during STS-107 (see Chapter 4), five were scheduled to work the next mission, and three were scheduled to work the next three missions (STS-114, -115, and -116). These controllers would have been constantly either supporting missions or supporting mission training, and were unlikely to have the time to complete the recertification requirements. With the pressure of the schedule, the things perceived to be less important, like recertification (which was not done before STS-107), would likely continue to be deferred. As a result of the schedule pressure, managers either were willing to delay recertification or were too busy to notice that deadlines for recertification had passed.

Columbia: Caught in the Middle

STS-112 flew in October 2002. At 33 seconds into the flight, a piece of the bipod foam from the External Tank struck one of the Solid Rocket Boosters. As described in Section 6.1, the STS-112 foam strike was discussed at the Program Requirements Control Board following the flight. Although the initial recommendation was to treat the foam loss as an In-Flight Anomaly, the Shuttle Program instead assigned it as an action, with a due date after the next launch. (This was the first instance of bipod foam loss that was not designated an In-Flight Anomaly.) The action was noted at the STS-113 Flight Readiness Review. Those Flight Readiness Review charts (see Section 6.1) provided a flawed flight rationale by concluding that the foam loss was "not a safety-of-flight" issue.

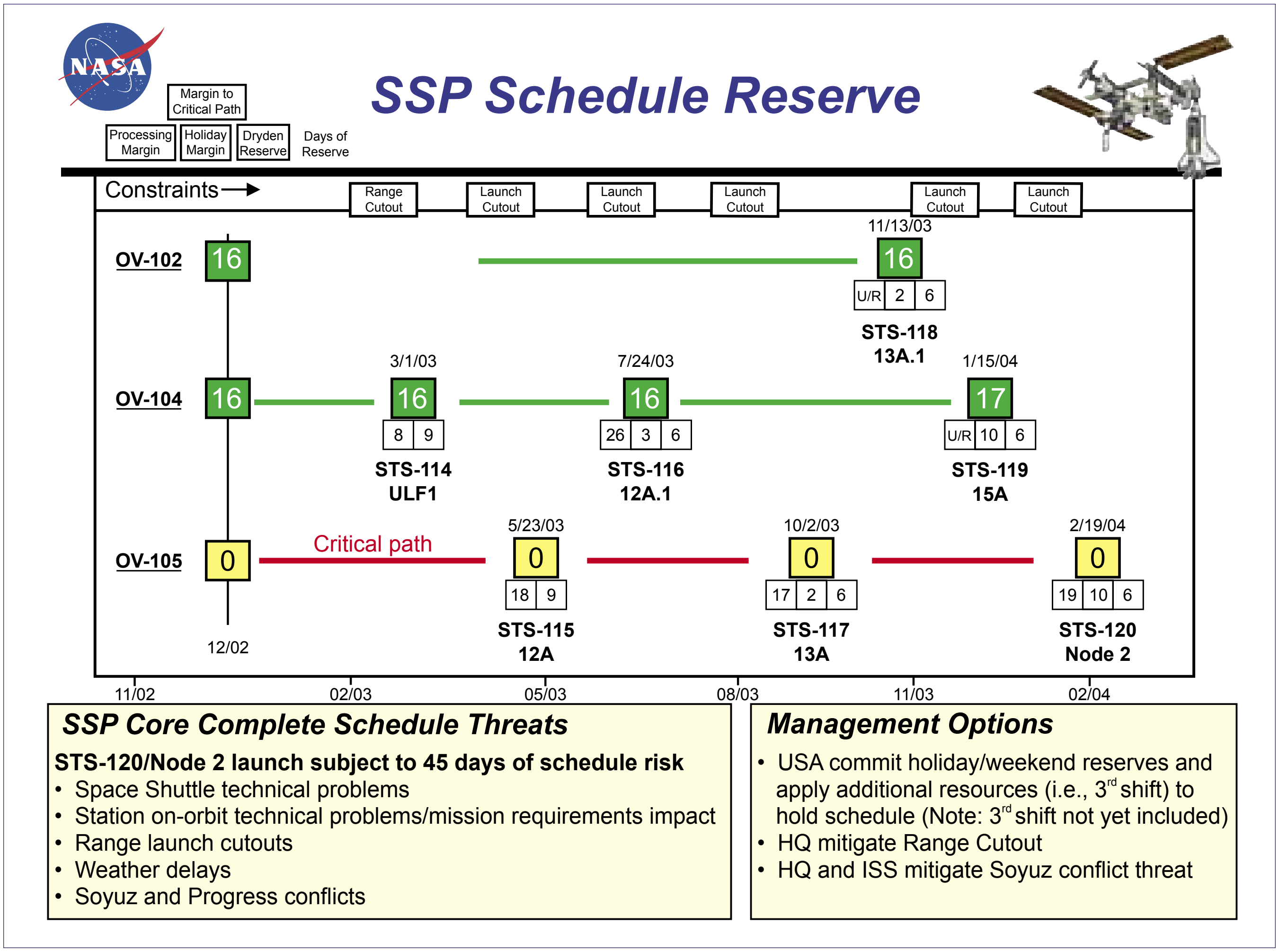


Figure 6.2-5. This slide shows the margin for each Orbiter. The large boxes show the number of days margin to the Node 2 launch date, while the three smaller boxes indicate vehicle processing margin, holiday margin, and the margin if a Dryden landing was not required.

Interestingly, during *Columbia's* mission, the Chair of the Mission Management Team, Linda Ham, would characterize that reasoning as "lousy" – though neither she nor Shuttle Program Manager Ron Dittemore, who were both present at the meeting, questioned it at the time. The pressing need to launch STS-113 to retrieve the International Space Station Expedition 5 crew before they surpassed the 180-day limit and to continue the countdown to Node 2 were surely in the back of managers' minds during these reviews.

By December 2002, every bit of padding in the schedule had disappeared. Another chart from the Shuttle and Station Program Managers' briefing to the NASA Administrator summarizes the schedule dilemma (see Figure 6.2-6).

Even with work scheduled on holidays, a third shift of workers being hired and trained, future crew rotations drifting beyond 180 days, and some tests previously deemed "requirements" being skipped or deferred, Program managers estimated that Node 2 launch would be one to two months late. They were slowly accepting additional risk in trying to meet a schedule that probably could not be met.

Interviews with workers provided insight into how this situation occurred. They noted that people who work at NASA have the legendary can-do attitude, which contributes to the agency's successes. But it can also cause problems. When workers are asked to find days of margin, they work furiously to do so and are praised for each extra day they find. But those same people (and this same culture) have difficulty admitting that something "can't" or "shouldn't" be done, that the margin has been cut too much, or that resources are being stretched too thin. No one at NASA wants to be the one to stand up and say, "We can't make that date."

STS-107 was launched on January 16, 2003. Bipod foam separated from the External Tank and struck *Columbia*'s left wing 81.9 seconds after liftoff. As the mission proceeded over the next 16 days, critical decisions about that event would be made.

The STS-107 Mission Management Team Chair, Linda Ham, had been present at the Program Requirements Control Board discussing the STS-112 foam loss and the STS-113 Flight Readiness Review. So had many of the other Shuttle Program managers who had roles in STS-107. Ham was also the Launch Integration Manager for the next mission, STS-114. In that capacity, she would chair many of the meetings leading up to the launch of that flight, and many of those individuals would have to confront *Columbia's* foam strike and its possible impact on the launch of STS-114. Would the *Columbia* foam strike be classified as an In-Flight Anomaly? Would the fact that foam had detached from the bipod ramp on two out of the last three flights have made this problem a constraint to flight that would need to be solved before the next launch? Could the Program develop a solid rationale to fly STS-114, or would additional analysis be required to clear the flight for launch?

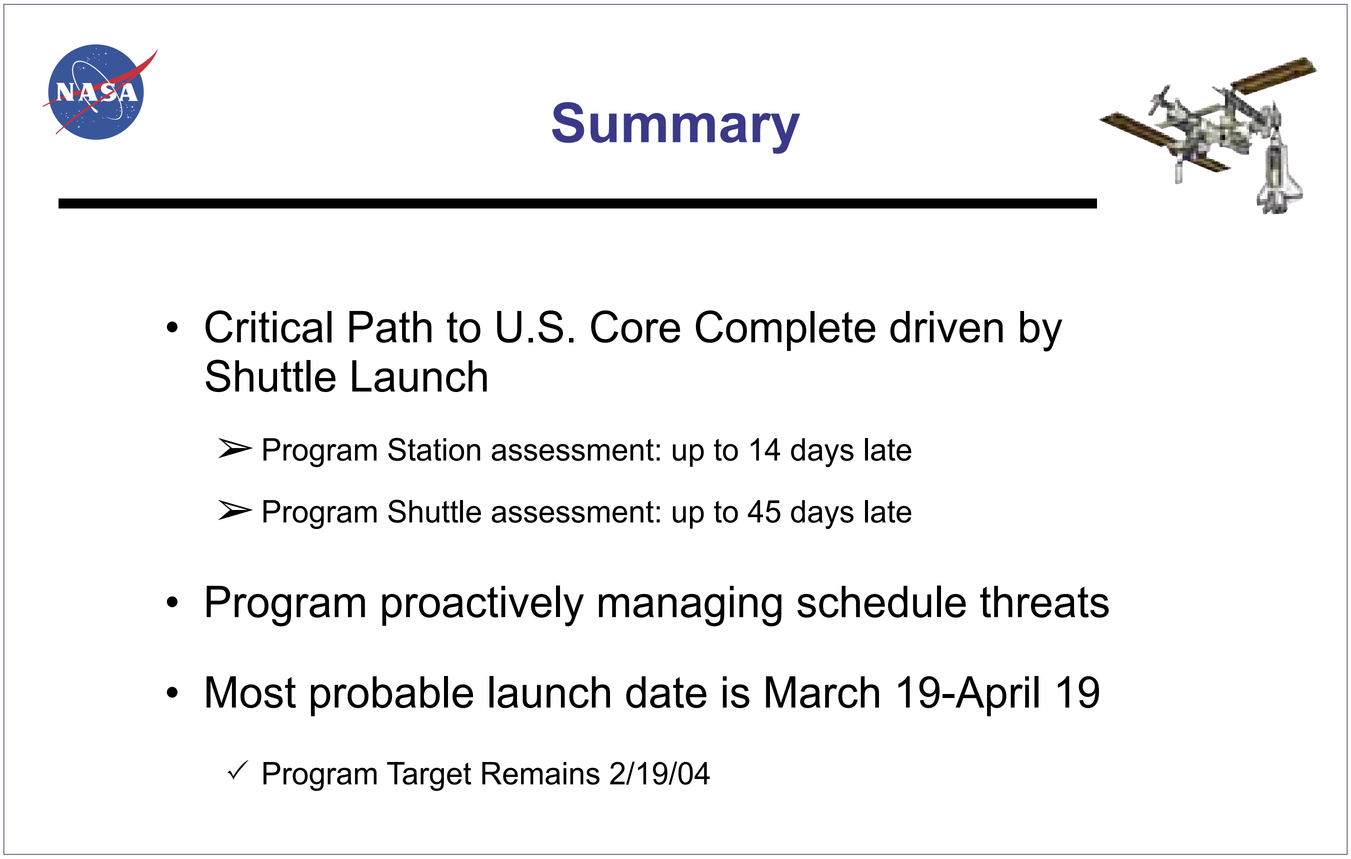


Figure 6.2-6. By December 2002, every bit of padding in the schedule had disappeared. Another chart from the Shuttle and Station Program Managers' briefing to the NASA Administrator summarizes the schedule dilemma.

-----Original Message-----
From: HAM, LINDA J. (JSC-MA2) (NASA)
Sent: Wednesday, January 22, 2003 10:16 AM
To: DITTEMORE, RONALD D. (JSC-MA) (NASA)
Subject: RE: ET Briefing - STS-112 Foam Loss

Yes, I remember....It was not good. I told Jerry to address it at the ORR next Tuesday (even though he won't have any more data and it really doesn't impact Orbiter roll to the VAB). I just want him to be thinking hard about this now, not wait until IFA review to get a formal action.

[ORR=Orbiter Rollout Review, VAB=Vehicle Assembly Building, IFA=In-Flight Anomaly]

In fact, most of Linda Ham's inquiries about the foam strike were not to determine what action to take during *Columbia's* mission, but to understand the implications for STS-114. During a Mission Management Team meeting on January 21, she asked about the rationale put forward at the STS-113 Flight Readiness Review, which she had attended. Later that morning she reviewed the charts presented at that Flight Readiness Review. Her assessment, which she e-mailed to Shuttle Program Manager Ron Dittemore on January 21, was *"Rationale was lousy then and still is …"* (See Section 6.3 for the e-mail.)

One of Ham's STS-114 duties was to chair a review to determine if the mission's Orbiter, *Atlantis*, should be rolled from the Orbiter Processing Facility to the Vehicle Assembly Building, per its pre-launch schedule. In the above e-mail to Ron Dittemore, Ham indicates a desire to have the same individual responsible for the "lousy" STS-113 flight rationale start working the foam shedding issue – and presumably present a new flight rationale – very soon.

As STS-107 prepared for re-entry, Shuttle Program managers prepared for STS-114 flight rationale by arranging to have post-flight photographs taken of *Columbia's* left wing rushed to Johnson Space Center for analysis.

As will become clear in the next section, most of the Shuttle Program's concern about *Columbia*'s foam strike were not about the threat it might pose to the vehicle in orbit, but about the threat it might pose to the schedule.

Conclusion

The agency's commitment to hold firm to a February 19, 2004, launch date for Node 2 influenced many of decisions in the months leading up to the launch of STS-107, and may well have subtly influenced the way managers handled the STS-112 foam strike and *Columbia*'s as well.

When a program agrees to spend less money or accelerate a schedule beyond what the engineers and program managers think is reasonable, a small amount of overall risk is added. These little pieces of risk add up until managers are no longer aware of the total program risk, and are, in fact, gambling. Little by little, NASA was accepting more and more risk in order to stay on schedule.

Findings

F6.2-1 NASA Headquarters' focus was on the Node 2 launch date, February 19, 2004.

F6.2-2 The intertwined nature of the Space Shuttle and Space Station programs significantly increased the complexity of the schedule and made meeting the schedule far more challenging.

F6.2-3 The capabilities of the system were being stretched to the limit to support the schedule. Projections into 2003 showed stress on vehicle processing at the Kennedy Space Center, on flight controller training at Johnson Space Center, and on Space Station crew rotation schedules. Effects of this stress included neglecting flight controller recertification requirements, extending crew rotation schedules, and adding incremental risk by scheduling additional Orbiter movements at Kennedy.

F6.2-4 The four flights scheduled in the five months from October 2003, to February 2004, would have required a processing effort comparable to the effort immediately before the *Challenger* accident.

F6.2-5 There was no schedule margin to accommodate unforeseen problems. When flights come in rapid succession, there is no assurance that anomalies on one flight will be identified and appropriately addressed before the next flight.

F6.2-6 The environment of the countdown to Node 2 and the importance of maintaining the schedule may have begun to influence managers' decisions, including those made about the STS-112 foam strike.

F6.2-7 During STS-107, Shuttle Program managers were concerned with the foam strike's possible effect on the launch schedule.

Recommendation:

R6.2-1 Adopt and maintain a Shuttle flight schedule that is consistent with available resources. Although schedule deadlines are an important management tool, those deadlines must be regularly evaluated to ensure that any additional risk incurred to meet the schedule is recognized, understood, and acceptable.

6.3 Decision-Making During the Flight of STS-107

Initial Foam Strike Identification

As soon as *Columbia* reached orbit on the morning of January 16, 2003, NASA's Intercenter Photo Working Group began reviewing liftoff imagery by video and film cameras on the launch pad and at other sites at and nearby the Kennedy Space Center. The debris strike was not seen during the first review of video imagery by tracking cameras, but it was noticed at 9:30 a.m. EST the next day, Flight Day Two, by Intercenter Photo Working Group engineers at Marshall Space Flight Center. Within an hour, Intercenter Photo Working Group personnel at Kennedy also identified the strike on higher-resolution film images that had just been developed.

The images revealed that a large piece of debris from the left bipod area of the External Tank had struck the Orbiter's left wing. Because the resulting shower of post-impact fragments could not be seen passing over the top of the wing, analysts concluded that the debris had apparently impacted the left wing below the leading edge. Intercenter Photo Working Group members were concerned about the size of the object and the apparent momentum of the strike. In searching for better views, Intercenter Photo Working Group members realized that none of the other cameras provided a higher-quality view of the impact and the potential damage to the Orbiter.

