Columbia Accident Investigation and Return-to-Flight Effort

By Matthew E. Melis; Mike Pereira, PhD; Duane Revilock; and Kelly S. Carney, PhD
NASA Glenn Research Center

On February 1, 2003, the Space Shuttle *Columbia* broke apart during reentry, resulting in the loss of seven crewmembers. For the next several months an extensive investigation of the accident involved a nationwide team of experts from the National Aeronautics and Space Administration (NASA), industry, and academia, spanning dozens of technical disciplines.

Keywords
Columbia accident, impact, testing, impact analysis

The *Columbia* Accident Investigation Board (CAIB), a group of experts assembled to conduct an investigation independent of NASA, concluded in August 2003 that the cause of the loss of the Space Shuttle *Columbia* and its crew was a breach in the left wing leading edge reinforced carbon-carbon (RCC) thermal protection system initiated by the impact of thermal insulating foam that had separated from the orbiter's external fuel tank (ET) 81 seconds into the mission's launch. During reentry, this breach allowed superheated air to penetrate behind the leading edge and erode the aluminum structure of the left wing, which ultimately led to the breakup of the orbiter.

Supporting the findings of the CAIB were numerous ballistic impact testing programs conducted to investigate and quantify the physics of ET foam impact on the RCC wing leading edge material. These tests ranged from fundamental material characterization tests to full-scale orbiter wing leading edge tests. Following the accident investigation, NASA turned its focus to returning the Shuttle system to flight. Numerous test programs to evaluate impact threats from various debris sources during ascent needed to be completed before certifying the remaining Shuttles safe to fly again.

Researchers at the NASA Glenn Research Center (GRC) Ballistic Impact Laboratory conducted several of the impact test programs supporting the accident investigation and return-to-flight efforts.

The story of the *Columbia*

On January 16, 2003, at 10:39 am (EST), the Space Shuttle *Columbia* lifted off from Launch Complex 39-A at Kennedy Space Center in Florida. At approximately 81 seconds into launch, *Columbia* was traveling at Mach 2.46 (2655 km/hr or 1650 mi/hr) at an altitude of nearly

20.12 km (66,000 ft) when it was struck by a large piece of foam that had separated from the shuttle's ET.

The foam, decelerated by the airflow past the orbiter, struck the left wing leading edge of *Columbia* at a relative speed of 670–922 km/hr (416–573 mi/hr), causing the breach in the leading edge thermal protection system that ultimately led to the tragedy. Two ground movie cameras captured the event. Figure 1 is an image taken from one of the movies just before the event and depicts two foam pieces separating from the bipod ramp.

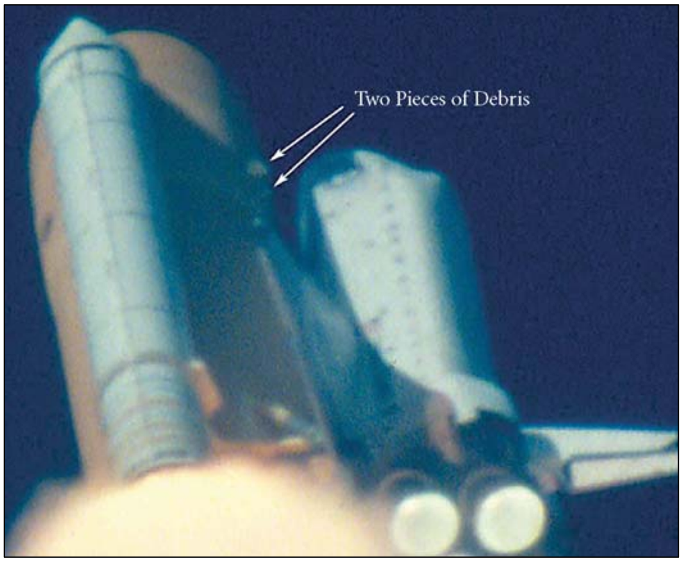

Figure 1. Two pieces of foam debris separating from the bipod ramp.

The Shuttle launch system, commonly referred to as the launch stack, consists of three components: the solid rocket boosters (SRBs), the ET, and the orbiter. The ET contains the cryogenic liquid hydrogen and oxygen propellants that feed the three Space Shuttle main engines at the rear of the orbiter. Various types of insulating foam cover the majority of the ET to keep the propellants cold and prevent the formation of ice on the outside of the tank. The foams account for the tank's characteristic deep orange color as these foams quickly turn orange when exposed to sunlight. Most areas on the ET require only an inch or so of foam, which is typically sprayed on by machine. Some locations, however, require more substantial build-ups of foam applied by hand. The bipod attachment is one such location and is considered to be the source of the foam debris that impacted *Columbia*. The foam at this location is made from a formulation designated BX-250.

The orbiter is attached to the ET at three locations: two support points at the rear of the vehicle and one at the front, referred to as the bipod. The bipod consists of two struts connecting the front of the orbiter to the ET. The bipod attachment at the ET requires additional insulation applied by hand in the shape of a ramp to optimize its aerodynamics. This foam build-up is referred to as the bipod ramp. Figure 2 highlights the bipod, the bipod ramp, and the general impact location on *Columbia*'s left wing leading edge.

