Recommendations:

R3.3-1 Develop and implement a comprehensive inspection plan to determine the structural integrity of all Reinforced Carbon-Carbon system components. This inspection plan should take advantage of advanced non-destructive inspection technology.

R3.3-2 Initiate a program designed to increase the Orbiter's ability to sustain minor debris damage by measures such as improved impact-resistant Reinforced Carbon-Carbon and acreage tiles. This program should determine the actual impact resistance of current materials and the effect of likely debris strikes.

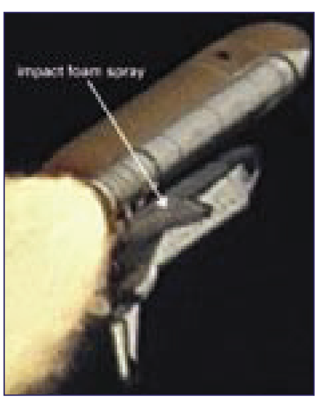
R3.3-3 To the extent possible, increase the Orbiter's ability to successfully re-enter the Earth's atmosphere with minor leading edge structural sub-system damage.

R3.3-4 In order to understand the true material characteristics of Reinforced Carbon-Carbon components, develop a comprehensive database of flown Reinforced Carbon-Carbon material characteristics by destructive testing and evaluation.

R3.3-5 Improve the maintenance of launch pad structures to minimize the leaching of zinc primer onto Reinforced Carbon-Carbon components.

3.4 Image and Transport Analyses

At 81.9 seconds after launch of STS-107, a sizable piece of foam struck the leading edge of *Columbia*'s left wing. Visual evidence established the source of the foam as the left bipod ramp area of the External Tank. The widely accepted implausibility of foam causing significant damage to the wing leading edge system led the Board to conduct independent tests to characterize the impact. While it was impossible to determine the precise impact parameters because of uncertainties about the foam's density, dimensions, shape, and initial velocity, intensive work by the Board, NASA, and contractors provided credible ranges for these elements. The Board used a combination of tests and analyses to conclude that the foam strike observed during the flight of STS-107 was the direct, physical cause of the accident.



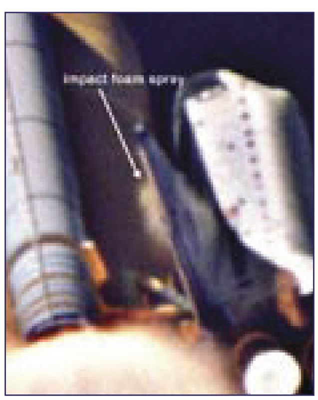


Figure 3.4-1 (color enhanced and "de-blurred" by Lockheed Martin Gaithersburg) and Figure 3.4-2 (processed by the National Imagery and Mapping Agency) are samples of the type of visual data used to establish the time of the impact (81.9 seconds), the altitude at which it occurred (65,860 feet), and the object's relative velocity at impact (about 545 mph relative to the Orbiter).

Image Analysis: Establishing Size, Velocity, Origin, and Impact Area

The investigation image analysis team included members from Johnson Space Center Image Analysis, Johnson Space Center Engineering, Kennedy Space Center Photo Analysis, Marshall Space Flight Center Photo Analysis, Lockheed Martin Management and Data Systems, the National Imagery and Mapping Agency, Boeing Systems Integration, and Langley Research Center. Each member of the image analysis team performed independent analyses using tools and methods of their own choosing. Representatives of the Board participated regularly in the meetings and deliberations of the image analysis team.

A 35-mm film camera, E212, which recorded the foam strike from 17 miles away, and video camera E208, which recorded it from 26 miles away, provided the best of the available evidence. Analysis of this visual evidence (see Figures 3.4-1 and 3.4-2) along with computer-aided design analysis, refined the potential impact area to less than 20 square feet in RCC panels 6 through 9 (see Figure 3.4-3), including a portion of the corresponding carrier panels and adjacent tiles. The investigation image analysis team found no conclusive visual evidence of post-impact debris flowing over the top of the wing.

