3 ASSESSMENT OF THE CAIB RECOMMENDATIONS

What follows is a section for each of the 15 Columbia Accident Investigation Board (CAIB) return-to-flight recommendations and the "raising-the-bar" SSP-3 action; the three Chapter 7 recommendations (R7.5-1, R7.5-2, and R7.5-3) that are subordinate to R9.1-1 are covered in Section 3.14. In each case the section repeats the original recommendation word-for-word, gives the RTF TG interpretation of the recommendation, provides a brief background (often taken directly from the CAIB report), details the NASA implementation, and concludes with the Task Group's final assessment of the progress NASA made toward implementing the recommendation.

The section entitled "NASA Implementation" contains descriptions taken from the appropriate version of the NASA *Implementation Plan for Space Shuttle Return to Flight and Beyond*, based on the date for the individual assessment was deliberated. (The RTF TG generally called this document the *NASA Implementation Plan* for brevity.) Additional information from the closure packages submitted by NASA, requests for information, and fact-finding activities are also included as necessary to ensure an adequate description. In general, the description presented in this section is a snapshot of the progress made when the Task Group concluded its assessment; in many cases, things changed between then and the release of this report. It is not the intent of the Task Group to "put words in NASA's mouth" and in case of disagreement between this document and any official NASA publication, the NASA document shall prevail.

The following table summarizes the Task Group's assessment of the CAIB return-to-flight recommendations.

3.1	3.2-1	External Tank Debris Shedding	June 27, 2005	Not Met
3.2	3.3-1	Reinforced Carbon-Carbon Non-Destructive Inspection	February 17, 2005	Met
3.3	3.3-2	Orbiter Hardening	June 27, 2005	Not Met
3.4	3.4-1	Ground-Based Imagery	June 8, 2005	Met
3.5	3.4-2	High-Resolution Images of External Tank	December 16, 2004	Met
3.6	3.4-3	High-Resolution Images of Orbiter	June 8, 2005	Met
3.7	4.2-1	Solid Rocket Booster Bolt Catcher	December 16, 2004	Met
3.8	4.2-3	Two-Person Closeout Inspections	December 16, 2004	Met
3.9	4.2-5	Kennedy Space Center Foreign Object Debris Definition	December 16, 2004	Met
3.10	6.2-1	Consistency with Resources	June 8, 2005	Met
3.11	6.3-1	Mission Management Team Improvements	June 8, 2005	Met
3.12	6.3-2	National Imagery and Mapping Agency Memorandum of Agreement	December 16, 2004	Met
3.13	6.4-1	Thermal Protection System Inspection and Repair	June 27, 2005	Not Met
3.14	9.1-1	Detailed Plan for Organizational Change	June 8, 2005	Met
3.15	10.3-1	Digitize Closeout Photos	December 16, 2004	Met
3.16	SSP-3	Contingency Shuttle Crew Support	June 8, 2005	n/a

Discovery, atop a Mobile Launch Platform (MLP), crawls toward Launch Complex 39B on April 6, 2005. The MLP is moved by the Crawler-Transporter underneath. The crawler stands 20 feet high, 131 feet long and 114 feet wide and moves on eight tracks, each containing 57 cleats weighing one ton each. The crawler moves at a maximum speed of approximately 0.8 mile per hour while carrying the 3 million pound Space Shuttle stack. Note the “We’re Behind You, Discovery” banner on the MLP.

3.1 CAIB Recommendation 3.2-1 – External Tank Debris Shedding

Initiate an aggressive program to eliminate all External Tank Thermal Protection System debris-shedding at the source with particular emphasis on the region where the bipod struts attach to the External Tank.

3.1.1 RTF TG Interpretation

Eliminate all sources of critical debris in locations where liberated debris might impact the Orbiter, eliminate the bipod strut foam entirely if possible, and determine the foam void size that produces debris of an acceptable size based on the transport and energy analyses.