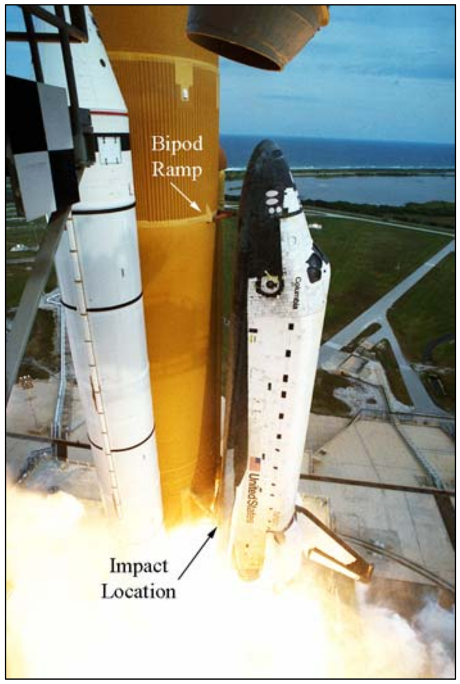

Figure 2. Shuttle *Columbia* just after liftoff showing the bipod attachment, the bipod ramp, and the location of impact.

During reentry, the wing leading edges of the orbiter can experience temperatures up to 1650 °C (3000 °F) and are thermally protected through the use of RCC—a brittle, plain-weave ceramic matrix composite material. The RCC material consists of a woven substrate and a silicon carbide ceramic coating to help prevent oxidation. Each orbiter wing has 22 unique RCC panels (numbered 1 through 22 from front to back on each wing) custom-built for their specific locations on the wing. The gaps between these panels are sealed with an RCC structure called a T-seal. Figure 3 shows a single leading edge panel with a T-seal.

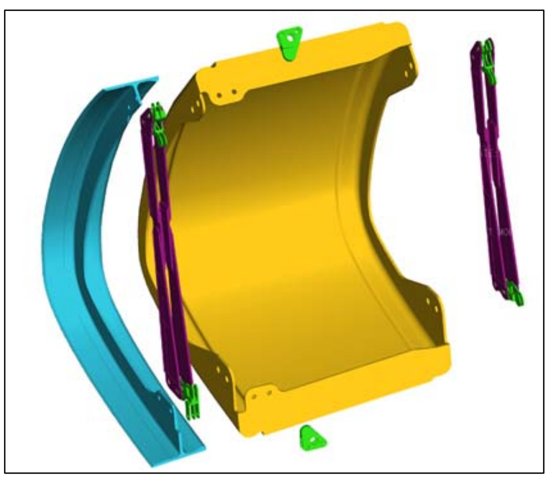

Figure 3. Rear view of reinforced carbon-carbon composite panel (in yellow) with T-seal (in blue). Purple and green objects are metallic support structures.

Post accident, an exhaustive reconstruction effort of the orbiter wreckage provided evidence of a breach in *Columbia*'s wing leading edge due to the foam impact event. The investigation that followed quickly established the need to develop an understanding of the impact behavior of ET foam and RCC both from an experimental and a computational standpoint. A detailed discussion and analysis of the *Columbia* accident can be found in the CAIB's report.[1]

The Role of the GRC Ballistic Impact Laboratory in the Accident Investigation

Little was known at the time of the accident about the impact characteristics of either BX-250 or RCC. Once it was determined that ET foam debris from the bipod ramp was a likely cause of the leading edge breach, the CAIB began an aggressive test program at Southwest Research Institute (SwRI) in San Antonio, Texas, to build a full-scale test article of a segment of an orbiter leading edge for impact testing. RCC panels from the remaining orbiters that had similar mission histories to those on *Columbia* were used for the testing. Figure 4 shows the test range at SwRI with the full-scale test article (consisting of panels 5 through 10 with respective T-seals).

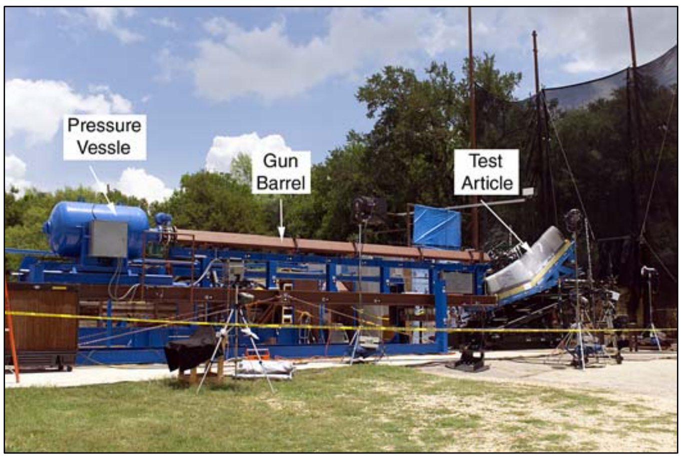

Figure 4. Ballistic test range at Southwest Research Institute shows gas gun and full-scale orbiter leading edge test article.

To support the investigation, the GRC Ballistic Impact Lab team was tasked with four primary technical responsibilities:

- Validate that the full-scale tests at SwRI would be appropriate in ambient atmospheric conditions 1.013E-01 megapascals (MPa) (14.6 lb/in^2 [psi]). This directive was derived from *Columbia* having been struck by the foam debris in a 6.894E-03-MPa (1-psi) environment, creating the requirement to quantify the effect of ambient pressure on the dynamic behavior of BX-250.
- Develop material models for physics-based explicit finite element techniques to computationally characterize foam impact on RCC.
- Characterize the static and impact behavior of BX-250 foam in support of this modeling effort.
- Provide expertise in digital high-speed photography to document the full-scale tests at SwRI.