Of the dozen ground-based camera sites used to obtain images of the ascent for engineering analyses, each of which has film and video cameras, five are designed to track the Shuttle from liftoff until it is out of view. Due to expected angle of view and atmospheric limitations, two sites did not capture the debris event. Of the remaining three sites positioned to "see" at least a portion of the event, none provided a clear view of the actual debris impact to the wing. The first site lost track of *Columbia* on ascent, the second site was out of focus – because of an improperly maintained lens – and the third site captured only a view of the upper side of *Columbia's* left wing. The Board notes that camera problems also hindered the *Challenger* investigation. Over the years, it appears that due to budget and camera-team staff cuts, NASA's ability to track ascending Shuttles has atrophied – a development that reflects NASA's disregard of the developmental nature of the Shuttle's technology. (See recommendation R3.4-1.)

Because they had no sufficiently resolved pictures with which to determine potential damage, and having never seen such a large piece of debris strike the Orbiter so late in ascent, Intercenter Photo Working Group members decided to ask for ground-based imagery of *Columbia*.

Imagery Request 1

To accomplish this, the Intercenter Photo Working Group's Chair, Bob Page, contacted Wayne Hale, the Shuttle Program Manager for Launch Integration at Kennedy Space Center, to request imagery of *Columbia*'s left wing on-orbit. Hale, who agreed to explore the possibility, holds a Top Secret clearance and was familiar with the process for requesting military imaging from his experience as a Mission Control Flight Director.

This would be the first of three discrete requests for imagery by a NASA engineer or manager. In addition to these three requests, there were, by the Board's count, at least eight "missed opportunities" where actions may have resulted in the discovery of debris damage.

Shortly after confirming the debris hit, Intercenter Photo Working Group members distributed a "L+1" (Launch plus one day) report and digitized clips of the strike via e-mail throughout the NASA and contractor communities. This report provided an initial view of the foam strike and served as the basis for subsequent decisions and actions.

Mission Management's Response to the Foam Strike

As soon as the Intercenter Working Group report was distributed, engineers and technical managers from NASA, United Space Alliance, and Boeing began responding. Engineers and managers from Kennedy Space Center called engineers and Program managers at Johnson Space Center. United Space Alliance and Boeing employees exchanged e-mails with details of the initial film analysis and the work in progress to determine the result of the impact. Details of the strike, actions taken in response to the impact, and records of telephone conversations were documented in the Mission Control operational log. The following section recounts in chronological order many of these exchanges and provides insight into why, in spite of the debris strike's severity, NASA managers ultimately declined to request images of *Columbia's* left wing on-orbit.

Flight Day Two, Friday, January 17, 2003

In the Mission Evaluation Room, a support function of the Shuttle Program office that supplies engineering expertise for missions in progress, a set of consoles are staffed by engineers and technical managers from NASA and contractor organizations. For record keeping, each Mission Evaluation Room member types mission-related comments into a running log. A log entry by a Mission Evaluation Room manager at 10:58 a.m. Central Standard Time noted that the vehicle may have sustained damage from a debris strike.

> *"John Disler [a photo lab engineer at Johnson Space Center] called to report a debris hit on the vehicle. The debris appears to originate from the ET Forward Bipod area…travels down the left side and hits the left wing leading edge near the fuselage…The launch video review team at KSC think that the vehicle may have been damaged by the impact. Bill Reeves and Mike Stoner (USA SAM) were notified."* [ET=External Tank, KSC=Kennedy Space Center, USA SAM=United Space Alliance Sub-system Area Manager]

At 3:15 p.m., Bob Page, Chair of the Intercenter Photo Working Group, contacted Wayne Hale, the Shuttle Program Manager for Launch Integration at Kennedy Space Center, and Lambert Austin, the head of the Space Shuttle Systems Integration at Johnson Space Center, to inform them that Boeing was performing an analysis to determine trajectories, velocities, angles, and energies for the debris impact. Page also stated that photo-analysis would continue over the Martin Luther King Jr. holiday weekend as additional film from tracking cameras was developed. Shortly thereafter, Wayne Hale telephoned Linda Ham, Chair of the Mission Management Team, and Ron Dittemore, Space Shuttle Program Manager, to pass along information about the debris strike and let them know that a formal report would be issued by the end of the day. John Disler, a member of the Intercenter Photo Working Group, notified the Mission Evaluation Room manager that a newly formed group of analysts, to be known as the Debris Assessment Team, needed the entire weekend to conduct a more thorough analysis. Meanwhile, early opinions about Reinforced Carbon-Carbon (RCC) resiliency were circulated via e-mail between United Space Alliance technical managers and NASA engineers, which may have contributed to a mindset that foam hitting the RCC was not a concern.

-----Original Message-----
From: Stoner-1, Michael D
Sent: Friday, January 17, 2003 4:03 PM
To: Woodworth, Warren H; Reeves, William D
Cc: Wilder, James; White, Doug; Bitner, Barbara K; Blank, Donald E; Cooper, Curt W; Gordon, Michael P.
Subject: RE: STS 107 Debris

Just spoke with Calvin and Mike Gordon (RCC SSM) about the impact.

Basically the RCC is extremely resilient to impact type damage. The piece of debris (most likely foam/ice) looked like it most likely impacted the WLE RCC and broke apart. It didn't look like a big enough piece to pose any serious threat to the system and Mike Gordon the RCC SSM concurs. At T +81seconds the piece wouldn't have had enough energy to create a large damage to the RCC WLE system. Plus they have analysis that says they have a single mission safe re-entry in case of impact that penetrates the system.

As far as the tile go in the wing leading edge area they are thicker than required (taper in the outer mold line) and can handle a large area of shallow damage which is what this event most likely would have caused. They have impact data that says the structure would get slightly hotter but still be OK.

Mike Stoner
USA TPS SAM

[RCC=Reinforced Carbon-Carbon, SSM=Sub-system Manager, WLE=Wing Leading Edge, TPS=Thermal Protection System, SAM= Sub-system Area Manager]

Engineering Coordination at NASA and United Space Alliance

After United Space Alliance became contractually responsible for most aspects of Shuttle operations, NASA developed procedures to ensure that its own engineering expertise was coordinated with that of contractors for any "out-of-family" issue. In the case of the foam strike on STS-107, which was classified as out-of-family, clearly defined written guidance led United Space Alliance technical managers to liaise with their NASA counterparts. Once NASA managers were officially notified of the foam strike classification, and NASA engineers joined their contractor peers in an early analysis, the resultant group should, according to standing procedures, become a Mission Evaluation Room Tiger Team. Tiger Teams have clearly defined roles and responsibilities.[43] Instead, the group of analysts came to be called a Debris Assessment Team. While they were the right group of engineers working the problem at the right time, by not being classified as a Tiger Team, they did not fall under the Shuttle Program procedures described in Tiger Team checklists, and as a result were not "owned" or led by Shuttle Program managers. This left the Debris Assessment Team in a kind of organizational limbo, with no guidance except the date by which Program managers expected to hear their results: January 24th.

Already, by Friday afternoon, Shuttle Program managers and working engineers had different levels of concern about what the foam strike might have meant. After reviewing available film, Intercenter Photo Working Group engineers believed the Orbiter may have been damaged by the strike. They wanted on-orbit images of *Columbia's* left wing to confirm their suspicions and initiated action to obtain them. Boeing and United Space Alliance engineers decided to work through the holiday weekend to analyze the strike. At the same time, high-level managers Ralph Roe, head of the Shuttle Program Office of Vehicle Engineering, and Bill Reeves, from United Space Alliance, voiced a lower level of concern. It was at this point, before any analysis had started, that Shuttle Program managers officially shared their belief that the strike posed no safety issues, and that there was no need for a review to be conducted over the weekend. The following is a 4:28 p.m. Mission Evaluation Room manager log entry:

> *"Bill Reeves called, after a meeting with Ralph Roe, it is confirmed that USA/Boeing will not work the debris issue over the weekend, but will wait till Monday when the films are released. The LCC constraints on ice, the energy/speed of impact at +81 seconds, and the toughness of the RCC are two main factors for the low concern. Also, analysis supports single mission safe re-entry for an impact that penetrates the system…"* [USA=United Space Alliance, LCC=Launch Commit Criteria]

The following is a 4:37 p.m. Mission Evaluation Room manager log entry.

> *"Bob Page told MER that KSC/TPS engineers were sent by the USA SAM/Woody Woodworth to review the video and films. Indicated that Page had said that Woody had said this was an action from the MER to work this issue and a possible early landing on Tuesday. MER Manager told Bob that no official action was given by USA or Boeing and they had no concern about landing early. Woody indicated that the TPS engineers at KSC have been 'turned away' from reviewing the films. It was stated that the film reviews wouldn't be finished till Monday."* [MER=Mission Evaluation Room, KSC=Kennedy Space Center, TPS=Thermal Protection System, USA SAM=United Space Alliance Sub-system Area Manager]

The Mission Evaluation Room manager also wrote:

> *"I also confirmed that there was no rush on this issue and that it was okay to wait till the film reviews are finished on Monday to do a TPS review."*

In addition to individual log entries by Mission Evaluation Room members, managers prepared "handover" notes for delivery from one working shift to the next. Handovers from Shift 1 to 2 on January 17 included the following entry under a "problem" category.

> "*Disler Report – Debris impact on port wing edge-appears to have originated at the ET fwd bipod – foam?- if so, it shouldn't be a problem – video clip will be available on the web soon – will look at high-speed film today."* [ET=External Tank, fwd=forward]

Shortly after these entries were made, the deputy manager of Johnson Space Center Shuttle Engineering notified Rodney Rocha, NASA's designated chief engineer for the Thermal Protection System, of the strike and the approximate debris size. It was Rocha's responsibility to coordinate NASA engineering resources and work with contract engineers at United Space Alliance, who together would form a Debris Assessment Team that would be Co-Chaired by United Space Alliance engineering manager Pam Madera. The United Space Alliance deputy manager of Shuttle Engineering signaled that the debris strike was initially classified as "out-of-family" and therefore of greater concern than previous debris strikes. At about the same time, the Intercenter Photo Working Group's L+1 report, containing both video clips and still images of the debris strike, was e-mailed to engineers and technical managers both inside and outside of NASA.

Flight Days Three and Four, Saturday and Sunday, January 18 and 19, 2003

Though senior United Space Alliance Manager Bill Reeves had told Mission Evaluation Room personnel that the debris problem would not be worked over the holiday weekend, engineers from Boeing did in fact work through the weekend. Boeing analysts conducted a preliminary damage assessment on Saturday. Using video and photo images, they generated two estimates of possible debris size – 20 inches by 20 inches by 2 inches, and 20 inches by 16 inches by 6 inches – and determined that the debris was traveling at a approximately 750 feet per second, or 511 miles per hour, when it struck the Orbiter at an estimated impact angle of less than 20 degrees. These estimates later proved remarkably accurate.

To calculate the damage that might result from such a strike, the analysts turned to a Boeing mathematical modeling tool called Crater that uses a specially developed algorithm to predict the depth of a Thermal Protection System tile to which debris will penetrate. This algorithm, suitable for estimating small (on the order of three cubic inches) debris impacts, had been calibrated by the results of foam, ice, and metal debris impact testing. A similar Crater-like algorithm was also developed and validated with test results to assess the damage caused by ice projectiles impacting the RCC leading edge panels. These tests showed that within certain limits, the Crater algorithm predicted more severe damage than was observed. This led engineers to classify Crater as a "conservative" tool – one that predicts more damage than will actually occur.

Until STS-107, Crater was normally used only to predict whether small debris, usually ice on the External Tank, would pose a threat to the Orbiter during launch. The use of Crater to assess the damage caused by foam during the launch of STS-107 was the first use of the model while a mission was on orbit. Also of note is that engineers used Crater during STS-107 to analyze a piece of debris that was at maximum 640 times larger in volume than the pieces of debris used to calibrate and validate the Crater model (the Board's best estimate is that it actually was 400 times larger). Therefore, the use of Crater in this new and very different situation compromised NASA's ability to accurately predict debris damage in ways that Debris Assessment Team engineers did not fully comprehend (see Figure 6.3-1).

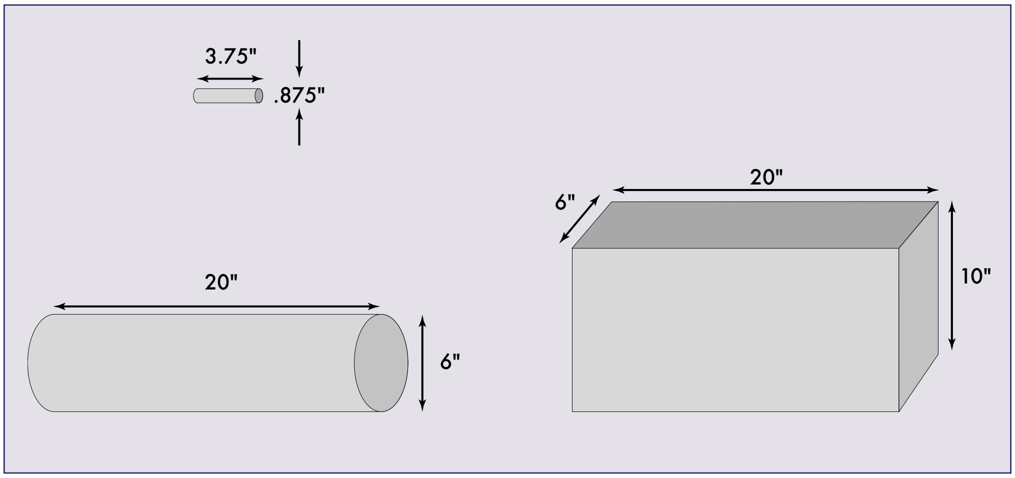


Figure 6.3-1. The small cylinder at top illustrates the size of debris Crater was intended to analyze. The larger cylinder was used for the STS-107 analysis; the block at right is the estimated size of the foam.

The Crater Model

$$p = \frac{0.0195(L/d)0.45(d)(\rho_P)^{0.27}(V-V^*)^{2/3}}{(S_T)^{1/4}(\rho_T)^{1/6}}$$

p = *penetration depth*
L = *length of foam projectile*
d = *diameter of foam projectile*
ρ_P = *density of foam*
V = *component of foam velocity at right angle to foam*
V^* = *velocity required to break through the tile coating*
S_T = *compressive strength of tile*
ρ_T = *density of tile*
0.0195 = *empirical constant*

In 1966, during the Apollo program, engineers developed an equation to assess impact damage, or "cratering," by micrometeoroids.[44] The equation was modified between 1979 and 1985 to enable the analysis of impacts to "acreage" tiles that cover the lower surface of the Orbiter.[45] The modified equation, now known as Crater, predicts possible damage from sources such as foam, ice, and launch site debris, and is most often used in the day-of-launch analysis of ice debris falling off the External Tank.[46]

When used within its validated limits, Crater provides conservative predictions (that is, Crater predictions are larger than actual damage). When used outside its validated limits, Crater's precision is unknown.

Crater has been correlated to actual impact data using results from several tests. Preliminary ice drop tests were performed in 1978,[47] and additional tests using sprayed-on foam insulation projectiles were conducted in 1979 and 1999.[48] However, the test projectiles were relatively small (maximum volume of 3 cubic inches), and targeted only single tiles, not groups of tiles as actually installed on the Orbiter. No tests were performed with larger debris objects because it was not believed such debris could ever impact the Orbiter. This resulted in a very limited set of conditions under which Crater's results were empirically validated.

During 1984, tests were conducted using ice projectiles against the Reinforced Carbon-Carbon used on the Orbiters' wing leading edges.[49] These tests used an 0.875-inch diameter, 3.75-inch long ice projectile to validate an algorithm that was similar to Crater. Unlike Crater, which was designed to predict damage during a flight, the RCC predictions were intended to determine the thickness of RCC required to withstand ice impacts as an aid to design engineers. Like Crater, however, the limited set of test data significantly restricts the potential application of the model.

Other damage assessment methods available today, such as hydrodynamic structural codes, like Dyna, are able to analyze a larger set of projectile sizes and materials than Crater. Boeing and NASA did not currently sanction these finite element codes because of the time required to correlate their results in order to use the models effectively.

Although Crater was designed, and certified, for a very limited set of impact events, the results from Crater simulations can be generated quickly. During STS-107, this led to Crater being used to model an event that was well outside the parameters against which it had been empirically validated. As the accompanying table shows, many of the STS-107 debris characteristics were orders of magnitude outside the validated envelope. For instance, while Crater had been designed and validated for projectiles up to 3 cubic inches in volume, the initial STS-107 analysis estimated the piece of debris at 1,200 cubic inches – 400 times larger.

