National Aeronautics and Space Administration

# Academy of Program/Project & Engineering Leadership

## Columbia's Last Mission

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The Space Shuttle *Columbia* thundered skyward at 10:39 AM on January 16, 2003 from Kennedy Space Center. Little more than a minute later, a chunk of insulating foam tore away from the external fuel tank and splintered against *Columbia's* left wing. The incident did not disrupt *Columbia's* planned path to orbit; indeed, nobody on the ground or in the orbiter even noticed it. It would be another day before routine reviews of launch photos revealed the foam strike and triggered discussions within NASA about what, if anything should be done about it.[1]

## Background

Established in January 1972, the Shuttle Program was charged with developing and deploying a fleet of reusable, cost-efficient vehicles that would make routine human space flight possible. The first Shuttle mission, STS-1, was flown by *Columbia* on April 12, 1981.

A vast team of workers – some 17,500 NASA employees and contractors spread across the country – were supporting Columbia's latest mission, STS-107, the Shuttle Program's 113th mission. The Shuttle Program workforce operated facilities hosted by various NASA Centers. The Space Shuttle Program Office at the Johnson Space Center was responsible for all aspects of developing, supporting, and flying the Space Shuttle.

The prime contractor for space flight operations was United Space Alliance (USA), a corporate partnership formed in 1995 between Lockheed Martin and Rockwell (later Boeing) exclusively to serve the Shuttle program. USA employees comprised the bulk of the contractor workforce at Johnson Space Center.

STS-107 featured a demanding set of scientific observations and experiments. Columbia's seven-person crew would need to work around the clock to finish their tasks by the end of the 16-day mission.

After exhaustive pre-launch checks, the usual check-outs for the Shuttle assembly, and additional procedures for the mission's science cargo, the countdown proceeded as planned.

## Launch and Debris Strike

At 81.7 seconds after launch, a large piece of foam approximately 21 to 27 inches long and 12 to 18 inches wide and at least two smaller pieces separated from the External Tank left bipod (–Y) ramp area. The larger piece, tumbling at least 18 times a second and moving at more than 400 miles per hour, relative to the Orbiter, struck Columbia on the underside of the left wing, around Reinforced Carbon-Carbon (RCC) panels 5 through 9.

[1] This case study uses the Columbia Accident Investigation Board's final report as its source material.

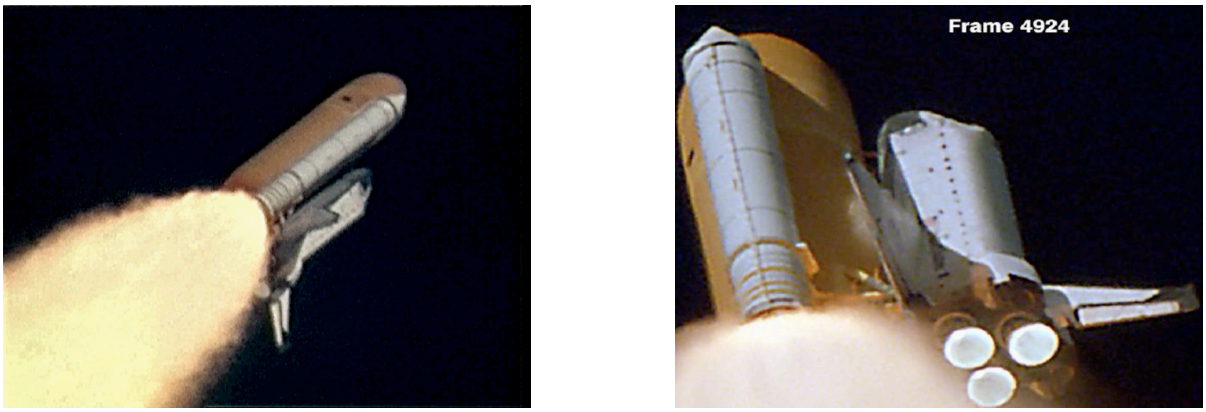


*Figure 1.1*. Two ground camera views of the debris strike show a shower of foam after impact on Columbia's left wing. The event was not observed in real time.