Validation of the Full-Scale Leading Edge Test Conditions

In the early stages of the accident investigation, it was determined that impact testing in a 1-psi environment on BX-250 foam would be necessary to validate the results of the full-scale testing. This capability did not exist within NASA so the GRC Ballistic Impact Laboratory team was directed to develop such capability. The challenge was to shoot 3.175-cm (1.25-in.) diameter × 7.62-cm (3-in.) long cylindrical foam projectiles at load cells in a vacuum chamber via a gas gun and restrict the propellant gasses from entering the chamber itself. This was accomplished through the use of sabots made of polycarbonate material, seated with two O-rings at the base. The sabots, seen in Figure 5, contain the foam projectile during the firing of the gun. At the end of the gun barrel, the sabot is stopped by a plate with a hole slightly larger than the projectile to stop the sabot yet allow the projectile to continue freely toward its target. The plate, or sabot stopper, is positioned such that the O-rings remain inside the barrel of the gun, thus containing the helium propellant from entering the vacuum chamber (Figure 6). The vacuum chamber impact test apparatus is shown in Figure 7.

Figure 5. Polycarbonate sabots shown with BX-250 foam projectile in before and after fired condition.

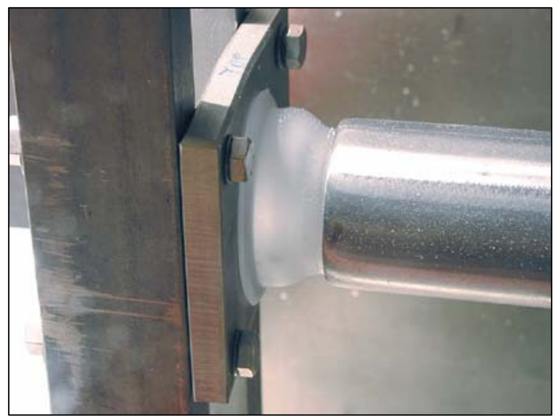

Figure 6. Sabot shown stopped at end of gun barrel. Note that O-rings remain inside barrel to maintain vacuum in the chamber.

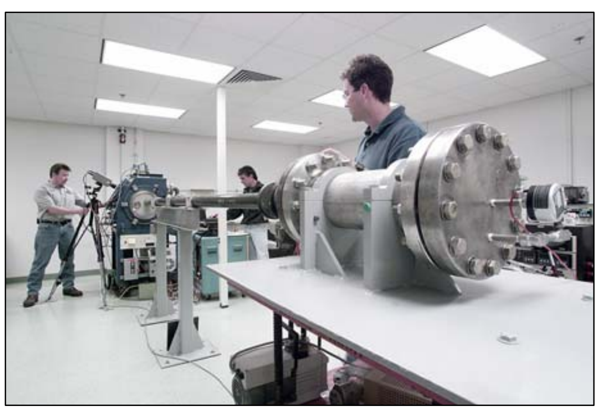

Figure 7. GRC Ballistic Impact Lab small vacuum chamber test setup.

An extensive series of impact tests were conducted at GRC on small cylindrical samples of BX-250 at various speeds between 183 and 244 m/sec (600–800 ft/sec) at 1.013E-01 MPa and 6.894E-03 MPa (14.6 psi and 1 psi). Digital high-speed cameras documented the tests and showed that the foam exhibited different characteristics at different pressures. Figure 8 shows the comparison between two impact tests at 244 m/sec (800 ft/sec) at different pressures depicting the time history of the break-up of the foam on rebound after impact when at 6.894E-03-MPa (1-psi) vacuum. Note that the break-up is not observed in the non-vacuum condition. Although it was discovered that BX-250 impact behavior was pressure-dependent, force-time histories demonstrated that the impact loads were virtually identical and led to the conclusion that the full-scale tests would be valid at SwRI.

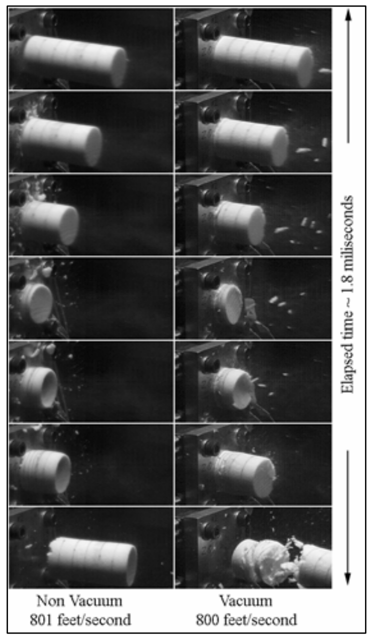

Figure 8. Comparison of BX-250 foam undergoing impact at vacuum and non-vacuum conditions.

Development of Material Models for RCC and BX-250 Foam

Commercial explicit finite element code software was selected as the tool to be used for the physics-based analysis. GRC was responsible for developing the software material models for both BX-250 and RCC materials. Materials subjected to impact experience high strain rates. Consequently, high-strain-rate materials data is required to completely develop an analysis model. Obtaining high-strain-rate material properties requires exotic test methods that are difficult to perform for monolithic materials. The nature of RCC and BX-250 foam further complicated the process of obtaining such data.

The software material model for the BX-250 foam was developed from the static tests performed at GRC as well as from high-strain-rate tests conducted at Langley Research Center. The BX-250 is a low-density elastic foam with highly nonlinear, strain-rate-dependent stress-strain behavior. The RCC composite material model created for the accident investigation was initially based on limited static stress-strain data generated years earlier. This data also showed nonlinear stress-strain behavior, in addition to compression-tension asymmetry with higher stiffness and strength observed in compression.

These models were provided to the NASA/Boeing impact analysis team and were used to demonstrate that a viable physics-based predictive capability with the commercial explicit finite element code software could be developed for future use by the Shuttle program. Near the conclusion of the full-scale testing at SwRI, this analysis capability was used to support decisions made in conducting those tests. Figure 9 shows the software predictions correlated well with the full-scale panel 8 test as seen in the high-speed video of the actual test.