Crater parameters used during development of experimental test data versus STS-107 analysis:

Test Parameter	*Test Value*	*STS-107 Analysis*
Volume	Up to 3 cu.in	10" x 6" x 20" = 1200 cu.in. *
Length	Up to 1 inch	~ 20 inches *
Cylinder Dimensions	<= 3/8" dia x 3"	6" dia x 20"
Projectile Block Dimensions	<= 3"x 1"x 1"	6" x 10" x 20" *
Tile Material	LI-900 "acreage" tile	LI-2200 * and LI-900
Projectile Shape	Cylinder	Block

** Outside experimental test limits*

Crater equation parameter limits:

Crater Equation Parameter	*Applicable Range*	*STS-107 Analysis*
L/d	1 – 20	3.3
L	n/a	~ 20 inches
ρ_d	1 – 3 pounds per cu.ft.	2.4 pounds per cu.ft.
d	0.4 – 2.0 inches	6 inches *
V	up to 810 fps	~ 700 fps

** Outside validated limits*

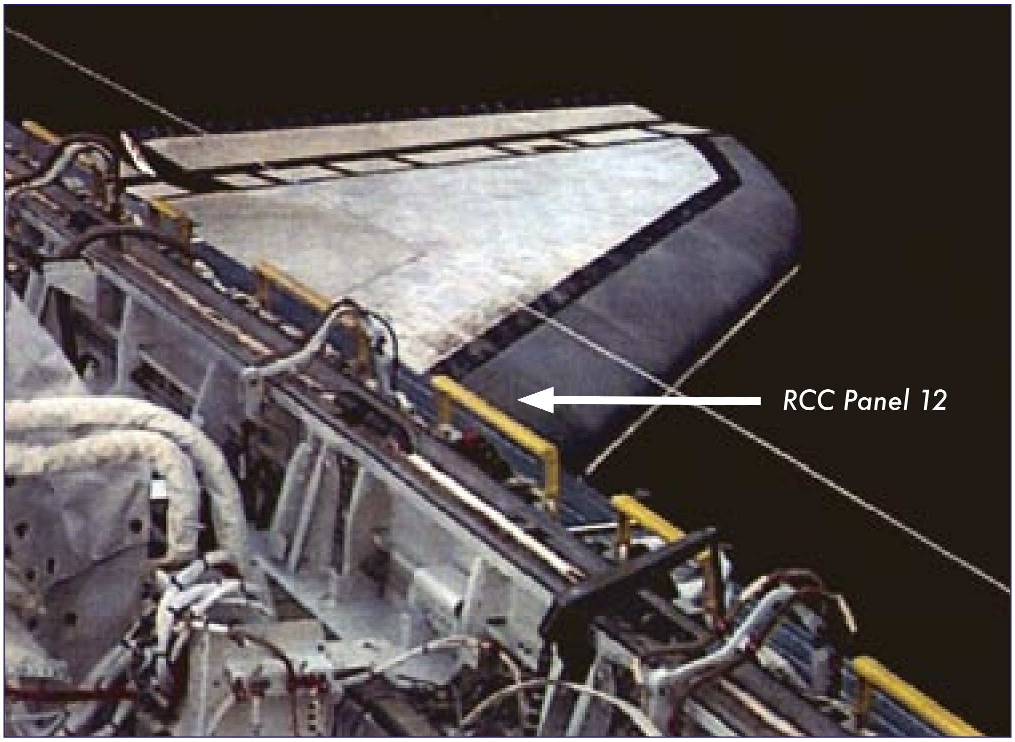
Over the weekend, an engineer certified by Boeing to use Crater entered the two estimated debris dimensions, the estimated debris velocity, and the estimated angle of impact. The engineer had received formal training on Crater from senior Houston-based Boeing engineering staff, but he had only used the program twice before, and had reservations about using it to model the piece of foam debris that struck *Columbia*. The engineer did not consult with more experienced engineers from Boeing's Huntington Beach, California, facility, who up until the time of STS-107 had performed or overseen Crater analysis. (Boeing completed the transfer of responsibilities for Crater analysis from its Huntington Beach engineers to its Houston office in January 2003. STS-107 was the first mission that the Huntington Beach engineers were not directly involved with.)

For the Thermal Protection System tile, Crater predicted damage deeper than the actual tile thickness. This seemingly alarming result suggested that the debris that struck *Columbia* would have exposed the Orbiter's underlying aluminum airframe to extreme temperatures, resulting in a possible burn-through during re-entry. Debris Assessment Team engineers discounted the possibility of burn through for two reasons. First, the results of calibration tests with small projectiles showed that Crater predicted a deeper penetration than would actually occur. Second, the Crater equation does not take into account the increased density of a tile's lower "densified" layer, which is much stronger than tile's fragile outer layer. Therefore, engineers judged that the actual damage from the large piece of foam lost on STS-107 would not be as severe as Crater predicted, and assumed that the debris did not penetrate the Orbiter's skin. This uncertainty, however, meant that determining the precise location of the impact was paramount for an accurate damage estimate. Some areas on the Orbiter's lower surface, such as the seals around the landing gear doors, are more vulnerable than others. Only by knowing precisely where the debris struck could the analysts more accurately determine if the Orbiter had been damaged.

To determine potential RCC damage, analysts used a Crater-like algorithm that was calibrated in 1984 by impact data from ice projectiles. At the time the algorithm was empirically tested, ice was considered the only realistic threat to RCC integrity. (See Appendix E.4, RCC Impact Analysis.) The Debris Assessment Team analysis indicated that impact angles greater than 15 degrees would result in RCC penetration. A separate "transport" analysis, which attempts to determine the path the debris took, identified 15 strike regions and angles of impact. Twelve transport scenarios predicted an impact in regions of Shuttle tile. Only one scenario predicted an impact on the RCC leading edge, at a 21-degree angle. Because the foam that struck *Columbia* was less dense than ice, Debris Assessment Team analysts used a qualitative extrapolation of the test data and engineering judgment to conclude that a foam impact angle up to 21 degrees would not penetrate the RCC. Although some engineers were uncomfortable with this extrapolation, no other analyses were performed to assess RCC damage. The Debris Assessment Team focused on analyzing the impact at locations other than the RCC leading edge. This may have been due, at least in part, to the transport analysis presentation and the long-standing belief that foam was not a threat to RCC panels. The assumptions and uncertainty embedded in this analysis were never fully presented to the Mission Evaluation Room or the Mission Management Team.

Missed Opportunity 1

On Sunday, Rodney Rocha e-mailed a Johnson Space Center Engineering Directorate manager to ask if a Mission Action Request was in progress for *Columbia*'s crew to visually inspect the left wing for damage. Rocha never received an answer.



This photo from the aft flight deck window of an Orbiter shows that RCC panels 1 – 11 are not visible from inside the Orbiter. Since Columbia did not have a manipulator arm for STS-107, it would have been necessary for an astronaut to take a spacewalk to visibly inspect the inboard leading edge of the wing.

Flight Day Five, Monday, January 20, 2003

On Monday morning, the Martin Luther King Jr. holiday, the Debris Assessment Team held an informal meeting before its first formal meeting, which was scheduled for Tuesday afternoon. The team expanded to include NASA and Boeing transport analysts expert in the movement of debris in airflows, tile and RCC experts from Boeing and NASA, aerothermal and thermal engineers from NASA, United Space Alliance, and Boeing, and a safety representative from the NASA contractor Science Applications International Corporation.

Engineers emerged from that informal meeting with a goal of obtaining images from ground-based assets. Uncertainty as to precisely where the debris had struck *Columbia* generated concerns about the possibility of a breach in the left main landing gear door seal. They conducted further analysis using angle and thickness variables and thermal data obtained by personnel at Boeing's Huntington Beach facility for STS-87 and STS-50, the two missions that had incurred Thermal Protection System damage. (See Section 6.1.)

Debris Assessment Team Co-Chair Pam Madera distributed an e-mail summarizing the day's events and outlined the agenda for Tuesday's first formal Debris Assessment Team meeting. Included on the agenda was the desire to obtain on-orbit images of *Columbia*'s left wing.

According to an 11:39 a.m. entry in the Mission Evaluation Room Manager's log:

> *"…the debris 'blob' is estimated at 20" +/-10" in some direction, using the Orbiter hatch as a basis. It appears to be similar size as that seen in STS-112. There will be more comparison work done, and more info and details in tomorrow's report."*

This entry illustrates, in NASA language, an initial attempt by managers to classify this bipod ramp foam strike as close to being within the experience base and therefore, being almost an "in-family" event, not necessarily a safety concern. While the size and source of STS-107 debris was somewhat similar to what STS-112 had experienced, the impact sites (the wing versus the Solid Rocket Booster) differed – a distinction not examined by mission managers.

Flight Day Six, Tuesday, January 21, 2003

At 7:00 a.m., the Debris Assessment Team briefed Don McCormack, the chief Mission Evaluation Room manager, that the foam's source and size was similar to what struck STS-112, and that an analysis of measured versus predicted tile damage from STS-87 was being scrutinized by Boeing. An hour later, McCormack related this information to the Mission Management Team at its first post-holiday meeting. Although Space Shuttle Program requirements state that the Mission Management Team will convene daily during a mission, the STS-107 Mission Management Team met only on January 17, 21, 24, 27, and 31. The transcript below is the first record of an official discussion of the debris impact at a Mission Management Team meeting. Before even referring to the debris strike, the Mission Management Team focused on end-of-mission "downweight" (the Orbiter was 150 pounds over the limit), a leaking water separator, a jammed Hasselblad camera, payload and experiment status, and a communications downlink problem. McCormack then stated that engineers planned to determine what could be done if *Columbia* had sustained damage. STS-107 Mission Management Team Chair Linda Ham suggested the team learn what rationale had been used to fly after External Tank foam losses on STS-87 and STS-112.

Transcript Excerpts from the January 21, Mission Management Team Meeting

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

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

Ham*: "That comment, I was thinking that the flight rationale at the FRR from tank and orbiter from STS-112 was.… I'm not sure that the area is exactly the same where the foam came from but the carrier properties and density of the foam wouldn't do any damage. So we ought to pull that along with the 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 that we had good flight rationale then."*

McCormack*: "Yeah, and we'll look at that, you mentioned 87, you know we saw some fairly significant damage in the area between RCC panels 8 and 9 and the main landing gear door on the bottom on STS-87 we did some analysis prior to STS-89 so uh…"*

Ham*: "And I'm really I don't think there is much we can do so it's not really a factor during the flight because there is not much we can do about it. But what I'm really interested in is making sure our flight rationale to go was good, and maybe this is foam from a different area and I'm not sure and it may not be co-related, but you can try to see what we have."*

McCormack*: "Okay."*

After the meeting, the rationale for continuing to fly after the STS-112 foam loss was sent to Ham for review. She then exchanged e-mails with her boss, Space Shuttle Program Manager Ron Dittemore:

-----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.

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-----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]

Ham's focus on examining the rationale for continuing to fly after the foam problems with STS-87 and STS-112 indicates that her attention had already shifted from the threat the foam posed to STS-107 to the downstream implications of the foam strike. Ham was due to serve, along with Wayne Hale, as the launch integration manager for the next mission, STS-114. If the Shuttle Program's rationale to fly with foam loss was found to be flawed, STS-114, due to be launched in about a month, would have to be delayed per NASA rules that require serious problems to be resolved before the next flight. An STS-114 delay could in turn delay completion of the International Space Station's Node 2, which was a high-priority goal for NASA managers. (See Section 6.2 for a detailed description of schedule pressures.)

During this same Mission Management Team meeting, the Space Shuttle Integration Office's Lambert Austin reported that engineers were reviewing long-range tracking film and that the foam debris that appeared to hit the left wing leading edge may have come from the bipod area of the External Tank. Austin said that the Engineering Directorate would continue to run analyses and compare this foam loss to that of STS-112. Austin also said that after STS-107 landed, engineers were anxious to see the crew-filmed footage of External Tank separation that might show the bipod ramp and therefore could be checked for missing foam.

Missed Opportunity 2

Reviews of flight-deck footage confirm that on Flight Day One, Mission Specialist David Brown filmed parts of the External Tank separation with a Sony PD-100 Camcorder, and Payload Commander Mike Anderson photographed it with a Nikon F-5 camera with a 400-millimeter lens. Brown later downlinked 35 seconds of this video to the ground as part of his Flight Day One mission summary, but the bipod ramp area had rotated out of view, so no evidence of missing foam was seen when this footage was reviewed during the mission. However, after the Intercenter Photo Working Group caught the debris strike on January 17, ground personnel failed to ask Brown if he had additional footage of External Tank separation. Based on how crews are trained to film External Tank separation, the Board concludes Brown did in fact have more film than the 35 seconds he downlinked. Such footage may have confirmed that foam was missing from the bipod ramp area or could have identified other areas of missing foam. Austin's mention of the crew's filming of External Tank separation should have prompted someone at the meeting to ask Brown if he had more External Tank separation film, and if so, to downlink it immediately.

Flight Director Steve Stich discussed the debris strike with Phil Engelauf, a member of the Mission Operations Directorate, after Engelauf returned from the Mission Management Team meeting. As written in a timeline Stich composed after the accident, the conversation included the following.

> *"Phil said the Space Shuttle Program community is not concerned and that Orbiter Project is analyzing ascent debris…relayed that there had been no direction for MOD to ask DOD for any photography of possible damaged tiles"* [MOD=Mission Operations Directorate, or Mission Control, DOD=Department of Defense]

"No direction for DOD photography" seems to refer to either a previous discussion of photography with Mission managers or an expectation of future activity. Since the interagency agreement on imaging support stated that the Flight Dynamics Officer is responsible for initiating such a request, Engelauf's comments demonstrates that an informal chain of command, in which the Mission Operations Directorate figures prominently, was at work.

About an hour later, Calvin Schomburg, a Johnson Space Center engineer with close connections to Shuttle management, sent the following e-mail to other Johnson engineering managers.

-----Original Message-----
From: SCHOMBURG, CALVIN (JSC-EA) (NASA)
Sent: Tuesday, January 21, 2003 9:26 AM
To: SHACK, PAUL E. (JSC-EA42) (NASA); SERIALE-GRUSH, JOYCE M. (JSC-EA) (NASA); HAMILTON, DAVID A. (DAVE) (JSC-EA) (NASA)
Subject: FW: STS-107 Post-Launch Film Review - Day 1

FYI-TPS took a hit-should not be a problem-status by end of week.

[FYI=For Your Information, TPS=Thermal Protection System]

Shuttle Program managers regarded Schomburg as an expert on the Thermal Protection System. His message downplays the possibility that foam damaged the Thermal Protection System. However, the Board notes that Schomburg was not an expert on Reinforced Carbon-Carbon (RCC), which initial debris analysis indicated the foam may have struck. Because neither Schomburg nor Shuttle management rigorously differentiated between tiles and RCC panels, the bounds of Schomburg's expertise were never properly qualified or questioned.

Seven minutes later, Paul Shack, Manager of the Shuttle Engineering Office, Johnson Engineering Directorate, e-mailed to Rocha and other Johnson engineering managers information on how previous bipod ramp foam losses were handled.

-----Original Message-----
From: SHACK, PAUL E. (JSC-EA42) (NASA)
Sent: Tuesday, January 21, 2003 9:33 AM
To: ROCHA, ALAN R. (RODNEY) (JSC-ES2) (NASA); SERIALE-GRUSH, JOYCE M. (JSC-EA) (NASA)
Cc: KRAMER, JULIE A. (JSC-EA4) (NASA); MILLER, GLENN J. (JSC-EA) (NASA); RICKMAN, STEVEN L. (JSC-ES3) (NASA); MADDEN, CHRISTOPHER B. (CHRIS) (JSC-ES3) (NASA)
Subject: RE: STS-107 Debris Analysis Team Plans

This reminded me that at the STS-113 FRR the ET Project reported on foam loss from the Bipod Ramp during STS-112. The foam (estimated 4X5X12 inches) impacted the ET Attach Ring and dented an SRB electronics box cover.

Their charts stated "ET TPS foam loss over the life of the Shuttle program has never been a 'Safety of Flight' issue". They were severely wire brushed over this and Brian O'Conner (Associate Administra-

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tor for Safety) asked for a hazard assessment for loss of foam.

The suspected cause for foam loss is trapped air pockets which expand due to altitude and aerothermal heating.