## Flight Day 1

An hour after launch, Columbia was in orbit 175 miles above Earth. The crew immediately began to configure onboard systems. Within two hours of liftoff the Intercenter Photo Working Group performed a routine examination of video from cameras tracking the launch. The review identified no unusual events.

## Flight Day 2

At 9:30 a.m. EST, Intercenter Photo Working Group engineers at Marshall Space Flight Center, examining imagery from video and film cameras on the launch pad and at other sites at and nearby the Kennedy Space Center, identified the debris strike for the first time. Within an hour, Intercenter Photo Working Group personnel at Kennedy also identified the strike on high-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. Analysts concluded that the debris had hit the left wing below the leading edge.

Members of the Intercenter Photo Working Group were concerned about the apparent momentum of the strike, and the fact that none of the imagery from 12 ground based camera sites showed a clear image of the impact or potential damage to the Orbiter. Also, while foam debris had been a common occurrence on prior Shuttle missions this was only the seventh incident of foam loss from the left bipod area of the External Tank, and no one had ever seen such a large debris strike so late in ascent.

With the debris strike confirmed, engineers and managers from across the Shuttle Program began discussing and assessing the significance of the strike. Shuttle Program managers and engineers at Kennedy Space Center called their counterparts at Johnson Space Center. United Space Alliance and Boeing employees exchanged e-mails regarding details of the initial film analysis.

### 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 contractual 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. 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 engineers. 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 24.

## *Imagery Request 1*

Intercenter Photo Working Group Chair, Bob Page, asked Wayne Hale, Shuttle Program Manager for Launch Integration at Kennedy Space Center to explore the possibility of obtaining on-orbit images of Columbia's left wing using Department of Defense assets, which were highly classified and had capabilities far beyond those available to NASA. Formal procedures for invoking those capabilities had long been in place, but had rarely been used. Hale, who had a Top Secret clearance and was familiar with the process for requesting military imaging, agreed to pursue Page's request, and did so on Flight Day 5.

## *Mixed Reactions*

As analysts sought better imagery, managers and engineers formed different views about how much damage was caused by the debris strike.

The launch video review team at Kennedy Space Center thought the Orbiter might have been damaged by the impact. United Space Alliance engineers classified the debris strike as "out-of-family," and therefore of greater concern than previous debris strikes. The out-of-family classification should have triggered the formation of a Tiger Team that would have had clearly defined roles and responsibilities.

## Definitions

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

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

Instead, concerned analysts formed a Debris Assessment Team led by two co-Chairs: NASA's Rodney Rocha, designated chief engineer for the Thermal Protection System, and United Space Alliance engineering manager Pam Madera. Rocha was responsible for coordinating NASA engineering resources with the new team. The Mission Evaluation Room manager was alerted to the team's existence, and that it would be analyzing the debris strike over the holiday weekend. Another group of engineers from Boeing and United Space Alliance also decided to work through the weekend to analyze the strike.

Other managers and analysts exhibited less concern with the strike. John Disler, an analyst with the Intercenter Photo Working Group, reported: "Debris impact on port wing edge-appears to have originated at the ET fwd bipod foam? – if so it shouldn't be a problem."

Several mid-level and senior managers at United Space Alliance and NASA believed that the areas most likely struck by the debris, the RCC panels and other Thermal Protection System (TPS) tiles could withstand a debris impact.

--------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 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+81 seconds 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]

Within an hour of Stoner's email, a Mission Evaluation Room manager made the following log entry: "*Bill Reeves called after a meeting with Ralph Roe, it is confirmed that USA/Boeing will not be working the 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]

A Mission Evaluation Room manager confirmed in a log entry, "*I also confirmed that there was no rush on this [debris strike] issue and that it was ok to wait till the film reviews are finished on Monday…*"

Later that day, Page informed Hale and Lambert Austin, the head of the Space Shuttle Systems Integration at Johnson Space Center, that Boeing was performing an analysis of the debris impact to determine trajectories, velocities, angles, and energies. Hale then telephoned Linda Ham, Chair of the Mission Management Team, and her boss, Ron Dittemore, Space Shuttle Program Manager, to pass along information about the debris strike.