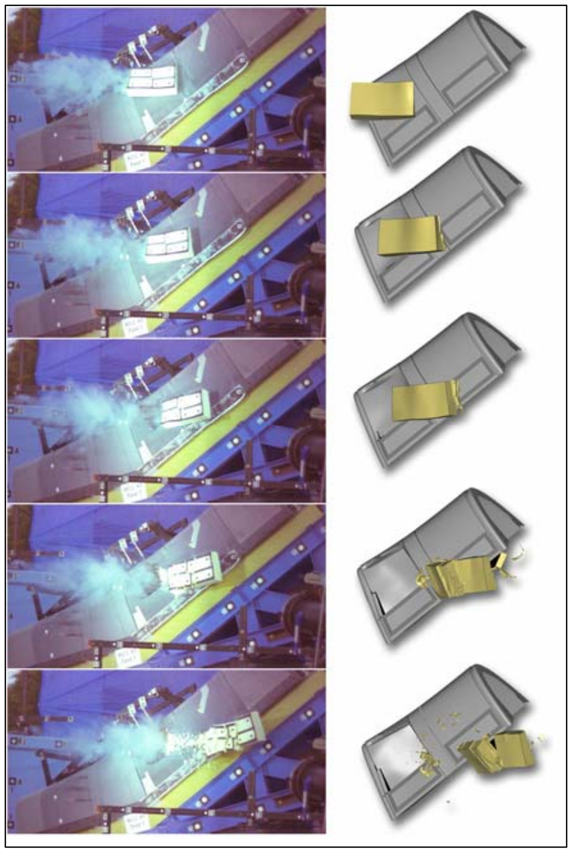

Figure 9. Comparison of predictions with actual panel 8 test at SwRI.

Characterization of Static and Dynamic Behavior of RCC and BX-250 Foam

Thorough static testing was performed on the BX-250 foam in the NASA GRC Fatigue Research Lab. Testing at cryogenic, room, and elevated temperatures was performed. In addition, room and elevated temperature tests were conducted in atmospheric as well as 1-psi environments.

During the accident investigation, virtually no RCC material was available for testing. NASA GRC was able to obtain four 3.81-cm (1.5-in.) × 15.24-cm (6-in.) RCC 19-ply coupons for conducting foam impact tests with the cylindrical BX-250 projectiles. These tests helped to demonstrate impact damage thresholds to better understand the RCC resistance to impact damage. Impact tests were made at 121, 169, 183, and 212 m/sec (397, 555, 600, and 695 ft/sec). Ultrasound and pulse thermography non-destructive evaluation (NDE) images were taken on each coupon before and after each test. At 121 m/sec (397 ft/sec), no damage to the coupon was seen either visibly or through NDE inspection. At 169 and 183 m/sec (555 and 600 ft/sec), the coupons were fractured partially but not broken in two. NDE inspection depicted significant internal ply delamination near the crack region. The coupon shot at 212 m/sec (695 ft/sec) was broken in two.

Photography Support of Full-Scale Tests at SwRI

GRC Ballistic Impact Lab personnel were on site for the entire full-scale test series to install, set up, and run the digital high-speed cameras used internally on the leading edge test article. Many tests were performed during the full-scale test series with the most significant test performed on panel 8. This test shot a 0.757-kg (1.67-lb) piece of foam at 236.22 m/sec (775 ft/sec) at the RCC panel. The impact created a hole in the panel 40.64 cm (16 in.) square, which can be seen in the high-speed images of Figure 9. This test was the last full-scale test in the accident investigation, providing the final supporting evidence to the CAIB conclusions.

The Role of the GRC Ballistic Impact Lab in the Return-To-Flight Effort

As the accident investigation concluded, NASA turned its attention to returning its remaining Shuttle fleet to safe flying status. An adequate understanding of the potential threat of any debris impacts to the launch system would need to be developed before NASA could launch a Shuttle again.

Much of the surface area of the ET and SRBs is covered with foam or ablator thermal protection system (TPS) materials. Several of these materials were identified to be potentially shed during ascent, requiring their threat as a debris impact source to be characterized. The threat characterization for each of these was expanded to include not only RCC wing leading edges, but also orbiter windows, ET structure, and orbiter tile.

In response to these challenges, the GRC Ballistic Impact Lab took responsibility for planning and executing numerous tasks, including several critical path elements key to the success of the return-to-flight program. The primary tasks were as follows:

- Extensive impact testing and characterization of potential debris materials.
- Impact testing on orbiter windows.
- Impact testing on external tank structure.
- Impact testing on flat RCC panels.
- Material model development and production analysis runs for the Shuttle program impact analysis team.
- Analysis and testing support at SwRI for phase II of the full-scale wing leading edge tests.

The majority of the tests for these programs were conducted in the GRC Ballistic Impact Lab's large vacuum chamber that was specifically built for the return-to-flight effort. The chamber, seen in Figure 10 with its 7.6-cm (3-in.) round barrel, has internal dimensions of 1.524 m × 1.219 m × 1.219 m (5 ft × 4 ft × 4 ft) and can accommodate a maximum barrel dimension of 15.2 cm (6 in.).