3.1.2 Background

The *Columbia* accident clearly demonstrated that the Orbiter Thermal Protection System, including the reinforced carbon-carbon (RCC) panels and acreage tiles, was vulnerable to impact damage from the existing debris environment. As a result, the Columbia Accident Investigation Board (CAIB) issued recommendations to eliminate debris (R3.2-1), determine the structural integrity of the RCC (R3.3-1), harden the Orbiter (R3.3-2) against impacts, and to develop on-orbit repair capabilities (R6.4-1).

The External Tank (ET) is the largest element of the Space Shuttle system. Because it is the common element to which the Solid Rocket Boosters and the Orbiter are connected, the ET serves as the main structural component during stacking, launch, and ascent. Lockheed Martin builds the tank at the Michoud Assembly Facility, Louisiana, under contract to the NASA Marshall Space Flight Center.

The External Tank is 153.8 feet long, 27.6 feet in diameter, and comprises three major sections: the forward (upper) liquid oxygen tank, the aft (lower) liquid hydrogen tank, and the intertank area between them. The ET holds 143,351 gallons of liquid oxygen at minus 297 degrees Fahrenheit and 385,265 gallons of liquid hydrogen at minus 423 degrees Fahrenheit.

ET-120, the External Tank originally scheduled for use on STS-114, arrives at the Kennedy Space Center. Various anomalies with this tank forced the program to switch to ET-121, the tank originally scheduled for STS-121.

Several different types of foam insulating material are applied to the ET. The acreage foam that covers the majority of the ET prevents the formation of ice as moist ambient air comes in contact with the aluminum skin of the ET when it is filled with cryogenic propellants. Other types of foam and lightweight ablator materials are designed to protect the External Tank from aerodynamic heating as the vehicle accelerates during ascent. The ET was designed to be economical to produce since it is the only "throw away" portion of the otherwise reusable Space Shuttle. The construction techniques chosen – both for economy and to minimize weight – made it infeasible to use an internal insulation instead of the acreage foam.

NASA maintains that foam remains the only viable technical solution for providing a lightweight, efficient, external thermal protection system. However, foam poses a variety of manufacturing challenges. For example, it is subject to small voids during application, especially around complex geometries such as joints or protrusions. This problem is exacerbated by the fact that foam for complicated areas must be manually applied, instead of the more consistent automated process that is used for the smooth areas. Using non-destructive inspection to find inconsistencies or defects in the foam is an engineering challenge that has eluded a reliable technical solution. NASA has conducted several searches for non-destructive inspection techniques in industry and research institutions and has made repeated attempts to develop a method of inspecting the foam for correct application; to date these have only been partially successful. As an alternative to inspection, NASA has incorporated strict process controls for both automated and manual foam applications.

The accident board found that foam loss had occurred on more than 80 percent of the 79 missions for which imagery was available, and foam was lost from the left bipod ramp on nearly 10 percent of the 72 missions where the left bipod ramp was visible following ET separation. It was foam debris from the left bipod ramp that caused the *Columbia* accident. For about 30 percent of all missions, there was no way to determine if foam was lost; these were either night launches, or the External Tank bipod ramp areas were not in view when the images were taken. The ET was not designed to be recovered after separation, depriving NASA of physical evidence that could help pinpoint why foam separates from it. Photography of the ET after separation – although routinely accomplished – was not a priority for the Space Shuttle Program prior to the *Columbia* accident.