The Intercenter Photo Working Group subsequently e-mailed a "Launch plus one day report" [L + 1 Report] that contained video clips and still images of the debris strike to engineers and technical managers inside and outside NASA. This report served as the basis for subsequent decisions and actions.

## Flight Days Three and Four

Despite what senior managers believed, Boeing engineers worked over the weekend to produce a preliminary damage assessment. Using video and photo images, the analysts 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.

To assess potential debris damage, analysts used a Boeing mathematical modeling tool called "Crater," a custom-designed algorithm that predicted impact effects of small icy objects on Thermal Protection System tiles (not RCC tiles however). Crater tended to predict deeper penetration and more severe damage than actually occurred, leading engineers to classify Crater a "conservative" tool. This would be the first use of Crater while a mission was on orbit.

Over the weekend, a Crater-certified Boeing engineer who had used the program only twice performed the analysis. Crater predicted damage deeper than the actual tile thickness, indicating a rupture all the way to the underlying aluminum frame. This result suggested that Columbia had a gaping hole in its wing and that the Orbiter's airframe would be exposed to extremely hot temperatures during re-entry, resulting in a possible burn-through.

Debris Assessment Team engineers discounted these results for two reasons. One was Crater's tendency to exaggerate damage. Another was that Crater modeled only the resilience of a tile's outer layer, not the increased density of a tile's lower "densified" layer, which was much stronger than the tile's fragile surface.

Another vulnerable site was the chain of RCC panels along the leading edge of each wing. To determine potential RCC damage, analysts used a Crater-like algorithm to test the effects of ice projectiles. Results suggested that an angle of impact greater than 15 degrees would result in RCC penetration. A separate "transport" analysis, which attempted to determine the path the debris took, identified 15 strike scenarios. A dozen scenarios predicted strikes only on TPS tiles. One scenario predicted a 21-degree angle of impact on the RCC leading edge, the only scenario with an angle of impact greater than 15 degrees.

These estimates assumed ice debris, not foam. Because foam is less dense than ice, Debris Assessment Team analysts had to extrapolate from the test data. They concluded that a foam impact angle up to 21 degrees would not penetrate the RCC.

Rodney Rocha was concerned by the results, however, and 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 to the e-mail.

## Flight Day Five

On Monday morning, the Martin Luther King Jr. holiday, the Debris Assessment Team gathered informally in advance of its first official meeting the next day. The team had 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 Science Applications International Corporation (SAIC), another NASA contractor. Several engineers were concerned that the debris strike might have caused a breach in the left main landing gear door seal.

Engineers left the informal meeting with a goal of obtaining images from ground-based assets. By this time, Mission Specialist David Brown had filmed the launch and the External Tank separation, and downloaded 35 seconds of video as part of his Flight Day One mission summary. Although his video did not show the bipod ramp, Brown was never asked if he had additional video.

## Flight Day Six

At 7:00 a.m. the Debris Assessment Team told Don McCormack, the chief Mission Evaluation Room manager, that the debris that struck Columbia was similar in size to the debris that struck STS-112, and that Boeing was analyzing RCC damage that had occurred on STS-87.

At 8:00 a.m., the Mission Management Team held its first post-holiday meeting. (Although the team was supposed to meet daily, it would meet only five times during the 16-day mission.) The Mission Management Team addressed the debris strike topic after discussing concerns about excessive orbiter weight (Columbia was 150 pounds over safety specifications for landing weight), a leaking water separator, a jammed Hasselblad camera, payload and equipment status, and a communications downlink problem.