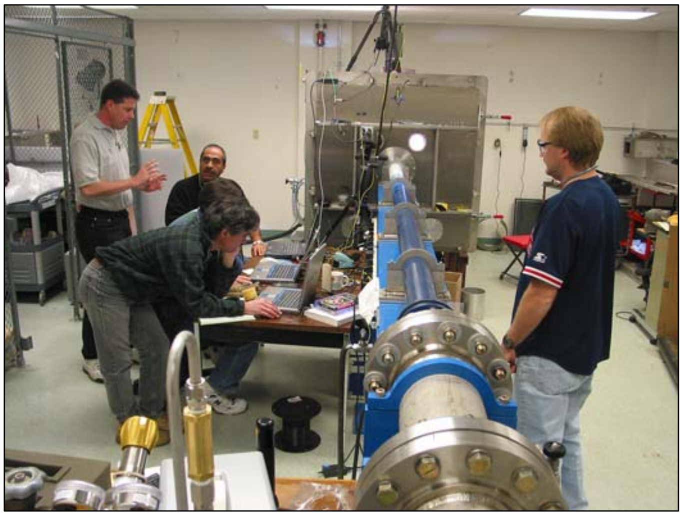

Figure 10. Large vacuum gun with 7.6-cm (3-in.) barrel in GRC Ballistic Impact Lab.

Impact Testing and Characterization of Potential Debris Materials

The TPS materials considered as potential debris sources included various foams (BX-265, NCFI, and PDL) as well as several ablators (RT 455, BTA, SLA, and MA). In addition, ice that forms on the ET was also included in this list. To better understand the impact threat from each of these materials, static and dynamic characterization was performed as was done on the BX-250 foam for the accident investigation. Although valuable to many areas in the Shuttle program, the primary motivation for doing this work was to provide the foundation and material properties for the software material models under development for each.

The GRC Fatigue Research Lab conducted comprehensive static testing of BX-265 and NCFI foams at 1 psi and atmospheric pressure. RT 455 and BTA ablators were tested in atmospheric pressure only as it was assumed that ambient pressure would have little effect on the mechanical response of either ablator. To account for strain-rate sensitivities, high-strain-rate tests in atmospheric pressures were performed on selected foams and ablators at NASA Langley to complement the GRC static data for the model development.

Impact testing was performed on each of these materials to establish force-time histories as well as qualitative impact behavior. Results from these tests were used to demonstrate the validity of the software code models such that reliable predictions of full-scale impacts could be made with confidence.

Two particular materials exhibiting interesting impact behavior were the ice and NCFI foam as shown in Figures 11 and 12, respectively. Both underwent a structural or phase change and became fluid in nature during the impact event, which significantly complicated the modeling process.

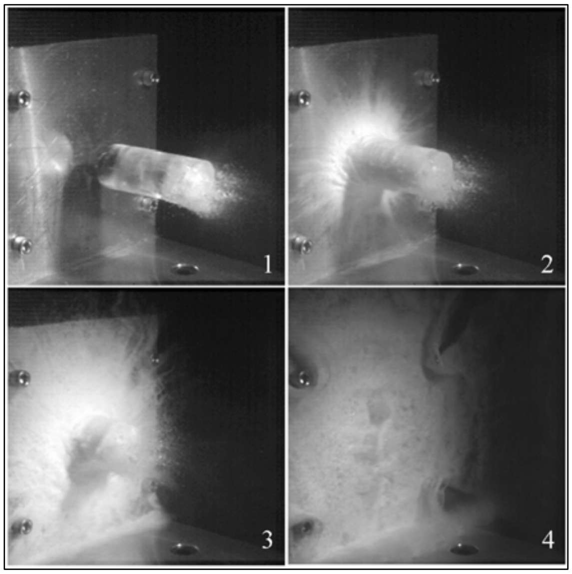

Figure 11. Impact of 3.175-cm (1.25-in.)-diameter × 7.62-cm (3-in.)-long ice cylinder on load cells at approximately 244 m/sec (800 ft/sec).

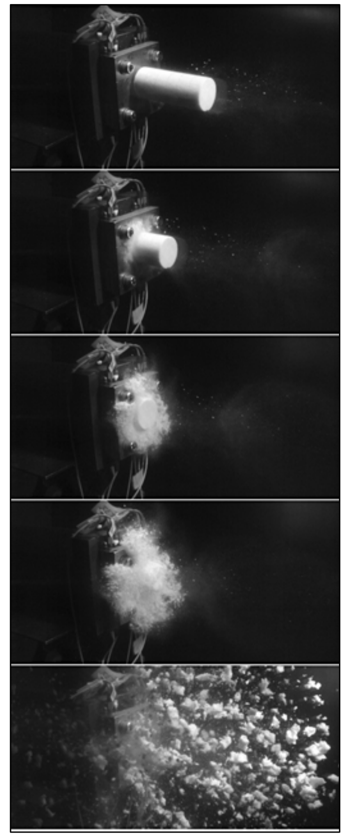

Figure 12. NCFI external tank foam undergoing impact at 244 m/sec (800 ft/sec) at 6.894E-03-MPa (1-psi) environment.

Impact Testing on Orbiter Windows

Each orbiter has six sets of forward/side windows indicated in Figure 13. Each set is comprised of three separate windows: two redundant windows to maintain crew cabin pressure and an exterior thermal pane to protect against aerothermal loading. Minute amounts of surface damage could lead to the brittle fracture of a thermal pane during its mission cycle loading; therefore, very low acceptable limits of such damage have been established for the program. Several impact threats to these windows were identified and the GRC Ballistic Impact Lab conducted tests to fully characterize each scenario.

The program evaluated impact damage due to BX-265 and NCFI TPS foams separating from the ET, ice formed on the ET, aluminum oxide particulates exhausted from the solid rocket booster separation motors (BSMs) at SRB separation, and paper rain (butcher paper) cover debris from the orbiter's forward reaction control motors. The butcher paper and BSMs are also identified in Figure 13.