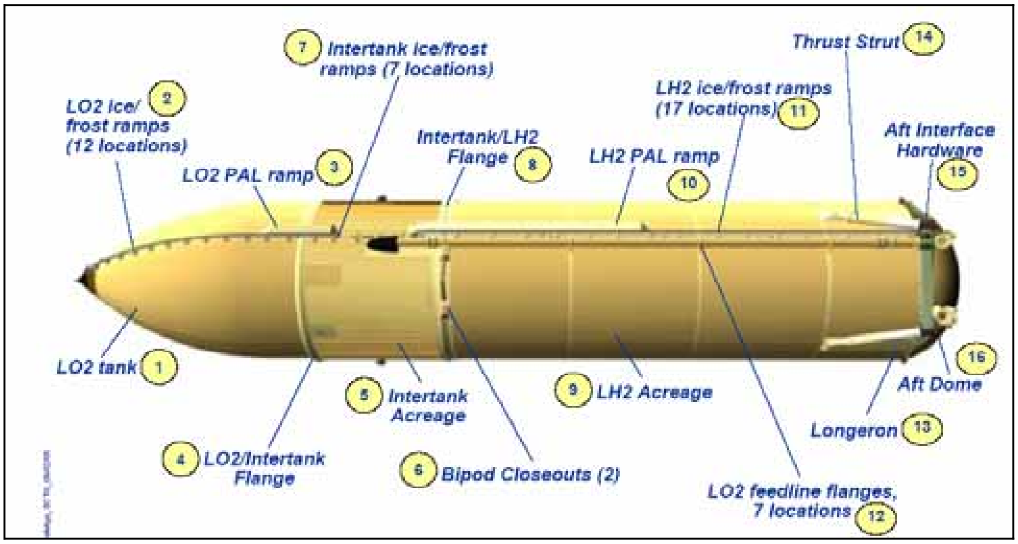
A complete description of the External Tank and this problem, as explained by the accident board, may be found in the CAIB final report, Volume I, Section 3.2.

3.1.2.1 ET Debris Sources

During the early 1990s, NASA attributed several instances of foam loss to de-bonds or voids in the "two-tone foam" bond layer on the intertank area forward of the bipod ramp. It was thought that when the intertank foam was liberated, it peeled portions of the bipod ramp off with it. Corrective action taken after STS-50 in June 1992 included the implementation of a two-gun spray technique in the ET bipod ramp area to eliminate the two-tone foam configuration. This appeared to have solved the problem until the sixth bipod ramp event occurred during STS-112 on October 7, 2002, two flights prior to STS-107.

A bipod ramp like the one shown here was the debris that doomed *Columbia* on her last flight. These ramps have been completely eliminated from the modified External Tanks.

After the STS-112 bipod ramp foam loss event, the ET Project began developing concepts to redesign the bipod ramp; this activity was still under way at the time of the STS-107 accident. The dissection of bipod ramps conducted for the *Columbia* accident investigation indicated that defects resulting from a manual foam spray operation over an extremely complex geometry could produce foam loss.



NASA evaluated 16 areas of the ET thermal protection system for debris shedding. Eventually five areas of foam (numbers 5, 6, 8, 10, 13) plus a source of ice debris at the LO2 feedline bellows (not shown) were selected for improvement or redesign based on their likelihood to liberate critical debris.

The LO2 and LH2 PAL (protuberance air load) ramps are designed to reduce adverse aerodynamic loading on the ET cable trays and pressurization lines. PAL ramp foam loss was observed on two flights, STS-4 and STS-7. The most likely cause of these losses were earlier repairs and cryo-pumping (air ingestion) into the super-lightweight ablator (SLA) panels under and adjacent to the PAL ramps. Configuration changes and repair criteria were revised early in the program, to mitigate recurrence of these failures. The PAL ramps are large, thick, manually sprayed foam areas that use a less complex spray process than that used on the bipod; however, if liberated the ramps could become large debris.

Another area of special interest was the intertank that separates the LO2 tank from the LH2 tank. The area where the intertank connects to the pressurized hydrogen tank is called the LH2/intertank flange. Imagery taken after ET separation showed repeated loss of foam from this flange area prior to STS-107.

Further investigation showed that another potential source of debris was the LO2 feedline, a large external pipe that runs the length of the External Tank. Bellows are located at three joints along the feedline to accommodate thermal expansion and contraction. The bellows shields are covered with foam, but the ends are exposed. Because of the cryogenic fluids in the pipe, ice and frost form when moisture in the air contacts the cold surface of the exposed bellows as well as on five brackets that hold the feedline to the ET.