When managers began discussing the debris strike, McCormack explained that a group was analyzing the debris strike, and would determine what could be done if Columbia had in fact sustained damage. Lambert Austin added that the foam debris may have come from the bipod area of the External Tank, and that the Engineering Directorate was running analyses and comparing this event to foam loss on STS-112. Linda Ham suggested the team learn what rationale had been used to fly after the External Tank foam losses on STS-87 and STS-112.

The transcript below is a record of the first official discussion of the debris impact at a Mission Management Team meeting.

Ham*: "Alright, I know you guys are looking at 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 have some damage, pull this data from 112 or whatever flight it was and make sure that…you know I hope we had good flight rationale then."*

McCormack: *"Yeah, 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's 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 be co-related, but you can try to see what we have."*

McCormack: *Okay."*

After the meeting, senior managers identified and discussed the rationale for continuing to fly after previous foam strikes; the history of foam debris incidents affecting the thermal protection system; and, consulted a thermal protection system expert.

Once Ham received the flight rationale, she 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 a.m.
To: HAM, LINDA J. (JSC-MA2) (NASA)
Subject: RE: ET Briefing – STS-112 Foam Loss

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

-------Original Message----------

From: MCCORMACK, DONALD L. (DON) (JSC-MV6) (NASA)
Sent: Tuesday, January 21, 2003 9:45 a.m.
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

-------Original Message----------

From: HAM, LINDA J. (JSC-MA2) (NASA)
Sent: Tuesday, January 21, 2003 11:14 a.m.
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 bipod ramp TPS is same as previous flights….So ET is safe to fly with no added risk.

Rationale was lousy then and still is…

Ham was slated to serve, along with Wayne Hale, as the launch integration manager for the next mission, STS-114. NASA rules required any serious problems identified in the course of one mission be resolved prior to the next flight. If the Shuttle Program's prevailing rationale to fly with foam loss were found to be flawed, STS-114, due to be launched in about a month, would have to be delayed. An STS-114 delay could in turn delay the completion of the International Space Station's Node 2, which was a high-priority goal for NASA managers.

About an hour later, Calvin Schomburg, a Johnson Space Center engineer who Shuttle Program senior managers regarded as an expert on the Thermal Protection System (but not RCC panels), 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 a.m.
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]

Schomburg advised Ralph Roe, Lambert Austin, and Linda Ham that any tile damage should be considered a turn-around maintenance concern, that is, an extra chore to be addressed after the mission 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.

Seven minutes later, Paul Shack of the Shuttle Engineering Office, Johnson Engineering Directorate, e-mailed his subordinate Rodney Rocha and other Johnson managers information on how previous bipod ramp foam loss incidents had been handled.

-----Original Message------

From: SHACK, PAUL E. (JSC-EA42) (NASA)
Sent: Tuesday, January 21, 2003 9:33 a.m.
To: ROCHA, ALAN R. (RODNEY) (JSC-ES2) (NASA); SERIALE-GRUSH, JOYCE M. (JSC-EA) (NASA); 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 Bryan O'Conner (Associate Administrator 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 Report, ET = External Tank, SRB = Solid Rocket Boost, TPS = Thermal Protection System, "wire brushed" = chastised]

According to the STS-113 Flight Readiness Review, foam loss was not considered a safety-of-flight issue, but rather an "accepted risk," which meant that the threat was not zero but rather a known and acceptable risk. The wire-brushing" that the External Tank Project received for stating that foam loss has "never been a 'Safety of Flight' issue" refers to the justification for continuing to fly, a rationale that Ham characterized as "lousy."

If senior managers were to agree that the foam strike on STS-107 was a safety-of-flight issue, they would contradict an established consensus established by the Shuttle Program's most rigorous review, a review in which many of them had been active participants. The comparison of STS-107 foam loss with foam loss and related tile damage on prior missions reinforced senior management's view that the foam strike on *Columbia* was an "in-family" event.

### *Imagery Request 2*

Responding to concerns expressed by his employees on the Debris Assessment Team, United Space Alliance manager Bob White called Lambert Austin and asked him how to obtain on-orbit imagery of Columbia. They discussed ongoing efforts to identify debris damage, and his team's desire for better imaging of the debris strike.