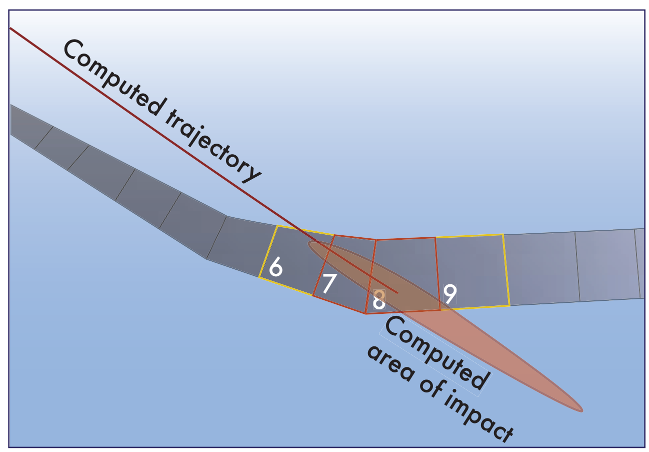


Figure 3.4-3: The best estimate of the site of impact by the center of the foam.

The image analysis team established impact velocities from 625 to 840 feet per second (about 400 to 600 mph) relative to the Orbiter, and foam dimensions from 21 to 27 inches long by 12 to 18 inches wide.[8] The wide range for these measurements is due primarily to the cameras' relatively slow frame rate and poor resolution. For example, a 20-inch change in the position of the foam near the impact point would change the estimated relative impact speed from 675 feet per second to 825 feet per second. The visual evidence could not reveal the foam's shape, but the team was able to describe it as flat and relatively thin. The mass and hence the volume of the foam was determined from the velocity estimates and their ballistic coefficients.

Image analysis determined that the foam was moving almost parallel to the Orbiter's fuselage at impact, with about a five-degree angle upward toward the bottom of the wing and slight motion in the outboard direction. If the foam had hit the tiles adjacent to the leading edge, the angle of incidence would have been about five degrees (the angle of incidence is the angle between the relative velocity of the projectile and the plane of the impacted surface). Because the wing leading edge curves, the angle of incidence increases as the point of impact approaches the apex of an RCC panel. Image and transport analyses estimated that for impact on RCC panel 8, the angle of incidence was between 10 and 20 degrees (see Figure 3.4-4).[9] Because the total force delivered by the impact depends on the angle of incidence, a foam strike near the apex of an RCC panel could have delivered about twice the force as an impact close to the base of the panel.

Despite the uncertainties and potential errors in the data, the Board concurred with conclusions made unanimously by the post-flight image analysis team and concludes the information available about the foam impact during the mission was adequate to determine its effect on both the thermal tiles and RCC. Those conclusions made during the mission follow:

- The bipod ramp was the source of the foam.
- Multiple pieces of foam were generated, but there was no evidence of more than one strike to the Orbiter.
- The center of the foam struck the leading edge structural subsystem of the left wing between panels 6 to 9. The potential impact location included the corresponding carrier panels, T-seals, and adjacent tiles. (Based on further image analysis performed by the National Imagery and Mapping Agency, the transport analysis that follows, and forensic evidence, the Board concluded that a smaller estimated impact area in the immediate vicinity of panel 8 was credible.)
- Estimates of the impact location and velocities rely on timing of camera images and foam position measurements.
- The relative velocity of the foam at impact was 625 to 840 feet per second. (The Board agreed on a narrower speed range based on a transport analysis that follows.)
- The trajectory of the foam at impact was essentially parallel to the Orbiter's fuselage.
- The foam was making about 18 revolutions per second as it fell.
- The orientation at impact could not be determined.
- The foam that struck the wing was 24 (plus or minus 3) inches by 15 (plus or minus 3) inches. The foam shape could only be described as flat. (A subsequent transport analysis estimated a thickness.)
- Ice was not present on the external surface of the bipod ramp during the last Ice Team camera scan prior to launch (at approximately T–5 minutes).
- There was no visual evidence of the presence of other materials inside the bipod ramp.
- The foam impact generated a cloud of pulverized debris with very little component of velocity away from the wing.