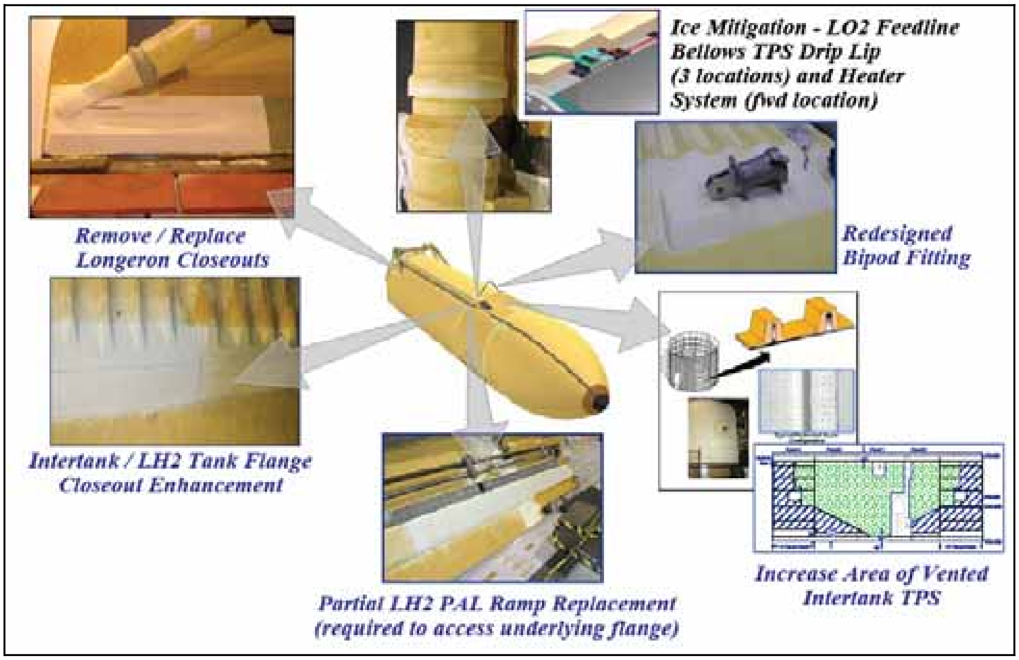
Space Shuttle Program requirements included provisions for ice on the feedline bellows, brackets, and adjacent lines. However, ice in these areas is a potential source of debris in the critical debris zone – the area from which liberated debris could impact the Orbiter. Ice has been seen on all missions, and after a review of flight history, NASA believes a portion of the historical debris damage was the result of ice impacts.

It should be noted that, despite extensive analysis and tests, to date, neither the CAIB nor NASA have been able to absolutely determine the root cause for the loss of the bipod ramp foam during the last flight of *Columbia*. Additionally, the accident board also was not able to determine that the SRB bolt catchers, while an unlikely cause, could be definitively excluded as a potential cause of the left wing damage on *Columbia*.

3.1.3 NASA Implementation

After the *Columbia* accident, NASA initiated a three-phase approach to eliminate the potential for debris shedding – such as ice and foam – from the External Tank. Phase 1 included those activities completed prior to the return-to-flight that would control critical debris on tanks already constructed. NASA determined that the Phase 2 activities were not required for return to flight, but rather focused on continuous improvement including debris elimination enhancements that could be incorporated into the ET production line for new tanks. Phase 3 would have examined additional means of further reducing ET debris potential; however, NASA does not plan to implement Phase 3 since the Space Shuttle is scheduled to be retired at the end of the decade.

NASA made several modifications to the External Tank to reduce foam and ice debris during ascent. Although all are considered successful, testing and analysis show that the ET can still shed critical debris.