Austin then telephoned the Department of Defense Manned Space Flight Office to ask how to obtain on-orbit imagery. While Austin characterized his request as information gathering, not a request for action, the Defense Department representative with whom Austin spoke began to act on the request.

Flight Director Steve Stich discussed the debris strike with Phil Engelauf, a member of the Mission Operations Directorate. Engelauf told Stich that the Space Shuttle Program community was not concerned about the debris, and that no one had directed the Mission Operations Directorate to ask the Department of Defense to image Orbiter's wing.

### *Debris Assessment Team Meeting #1*

The Debris Assessment Team held a formal meeting to discuss its analysis of Orbiter damage.

### *Imagery Request 3*

After a two hour discussion of Crater results, the team decided that Rodney Rocha would pursue a request for imagery through his division, the Engineering Directorate at Johnson Space Center instead of working the request up the mission chain of command (from the Mission Evaluation Room to the Mission Management Team to the Flight Dynamics Officer). The Engineering Directorate was the normal conduit for addressing technical issues germane to the overall Shuttle program, but was not central to the information loop for critical issues relating to a mission in progress.

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-EA) (NASA); GALBREATH, GREGORY F. (GREG) (JSC-ES2) (NASA)
Subject: STS-107 Wing Debris Impact, Request for Outside Photo-Imaging Help

Paul and Dave,

The meeting participants (Boeing, USA, NASA ES2 and ES3, KSC) all agreed we will always have big uncertainties in any transport/trajectory analyses and applicability/extrapolation of the old Arc-Jet test data until we get definitive, better, clearer photos of the wing and body underside. Without better images it will be very difficult to even bound the problem and initialize thermal, trajectory, and structural analyses. Their answers may have a wide spread ranging from acceptable to not-acceptable to horrible, and no way to reduce uncertainty. Thus, giving MOD options for entry will be very difficult. Can we petition (beg) for outside agency assistance? We are asking for Frank Benz with Ralph Roe or Ron Dittemore to ask for such. Some of the old-timers here remember we got such help

## Flight Day Seven

At 7 a.m., Wayne Hale called a Department of Defense representative at Kennedy Space Center 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 how to obtain DoD images of *Columbia*. (This request was also characterized as "information gathering.") A USSTRATCOM representative then began taking steps to identify imaging assets that could execute the request.

Hale's call to the Defense of Department was "unofficial" in two senses: It was not authorized by Linda Ham, and was not directed to the designated Defense Department liaison responsible for handling such requests.

Hale then pursued the imagery request through official channels. He called Phil Engelauf at the Mission Operations Directorate, told him he had started Defense Department action, and asked him to have the Flight Dynamics Officer at Johnson Space Center make an official request to the Cheyenne Mountain Operations Center. Engelauf started to follow through on Hale's request.

After the Department of Defense representatives were called, Lambert Austin telephoned Linda Ham to inform her of the imagery requests that he and Hale had initiated. Ham asked Lambert Austin who was requesting the imagery. After acknowledging his role in the imagery outside the

official chain of command and without first gaining Ham's permission request, Austin referred to his conversation with United Space Alliance Shuttle Integration manager Bob White who had asked Austin on Flight Day 6 to look into obtaining on-orbit imagery of the Orbiter.

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, NASA's highest-ranking safety official, said he would defer to Shuttle management regarding the need for such imagery. Neither of these senior safety officials became directly involved in the effort to obtain on-orbit images.

### *Cancellation of Imagery Requests*

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

Linda Ham had several reasons for canceling the request for imagery. She had confirmed that no one had a "requirement" for using DoD assets to obtain on-orbit imagery. 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), as well as Flight Director Phil Engelauf (who was not on the Mission Management Team) all told Ham that they had not themselves 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.

Ham also had concerns that the extra time spent maneuvering Columbia to make the left wing visible for on-orbit imaging would disrupt the mission schedule, since science experiments would have to stop while images were taken.