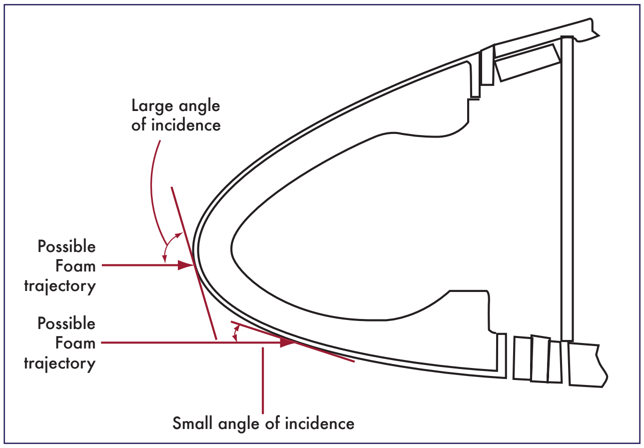


Figure 3.4-4. This drawing shows the curve of the wing leading edge and illustrates the difference the angle of incidence has on the effect of the foam strike.

- In addition, the visual evidence showed two sizable, traceable post-strike debris pieces with a significant component of velocity away from the wing.

Although the investigation image analysis team found no evidence of post-strike debris going over the top of the wing before or after impact, a colorimetric analysis by the National Imagery and Mapping Agency indicated the potential presence of debris material over the top of the left wing immediately following the foam strike. This analysis suggests that some of the foam may have struck closer to the apex of the wing than what occurred during the impact tests described below.

Imaging Issues

The image analysis was hampered by the lack of high resolution and high speed ground-based cameras. The existing camera locations are a legacy of earlier NASA programs, and are not optimum for the high-inclination Space Shuttle missions to the International Space Station and oftentimes

The Orbiter "Ran Into" the Foam

"How could a lightweight piece of foam travel so fast and hit the wing at 545 miles per hour?"

Just prior to separating from the External Tank, the foam was traveling with the Shuttle stack at about 1,568 mph (2,300 feet per second). Visual evidence shows that the foam debris impacted the wing approximately 0.161 seconds after separating from the External Tank. In that time, the velocity of the foam debris slowed from 1,568 mph to about 1,022 mph (1,500 feet per second). Therefore, the Orbiter hit the foam with a relative velocity of about 545 mph (800 feet per second). In essence, the foam debris slowed down and the Orbiter did not, so the Orbiter ran into the foam. The foam slowed down rapidly because such low-density objects have low ballistic coefficients, which means their speed rapidly decreases when they lose their means of propulsion.

	Minimum Impact Speed (mph)	Maximum Impact Speed (mph)	Best Estimated Impact Speed (mph)	Minimum Volume (cubic inches)	Maximum Volume (cubic inches)	Best Estimated Volume (cubic inches)
During STS-107	375	654	477	400	1,920	1,200
After STS-107	528	559	528	1,026	1,239	1,200

Figure 3.4-5. The best estimates of velocities and volumes calculated during the mission and after the accident based on visual evidence and computer analyses. Information available during the mission was adequate to determine the foam's effect on both thermal tiles and RCC.

cameras are not operating or, as in the case of STS-107, out of focus. Launch Commit Criteria should include that sufficient cameras are operating to track the Shuttle from liftoff to Solid Rocket Booster separation.

Similarly, a developmental vehicle like the Shuttle should be equipped with high resolution cameras that monitor potential hazard areas. The wing leading edge system, the area around the landing gear doors, and other critical Thermal Protection System elements need to be imaged to check for damage. Debris sources, such as the External Tank, also need to be monitored. Such critical images need to be downlinked so that potential problems are identified as soon as possible.