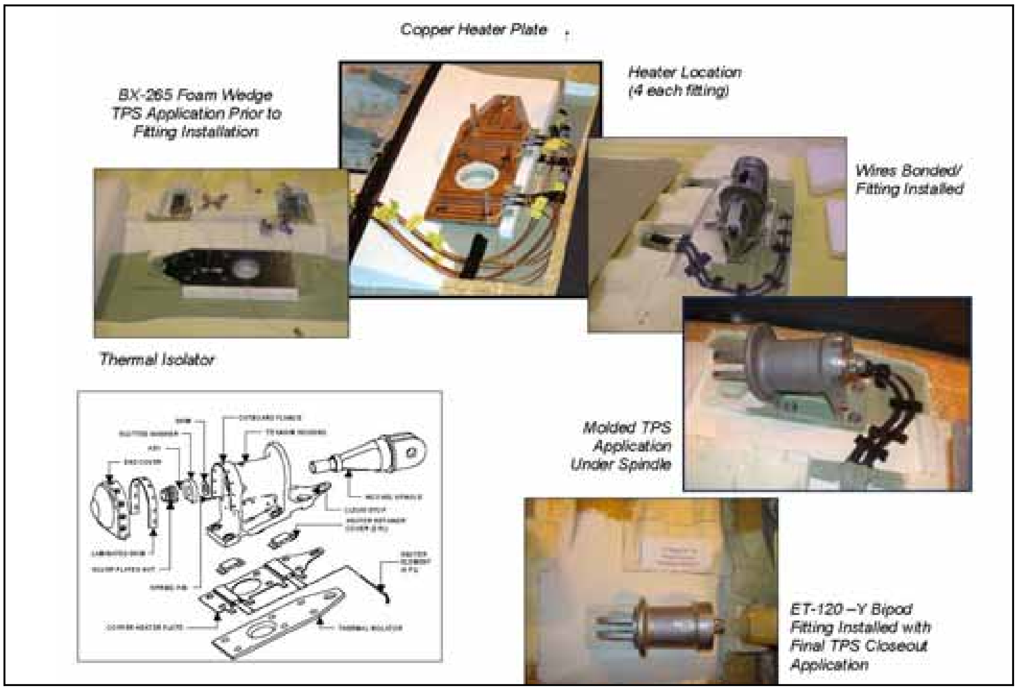


As part of the Phase 1 effort for return to flight, NASA modified the areas of known critical debris sources, although NASA has never determined the root cause for all instances of foam shedding. This included redesigning the forward bipod fitting and associated thermal protection system closeout, redesigning the LH2/intertank flange thermal protection system closeout, and reducing ice formation on the LO2 feedline bellows. ET intertank venting was increased to reduce popcorning masses in the ET foam.

In addition to addressing these known areas of debris, NASA has reassessed all areas of the ET to verify the robustness of the thermal protection system configuration, including both automated and manual spray applications. Special consideration was given to the LO2 and LH2 PAL ramps due to size and location. Although there is no significant history of foam liberation from the longeron area, the ET Project took the conservative path of removing and reapplying part of this area with an improved foam application process.

NASA also pursued a testing program to understand the root causes of foam shedding from various areas (with varying degrees of success) and developed alternative design solutions to reduce the debris loss potential. Additionally, NASA is continuing the development of two non-destructive inspection techniques – tetrahertz imaging and backscatter radiography – to conduct ET thermal protection system inspection without damaging the fragile insulating foam. During Phase 1, non-destructive inspection was used on the LO2 and LH2 PAL ramps as engineering information only; certification of the foam was achieved primarily through verifying the application and design.

The bipod fitting design, fitting closeout, and heater system were reviewed during the ET Design Certification Review. The verification included thermal tests to determine the capability of the design to preclude prelaunch ice, with an automated heater control baselined and validated based on bipod web temperature measurements. Structural verification tests have confirmed the performance of the modified fitting in simulated flight environments. Wind tunnel testing has verified the thermal protection system closeout performance when exposed to the expected ascent aerodynamic and thermal environments.