Moreover, Ham, along with other Shuttle managers, was skeptical about the usefulness of on-orbit imagery. The areas along the leading edge were quite small, and the quality of resolution of on-orbit images Ham and others had seen in the past was not very good. Nobody in the STS-107 operational chain of command, however, had the security clearance necessary for detailed knowledge of what Department of Defense imaging assets could actually accomplish, and nobody from NASA, United Space Alliance, or Boeing determined the likely cost and quality of images or the difficulty of obtaining Department of Defense assistance.

What had started on Flight Day Two as a request by the Intercenter Photo Working Group to seek outside help in obtaining images had become by Flight Day Six an actual engineering request by members of the Debris Assessment Team. This request had been relayed, both 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. By terminating actions the Department of Defense had begun, Ham effectively terminated both the Intercenter Photo Working Group request and the Debris Assessment Team request. She never asked directly if the requests were theirs, even though they were the team analyzing the foam strike.
After canceling the Department of Defense imagery request, Linda Ham explored 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 loss, no 'safety of flight' damage can occur to the Orbiter because of the density?

[ET = External Tank]

Responses included the following four replies.

-----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?

-----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.

-----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 the vehicle and crew about 200-400 tile locations (out of 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 ¾ to an 1 inch deep across two or three tiles. This is what I expect this time nothing worst. If that is all we get we have no problem will have to replace a couple tiles but nothing else.

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

-----Original Message-----

From: AUSTIN, LAMBERT D. (JSC-MS) (NASA)
Sent: Wednesday, January 22, 2003 9:33 AM
To: HAM, LINDA J. (JSC-MA2) (NASA)
Cc: WALLACE, RODNEY O. (ROD) (JCS-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 an 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 Schomburg 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 a loss of that function. My recollection of the most critical Orbiter bottom acreage areas are the wing spar, main landing gear door seal and RCC panels…of course Cal can give you a much better rundown.

We can and have generated parametric impact zone characterizations for many areas of the Orbiter for a few of our more typical ET foam loss areas. Of course, the impact/damage significance is always a function of debris size and density, impact velocity, and impact angle these latter 2 being a function of the flight time at which the ET foam becomes debris. For STS-107 specifically, we have generated this info and provided it to the 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]

A United Space Alliance manager subsequently informed Pam Madera that imagery would be sought only if the request was a "mandatory need." Madera then e-mailed Debris Assessment Team members that the upcoming team meeting would include a discussion of how to generate a "mandatory" rationale for their imaging request.

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 of which centered on technical matters to be discussed at the Debris Assessment Team's afternoon meeting. One e-mail from Rocha to his managers and other Johnson engineers at 11:19 a.m., included the following passage:

*"...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 locations 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 ..."*

### *Debris Assessment Team Meeting #2*

At the Debris Assessment Team's second meeting, analysts discussed the rejection of their imaging request 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. They believed the need for imagery was obvious: Without better pictures, they would be unable to make reliable estimates of the damage the debris strike might have caused. Whether or not the damage was severe enough to warrant the term "mandatory," though, was unknowable based on current information. The team concluded that they could not cite a "mandatory" requirement for the request. Analysts on the Debris Assessment Team were in the unenviable position of needing 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 an e-mail from Paul Shack announcing that the Orbiter Project was not requesting any outside imaging help. Rocha called Shack to ask whether his boss, Johnson Space Center engineering director, Frank Benz, knew about the request. Rocha sent several e-mails posing questions about ongoing analyses and soliciting details about the Shuttle Program's cancellation of the imaging request. Rocha then drafted the following email:

*"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]

Rocha reviewed his draft and pondered whether to hit the "send" key.

## Instructor's Notes

This case has been designed for use in an interactive session. Instructors should pass out the first section of the case (pp. 1-17) for participants to read prior to the session. The following questions can be used to guide the discussion.