[FRR=Flight Readiness Review, ET=External Tank, SRB=Solid Rocket Booster, TPS=Thermal Protection System]

Shack's message informed Rocha that during the STS-113 Flight Readiness Review, foam loss was not considered to be a safety-of-flight issue. The "wirebrushing" that the External Tank Project received for stating that foam loss has "never been a 'Safety of Flight' issue" refers to the wording used to justify continuing to fly. Officials at the Flight Readiness Review insisted on classifying the foam loss as an "accepted risk" rather than "not a safety-of-flight problem" to indicate that although the Shuttle would continue to fly, the threat posed by foam is not zero but rather a known and acceptable risk.

It is here that the decision to fly before resolving the foam problem at the STS-113 Flight Readiness Review influences decisions made during STS-107. Having at hand a previously accepted rationale – reached just one mission ago – that foam strikes are not a safety-of-flight issue provides a strong incentive for Mission managers and working engineers to use that same judgment for STS-107. If managers and engineers were to argue that foam strikes are a safety-of-flight issue, they would contradict an established consensus that was a product of the Shuttle Program's most rigorous review – a review in which many of them were active participants.

An entry in a Mission Evaluation Room console log included a 10:30 a.m. report that compared the STS-107 foam loss to previous foam losses and subsequent tile damage, which reinforced management acceptance about foam strikes by indicating that the foam strike appeared to be more of an "in-family" event.

> *"…STS-107 debris measured at 22" long +/- 10". On STS-112 the debris spray pattern was a lot smaller than that of STS-107. On STS-50 debris that was determined to be the Bipod ramp which measured 26" x 10" caused damage to the left wing…to 1 tile and 20% of the adjacent tile. Same event occurred on STS-7 (no data available)."*

Missed Opportunity 3

The foam strike to STS-107 was mentioned by a speaker at an unrelated meeting of NASA Headquarters and National Imagery and Mapping Agency personnel, who then discussed a possible NASA request for Department of Defense imagery support. However, no action was taken.

Imagery Request 2

Responding to concerns from his employees who were participating in the Debris Assessment Team, United Space Alliance manager Bob White called Lambert Austin on Flight Day Six to ask what it would take to get imagery of *Columbia* on orbit. They discussed the analytical debris damage work plan, as well as the belief of some integration team members that such imaging might be beneficial.

Austin subsequently telephoned the Department of Defense Manned Space Flight Support Office representative to ask about actions necessary to get imagery of *Columbia* on orbit. Austin emphasized that this was merely information gathering, not a request for action. This call indicates that Austin was unfamiliar with NASA/National Imagery and Mapping Agency imagery request procedures.

An e-mail that Lieutenant Colonel Timothy Lee sent to Don McCormack the following day shows that the Defense Department had begun to implement Austin's request.

-----Original Message-----
From: LEE, TIMOTHY F., LTCOL. (JSC-MT) (USAF)
Sent: Wednesday, January 22, 2003 9:01 AM
To: MCCORMACK, DONALD L. (DON) (JSC-MV6) (NASA)
Subject: NASA request for DOD

Don,

FYI: Lambert Austin called me yesterday requesting DOD photo support for STS-107. Specifically, he is asking us if we have a ground or satellite asset that can take a high resolution photo of the shuttle while on-orbit--to see if there is any FOD damage on the wing. We are working his request.

Tim

[DOD=Department of Defense, FOD=Foreign Object Debris]

At the same time, managers Ralph Roe, Lambert Austin, and Linda Ham referred to conversations with Calvin Schomburg, whom they referred to as a Thermal Protection System "expert." They indicated that Schomburg had advised that any tile damage should be considered a turn-around maintenance concern and not a safety-of-flight issue, and that imagery of *Columbia*'s left wing was not necessary. There was no discussion of potential RCC damage.

First Debris Assessment Team Meeting

On Flight Day Six, the Debris Assessment Team held its first formal meeting to finalize Orbiter damage estimates and their potential consequences. Some participants joined the proceedings via conference call.

Imagery Request 3

After two hours of discussing the Crater results and the need to learn precisely where the debris had hit *Columbia*, the Debris Assessment Team assigned its NASA Co-Chair, Rodney Rocha, to pursue a request for imagery of the vehicle on-orbit. Each team member supported the idea to seek imagery from an outside source. Rather than working the request up the usual mission chain of command through the Mission Evaluation Room to the Mission Management Team to the Flight Dynamics Officer, the Debris Assessment Team agreed, largely due to a lack of participation by Mission Management Team and Mission Evaluation Room managers, that Rocha would pursue the request through his division, the Engineering Directorate at Johnson Space Center. Rocha sent the following e-mail to Paul Shack shortly after the meeting adjourned.

-----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.

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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]

Routing the request through the Engineering department led in part to it being viewed by Shuttle Program managers as a non-critical engineering desire rather than a critical operational need.

Flight Day Seven, Wednesday, January 22, 2003

Conversations and log entries on Flight Day Seven document how three requests for images (Bob Page to Wayne Hale, Bob White to Lambert Austin, and Rodney Rocha to Paul Shack) were ultimately dismissed by the Mission Management Team, and how the order to halt those requests was then interpreted by the Debris Assessment Team as a direct and final denial of their request for imagery.

Missed Opportunity 4

On the morning of Flight Day Seven, Wayne Hale responded to the earlier Flight Day Two request from Bob Page and a call from Lambert Austin on Flight Day Five, during which Austin mentioned that "some analysts" from the Debris Assessment Team were interested in getting imagery. Hale called a Department of Defense representative at Kennedy Space Center (who was not the designated Department of Defense official for coordinating imagery requests) and asked that the military start the planning process for imaging *Columbia* on orbit.

Within an hour, the Defense Department representative at NASA contacted U.S. Strategic Command (USSTRATCOM) at Colorado's Cheyenne Mountain Air Force Station and asked what it would take to get imagery of *Columbia* on orbit. (This call was similar to Austin's call to the Department of Defense Manned Space Flight Support Office in that the caller characterized it as "information gathering" rather than a request for action.) A representative from the USSTRATCOM Plans Office initiated actions to identify ground-based and other imaging assets that could execute the request.

Hale's earlier call to the Defense Department representative at Kennedy Space Center was placed without authorization from Mission Management Team Chair Linda Ham. Also, the call was made to a Department of Defense Representative who was not the designated liaison for handling such requests. In order to initiate the imagery request through official channels, Hale also called Phil Engelauf at the Mission Operations Directorate, told him he had started Defense Department action, and asked if Engelauf could have the Flight Dynamics Officer at Johnson Space Center make an official request to the Cheyenne Mountain Operations Center. Engelauf started to comply with Hale's request.

After the Department of Defense representatives were called, Lambert Austin telephoned Linda Ham to inform her about the imagery requests that he and Hale had initiated. Austin also told Wayne Hale that he had asked Lieutenant Colonel Lee at the Department of Defense Manned Space Flight Support Office about what actions were necessary to get on-orbit imagery.

Missed Opportunities 5 and 6

Mike Card, a NASA Headquarters manager from the Safety and Mission Assurance Office, called Mark Erminger at the Johnson Space Center Safety and Mission Assurance for Shuttle Safety Program and Bryan O'Connor, Associate Administrator for Safety and Mission Assurance, to discuss a potential Department of Defense imaging request. Erminger said that he was told this was an "in-family" event. O'Connor stated he would defer to Shuttle management in handling such a request. Despite two safety officials being contacted, one of whom was NASA's highest-ranking safety official, safety personnel took no actions to obtain imagery.

The following is an 8:09 a.m. entry in the Mission Evaluation Room Console log.

> *"We received a visit from Mission Manager/Vanessa Ellerbe and FD Office/Phil Engelauf regarding two items: (1) the MMT's action item to the MER to determine the impacts to the vehicle's 150 lbs of additional weight…and (2) Mr. Engelauf wants to know who is requesting the Air Force to look at the vehicle."* [FD=Flight Director, MMT=Mission Management Team, MER=Mission Evaluation Room]

Cancellation of the Request for Imagery

At 8:30 a.m., the NASA Department of Defense liaison officer called USSTRATCOM and cancelled the request for imagery. The reason given for the cancellation was that NASA had identified its own in-house resources and no longer needed the military's help. The NASA request to the Department of Defense to prepare to image *Columbia* on-orbit was both made and rescinded within 90 minutes.

The Board has determined that the following sequence of events likely occurred within that 90-minute period. Linda Ham asked Lambert Austin if he knew who was requesting the imagery. After admitting his participation in helping to make the imagery request outside the official chain of command and without first gaining Ham's permission, Austin referred to his conversation with United Space Alliance Shuttle Integration manager Bob White on Flight Day Six, in which White had asked Austin, in response to White's Debris Assessment Team employee concerns, what it would take to get Orbiter imagery.

Even though Austin had already informed Ham of the request for imagery, Ham later called Mission Management Team members Ralph Roe, Manager of the Space Shuttle Vehicle Engineering Office, Loren Shriver, United Space Alliance Deputy Program Manager for Shuttle, and David Moyer, the on-duty Mission Evaluation Room manager, to determine the origin of the request and to confirm that there was a "requirement" for a request. Ham also asked Flight Director Phil Engelauf if he had a "requirement" for imagery of *Columbia's* left wing. These individuals all stated that they had not requested imagery, were not aware of any "official" requests for imagery, and could not identify a "requirement" for imagery. Linda Ham later told several individuals that nobody had a requirement for imagery.

What started as a request by the Intercenter Photo Working Group to seek outside help in obtaining images on Flight Day Two in anticipation of analysts' needs had become by Flight Day Six an actual engineering request by members of the Debris Assessment Team, made informally through Bob White to Lambert Austin, and formally in Rodney Rocha's e-mail to Paul Shack. These requests had then caused Lambert Austin and Wayne Hale to contact Department of Defense representatives. When Ham officially terminated the actions that the Department of Defense had begun, she effectively terminated both the Intercenter Photo Working Group request and the Debris Assessment Team request. While Ham has publicly stated she did not know of the Debris Assessment Team members' desire for imagery, she never asked them directly if the request was theirs, even though they were the team analyzing the foam strike.

Also on Flight Day Seven, Ham raised concerns that the extra time spent maneuvering *Columbia* to make the left wing visible for imaging would unduly impact the mission schedule; for example, science experiments would have to stop while the imagery was taken. According to personal notes obtained by the Board:

> *"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."*

Shuttle managers, including Ham, also said they were looking for very small areas on the Orbiter and that past imagery resolution was not very good. The Board notes that no individuals in the STS-107 operational chain of command had the security clearance necessary to know about National imaging capabilities. Additionally, no evidence has been uncovered that anyone from NASA, United Space Alliance, or Boeing sought to determine the expected quality of images and the difficulty and costs of obtaining Department of Defense assistance. Therefore, members of the Mission Management Team were making critical decisions about imagery capabilities based on little or no knowledge.

The following is an entry in the Flight Director Handover Log.

> *"NASA Resident Office, Peterson AFB called and SOI at USSPACECOM was officially turned off. This went all the way up to 4 star General. Post flight we will write a memo to USSPACECOM telling them whom they should take SOI requests from."*[50] *[AFB=Air Force Base, SOI=Spacecraft Object Identification, USSPACECOM=U.S. Space Command]*

After canceling the Department of Defense imagery request, Linda Ham continued to explore whether foam strikes posed a safety of flight issue. She sent an e-mail to Lambert Austin and Ralph Roe.

-----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]

Responses included the following.

-----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]

Ron Dittermore e-mailed Linda Ham the following.

-----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.

The following is an e-mail from Calvin Schomburg to Ralph Roe.

-----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]

The following is a response from Lambert Austin to Linda Ham.

-----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

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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]

The Board notes that these e-mail exchanges indicate that senior Mission Management Team managers, including the Shuttle Program Manager, Mission Management Team Chair, head of Space Shuttle Systems Integration, and a Shuttle tile expert, correctly identified the technical bounds of the foam strike problem and its potential seriousness. Mission managers understood that the relevant question was not whether foam posed a safety-of-flight issue – it did – but rather whether the observed foam strike contained sufficient kinetic energy to cause damage that could lead to a burn-through. Here, all the key managers were asking the right question and admitting the danger. They even identified RCC as a critical impact zone. Yet little follow-through occurred with either the request for imagery or the Debris Assessment Team analysis. (See Section 3.4 and 3.6 for details on the kinetics of foam strikes.)

A Mission Evaluation Room log entry at 10:37 a.m. records the decision not to seek imaging of *Columbia's* left wing.

> *"USA Program Manager/Loren Shriver, NASA Manager, Program Integration/Linda Ham, & NASA SSVEO/Ralph Roe have stated that there is no need for the Air Force to take a look at the vehicle."* [USA=United Space Alliance, SSVEO=Space Shuttle Vehicle Engineering Office]

At 11:22 a.m., Debris Assessment Team Co-Chair Pam Madera sent an e-mail to team members setting the agenda for the team's second formal meeting that afternoon that included:

> *"… Discussion on Need/Rationale for Mandatory Viewing of damage site (All)…"*

Earlier e-mail agenda wording did not include "Need/Rationale for Mandatory" wording as listed here, which indicates that Madera knew of management's decision to not seek images of *Columbia's* left wing and anticipated having to articulate a "mandatory" rationale to reverse that decision. In fact, a United Space Alliance manager had informed Madera that imagery would be sought only if the request was a "mandatory need." Twenty-three minutes later, an e-mail from Paul Shack to Rodney Rocha, who the day before had carried forward the Debris Assessment Team's request for imaging, stated the following.

> *"… FYI, According to the MER, Ralph Roe has told program that Orbiter is not requesting any outside imaging help …"* [MER=Mission Evaluation Room]

Earlier that morning, Ralph Roe's deputy manager, Trish Petite, had separate conversations with Paul Shack and tile expert Calvin Schomburg. In those conversations, Petite noted that an analysis of potential damage was in progress, and they should wait to see what the analysis showed before asking for imagery. Schomburg, though aware of the Debris Assessment Team's request for imaging, told Shack and Petite that he believed on-orbit imaging of potentially damaged areas was not necessary.

As the morning wore on, Debris Assessment Team engineers, Shuttle Program management, and other NASA personnel exchanged e-mail. Most messages centered on technical matters to be discussed at the Debris Assessment Team's afternoon meeting, including debris density, computer-aided design models, and the highest angle of incidence to use for a particular material property. One e-mail from Rocha to his managers and other Johnson engineers at 11:19 a.m., included the following.

> *"… there are good scenarios (acceptable and minimal damage) to horrible ones, depending on the extent of the damage incurred by the wing and location. The most critical loca-*

tions seem to be the 1191 wing spar region, the main landing gear door seal, and the RCC panels. We do not know yet the exact extent or nature of the damage without being provided better images, and without such all the high powered analyses and assessments in work will retain significant uncertainties …"

Second Debris Assessment Team Meeting

Some but not all of the engineers attending the Debris Assessment Team's second meeting had learned that the Shuttle Program was not pursuing imaging of potentially damaged areas. What team members did not realize was the Shuttle Program's decision not to seek on-orbit imagery was not necessarily a direct and final response to their request. Rather, the "no" was partly in response to the Kennedy Space Center action initiated by United Space Alliance engineers and managers and finally by Wayne Hale.

Not knowing that this was the case, Debris Assessment Team members speculated as to why their request was rejected and whether their analysis was worth pursuing without new imagery. Discussion then moved on to whether the Debris Assessment Team had a "mandatory need" for Department of Defense imaging. Most team members, when asked by the Board what "mandatory need" meant, replied with a shrug of their shoulders. They believed the need for imagery was obvious: without better pictures, engineers would be unable to make reliable predictions of the depth and area of damage caused by a foam strike that was outside of the experience base. However, team members concluded that although their need was important, they could not cite a "mandatory" requirement for the request. *Analysts on the Debris Assessment Team were in the unenviable position of wanting images to more accurately assess damage while simultaneously needing to prove to Program managers, as a result of their assessment, that there was a need for images in the first place.*

After the meeting adjourned, Rocha read the 11:45 a.m. e-mail from Paul Shack, which said that the Orbiter Project was not requesting any outside imaging help. Rocha called Shack to ask if Shack's boss, Johnson Space Center engineering director Frank Benz, knew about the request. Rocha then sent several e-mails consisting of questions about the ongoing analyses and details on the Shuttle Program's cancellation of the imaging request. An e-mail that he did not send but instead printed out and shared with a colleague follows.

"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]

When asked why he did not send this e-mail, Rocha replied that he did not want to jump the chain of command. Having already raised the need to have the Orbiter imaged with Shack, he would defer to management's judgment on obtaining imagery.