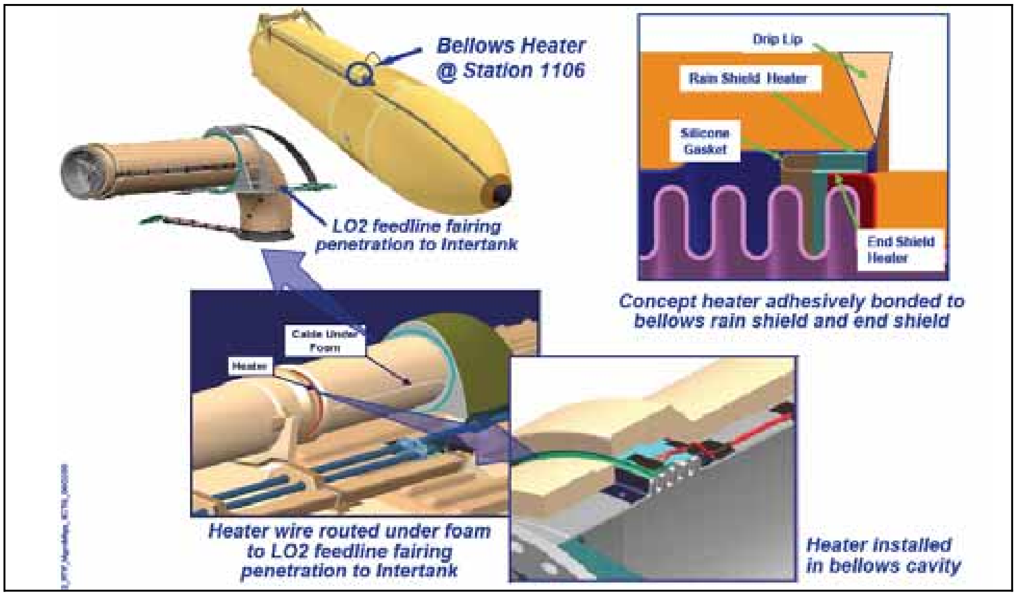


The most visible change to the External Tank was the elimination of the bipod ramps on the forward ET attach point and the installation of heaters in the same area. The loss of one of these foam ramps was responsible for the loss of *Columbia*.

Initially, NASA selected a “drip lip” to reduce ice formation on the three LO2 feedline bellows. The drip lip diverts condensate from the bellows and significantly reduces ice formation. However, since the drip lip alone was not sufficient to completely eliminate the ice, NASA continued to pursue complementary solutions. By April 2005, analysis of the ice formation, estimates of the liberated ice, and transport analyses identified the residual ice at the forward LO2 feedline bellows location as an unacceptable debris source; therefore, additional reduction of ice at the forward location was required before return to flight and resulted in moving the launch date from May 2005 to July 2005.

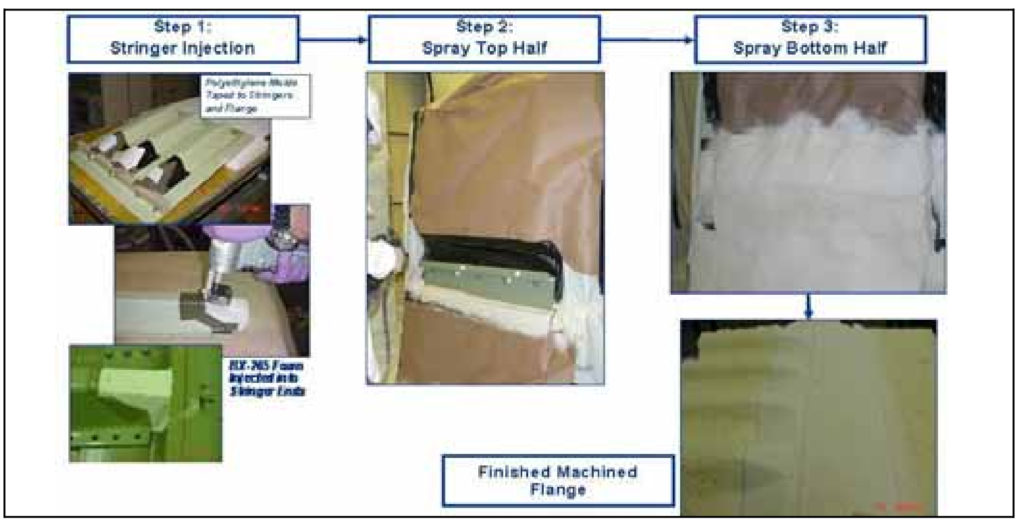
Three photos showing ice accumulation on the forward LO2 feedline bellows. The drip lip was initially chosen for return to flight, but ultimately the heater was installed to further mitigate the problem.