Transport Analysis: Establishing Foam Path by Computational Fluid Dynamics

Transport analysis is the process of determining the path of the foam. To refine the Board's understanding of the foam strike, a transport analysis team, consisting of members from Johnson Space Center, Ames Research Center, and Boeing, augmented the image analysis team's research.

A variety of computer models were used to estimate the volume of the foam, as well as to refine the estimates of its velocity, its other dimensions, and the impact location. Figure 3.4-5 lists the velocity and foam size estimates produced during the mission and at the conclusion of the investigation.

The results listed in Figure 3.4-5 demonstrate that reasonably accurate estimates of the foam size and impact velocity were available during the mission. Despite the lack of high-quality visual evidence, the input data available to assess the impact damage during the mission was adequate.

The input data to the transport analysis consisted of the computed airflow around the Shuttle stack when the foam was shed, the estimated aerodynamic characteristics of the foam, the image analysis team's trajectory estimates, and the size and shape of the bipod ramp.

The transport analysis team screened several of the image analysis team's location estimates, based on the feasible aerodynamic characteristics of the foam and the laws of physics. Optical distortions caused by the atmospheric density gradients associated with the shock waves off the Orbiter's nose, External Tank, and Solid Rocket Boosters may have compromised the image analysis team's three position estimates closest to the bipod ramp. In addition, the image analysis team's position estimates closest to the wing were compromised by the lack of two camera views and the shock region ahead of the wing, making triangulation impossible and requiring extrapolation. However, the transport analysis confirmed that the image analysis team's estimates for the central portion of the foam trajectory were well within the computed flow field and the estimated range of aerodynamic characteristics of the foam.

The team identified a relatively narrow range of foam impact velocities and ballistic coefficients. The ballistic coefficient of an object expresses the relative influence of weight and atmospheric drag on it, and is the primary aerodynamic characteristic of an object that does not produce lift. An object with a large ballistic coefficient, such as a cannon ball, has a trajectory that can be computed fairly accurately without accounting for drag. In contrast, the foam that struck the wing had a relatively small ballistic coefficient with a large drag force relative to its weight, which explains why it slowed down quickly after separating from the External Tank. Just prior to separation, the speed of the foam was equal to the speed of the Shuttle, about 1,568 mph (2,300 feet per second). Because of a large drag force, the foam slowed to about 1,022 mph (1,500 feet per second) in about 0.2 seconds, and the Shuttle struck the foam at a relative

Figure 3.4-6. These are the results of a trajectory analysis that used a computational fluid dynamics approach in a program called CART-3D, a comprehensive (six-degree-of-freedom) computer simulation based on the laws of physics. This analysis used the aerodynamic and mass properties of bipod ramp foam, coupled with the complex flow field during ascent, to determine the likely position and velocity histories of the foam.

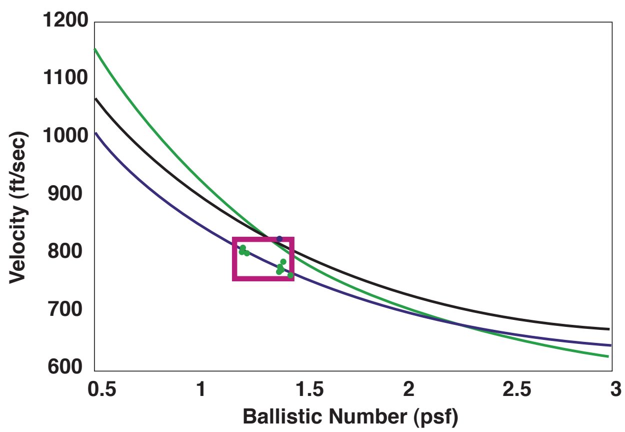


Figure 3.4-7. The results of numerous possible trajectories based on various assumed sizes, shapes, and densities of the foam. Either the foam had a slightly higher ballistic coefficient and the Orbiter struck the foam at a lower speed relative to the Orbiter, or the foam was more compact and the wing struck the foam at a higher speed. The "best fit" box represents the overlay of the data from the image analysis with the transport analysis computations. This data enabled a final selection of projectile characteristics for impact testing.

speed of about 545 mph (800 feet per second). (See Appendix D.8.)