Even after the imagery request had been cancelled by Program management, engineers in the Debris Assessment Team and Mission Control continued to analyze the foam strike. A structural engineer in the Mechanical, Maintenance, Arm and Crew Systems sent an e-mail to a flight dynamics engineer that stated:

"There is lots of speculation as to extent of the damage, and we could get a burn through into the wheel well upon entry."

Less than an hour later, at 6:09 p.m., a Mission Evaluation Room Console log entry stated the following.

"MMACS is trying to view a Quicktime movie on the debris impact but doesn't have Quick-

time software on his console. He needs either an avi, mpeg file or a vhs tape. He is asking us for help." *[MMACS=Mechanical, Maintenance, Arm and Crew Systems]*

The controller at the Mechanical, Maintenance, Arm and Crew Systems console would be among the first in Mission Control to see indications of burn-through during *Columbia*'s re-entry on the morning of February 1. This log entry also indicates that Mission Control personnel were aware of the strike.

Flight Day Eight, Thursday, January 23, 2003

The morning after Shuttle Program Management decided not to pursue on-orbit imagery, Rodney Rocha received a return call from Mission Operations Directorate representative Barbara Conte to discuss what kinds of imaging capabilities were available for STS-107.

Missed Opportunity 7

Conte explained to Rocha that the Mission Operations Directorate at Johnson did have U.S. Air Force standard services for imaging the Shuttle during Solid Rocket Booster separation and External Tank separation. Conte explained that the Orbiter would probably have to fly over Hawaii to be imaged. The Board notes that this statement illustrates an unfamiliarity with National imaging assets. Hawaii is only one of many sites where relevant assets are based. Conte asked Rocha if he wanted her to pursue such a request through Missions Operations Directorate channels. Rocha said no, because he believed Program managers would still have to support such a request. Since they had already decided that imaging of potentially damaged areas was not necessary, Rocha thought it unlikely that the Debris Assessment Team could convince them otherwise without definitive data.

Later that day, Conte and another Mission Operations Directorate representative were attending an unrelated meeting with Leroy Cain, the STS-107 ascent/entry Flight Director. At that meeting, they conveyed Rocha's concern to Cain and offered to help with obtaining imaging. After checking with Phil Engelauf, Cain distributed the following e-mail.

-----Original Message-----
From: CAIN, LEROY E. (JSC-DA8) (NASA)
Sent: Thursday, January 23, 2003 12:07 PM
To: JONES, RICHARD S. (JSC-DM) (NASA); OLIVER, GREGORY T. (GREG) (JSC-DM4) (NASA); CONTE, BARBARA A. (JSC-DM) (NASA)
Cc: ENGELAUF, PHILIP L. (JSC-DA8) (NASA); AUSTIN, BRYAN P. (JSC-DA8) (NASA); BECK, KELLY B. (JSC-DA8) (NASA); HANLEY, JEFFREY M. (JEFF) (JSC-DA8) (NASA); STICH, J. S. (STEVE) (JSC-DA8) (NASA)
Subject: Help with debris hit

The SSP was asked directly if they had any interest/desire in requesting resources outside of NASA to view the Orbiter (ref. the wing leading edge debris concern).

They said, No.

After talking to Phil, I consider it to be a dead issue.

[SSP=Space Shuttle Program]

Also on Flight Day Eight, Debris Assessment Team engineers presented their final debris trajectory estimates to their NASA, United Space Alliance, and Boeing managers. These estimates formed the basis for predicting the Orbiter's damaged areas as well as the extent of damage, which in turn determined the ultimate threat to the Orbiter during re-entry.

Mission Control personnel thought they should tell Commander Rick Husband and Pilot William McCool about the debris strike, not because they thought that it was worthy of the crew's attention but because the crew might be asked about it in an upcoming media interview. Flight Director Steve Stitch sent the following e-mail to Husband and McCool and copied other Flight Directors.

-----Original Message-----
From: STICH, J. S. (STEVE) (JSC-DA8) (NASA)
Sent: Thursday, January 23, 2003 11:13 PM
To: CDR; PLT
Cc: BECK, KELLY B. (JSC-DA8) (NASA); ENGELAUF, PHILIP L. (JSC-DA8) (NASA); CAIN, LEROY E. (JSC-DA8) (NASA); HANLEY, JEFFREY M. (JEFF) (JSC-DA8) (NASA); AUSTIN, BRYAN P. (JSC-DA8) (NASA)
Subject: INFO: Possible PAO Event Question

Rick and Willie,

You guys are doing a fantastic job staying on the timeline and accomplishing great science. Keep up the good work and let us know if there is anything that we can do better from an MCC/POCC standpoint.

There is one item that I would like to make you aware of for the upcoming PAO event on Blue FD 10 and for future PAO events later in the mission. This item is not even worth mentioning other than wanting to make sure that you are not surprised by it in a question from a reporter.

During ascent at approximately 80 seconds, photo analysis shows that some debris from the area of the -Y ET Bipod Attach Point came loose and subsequently impacted the orbiter left wing, in the area of transition from Chine to Main Wing, creating a shower of smaller particles. The impact appears to be totally on the lower surface and no particles are seen to traverse over the upper surface of the wing. Experts have reviewed the high speed photography and there is no concern for RCC or tile damage. We have seen this same phenomenon on several other flights and there is absolutely no concern for entry.

That is all for now. It's a pleasure working with you every day.

[MCC/POCC=Mission Control Center/Payload Operations Control Center, PAO=Public Affairs Officer, FD 10=Flight Day Ten, -Y=left, ET=External Tank]

This e-mail was followed by another to the crew with an attachment of the video showing the debris impact. Husband acknowledged receipt of these messages.

Later, a NASA liaison to USSTRATCOM sent an e-mail thanking personnel for the prompt response to the imagery request. The e-mail asked that they help NASA observe "official channels" for this type of support in the future. Excerpts from this message follow.

> *"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,

MOA=Memorandum of Agreement, POC=Point of Contact, CMOC=Cheyenne Mountain Operations Center, DDMS=Department of Defense Manned Space Flight Support Office]

Third Debris Assessment Team Meeting

The Debris Assessment Team met for the third time Thursday afternoon to review updated impact analyses. Engineers noted that there were no alternate re-entry trajectories that the Orbiter could fly to substantially reduce heating in the general area of the foam strike. Engineers also presented final debris trajectory data that included three debris size estimates to cover the continuing uncertainty about the size of the debris. Team members were told that imaging would not be forthcoming. In the face of this denial, the team discussed whether to include a presentation slide supporting their desire for images of the potentially damaged area. Many still felt it was a valid request and wanted their concerns aired at the upcoming Mission Evaluation Room brief and then at the Mission Management Team level. Eventually, the idea of including a presentation slide about the imaging request was dropped.

Just prior to attending the third assessment meeting, tile expert Calvin Schomburg and Rodney Rocha met to discuss foam impacts from other missions. Schomburg implied that the STS-107 foam impact was in the Orbiter's experience base and represented only a maintenance issue. Rocha disagreed and argued about the potential for burn-through on re-entry. Calvin Schomburg stated a belief that if there was severe damage to the tiles, *"nothing could be done."* (See Section 6.4.) Both then joined the meeting already in progress.

According to Boeing analysts who were members of the Debris Assessment Team, Schomburg called to ask about their rationale for pursuing imagery. The Boeing analysts told him that something the size of a large cooler had hit the Orbiter at 500 miles per hour. Pressed for additional reasons and not fully understanding why their original justification was insufficient, the analysts said that at least they would know what happened if something were to go terribly wrong. The Boeing analysts next asked why they were working so hard analyzing potential damage areas if Shuttle Program management believed the damage was minor and that no safety-of-flight issues existed. Schomburg replied that the analysts were new and would learn from this exercise.

Flight Day Nine, Friday, January 24, 2003

At 7:00 a.m., Boeing and United Space Alliance contract personnel presented the Debris Assessment Team's findings to Don McCormack, the Mission Evaluation Room manager. In yet another signal that working engineers and mission personnel shared a high level of concern for *Columbia*'s condition, so many engineers crowded the briefing room that it was standing room only, with people lining the hallway.

The presentation included viewgraphs that discussed the team's analytical methodology and five scenarios for debris damage, each based on different estimates of debris size and impact point. A sixth scenario had not yet been completed, but early indications suggested that it would not differ significantly from the other five. Each case was presented with a general overview of transport mechanics, results from the Crater modeling, aerothermal considerations, and predicted thermal and structural effects for *Columbia*'s re-entry. The briefing focused primarily on potential damage to the tiles, not the RCC panels. (An analysis of how the poor construction of these viewgraphs effectively minimized key assumptions and uncertainties is presented in Chapter 7.)

While the team members were confident that they had conducted the analysis properly – within the limitations of the information they had – they stressed that many uncertainties remained. First, there was great uncertainty about where the debris had struck. Second, Crater, the analytical tool they used to predict the penetration depth of debris impact, was being used on a piece of debris that was 400 times larger than the standard in Boeing's database. (At the time, the team believed that the debris was 640 times larger.) Engineers ultimately concluded that their analysis, limited as it was, did not show that a safety-of-flight issue existed. Engineers who attended this briefing indicated a belief that management focused on the answer – that analysis proved there was no safety-of-flight issue – rather than concerns about the large uncertainties that may have undermined the analysis that provided that answer.

At the Mission Management Team's 8:00 a.m. meeting, Mission Evaluation Room manager Don McCormack verbally summarized the Debris Assessment Team's 7:00 a.m. brief. It was the third topic discussed. Unlike the earlier briefing, McCormack's presentation did not include the Debris Assessment Team's presentation charts. The Board notes that no supporting analysis or examination of minority engineering views was asked for or offered, that neither Mission Evaluation Room nor Mission Management Team members requested a technical paper of the Debris Assessment Team analysis, and that no technical questions were asked.

January 24, 2003, Mission Management Team Meeting Transcript

The following is a transcript of McCormack's verbal briefing to the Mission Management Team, which Linda Ham Chaired. Early in the meeting, Phil Engelauf, Chief of the Flight Director's office, reported that he had made clear in an e-mail to *Columbia's* crew that there were "no concerns" that the debris strike had caused serious damage. The Board notes that this conclusion about whether the debris strike posed a safety-of-flight issue was presented to Mission Management Team members before they discussed the debris strike damage assessment.

Engelauf: "*I will say that crew did send down a note last night asking if anybody is talking about extension days or going to go with that and we sent up to the crew about a 15 second video clip of the strike just so they are armed if they get any questions at the press conferences or that sort of thing, but we made it very clear to them no, no concerns.*"

Linda Ham: "*When is the press conference? Is it today?*"

Engelauf: "*It's later today.*"

Ham: "*They may get asked because the press is aware of it.*"

Engelauf: "*The press is aware of it I know folks have asked me because the press corps at the cape have been asking…wanted to make sure they were properly…*"

Ham: "*Okay, back on the temperature…*"

The meeting went on for another 25 minutes. Other mission-related subjects were discussed before team members returned to the debris strike.

Ham: "*Go ahead, Don.*"

Don McCormack: "*Okay. And also we've received the data from the systems integration guys of the potential ranges of sizes and impact angles and where it might have hit. And the guys have gone off and done an analysis, they use a tool they refer to as Crater which is their official evaluation tool to determine the potential size of the damage. So they went off and done all that work and they've done thermal analysis to the areas where there may be damaged tiles. The analysis is not complete. There is one case yet that they wish to run, but kind of just jumping to the conclusion of all that, they do show that, obviously, a potential for significant tile damage here, but thermal analysis does not indicate that there is potential for a burn-through. I mean there could be localized heating damage. There is… 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.*"

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

McCormack: "*Right, it would mean possible impacts to turnaround repairs and that sort of thing, but we do not see any kind of safety of flight issue here yet in anything that we've looked at.*"

Ham: "*And no safety of flight, no issue for this mission, nothing that we're going to do different, there may be a turnaround.*"

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

Ham: "*What do you mean by that?*"

McCormack: "*Well it could be down through the … we could lose an entire tile and then the ramp into and out of that, I mean it could be a significant area of tile damage down to the SIP perhaps, so it could be a significant piece missing, but…*" [SIP refers to the denser lower layers of tile to which the debris may have penetrated.]

Ham.: "*It would be a turnaround issue only?*"

McCormack: "*Right.*"

(Unintelligible speaker)

At this point, tile expert Calvin Schomburg states his belief that no safety-of-flight issue exists. However, some participants listening via teleconference to the meeting are unable to hear his comments.

Ham: "*Okay. Same thing you told me about the other day in my office. We've seen pieces of this size before haven't we?*"

Unknown speaker. "*Hey Linda, we're missing part of that conversation.*"

Ham: "*Right.*"

Unknown speaker: "*Linda, we can't hear the speaker.*"

Ham: "*He was just reiterating with Calvin that he doesn't believe that there is any burn-through so no safety of flight kind of issue, it's more of a turnaround issue similar to what we've had on other flights. That's it? Alright, any questions on that?*"

The Board notes that when the official minutes of the January 24 Mission Management Team were produced and distributed, there was no mention of the debris strike. These minutes were approved and signed by Frank Moreno, STS-107 Lead Payload Integration Manager, and Linda Ham. For anyone not present at the January 24 Mission Management Team who was relying on the minutes to update them on key issues, they would have read nothing about the debris-strike discussions between Don McCormack and Linda Ham.

A subsequent 8:59 a.m. Mission Evaluation Room console log entry follows.

> *"MMT Summary…McCormack also summarized the debris assessment. Bottom line is that there appears to be no safety of flight issue, but good chance of turnaround impact to repair tile damage."* [MMT=Mission Management Team]

Flight Day 10 through 16, Saturday through Friday, January 25 through 31, 2003

Although "no safety-of-flight issue" had officially been noted in the Mission Evaluation Room log, the Debris Assessment Team was still working on parts of its analysis of potential damage to the wing and main landing gear door. On Sunday, January 26, Rodney Rocha spoke with a Boeing thermal analyst and a Boeing stress analyst by telephone to express his concern about the Debris Assessment Team's overall analysis, as well as the remaining work on the main landing gear door analysis. After the Boeing engineers stated their confidence with their analyses, Rocha became more comfortable with the damage assessment and sent the following e-mail to his management.

-----Original Message-----
From: ROCHA, ALAN R. (RODNEY) (JSC-ES2) (NASA)
Sent: Sunday, January 26, 2003 7:45 PM
To: SHACK, PAUL E. (JSC-EA42) (NASA); MCCORMACK, DONALD L. (DON) (JSC-MV6) (NASA); OUELLETTE, FRED A. (JSC-MV6) (NASA)
Cc: ROGERS, JOSEPH E. (JOE) (JSC-ES2) (NASA); GALBREATH, GREGORY F. (GREG) (JSC-ES2) (NASA); JACOBS, JEREMY B. (JSC-ES4) (NASA); SERIALE-GRUSH, JOYCE M. (JSC-EA) (NASA); KRAMER, JULIE A. (JSC-EA4) (NASA); CURRY, DONALD M. (JSC-ES3) (NASA); KOWAL, T. J. (JOHN) (JSC-ES3) (NASA); RICKMAN, STEVEN L. (JSC-ES3) (NASA); SCHOMBURG, CALVIN (JSC-EA) (NASA); CAMPBELL, CARLISLE C., JR (JSC-ES2) (NASA)
Subject: STS-107 Wing Debris Impact on Ascent: Final analysis case completed

As you recall from Friday's briefing to the MER, there remained open work to assess analytically predicted impact damage to the wing underside in the region of the main landing gear door. This area was considered a low probability hit area by the image analysis teams, but they admitted a debris strike here could not be ruled out.

As with the other analyses performed and reported on Friday, this assessment by the Boeing multi-technical discipline engineering teams also employed the system integration's dispersed trajectories followed by serial results from the *Crater* damage prediction tool, thermal analysis, and stress analysis. It was reviewed and accepted by the ES-DCE (R. Rocha) by Sunday morning, Jan. 26. The case is defined by a large area gouge about 7 inch wide and about 30 inch long with sloped sides like a crater, and reaching down to the densified layer of the TPS.

SUMMARY: Though this case predicted some higher temperatures at the outer layer of the honeycomb aluminum face sheet and subsequent debonding of the sheet, there is no predicted burn-through of the door, no breeching of the thermal and gas seals, nor is there door structural deformation or thermal warpage to open the seal to hot plasma intrusion. Though degradation of the TPS and door structure is likely (if the impact occurred here), there is no safety of flight (entry, descent, landing) issue.