1. What decisions points shaped the organization's response to the discovery of the debris strike?

2. How did the organization's formal and informal processes differ from each other in the response to the debris strike?

3. What role did the previous flight rationale about earlier foam strikes (STS-112 and STS-87) play in the Mission Management Team's decision making?

4. What questions would you want answered at this point in the mission?

Rodney Rocha never sent the email. When asked why later, Rocha replied that he did not want to jump the chain of command. Having already raised the need to have images of the Orbiter, he would defer to management's judgment.

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.

On Flight Day Eight, Debris Assessment Team engineers presented their final debris trajectory estimates to the 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 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 Stich sent the following e-mail to Husband and McCool and copied other Flight Directors.

-----Original Message-----

From: STICH, 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 (JSC0DA8) (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 a 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 the 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 10, -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.

The Debris Assessment Team met for the third time on Flight Day Eight to review updated impact analyses. Engineers noted that there were no alternate re-entry trajectories that the Orbiter could fly that would 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 light of this, the team discussed whether to include a presentation slide reinforcing the case for images to assess damage. 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. But the idea of including a presentation slide about the imaging request was eventually dropped.

On Flight Day Nine, Boeing and United Space Alliance contract personnel presented the Debris Assessment Team's findings to Don McCormack, the Mission Evaluation Room manager. So many engineers crowded the briefing room that it was standing room only, with people lining the hallway, suggesting the level of concern about *Columbia's* condition among NASA's technical personnel.

The presentation included viewgraphs describing 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.

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 applied to a piece of debris that was orders of magnitude larger than the standard in Boeing's database.[2] Engineers ultimately concluded that their analysis, given data constraints, could 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 found no safety-of-flight issue, rather than concerns about the large uncertainties surrounding that answer.

At the Mission Management Team's 8:00 a.m. meeting that day, which Linda Ham chaired, Mission Evaluation Room manager Don McCormack orally summarized the Debris Assessment Team's 7:00 a.m. brief. It was the third topic discussed. Early in the meeting, Phil Engelauf, Chief of the Flight Director's office, reported that he had made

[1] An order of magnitude equates to a tenfold increase.

clear in an e-mail to *Columbia's* crew that there were "no concerns" that the debris strike had caused serious damage. 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. McCormack's presentation did not include the Debris Assessment Team's presentation charts. No supporting analysis or examination of minority opinions among the engineering team was asked for or offered. Neither Mission Evaluation Room nor Mission Management Team members requested a technical paper of the Debris Assessment Team analysis. No technical questions were asked.

-----Original Message-----

From: ROCHA, ALAN R. (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); OULETTE, 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 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, no 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 there), 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 and Dynamics Panel

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

Although "no safety-of-flight issue" had officially been noted in Flight Day Nine's 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 in the analyses, Rocha became more comfortable with the damage assessment and sent the following e-mail to his management.

Although the Debris Assessment 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 and 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.

After four days of correspondence with other engineers about simulations of various landing scenarios, Campbell sent the following e-mail to Johnson Space Center engineering managers on January 31, the day before the Shuttle was scheduled to return to Earth.

> *"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]*

At the January 31 Mission Management Team meeting, 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 mentioned that Linda Ham had requested that once *Columbia* landed, the crew's hand-held cameras and External Tank films would be expedited to Marshall Space Flight Center for analysis.

In the early hours of February 1, the Entry Flight Control Team began duty in the Mission Control Center. The Flight Control Team was not working any issues or