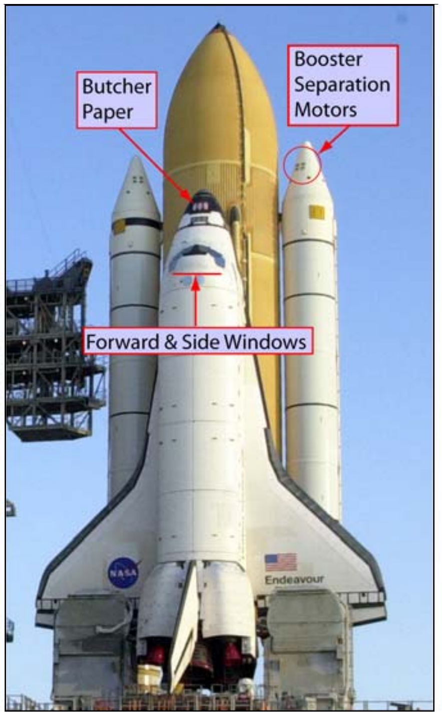

Figure 13. Forward and side windows on the orbiter with butcher paper and aluminum oxide debris source points identified.

To clear the windows for safe flight, foam and ice projectiles for each of these materials were fired at previously flown front and side windows that had been pulled from service for various reasons. Aluminum oxide particulates were fired at window 2.54-cm (1-in.) × 22.86-cm (9-in.) witness coupons (MOR bars) typically used for modulus of rupture tests. These witness coupons were processed simultaneously alongside each individual window to verify processing quality. Size, velocity, and angle of impact on the windows for each of the projectiles were determined by the debris transport analysis group (DTA) in the Shuttle program.

Foam, paper, and ice tests were performed in the GRC Ballistic Impact Lab's large vacuum chamber. Full-scale windows were mounted in an aluminum frame fixed inside the chamber at the prescribed angle to the gun barrel. Figure 14 shows a window mounted to the test frame inside the chamber in preparation for a test.

Figure 14. Orbiter window mounted in GRC Ballistic Impact Lab's large vacuum chamber in preparation for test.

Aluminum oxide particulates of concern ranged from 100 to 450 µm and were fired at the MOR bars using the 0.3175-cm (0.125-in.) vacuum gun. This setup, built specifically for this test series, is shown in Figure 15 with the external lighting system and the digital camera. Each window and MOR bar was fully inspected by certified Shuttle windows inspectors prior to testing to identity any preexisting damage to exclude in the post-test examination. Following each test, the windows were reexamined for any surface damage using a fiber-optic lighting system. Molded impressions were taken of any suspect damage sites and quantified with an optical comparator to establish whether the damage fell in or outside the acceptable safety limits.

Figure 15. The 0.3175-cm (0.125-in.) vacuum gun with digital camera and lighting system used to shoot 100-450 µm particles at MOR bars.

Impact Testing on External Tank Structure

The DTA determined that ET BX-265, NCFI, or PDL foam debris could potentially shed and impact the tank downstream from the point of separation. Such an event might possibly result in significant TPS foam loss at the impact site that could put the launch system at risk. As with the windows, a variety of tests at varying angles, velocities, and projectile configurations were conducted at GRC to characterize TPS foam on foam impact. Target panels were made from 0.6096 m (2 ft) × 0.6096 m (2 ft) aluminum plates sprayed with approximately 2.54 cm (1 in.) of foam to represent actual coverage on the ET. The panels were mounted in the large vacuum chamber at each corner onto a load cell frame for measuring the force-time history of each impact. Figure 16 shows a panel mounted in the load frame in preparation for a 90° impact test.

Figure 16. Aluminum test panel with ET TPS foam mounted in large vacuum chamber load frame for 90° impact test.

Both cylindrical and square projectiles were machined for this test series to establish shape sensitivity to impact damage; however, rectangular projectiles were used for the majority of this test series and were shot from square barrels using no sabot as a result of higher velocity requirements and the square barrel geometry. Figure 17 shows high-speed footage of a typical impact event observed in this test series.

Figure 17. High-speed images of BX-250 foam projectile impacting NCFI foam sprayed on an aluminum test panel.

Impact Testing on RCC Flat Panels

As a result of the limited supply of RCC test material, this series of tests was perhaps the most significant at the GRC Ballistic Impact Lab. This program was motivated by the requirement to validate the accuracy and reliability of the software prediction capability developed under return-to-flight. RCC deformation and damage thresholds due to impact were to be quantified for these tests.

The program was designed to shoot BX-265, ablator, and ice projectiles at 15.24-cm (6-in.) × 15.24-cm (6-in.) RCC 19-ply flat panels at 45° and 90°. For each projectile, a spectrum of tests was conducted to establish both a maximum velocity at which no damage would occur as well as the minimum velocity resulting in severe damage to both the front and back side of the panel. Pre- and post-test ultrasound and pulse thermography NDE were done to detect internal delaminations due to impact. This examination was particularly important in detecting internal damage when no external visible damage was observed. Figure 18 shows high-speed imagery from both the front and back side of a panel undergoing impact with BX-265. Note the coating separation on the back side of the panel.