Note to Don M. and Fred O.: On Friday I believe the MER was thoroughly briefed and it was clear that open work remained (viz., the case summarized above), the message of open work was not clearly given, in my opinion, to Linda Ham at the MMT. I believe we left her the impression that engineering assessments and cases were all finished and we could state with finality no safety of flight issues or questions remaining. This very serious case could not be ruled out and it was a very good thing we carried it through to a finish.

Rodney Rocha (ES2)
- Division Shuttle Chief Engineer (DCE), ES-Structural Engineering Division
- Chair, Space Shuttle Loads & Dynamics Panel

[MER=Mission Evaluation Room, ES-DCE=Structural Engineering-Division Shuttle Chief Engineer, TPS=Thermal Protection System]

In response to this e-mail, Don McCormack told Rocha that he would make sure to correct Linda Ham's possible misconception that the Debris Assessment Team's analysis was finished as of the briefing to the Mission Management Team. McCormack informed Ham at the next Mission Management Team meeting on January 27, that the damage assessment had in fact been ongoing and that their final conclusion was that no safety-of-flight issue existed. The debris strike, in the official estimation of the Debris Assessment Team, amounted to only a post-landing turn-around maintenance issue.

On Monday morning, January 27, Doug Drewry, a structural engineering manager from Johnson Space Center, summoned several Johnson engineers and Rocha to his office and asked them if they all agreed with the completed analyses and with the conclusion that no safety-of-flight issues existed. Although all participants agreed with that conclusion, they also knew that the Debris Assessment Team members and most structural engineers at Johnson still wanted images of *Columbia*'s left wing but had given up trying to make that desire fit the "mandatory" requirement that Shuttle management had set.

Langley Research Center

Although the Debris Analysis Team had completed its analysis and rendered a "no safety-of-flight" verdict, concern persisted among engineers elsewhere at NASA as they learned about the debris strike and potential damage. On Monday, January 27, Carlisle Campbell, the design engineer responsible for landing gear/tires/brakes at Johnson Space Center forwarded Rodney Rocha's January 26, e-mail to Bob Daugherty, an engineer at Langley Research Center who specialized in landing gear design. Engineers at Langley and Ames Research Center and Johnson Space Center did not entertain the possibility of *Columbia* breaking up during re-entry, but rather focused on the idea that landing might not be safe, and that the crew might need to "ditch" the vehicle (crash land in water) or be prepared to land with damaged landing gear.

Campbell initially contacted Daugherty to ask his opinion of the arguments used to declare the debris strike "not a safety-of-flight issue." Campbell commented that someone had brought up worst-case scenarios in which a breach in the main landing gear door causes two tires to go flat. To help Daugherty understand the problem, Campbell forwarded him e-mails, briefing slides, and film clips from the debris damage analysis.

Both engineers felt that the potential ramifications of landing with two flat tires had not been sufficiently explored. They discussed using Shuttle simulator facilities at Ames Research Center to simulate a landing with two flat tires, but initially ruled it out because there was no formal request from the Mission Management Team to work the problem. Because astronauts were training in the Ames simulation facility, the two engineers looked into conducting the simulations after hours. Daugherty contacted his management on Tuesday, January 28, to update them on the plan for after-hours simulations. He reviewed previous data runs, current simulation results, and prepared scenarios that could result from main landing gear problems.

The simulated landings with two flat tires that Daugherty eventually conducted indicated that it was a survivable but very serious malfunction. Of the various scenarios he prepared, Daugherty shared the most unfavorable only with his management and selected Johnson Space Center engineers. In contrast, his favorable simulation results were forwarded to a wider Johnson audience for review, including Rodney Rocha and other Debris Assessment Team members. The Board is disappointed that Daugherty's favorable scenarios received a wider distribution than his discovery of a potentially serious malfunction, and also does not approve of the reticence that he and his managers displayed in not notifying the Mission Management Team of their concerns or his assumption that they could not displace astronauts who were training in the Ames simulator.

At 4:36 p.m. on Monday, January 27, Daugherty sent the following to Campbell.

-----Original Message-----
From: Robert H. Daugherty
Sent: Monday, January 27, 2003 3:35 PM
To: CAMPBELL, CARLISLE C., JR (JSC-ES2) (NASA)
Subject: Video you sent

WOW!!!
I bet there are a few pucker strings pulled tight around there!
Thinking about a belly landing versus bailout...... (I would say that if there is a question about main gear well burn thru that its crazy to even hit the deploy gear button...the reason being that you might have failed the wheels since they are aluminum..they will fail before the tire heating/pressure makes them fail..and you will send debris all over the wheel well making it a possibility that the gear would not even deploy due to ancillary damage...300 feet is the wrong altitude to find out you have one gear down and the other not down...you're dead in that case)
Think about the pitch-down moment for a belly landing when hitting not the main gear but the trailing edge of the wing or body flap when landing gear up...even if you come in fast and at slightly less pitch attitude...the nose slapdown with that pitching moment arm seems to me to be pretty scary...so much so that I would bail out before I would let a loved one land like that.
My two cents.
See ya,
Bob

The following reply from Campbell to Daugherty was sent at 4:49 p.m.

-----Original Message-----
From: "CAMPBELL, CARLISLE C., JR (JSC-ES2) (NASA)"
To: "'Bob Daugherty'"
Subject: FW: Video you sent
Date: Mon, 27 Jan 2003 15:59:53 -0600
X-Mailer: ßInternet Mail Service (5.5.2653.19)

Thanks. That's why they need to get all the facts in early on--such as look at impact damage from the spy telescope. Even then, we may not know the real effect of the damage.

The LaRC ditching model tests 20 some years ago showed that the Orbiter was the best ditching shape that they had ever tested, of many. But, our structures people have said that if we ditch we would blow such big holes in the lower panels that the orbiter might break up. Anyway, they refuse to even consider water ditching any more--I still have the test results[Bailout seems best.

[LaRC=Langley Research Center]

On the next day, Tuesday, Daugherty sent the following to Campbell.

-----Original Message-----
From: Robert H. Daugherty
Sent: Tuesday, January 28, 2003 12:39 PM
To: CAMPBELL, CARLISLE C., JR (JSC-ES2) (NASA)
Subject: Tile Damage

Any more activity today on the tile damage or are people just relegated to
crossing their fingers and hoping for the best?
See ya,
Bob

Campbell's reply:

-----Original Message-----
From: "CAMPBELL, CARLISLE C., JR (JSC-ES2) (NASA)"
To: "'Robert H. Daugherty'"
Subject: RE: Tile Damage
Date: Tue, 28 Jan 2003 13:29:58 -0600
X-Mailer: Internet Mail Service (5.5.2653.19)

I have not heard anything new. I'll let you know if I do.

CCC

Carlisle Campbell sent the following e-mail to Johnson Space Center engineering managers on January 31.

> *"In order to alleviate concerns regarding the worst case scenario which could potentially be caused by the debris impact under the Orbiter's left wing during launch, EG conducted some landing simulations on the Ames Vertical Motion Simulator which tested the ability of the crew and vehicle to survive a condition where two main gear tires are deflated before landing. The results, although limited, showed that this condition is controllable, including the nose slap down rates. These results may give MOD a different decision path should this scenario become a reality. Previous opinions were that bailout was the only answer."*
> *[EG=Aeroscience and Flight Mechanics Division, MOD=Mission Operations Directorate]*

In the Mission Evaluation Room, a safety representative from Science Applications International Corporation, NASA's contract safety company, made a log entry at the Safety and Quality Assurance console on January 28, at 12:15 p.m. It was only the second mention of the debris strike in the safety console log during the mission (the first was also minor).

> *"[MCC SAIC] called asking if any SR&QA people were involved in the decision to say that the ascent debris hit (left wing) is safe. [SAIC engineer] has indeed been involved in the analysis and stated that he concurs with the analysis. Details about the debris hit are found in the Flight Day 12 MER Manager and our Daily Report."* [MCC=Mission Control Center, SAIC=Science Applications International Corporation, SR&QA=Safety, Reliability, and Quality Assurance, MER=Mission Evaluation Room]

Missed Opportunity 8

According to a Memorandum for the Record written by William Readdy, Associate Administrator for Space Flight, Readdy and Michael Card, from NASA's Safety and Mission Assurance Office, discussed an offer of Department of Defense imagery support for *Columbia*. This January 29, conversation ended with Readdy telling Card that NASA would accept the offer but because the Mission Management Team had concluded that this was not a safety-of-flight issue, the imagery should be gathered only on a low priority "not-to-interfere" basis. Ultimately, no imagery was taken.

The Board notes that at the January 31, Mission Management Team meeting, there was only a minor mention of the debris strike. Other issues discussed included onboard crew consumables, the status of the leaking water separator, an intercom anomaly, SPACEHAB water flow rates, an update of the status of onboard experiments, end-of-mission weight concerns, landing day weather forecasts, and landing opportunities. The only mention of the debris strike was a brief comment by Bob Page, representing Kennedy Space Center's Launch Integration Office, who stated that the crew's hand-held cameras and External Tank films would be expedited to Marshall Space Flight Center via the Shuttle Training Aircraft for post-flight foam/debris imagery analysis, per Linda Ham's request.

Summary: Mission Management Decision Making

Discovery and Initial Analysis of Debris Strike

In the course of examining film and video images of *Columbia's* ascent, the Intercenter Photo Working Group identified, on the day after launch, a large debris strike to the leading edge of *Columbia*'s left wing. Alarmed at seeing so severe a hit so late in ascent, and at not having a clear view of damage the strike might have caused, Intercenter Photo Working Group members alerted senior Program managers by phone and sent a digitized clip of the strike to hundreds of NASA personnel via e-mail. These actions initiated a contingency plan that brought together an interdisciplinary group of experts from NASA, Boeing, and the United Space Alliance to analyze the strike. So concerned were Intercenter Photo Working Group personnel that on the day they discovered the debris strike, they tapped their Chair, Bob Page, to see through a request to image the left wing with Department of Defense assets in anticipation of analysts needing these images to better determine potential damage. By the Board's count, this would be the first of three requests to secure imagery of *Columbia* on-orbit during the 16-day mission.

Imagery Requests

1. Flight Day 2. Bob Page, Chair, Intercenter Photo Working Group to Wayne Hale, Shuttle Program Manager for Launch Integration at Kennedy Space Center (in person).
2. Flight Day 6. Bob White, United Space Alliance manager, to Lambert Austin, head of the Space Shuttle Systems Integration at Johnson Space Center (by phone).
3. Flight Day 6. Rodney Rocha, Co-Chair of Debris Assessment Team to Paul Shack, Manager, Shuttle Engineering Office (by e-mail).

Missed Opportunities

1. Flight Day 4. Rodney Rocha inquires if crew has been asked to inspect for damage. No response.
2. Flight Day 6. Mission Control fails to ask crew member David Brown to downlink video he took of External Tank separation, which may have revealed missing bipod foam.
3. Flight Day 6. NASA and National Imagery and Mapping Agency personnel discuss possible request for imagery. No action taken.
4. Flight Day 7. Wayne Hale phones Department of Defense representative, who begins identifying imaging assets, only to be stopped per Linda Ham's orders.
5. Flight Day 7. Mike Card, a NASA Headquarters manager from the Safety and Mission Assurance Office, discusses imagery request with Mark Erminger, Johnson Space Center Safety and Mission Assurance. No action taken.
6. Flight Day 7. Mike Card discusses imagery request with Bryan O'Connor, Associate Administrator for Safety and Mission Assurance. No action taken.
7. Flight Day 8. Barbara Conte, after discussing imagery request with Rodney Rocha, calls LeRoy Cain, the STS-107 ascent/entry Flight Director. Cain checks with Phil Engelauf, and then delivers a "no" answer.
8. Flight Day 14. Michael Card, from NASA's Safety and Mission Assurance Office, discusses the imaging request with William Readdy, Associate Administrator for Space Flight. Readdy directs that imagery should only be gathered on a "not-to-interfere" basis. None was forthcoming.

Upon learning of the debris strike on Flight Day Two, the responsible system area manager from United Space Alliance and her NASA counterpart formed a team to analyze the debris strike in accordance with mission rules requiring the careful examination of any "out-of-family" event. Using film from the Intercenter Photo Working Group, Boeing systems integration analysts prepared a preliminary analysis that afternoon. (Initial estimates of debris size and speed, origin of debris, and point of impact would later prove remarkably accurate.)

As Flight Day Three and Four unfolded over the Martin Luther King Jr. holiday weekend, engineers began their analysis. One Boeing analyst used Crater, a mathematical prediction tool, to assess possible damage to the Thermal Protection System. Analysis predicted tile damage deeper than the actual tile depth, and penetration of the RCC coating at impact angles above 15 degrees. This suggested the potential for a burn-through during re-entry. Debris Assessment Team members judged that the actual damage would not be as severe as predicted because of the inherent conservatism in the Crater model and because, in the case of tile, Crater does not take into account the tile's stronger and more impact-resistant "densified" layer, and in the case of RCC, the lower density of foam would preclude penetration at impact angles under 21 degrees.

On Flight Day Five, impact assessment results for tile and RCC were presented at an informal meeting of the Debris Assessment Team, which was operating without direct Shuttle Program or Mission Management leadership. Mission Control's engineering support, the Mission Evaluation Room, provided no direction for team activities other than to request the team's results by January 24. As the problem was being worked, Shuttle managers did not formally direct the actions of or consult with Debris Assessment Team leaders about the team's assumptions, uncertainties, progress, or interim results, an unusual circumstance given that NASA managers are normally engaged in analyzing what they view as problems. At this meeting, participants agreed that an image of the area of the wing in question was essential to refine their analysis and reduce the uncertainties in their damage assessment.

Each member supported the idea to seek imagery from an outside source. Due in part to a lack of guidance from the Mission Management Team or Mission Evaluation Room managers, the Debris Assessment Team chose an unconventional route for its request. Rather than working the request up the normal chain of command – through the Mission Evaluation Room to the Mission Management Team for action to Mission Control – team members nominated Rodney Rocha, the team's Co-Chair, to pursue the request through the Engineering Directorate at Johnson Space Center. As a result, even after the accident the Debris Assessment Team's request was viewed by Shuttle Program managers as a non-critical engineering desire rather than a critical operational need.

When the team learned that the Mission Management Team was not pursuing on-orbit imaging, members were concerned. What Debris Assessment Team members did not realize was the negative response from the Program was not necessarily a direct and final response to their official request. Rather, the "no" was in part a response to requests for imagery initiated by the Intercenter Photo Working Group at Kennedy on Flight Day 2 in anticipation of analysts' needs that had become by Flight Day 6 an actual engineering request by the Debris Assessment Team, made informally through Bob White to Lambert Austin, and formally through Rodney Rocha's e-mail to Paul Shack. Even after learning that the Shuttle Program was not going to provide the team with imagery, some members sought information on how to obtain it anyway.

Debris Assessment Team members believed that imaging of potentially damaged areas was necessary even after the January 24, Mission Management Team meeting, where they had reported their results. Why they did not directly approach Shuttle Program managers and share their concern and uncertainty, and why Shuttle Program managers claimed to be isolated from engineers, are points that the Board labored to understand. Several reasons for this communications failure relate to NASA's internal culture and the climate established by Shuttle Program management, which are discussed in more detail in Chapters 7 and 8.

A Flawed Analysis

An inexperienced team, using a mathematical tool that was not designed to assess an impact of this estimated size, performed the analysis of the potential effect of the debris impact. Crater was designed for "in-family" impact events and was intended for day-of-launch analysis of debris impacts. It was not intended for large projectiles like those observed on STS-107. Crater initially predicted possible damage, but the Debris Assessment Team assumed, without theoretical or experimental validation, that because Crater is a conservative tool – that is, it predicts more damage than will actually occur – the debris would stop at the tile's densified layer, even though their experience did not involve debris strikes as large as STS-107's. Crater-like equations were also used as part of the analysis to assess potential impact damage to the wing leading edge RCC. Again, the tool was used for something other than that for which it was designed; again, it predicted possible penetration; and again, the Debris Assessment Team used engineering arguments and their experience to discount the results.

As a result of a transition of responsibility for Crater analysis from the Boeing Huntington Beach facility to the Houston-based Boeing office, the team that conducted the Crater analyses had been formed fairly recently, and therefore could be considered less experienced when compared with the more senior Huntington Beach analysts. In fact, STS-107 was the first mission for which they were solely responsible for providing analysis with the Crater tool. Though post-accident interviews suggested that the training for the Houston Boeing analysts was of high quality and adequate in substance and duration, communications and theoretical understandings of the Crater model among the Houston-based team members had not yet developed to the standard of a more senior team. Due in part to contractual arrangements related to the transition, the Houston-based team did not take full advantage of the Huntington Beach engineers' experience.