During the delay, NASA installed a heater in the forward LO2 bellows cavity to reduce ice formation to an acceptable level. Bonding of the heaters required removal and replacement of a 3-inch wide strip of foam along the existing drip lip and LO2 feedline surface. The heater has been installed in the tanks that will be used for STS-114, STS-121, and all future flights. No modifications other than the drip lips have been implemented for the mid and aft bellows for STS-114; NASA continues to assess other ice mitigation techniques for these locations for future flights.



Details of the bellows heater installation. This heater was installed at the Michoud Assembly Facility on the third post-*Columbia* ET (ET-119), but was retrofitted at the Kennedy Space Center on the first two tanks (ET-120 and 121).

NASA determined the primary root cause of foam loss in the intertank/LH2 tank flange area was the gaseous nitrogen used as a safety purge in the intertank coming into contact with the extremely cold hydrogen tank dome and condensing into liquid. The liquid nitrogen migrated through intertank joints, fasteners, vent paths, and other penetrations into the foam and then filled voids in the foam caused by variability in the manual foam application. During ascent, the LN2 returned to a gaseous state, pressurizing the voids and causing the foam to detach. With this knowledge, NASA evaluated the LH2/intertank closeout design to minimize foam voids and nitrogen leakage from the intertank into the foam.



The new three-step enhanced closeout process for the LH2 intertank area.

The solution ultimately chosen for this area was replacement of the existing intertank closeout with a three-step enhanced closeout process. NASA is relying on the enhanced process in the LH2 intertank area to reduce the presence of defects within the foam to reduce or eliminate void formations in the area of the flange joining the LH2 tank to the intertank.

Because NASA believed the PAL ramps had a satisfactory flight history and there was no evidence of foam loss since the last configuration change after STS-7, the baseline approach for return to flight was to develop sufficient certification data to accept the minimal debris risk of the existing design. However, a portion of the LH2 PAL ramp spans the high-risk LH2 flange closeout. The forward 10 feet of the 38-foot-long LH2 PAL ramp was removed to access the underlying intertank/LH2 tank flange closeout and then replaced using an improved manual spray application process.

Changes were also implemented on the intertank thrust panels to increase venting to reduce foam loss from "popcorning" and additional changes to the aft longeron were made to reduce likelihood of foam cracks and ice balls.

The improved processes developed for the manual application of foam on the ET were used in limited areas of the External Tanks slated for STS-114 and STS-121 because those tanks had been completed prior to the *Columbia* accident. The use of these improved processes will be expanded on future tanks depending on how far through the manufacturing process those tanks had progressed prior to the introduction of the processes.

Since the Phase 2 and Phase 3 efforts are not directly related to STS-114, they are not covered here. Details of these efforts may be found in the NASA Implementation Plan.

Improved non-destructive inspection capabilities will provide greater knowledge of the condition of the External Tank foam in critical areas and the integrity of the Orbiter RCC prior to launch. Although an improvement, these capabilities use the best available technology to provide a view of what is beneath the surface, but will not allow NASA to verify the precise condition of foam. NASA has elected to accept the risk associated with the limitations of the available non-destructive inspection capabilities.