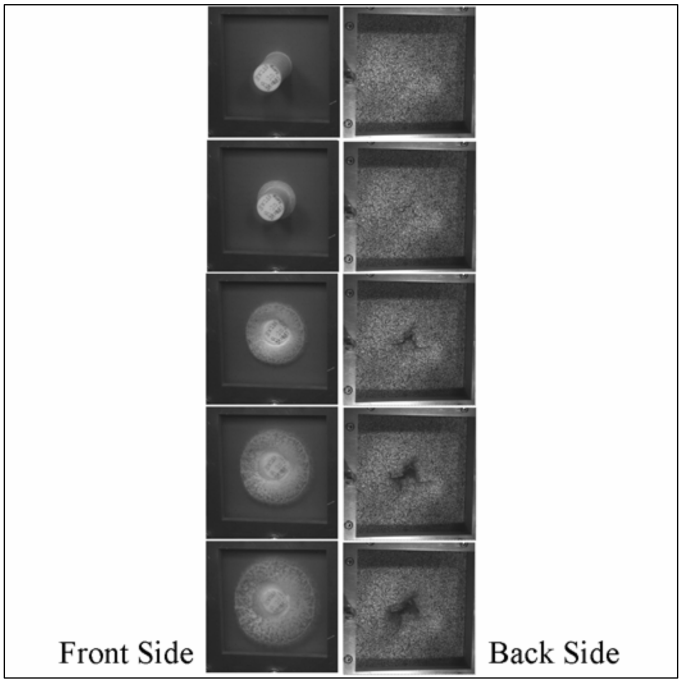

Figure 18. High-speed images of RCC flat panel impact with BX-265 foam from front and back sides of panels.

Of major significance for this test series was the method in which deformations were measured. A commercial full-field displacement measurement system utilized stereographic photogrammetry techniques to establish 3-D displacements at static and dynamic conditions.[2,3] The system, used in conjunction with two digital cameras to view the same field of interest from slightly different angles, correlated synchronized high-speed images from the cameras to compute 3-D displacements. Random speckle patterns painted on the surface being viewed insured correlation by the measurement system. While perhaps difficult to resolve in the back side panel images of Figure 17, this speckle pattern can be identified. Displacement measurements had good correlation with the code software predictions.

This accomplishment with the displacement measurement system using high-speed imagery was groundbreaking in nature and was of high value to the return-to-flight effort. The system was also used for the ET foam-on-foam impact tests in the same capacity as for the RCC panel tests. Figure 19 shows example output from one of the RCC panel tests depicting out-of-plane displacement contours and the time-displacement history of the center point of the panel.

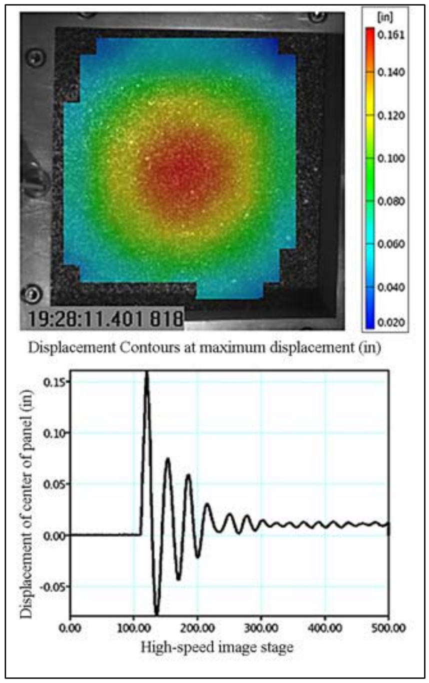

Figure 19. Sample output from displacement measurement system depicting out-of-plane RCC panel displacement as it undergoes impact.

Material Model Development and Production Analysis Runs for the Ballistic Impact Analysis Team

The ballistic impact analysis team assembled for the accident investigation was asked to continue its work for return-to-flight. This team, comprised of impact dynamics experts from NASA Glenn, NASA Langley, and Boeing Philadelphia, was directed to implement and validate the code software impact analysis capability and use it to quantify the threat of a spectrum of impact scenarios on wing leading edge RCC panels provided from the DTA. This evolved into an extensive parametric study of impacts (production runs) due to BX-265 foam, ablator material, and ice on several different RCC panels and T-seals of the wing leading edge with the goal of establishing impact damage thresholds.[4-8]

To accomplish this task, the team built detailed finite element meshes for specified RCC panels and T-seals to be used in the code software analyses. In parallel, validated software material models for RCC, ice, ablator, and BX-265 foam were developed for the production runs. Hundreds of impact analyses were made with the intent to quantify the threat of each scenario provided by the DTA. Figure 20 shows a typical analysis with foam impacting a panel and T-seal. GRC participated in all aspects of this team's activity; however, its primary responsibility was the material model development.

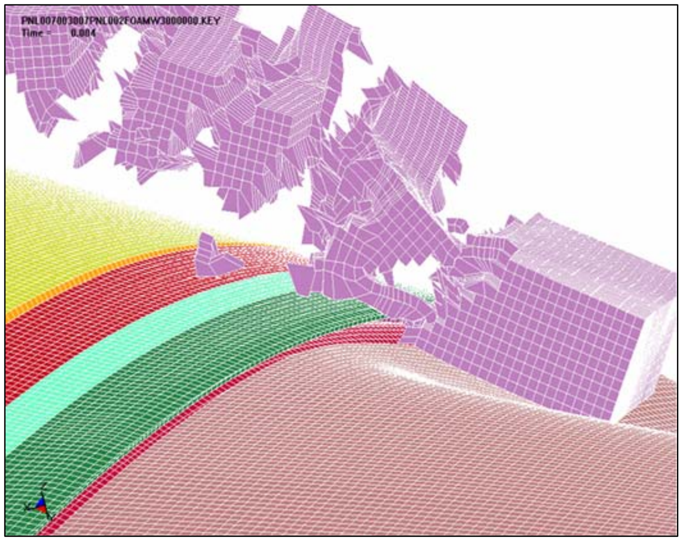

Figure 20. Foam projectile impacting RCC panel and T-seal.