At the January 24, Mission Management Team meeting at which the "no safety-of-flight" conclusion was presented, there was little engineering discussion about the assumptions made, and how the results would differ if other assumptions were used.

Engineering solutions presented to management should have included a quantifiable range of uncertainty and risk analysis. Those types of tools were readily available, routinely used, and would have helped management understand the risk involved in the decision. Management, in turn, should have demanded such information. The very absence of a clear and open discussion of uncertainties and assumptions in the analysis presented should have caused management to probe further.

Shuttle Program Management's Low Level of Concern

While the debris strike was well outside the activities covered by normal mission flight rules, Mission Management Team members and Shuttle Program managers did not treat the debris strike as an issue that required operational action by Mission Control. Program managers, from Ron Dittemore to individual Mission Management Team members, had, over the course of the Space Shuttle Program, gradually become inured to External Tank foam losses and on a fundamental level did not believe foam striking the vehicle posed a critical threat to the Orbiter. In particular, Shuttle managers exhibited a belief that RCC panels are impervious to foam impacts. Even after seeing the video of *Columbia*'s debris impact, learning estimates of the size and location of the strike, and noting that a foam strike with sufficient kinetic energy could cause Thermal Protection System damage, management's level of concern did not change.

The opinions of Shuttle Program managers and debris and photo analysts on the potential severity of the debris strike diverged early in the mission and continued to diverge as the mission progressed, making it increasingly difficult for the Debris Assessment Team to have their concerns heard by those in a decision-making capacity. In the face of Mission managers' low level of concern and desire to get on with the mission, Debris Assessment Team members had to prove unequivocally that a safety-of-flight issue existed before Shuttle Program management would move to obtain images of the left wing. The engineers found themselves in the unusual position of having to prove that the situation was *unsafe* – a reversal of the usual requirement to prove that a situation *is safe*.

Other factors contributed to Mission management's ability to resist the Debris Assessment Team's concerns. A tile expert told managers during frequent consultations that strike damage was only a maintenance-level concern and that on-orbit imaging of potential wing damage was not necessary. Mission management welcomed this opinion and sought no others. This constant reinforcement of managers' pre-existing beliefs added another block to the wall between decision makers and concerned engineers.

Another factor that enabled Mission management's detachment from the concerns of their own engineers is rooted in the culture of NASA itself. The Board observed an unofficial hierarchy among NASA programs and directorates that hindered the flow of communications. The effects of this unofficial hierarchy are seen in the attitude that members of the Debris Assessment Team held. Part of the reason they chose the institutional route for their imagery request was that without direction from the Mission Evaluation Room and Mission Management Team, they felt more comfortable with their own chain of command, which was outside the Shuttle Program. Further, when asked by investigators why they were not more vocal about their concerns, Debris Assessment Team members opined that by raising contrary points of view about Shuttle mission safety, they would be singled out for possible ridicule by their peers and managers.

A Lack of Clear Communication

Communication did not flow effectively up to or down from Program managers. As it became clear during the mission that managers were not as concerned as others about the danger of the foam strike, the ability of engineers to challenge those beliefs greatly diminished. Managers' tendency to accept opinions that agree with their own dams the flow of effective communications.

After the accident, Program managers stated privately and publicly that if engineers had a safety concern, they were obligated to communicate their concerns to management. Managers did not seem to understand that as leaders they had a corresponding and perhaps greater obligation to create viable routes for the engineering community to express their views and receive information. This barrier to communications not only blocked the flow of information to managers, but it also prevented the downstream flow of information from managers to engineers, leaving Debris Assessment Team members no basis for understanding the reasoning behind Mission Management Team decisions.

The January 27 to January 31, phone and e-mail exchanges, primarily between NASA engineers at Langley and Johnson, illustrate another symptom of the "cultural fence" that impairs open communications between mission managers and working engineers. These exchanges and the reaction to them indicated that during the evaluation of a mission contingency, the Mission Management Team failed to disseminate information to all system and technology experts who could be consulted. Issues raised by two Langley and Johnson engineers led to the development of "what-if" landing scenarios of the potential outcome if the main landing gear door sustained damaged. This led to behind-the-scenes networking by these engineers to use NASA facilities to make simulation runs of a compromised landing configuration. These engineers – who understood their systems and related technology – saw the potential for a problem on landing and ran it down in case the unthinkable occurred. But their concerns never reached the managers on the Mission Management Team that had operational control over *Columbia*.

A Lack of Effective Leadership

The Shuttle Program, the Mission Management Team, and through it the Mission Evaluation Room, were not actively directing the efforts of the Debris Assessment Team. These management teams were not engaged in scenario selection or discussions of assumptions and did not actively seek status, inputs, or even preliminary results from the individuals charged with analyzing the debris strike. They did not investigate the value of imagery, did not intervene to consult the more experienced Crater analysts at Boeing's Huntington Beach facility, did not probe the assumptions of the Debris Assessment Team's analysis, and did not consider actions to mitigate the effects of the damage on re-entry. Managers' claims that they didn't hear the engineers' concerns were due in part to their not asking or listening.

The Failure of Safety's Role

As will be discussed in Chapter 7, safety personnel were present but passive and did not serve as a channel for the voicing of concerns or dissenting views. Safety representatives attended meetings of the Debris Assessment Team, Mission Evaluation Room, and Mission Management Team, but were merely party to the analysis process and conclusions instead of an independent source of questions and challenges. Safety contractors in the Mission Evaluation Room were only marginally aware of the debris strike analysis. One contractor did question the Debris Assessment Team safety representative about the analysis and was told that it was adequate. No additional inquiries were made. The highest-ranking safety representative at NASA headquarters deferred to Program managers when asked for an opinion on imaging of *Columbia*. The safety manager he spoke to also failed to follow up.

Summary

Management decisions made during *Columbia*'s final flight reflect missed opportunities, blocked or ineffective communications channels, flawed analysis, and ineffective leadership. Perhaps most striking is the fact that management – including Shuttle Program, Mission Management Team, Mission Evaluation Room, and Flight Director and Mission Control – displayed no interest in understanding a problem and its implications. Because managers failed to avail themselves of the wide range of expertise and opinion necessary to achieve the best answer to the debris strike question – "*Was this a safety-of-flight concern?*" – some Space Shuttle Program managers failed to fulfill the implicit contract to do whatever is possible to ensure the safety of the crew. In fact, their management techniques unknowingly imposed barriers that kept at bay both engineering concerns and dissenting views, and ultimately helped create "blind spots" that prevented them from seeing the danger the foam strike posed.

Because this chapter has focused on key personnel who participated in STS-107 bipod foam debris strike decisions, it is tempting to conclude that replacing them will solve all NASA's problems. However, solving NASA's problems is not quite so easily achieved. Peoples' actions are influenced by the organizations in which they work, shaping their choices in directions that even they may not realize. The Board explores the organizational context of decision making more fully in Chapters 7 and 8.

Findings

Intercenter Photo Working Group

F6.3-1 The foam strike was first seen by the Intercenter Photo Working Group on the morning of Flight Day Two during the standard review of launch video and high-speed photography. The strike was larger than any seen in the past, and the group was concerned about possible damage to the Orbiter. No conclusive images of the strike existed. One camera that may have provided an additional view was out of focus because of an improperly maintained lens.

F6.3-2 The Chair of the Intercenter Photo Working Group asked management to begin the process of getting outside imagery to help in damage assessment. This request, the first of three, began its journey through the management hierarchy on Flight Day Two.

F6.3-3 The Intercenter Photo Working Group distributed its first report, including a digitized video clip and initial assessment of the strike, on Flight Day Two. This information was widely disseminated to NASA and contractor engineers, Shuttle Program managers, and Mission Operations Directorate personnel.

F6.3-4 Initial estimates of debris size, speed, and origin were remarkably accurate. Initial information available to managers stated that the debris originated in the left bipod area of the External Tank, was quite large, had a high velocity, and struck the underside of the left wing near its leading edge. The report stated that the debris could have hit the RCC or tile.

The Debris Assessment Team

F6.3-5 A Debris Assessment Team began forming on Flight Day two to analyze the impact. Once the debris strike was categorized as "out of family" by United Space Alliance, contractual obligations led to the Team being Co-Chaired by the cognizant contractor sub-system manager and her NASA counterpart. The team was not designated a Tiger Team by the Mission Evaluation Room or Mission Management Team.

F6.3-6 Though the Team was clearly reporting its plans (and final results) through the Mission Evaluation Room to the Mission Management Team, no Mission manager appeared to "own" the Team's actions. The Mission Management Team, through the Mission Evaluation Room, provided no direction for team activities, and Shuttle managers did not formally consult the Team's leaders about their progress or interim results.

F6.3-7 During an organizational meeting, the Team discussed the uncertainty of the data and the value of on-orbit imagery to "bound" their analysis. In its first official meeting the next day, the Team gave its NASA Co-Chair the action to request imagery of *Columbia* on-orbit.

F6.3-8 The Team routed its request for imagery through Johnson Space Center's Engineering Directorate rather than through the Mission Evaluation Room to the Mission Management Team to the Flight Dynamics Officer, the channel used during a mission. This routing diluted the urgency of their request. Managers viewed it as a non-critical engineering desire rather than a critical operational need.

F6.3-9 Team members never realized that management's decision against seeking imagery was not intended as a direct or final response to their request.

F6.3-10 The Team's assessment of possible tile damage was performed using an impact simulation that was well outside Crater's test database. The Boeing analyst was inexperienced in the use of Crater and the interpretation of its results. Engineers with extensive Thermal Protection System expertise at Huntington Beach were not actively involved in determining if the Crater results were properly interpreted.

F6.3-11 Crater initially predicted tile damage deeper than the actual tile depth, but engineers used their judgment to conclude that damage would not penetrate the densified layer of tile. Similarly, RCC damage conclusions were based primarily on judgment and experience rather than analysis.

F6.3-12 For a variety of reasons, including management failures, communication breakdowns, inadequate imagery, inappropriate use of assessment tools, and flawed engineering judgments, the damage assessments contained substantial uncertainties.

F6.3-13 The assumptions (and their uncertainties) used in the analysis were never presented or discussed in full to either the Mission Evaluation Room or the Mission Management Team.

F6.3-14 While engineers and managers knew the foam could have struck RCC panels; the briefings on the analysis to the Mission Evaluation Room and Mission Management Team did not address RCC damage, and neither Mission Evaluation Room nor Mission Management Team managers asked about it.

Space Shuttle Program Management

F6.3-15 There were lapses in leadership and communication that made it difficult for engineers to raise concerns or understand decisions. Management failed to actively engage in the analysis of potential damage caused by the foam strike.

F6.3-16 Mission Management Team meetings occurred infrequently (five times during a 16 day mission), not every day, as specified in Shuttle Program management rules.

F6.3-17 Shuttle Program Managers entered the mission with the belief, recently reinforced by the STS-113 Flight Readiness Review, that a foam strike is not a safety-of-flight issue.

F6.3-18 After Program managers learned about the foam strike, their belief that it would not be a problem was confirmed (early, and without analysis) by a trusted expert who was readily accessible and spoke from "experience." No one in management questioned this conclusion.

F6.3-19 Managers asked *"Who's requesting the photos?"* instead of assessing the merits of the request. Management seemed more concerned about the staff following proper channels (even while they were themselves taking informal advice) than they were about the analysis.

F6.3-20 No one in the operational chain of command for STS-107 held a security clearance that would enable them to understand the capabilities and limitations of National imagery resources.

F6.3-21 Managers associated with STS-107 began investigating the implications of the foam strike on the launch schedule, and took steps to expedite post-flight analysis.

F6.3-22 Program managers required engineers to prove that the debris strike created a safety-of-flight issue: that is, engineers had to produce evidence that the system was unsafe rather than prove that it was safe.

F6.3-23 In both the Mission Evaluation Room and Mission Management Team meetings over the Debris Assessment Team's results, the focus was on the bottom line – was there a safety-of-flight issue, or not? There was little discussion of analysis, assumptions, issues, or ramifications.

Communication

F6.3-24 Communication did not flow effectively up to or down from Program managers.

F6.3-25 Three independent requests for imagery were initiated.

F6.3-26 Much of Program managers' information came through informal channels, which prevented relevant opinion and analysis from reaching decision makers.

F6.3-27 Program Managers did not actively communicate with the Debris Assessment Team. Partly as a result of this, the Team went through institutional, not mission-related, channels with its request for imagery, and confusion surrounded the origin of imagery requests and their subsequent denial.

F6.3-28 Communication was stifled by the Shuttle Program attempts to find out who had a "mandatory requirement" for imagery.

Safety Representative's Role

F6.3-29 Safety representatives from the appropriate organizations attended meetings of the Debris Assessment Team, Mission Evaluation Room, and Mission Management Team, but were passive, and therefore were not a channel through which to voice concerns or dissenting views.

Recommendation:

R6.3-1 Implement an expanded training program in which the Mission Management Team faces potential crew and vehicle safety contingences beyond launch and ascent. These contingences should involve potential loss of Shuttle or crew, contain numerous uncertainties and unknowns, and require the Mission Management Team to assemble and interact with support organizations across NASA/Contractor lines and in various locations.

R6.3-2 Modify the Memorandum of Agreement with the National Imagery and Mapping Agency (NIMA) to make the imaging of each Shuttle flight while on orbit a standard requirement.

6.4 Possibility of Rescue or Repair

To put the decisions made during the flight of STS-107 into perspective, the Board asked NASA to determine if there were options for the safe return of the STS-107 crew. In this study, NASA was to assume that the extent of damage to the leading edge of the left wing was determined by national imaging assets or by a spacewalk. NASA was then asked to evaluate the possibility of:

1. Rescuing the STS-107 crew by launching *Atlantis*. *Atlantis* would be hurried to the pad, launched, rendezvous with *Columbia*, and take on *Columbia*'s crew for a return. It was assumed that NASA would be willing to expose *Atlantis* and its crew to the same possibility of External Tank bipod foam loss that damaged *Columbia*.
2. Repairing damage to *Columbia*'s wing on orbit. In the repair scenario, astronauts would use onboard materials to rig a temporary fix. Some of *Columbia*'s cargo might be jettisoned and a different re-entry profile would be flown to lessen heating on the left wing leading edge. The crew would be prepared to bail out if the wing structure was predicted to fail on landing.

In its study of these two options, NASA assumed the following timeline. Following the debris strike discovery on Flight Day Two, Mission Managers requested imagery by Flight Day Three. That imagery was inconclusive, leading to a decision on Flight Day Four to perform a spacewalk on Flight Day Five. That spacewalk revealed potentially catastrophic damage. The crew was directed to begin conserving consumables, such as oxygen and water, and Shuttle managers began around-the-clock processing of *Atlantis* to prepare it for launch. Shuttle managers pursued both the rescue and the repair options from Flight Day Six to Flight Day 26, and on that day (February 10) decided which one to abandon.

The NASA team deemed this timeline realistic for several reasons. First, the team determined that a spacewalk to inspect the left wing could be easily accomplished. The team then assessed how the crew could limit its use of consumables to determine how long *Columbia* could stay in orbit. The limiting consumable was the lithium hydroxide canisters, which scrub from the cabin atmosphere the carbon dioxide the crew exhales. After consulting with flight surgeons, the team concluded that by modifying crew activity and sleep time carbon dioxide could be kept to acceptable levels until Flight Day 30 (the morning of February 15). All other consumables would last longer. Oxygen, the next most critical, would require the crew to return on Flight Day 31.