The undetermined and yet certainly irregular shape of the foam introduced substantial uncertainty about its estimated aerodynamic characteristics. Appendix D.8 contains an independent analysis conducted by the Board to confirm that the estimated range of ballistic coefficients of the foam in Figure 3.4-6 was credible, given the foam dimension results from the image analyses and the expected range of the foam density. Based on the results in Figure 3.4-7, the physical dimensions of the bipod ramp, and the sizes and shapes of the available barrels for the compressed-gas gun used in the impact test program described later in this chapter, the Board and the NASA Accident Investigation Team decided that a foam projectile 19 inches by 11.5 inches by 5.5 inches, weighing 1.67 pounds, and with a weight density of 2.4 pounds per cubic foot, would best represent the piece of foam that separated from the External Tank bipod ramp and was hit by the Orbiter's left wing. See Section 3.8 for a full discussion of the foam impact testing.

Findings:

F3.4-1 Photographic evidence during ascent indicates the projectile that struck the Orbiter was the left bipod ramp foam.

F3.4-2 The same photographic evidence, confirmed by independent analysis, indicates the projectile struck the underside of the leading edge of the left wing in the vicinity of RCC panels 6 through 9 or the tiles directly behind, with a velocity of approximately 775 feet per second.

F3.4-3 There is a requirement to obtain and downlink on-board engineering quality imaging from the Shuttle during launch and ascent.

F3.4-4 The current long-range camera assets on the Kennedy Space Center and Eastern Range do not provide best possible engineering data during Space Shuttle ascents.

F3.4-5 Evaluation of STS-107 debris impact was hampered by lack of high resolution, high speed cameras (temporal and spatial imagery data).

F3.4-6 Despite the lack of high quality visual evidence, the information available about the foam impact during the mission was adequate to determine its effect on both the thermal tiles and RCC.

Recommendations:

R3.4-1 Upgrade the imaging system to be capable of providing a minimum of three useful views of the Space Shuttle from liftoff to at least Solid Rocket Booster separation, along any expected ascent azimuth. The operational status of these assets should be included in the Launch Commit Criteria for future launches. Consider using ships or aircraft to provide additional views of the Shuttle during ascent.

R3.4-2 Provide a capability to obtain and downlink high-resolution images of the External Tank after it separates.

R3.4-3 Provide a capability to obtain and downlink high-resolution images of the underside of the Orbiter wing leading edge and forward section of both wings' Thermal Protection System.

3.5 ON-ORBIT DEBRIS SEPARATION – THE "FLIGHT DAY 2" OBJECT

Immediately after the accident, Air Force Space Command began an in-depth review of its Space Surveillance Network data to determine if there were any detectable anomalies during the STS-107 mission. A review of the data resulted in no information regarding damage to the Orbiter. However, Air Force processing of Space Surveillance Network data yielded 3,180 separate radar or optical observations of the Orbiter from radar sites at Eglin, Beale, and Kirtland Air Force Bases, Cape Cod Air Force Station, the Air Force Space Command's Maui Space Surveillance System in Hawaii, and the Navy Space Surveillance System. These observations, examined after the accident, showed a small object in orbit with *Columbia*. In accordance with the International Designator system, the object was named 2003-003B (*Columbia* was designated 2003-003A). The timeline of significant events includes:

1. January 17, 2003, 9:42 a.m. Eastern Standard Time**:** Orbiter moves from tail-first to right-wing-first orientation
2. January 17, 10:17 a.m.: Orbiter returns to tail-first orientation
3. January 17, 3:57 p.m.: First confirmed sensor track of object 2003-003B
4. January 17, 4:46 p.m.: Last confirmed sensor track for this date