A comprehensive set of models representing BX-265 foam in a variety of conditions and properties was created. These conditions included room and cryogenic temperatures and stronger and weaker foam. The data used to create these models was compiled from a series of high rate and static compressive tests completed at Langley Research Center and tension tests performed at Marshall Space Flight Center. A set of parameter studies was then performed to select the foam that would produce the greatest load, to be used in the Shuttle re-certification analysis effort.

In addition, other potential projectile materials were modeled, including the SRB ablators composed of cork and epoxy. These were modeled as viscoelastic materials, using a rubber model that includes a definable Poisson's ratio. The data used to create these models was also compiled from a series of high rate and static compressive tests completed at Langley Research Center and tension tests performed at Marshall Space Flight Center. Loads produced by analysis using these material models were compared to ballistic test load data, performed at GRC, and were found to give excellent agreement.

A series of new tests on RCC were conducted in order to better define the RCC behavior. Static tests of RCC with and without coating were conducted at SwRI. A series of high-strain-rate tension tests using a Hopkinson-Bar Technique[9] were conducted by GRC, through a contract with Ohio State University, in order to fully quantify the strain-rate behavior of the RCC composite. These tests were also conducted on both coated and uncoated samples, allowing the separate characteristics to be modeled.

As mentioned in the "Impact Testing and Characterization of Potential Debris Materials" section, testing on the projectile materials was performed to support the development of the material models to be used for the production runs. The results of the RCC/foam flat panel impact tests showed excellent displacement correlation to representative code software predictions supporting the validity of production runs assessing foam impacts. The significance of this work was the development of an analysis prediction capability that was non-existent prior to the *Columbia* tragedy and will undoubtedly be used extensively for future launch operations.

Analysis and Testing Support of Full-Scale Wing Leading Edge Tests

As a final validation of the code software predictive capability, follow-on full-scale wing leading edge impact tests, with ice and foam projectiles, were performed at SwRI on two panel 9 test articles. As before, the GRC Ballistic Impact Lab provided high-speed digital photographic support as well as support for using the displacement measurement system to acquire panel deformations for each of the tests.

Results from these tests provided the data required to establish a reasonable level of confidence in the ability of the explicit finite element code software to accurately simulate impact events on the Shuttle leading edges.

Acknowledgements

As with most technical efforts of this magnitude, many individuals contributed to its success. Dozens at GRC and NASA were key to supporting these programs. The authors wish to express their sincere appreciation for the commitment and perseverance of each person, too numerous to mention, who worked so hard to complete these test programs. We all celebrated on July 26, 2005 when the Shuttle *Discovery* lifted off on mission STS-114 to the International Space Station, returning the Shuttle program to safe flight.

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Matthew E. Melis received a BS in civil engineering and an MS in engineering mechanics from Michigan State University. He has worked at the NASA Glenn Research Center for 20 years, with his primary area of focus in advanced finite element modeling and analysis methods including nonlinear and dynamic impact loading. His research is being used to predict ballistic impact response of jet engine fan containment concepts. For more than 3 years, Melis dedicated full time to the Columbia accident investigation and NASA's return-to-flight efforts.

Author contact information: Matt Melis, NASA Glenn Research Center, 21000 Brookpark Road Mail Stop 49-8, Cleveland, OH 44138. E-mail: Matthew.E.Melis@nasa.gov.

Dr. Michael Pereira manages the NASA Glenn Research Center Ballistic Impact Laboratory. He has conducted extensive experimental research in the area of impact, penetration, and high-strain-rate behavior of structures and materials, particularly as they apply to jet engine containment and propulsion systems. Dr. Pereira received a PhD in mechanical and aerospace engineering from Case Western Reserve University, Cleveland, Ohio, in 1989, and an MS in mechanical engineering from Ohio State University, Columbus, Ohio, in 1981. For more than 3 years, he was dedicated full time to the Columbia accident investigation and the return-to-flight efforts.

Author contact information: J. Michael Pereira, NASA Glenn Research Center, 21000 Brookpark Road Mail Stop 49-8, Cleveland, OH 44138. E-mail: J.M.Pereira@grc.nasa.gov.

Duane Revilock has worked for the NASA Glenn Research Center since 1989. He became an aerospace engineer in 1996 after receiving BS and MS degrees from Cleveland State University, Cleveland, Ohio. His primary area of research has been in the area of ballistic impact testing. Revilock was responsible for the design and development of the NASA Glenn Ballistic Impact Laboratory, a facility serving researchers in academia, government, and industry. His work supports a number of NASA programs, as well as external programs through Space Act Agreements. For more than 3 years, he was dedicated full time to the Columbia accident investigation and the return-to-flight efforts.

Author contact information: Duane Revilock, NASA Glenn Research Center, 21000 Brookpark Road Mail Stop 49-8, Cleveland, OH 44138. E-mail: Duane.M.Revilock@grc.nasa.gov.

Dr. Kelly Carney received a BS in mechanical engineering from Michigan State University, an MS from the University of Toledo, and a PhD from Case Western Reserve University. Dr. Carney has worked at NASA Glenn Research Center for 23 years. His past experience includes analysis of launch vehicles and space structures on projects such as Shuttle-Centaur, Atlas-Centaur, ACTS, and Space Station. In recent years, he has focused on the research area of ballistic impact dynamics. For more than 3 years, Dr. Carney assisted in the Columbia accident investigation and the return-to-flight efforts.

Author contact information: Kelly S. Carney, NASA Glenn Research Center, 21000 Brookpark Road Mail Stop 49-8, Cleveland, OH 44138. E-mail: Kelly.S.Carney@grc.nasa.gov.