Repairing Damage On Orbit

The repair option (see Figure 6.4-1), while logistically viable using existing materials onboard *Columbia*, relied on so many uncertainties that NASA rated this option "high risk." To complete a repair, the crew would perform a spacewalk to fill an assumed 6-inch hole in an RCC panel with heavy metal tools, small pieces of titanium, or other metal scavenged from the crew cabin. These heavy metals, which would help protect the wing structure, would be held in place during

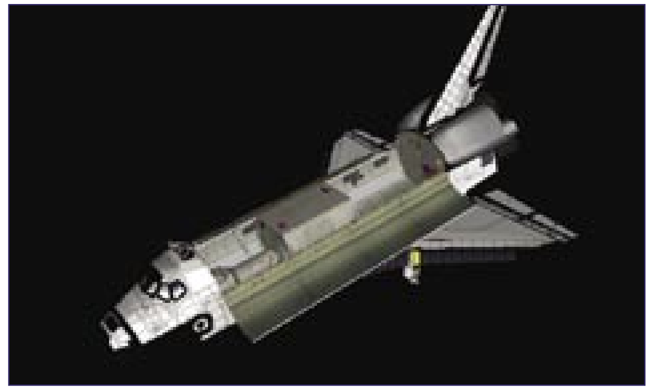
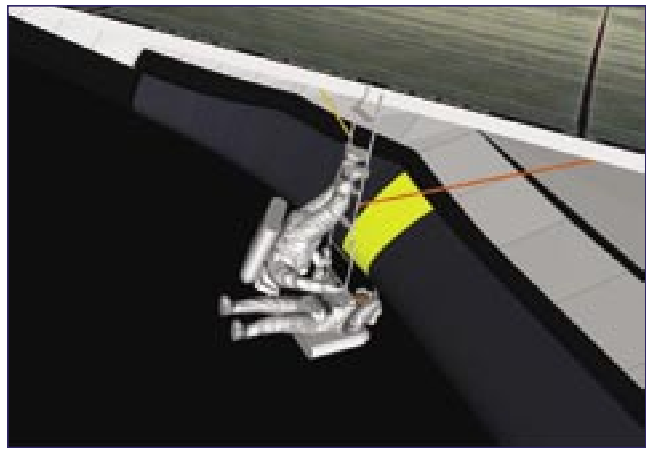


Figure 6.4-1. The speculative repair option would have sent astronauts hanging over the payload bay door to reach the left wing RCC panels using a ladder scavenged from the crew module.



re-entry by a water-filled bag that had turned into ice in the cold of space. The ice and metal would help restore wing leading edge geometry, preventing a turbulent airflow over the wing and therefore keeping heating and burn-through levels low enough for the crew to survive re-entry and bail out before landing. Because the NASA team could not verify that the repairs would survive even a modified re-entry, the rescue option had a considerably higher chance of bringing *Columbia's* crew back alive.

Rescuing the STS-107 Crew with Atlantis

Accelerating the processing of *Atlantis* for early launch and rendezvous with *Columbia* was by far the most complex task in the rescue scenario. On *Columbia's* Flight Day Four, *Atlantis* was in the Orbiter Processing Facility at Kennedy Space Center with its main engines installed and only 41 days from its scheduled March 1 launch. The Solid Rocket Boosters were already mated with the External Tank in the Vehicle Assembly Building. By working three around-the-clock shifts seven days a week, *Atlantis* could be readied for launch, with no necessary testing skipped, by February 10. If launch processing and countdown proceeded smoothly, this would provide a five-day window, from February 10 to February 15, in which *Atlantis* could rendezvous with *Columbia* before *Columbia*'s consumables ran out. According to records, the weather on these days allowed a launch. *Atlantis* would be launched with a crew of four: a command-

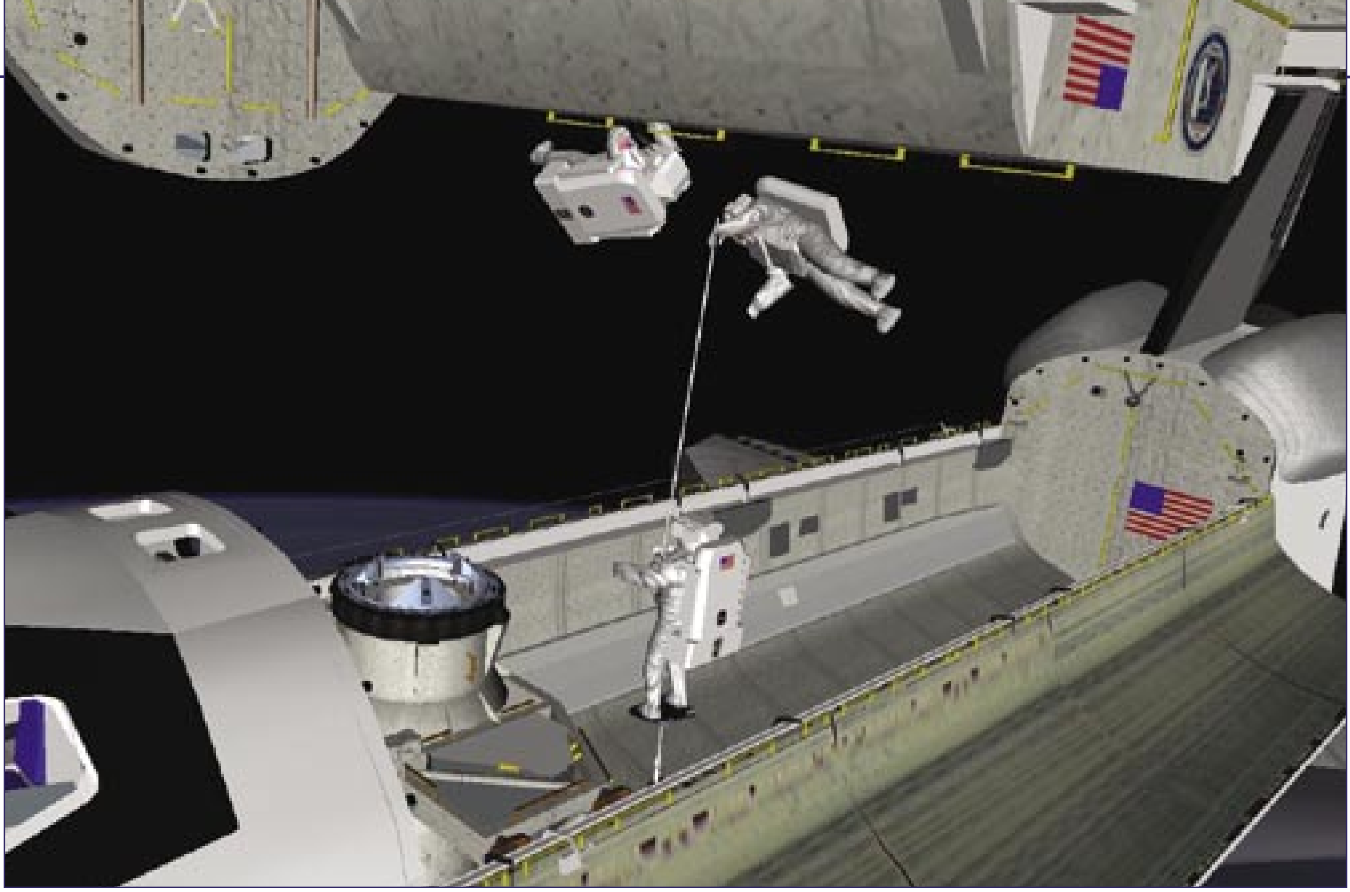


Figure 6.4-2. The rescue option had Atlantis *(lower vehicle) rendezvousing with* Columbia *and the STS-107 crew transferring via ropes. Note that the payload bay of* Atlantis *is empty except for the external airlock/docking adapter.*

er, pilot, and two astronauts trained for spacewalks. In January, seven commanders, seven pilots, and nine spacewalk-trained astronauts were available. During the rendezvous on *Atlantis*'s first day in orbit, the two Orbiters would maneuver to face each other with their payload bay doors open (see Figure 6.4-2). Suited *Columbia* crew members would then be transferred to *Atlantis* via spacewalks. *Atlantis* would return with four crew members on the flight deck and seven in the mid-deck. Mission Control would then configure *Columbia* for a de-orbit burn that would ditch the Orbiter in the Pacific Ocean, or would have the *Columbia* crew take it to a higher orbit for a possible subsequent repair mission if more thorough repairs could be developed.

This rescue was considered challenging but feasible. To succeed, it required problem-free processing of *Atlantis* and a flawless launch countdown. If Program managers had understood the threat that the bipod foam strike posed and were able to unequivocally determine before Flight Day Seven that there was potentially catastrophic damage to the left wing, these repair and rescue plans would most likely have been developed, and a rescue would have been conceivable. For a detailed discussion of the rescue and repair options, see Appendix D.13.

Findings:

F6.4-1 The repair option, while logistically viable using existing materials onboard *Columbia*, relied on so many uncertainties that NASA rated this option "high risk."

F6.4-2 If Program managers were able to unequivocally determine before Flight Day Seven that there was potentially catastrophic damage to the left wing, accelerated processing of *Atlantis* might have provided a window in which *Atlantis* could rendezvous with *Columbia* before *Columbia*'s limited consumables ran out.

Recommendation:

R6.4-1 For missions to the International Space Station, develop a practicable capability to inspect and effect emergency repairs to the widest possible range of damage to the Thermal Protection System, including both tile and Reinforced Carbon-Carbon, taking advantage of the additional capabilities available when near to or docked at the International Space Station.

For non-Station missions, develop a comprehensive autonomous (independent of Station) inspection and repair capability to cover the widest possible range of damage scenarios.

Accomplish an on-orbit Thermal Protection System inspection, using appropriate assets and capabilities, early in all missions.

The ultimate objective should be a fully autonomous capability for all missions to address the possibility that an International Space Station mission fails to achieve the correct orbit, fails to dock successfully, or is damaged during or after undocking.

The crew cabin access arm in position against Columbia *on Launch Complex 39-A.*

ENDNOTES FOR CHAPTER 6

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 "Space Shuttle Program Description and Requirements Baseline," NSTS-07700, Volume X, Book 1. CAIB document CTF028-32643667.

2 "External Tank End Item (CEI) Specification – Part 1," CPT01M09A, contract NAS8 –30300, April 9, 1980, WBS 1.6.1.2 and 1.6.2.2.

3 "STS-1 Orbiter Final Mission Report," JSC-17378, August 1981, p. 85.

4 Discussed in Craig Covault, "Investigators Studying Shuttle Tiles, *Aviation Week & Space Technology*, May 11, 1981, pg. 40.

5 *Report of the Presidential Commission on the Space Shuttle Challenger Accident*, Volume V, 1986, pp. 1028-9, hearing section pp. 1845-1849.

6 "Orbiter Vehicle End Item Specification for the Space Shuttle System, Part 1, Performance and Design Requirements," contract NAS9-20000, November 7, 2002. CAIB documents CAB006-06440645 and CAB033-20242971.

7 "Problem Reporting and Corrective Action System Requirements," NSTS-08126, Revision H, November 22, 2000, Appendix C, Definitions, In Family. CAIB document CTF044-28652894.

8 Ibid.

9 Ibid.

10 The umbilical wells are compartments on the underside of the Orbiter where External Tank liquid oxygen and hydrogen lines connect. After the Orbiters land, the umbilical well camera film is retrieved and developed.

11 NSTS-08126, Paragraph 3.4, Additional Requirements for In-Flight Anomaly (IFA) Reporting.

12 Integrated Hazard Analysis INTG 037, "Degraded Functioning of Orbiter TPS or Damage to the Windows Caused by SRB/ET Ablatives or Debonded ET or SRB TPS."

13 Ibid.

14 Ibid.

15 During the flight of STS-112, the Intercenter Photo Working Group speculated that a second debris strike occurred at 72 seconds, possibly to the right wing. Although post-flight analysis showed that this did not occur, the Board notes that the Intercenter Photo Working Group failed to properly inform the Mission Management Team of this strike, and that the Mission Management Team subsequently failed to aggressively address the event during flight.

16 "Safety and Mission Assurance Report for the STS-113 Mission, Pre-Launch Mission Management Team Edition," Enterprise Safety and Mission Assurance Division, November 7, 2002. CAIB Document CTF024-00430061.

17 Orbiter TPS damage numbers come from the Shuttle Flight Data and In-Flight Anomaly List (JSC-19413).

18 CAIB Meeting Minutes, presentation and discussion on IFAs for STS-27 and STS-28, March 28, 2003, Houston, Texas.

19 "STS-27R National Space Transportation System Mission Report," NSTS-23370, February 1989, p. 2.

20 CAIB Meeting Minutes, presentation and discussion on IFAs for STS-27 and STS-28, March 28, 2003, Houston, Texas.

21 Corrective Action Record, 27RF13, Closeout Report (no date). CAIB document CTF010-20822107.

22 "STS-27R OV-104 Orbiter TPS Damage Review Team Summary Report," Volume I, February 1989, TM-100355, p. 64. CAIB document CAB035-02290303.

23 Ibid.

24 "In-Flight Anomaly: STS-35/ET-35," External Tank Flight Readiness Report 3500.2.3/91. CAIB document CAB057-51185119.

25 STS-36 PRCB, IFA Closure Rationale for STS-35. CAIB document CAB029-03620433.

26 Identified by MSFC in PRACA database as "not a safety of flight" concern. Briefed at post-STS-42 PRCB and STS-45 Flight Readiness Review.

27 "STS-45 Space Shuttle Mission Report," NSTS-08275, May 1992, pg. 17. CAIB document CTF003-00030006.

28 "STS-45 Space Shuttle Mission Report," NSTS-08275, May 1992. CAIB document CTF003-00030006.

29 Both STS-56 and STS-58 post mission PRCBs discussed the debris events and IFAs. Closeout rationale was based upon the events being considered "in family" and "within experience base."

30 "Problem Reporting and Corrective Action System Requirements," NSTS-08126, Revision H, November 22, 2000, Appendix C, Definitions, Out of Family. CAIB document CTF044-28652894.

31 Post STS-87 PRCBD, S 062127, 18 Dec 1997.

32 M. Elisabeth Paté-Cornell and Paul S. Fischbeck, "Risk Management for the Tiles of the Space Shuttle," pp. 64-86, *Interfaces* 24, January-February 1994. CAIB document CAB005-0141.

33 Letter to M. Elisabeth Paté-Cornell, Stanford University, from Benjamin Buchbinder, Risk Management Program Manager, NASA, 10 May 1993. CAIB document CAB038-36973698.

34 M. Elisabeth Paté-Cornell, "Follow-up on the Standard 1990 Study of the Risk of Loss of Vehicle and Crew of the NASA Space Shuttle Due to Tile Failure," Report to the Columbia Accident Investigation Board, 18 June 2003. CAIB document CAB006-00970104.

35 M. Litwinsk and G. Wilson, et al., "End-to-End TPS Upgrades Plan for Space Shuttle Orbiter," February 1997; K. Hinkle and G. Wilson, "Advancements in TPS," *M&P Engineering*, 22 October 1998.

36 Daniel B. Leiser, et al., "Toughened Uni-piece Fibrous Insulation (TUFI)" Patent #5,079,082, 7 January 1992.

37 Karrie Hinkle, "High Density Tile for Enhanced Dimensional Stability," Briefing to Space Shuttle Program, October 19, 1998. CAIB document CAB033-32663280.

38 Daniel B. Leiser, "Present/Future Tile Thermal Protection Systems," A presentation to the CAIB (Group 1), 16 May 2003.

39 John Kowal, "Orbiter Thermal Protection System (TPS) Upgrades." Space Shuttle Upgrades Safety Panel Review, 10 February 2003.

40 "Problem Reporting and Corrective Action System Requirements," NSTS-08126, Revision H, November 22, 2000. CAIB document CTF044-28652894.

41 Diane Vaughan, *The Challenger Launch Decision: Risky Technology, Culture, and Deviance at NASA* (Chicago: University of Chicago Press, 1996).

42 Richard Feynman, Minority Report on Challenger, *The Pleasure of Finding Things Out*, (New York: Perseus Publishing, 2002).

43 See Appendix D.17 Tiger Team Checklists.

44 Allen J. Richardson and A. H. McHugh, "Hypervelocity Impact Penetration Equation for Metal By Multiple Regression Analysis," STR153, North American Aviation, Inc., March 1966.

45 Allen J. Richardson and J. C. Chou, "Correlation of TPS Tile Penetration Equation & Impact Test Data," 3 March 1985.

46 "Review of Crater Program for Evaluating Impact Damage to Orbiter TPS Tiles," presented at Boeing-Huntington Beach, 29 Apr 2003. CAIB document CTF070-29492999.

47 J. L. Rand, "Impact Testing of Orbiter HRSI Tiles," Texas Engineering Experiment Station Report (Texas A&M), 1979; Tests conducted by NASA (D. Arabian) ca. 1979.

48 Drew L. Goodlin, "Orbiter Tile Impact Testing, Final Report", SwRI Project # 18-7503-005, March 5, 1999.

49 Allen J. Richardson, "Evaluation of Flight Experience & Test Results for Ice Impaction on Orbiter RCC & ACC Surfaces," Rockwell International, November 26, 1984.

50 Though this entry indicates that NASA contacted USSPACECOM, the correct entity is USSTRATCOM. USSPACECOM ceased to exist in October 2002.