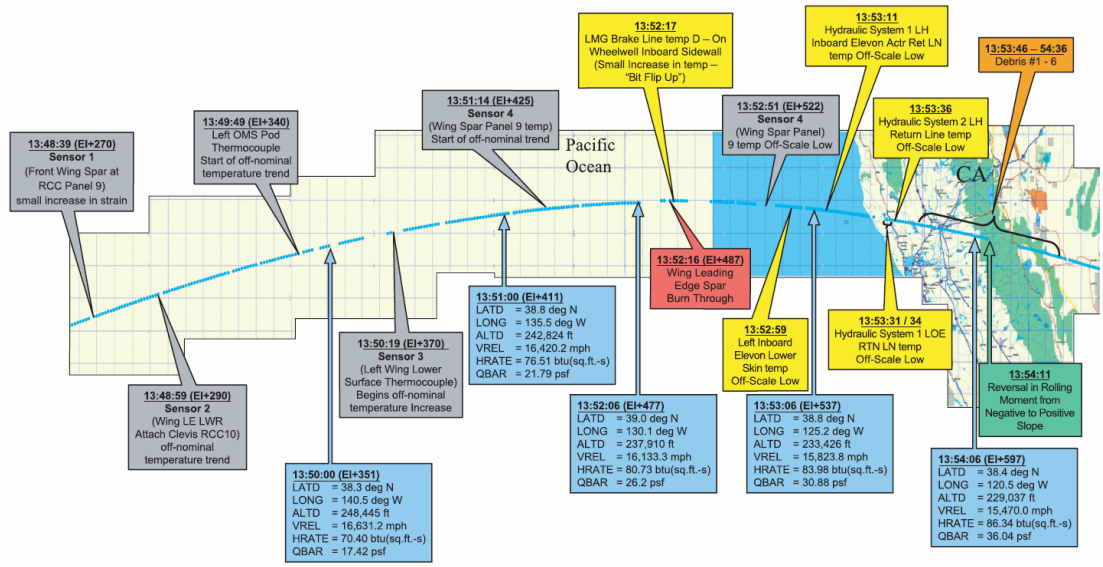


*Figure 2.1*. This simplified timeline shows the re-entry path of Columbia on February 1, 2003. The chart is color-coded: blue boxes contain position, attitude, and velocity information; orange boxes indicate when debris was shed from the Orbiter; green boxes are significant aerodynamic control events; gray boxes contain sensor information from the Modular Auxiliary Data System; and yellow boxes contain telemetered sensor information. The red boxes indicate other significant events.

problems related to the planned de-orbit and re-entry of *Columbia*. The team indicated no concerns about the debris impact to the left wing during ascent, and treated the re-entry like any other.

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

*Columbia* re-entered the Earth's atmosphere and moved into position to traverse the United States from west to east en route to landing at Kennedy Space Center in Florida. Crossing California, the Orbiter appeared to observers on the ground as a bright spot of light moving rapidly across the sky. Signs of debris were sighted at 8:53 a.m., when the superheated air surrounding the Orbiter suddenly brightened, causing a noticeable streak in the Orbiter's luminescent trail. Observers witnessed another four similar events during the next 23 seconds, and a bright flash just after *Columbia* crossed from California into Nevada airspace.

In Mission Control, re-entry appeared normal until 8:54 a.m., when the Flight Director was informed that four hydraulic sensors in the left wing were indicating "off-scale low," a reading that falls below the minimum capability of the sensor.

At 8:58 a.m., as *Columbia* crossed from New Mexico into Texas, it shed a Thermal Protection tile, which was the most westerly piece of debris that was later recovered.
At 8:59 a.m., the Flight Director was informed that pressure readings had been lost on both left main landing gear tires. The Flight Director then told the Capsule Communicator to let the crew know that Mission Control saw the messages, and added that the Flight Control team did not understand the crew's last transmission. A broken response from the mission commander was recorded: "Roger, [cut off in midword]..." It was the last communication from the crew and the last telemetry signaled received in Mission Control. Videos made by observers on the ground at 9:00 a.m. revealed that the Orbiter was disintegrating.

The Flight Control team still had no indications of any serious problems onboard the Orbiter. In Mission Control there was no way to know the exact cause of the failed sensor measurements, and while there was concern for the extended loss of signal, the recourse was to try and regain communications and determine if other systems continued to appear as expected.

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

The Flight Director commanded Ground Control to lock the doors and directed the Flight Control Team to begin contingency procedures.


*Figure 2.2.* An infrared image taken by a military helicopter shows the breakup of Columbia.