NASA intended to use a "lead tank/trail tank" approach to support the return to flight activities, with the trail tank (ET-121, intended for STS-121) or a launch-on-need rescue mission) not shipping until after the final Design Certification Review (DCR). Because the final DCR was rescheduled after the required ship date for the trail ET, the Space Shuttle Program reassessed the risk of shipping the trail ET after the DCR versus the risk of shipping prior to DCR to protect the capability for a rescue mission (STS-300). Since the ET DCR Pre-Board on February 23-25, 2005 did not disclose any issues that would prevent shipping the trail tank, the program decided the approach with the least total risk was to ship the trail ET on March 5, prior to the first ET DCR Board on March 8, 2005.

NASA acknowledges that the elimination of all critical debris is not attainable, and has analyzed and formally accepted the remaining risk as a condition for the return-to-flight. Additional information on this risk analysis can be found in Section 3.3 (R3.3-2).

3.1.4 RTF TG Assessment

For two days beginning on September 30, 2003, several members attended a series of informal one-on-one meetings with members of the ET Project at the Michoud Assembly Facility. Numerous fact-finding activities were held at a variety of locations throughout 2004. Subsequently, the RTF TG attended the External Tank DCR Pre-Board on February 24-25, 2005 and the ET Program DCR on March 8-9, 2005. The Task Group also attended the second ET DCR on June 20, 2005 that addressed the addition of the feedline bellows heater.

To their credit, the External Tank DCRs were accomplished in a traditional manner, including formal data packages, screening of discrepancies, pre-boards, and formal boards. The two most significant issues for the DCR Board in March 2005 were pertaining to the verification of "use as-is" foam insulation on ET-120 (for STS-114) and ET-121 (for STS-121), and the limited amount of data from formal certification testing. The approach taken for the use as-is foam was to "verify by similarity" using data from the dissection of ET-94 (the thermal protection system on ET-94 was carefully examined by removing parts of it during the accident investigation). The ET Project documented all exceptions to the verification process in a new document, NSTS 60555, *Verification Limitations for the External Tank Thermal Protection System,* instead of processing individual waivers.

As observed during the fact-finding, the ET Project conducted an extensive effort to understand the root causes of foam and ice debris generation, and this has resulted in new knowledge about foam and ice and what causes them to be shed from the tank during ascent. The ET Project determined that the most likely cause of debris generation was the "adhesive/cohesive" failure mode and used this as their basis of acceptance based on observed subsurface void size. Other failure modes, including "knit line failure" and "surface/kissing debonds" in acreage areas, were not addressed through design or process modifications. These additional failure modes offer a potential for the production of debris, although flight history has indicated that this debris production has not been previously observed. The processes for manual application of foam insulation have been changed to include greater process control and quality inspection. The Task Group notes that investigations into ice formation came very late during the return-to-flight effort due to the amount of time spent evaluating foam.

The ET Project implemented an aggressive program to eliminate critical foam and ice debris and met the initial debris-allowable requirements allocated to them by the Space Shuttle Program. Even so, the debris-allowable requirements provided to the ET Project did not match what was later determined to be the impact tolerance of the Orbiter. Thus, in spite of a great deal of excellent work on the part of the Agency and its contractors, the External Tank can still shed debris that could potentially result in critical damage to the Orbiter. It should be noted that the potential to liberate critical debris has been significantly reduced.

In the final analysis, the Task Group believes that the ET Project worked diligently and successfully met the requirements they were provided; unfortunately, those requirements were later determined to be inadequate. Updated requirements have been delayed mainly because the development of debris models and transport analysis has been hampered by a lack of rigor in both development and testing. However, as discussed in Section 3.3 (R3.3-2), the Space Shuttle Program has developed an accepted-risk rationale for the return to flight which was approved by program and agency leadership.

The RTF TG assessment of NASA's actions was completed at the June 27, 2005 meeting. The intent of CAIB Recommendation 3.2-1 has not been met.

3.1.5 RTF TG Observation

Although the Space Shuttle Program has performed an extensive effort to reduce debris for return to flight, there still is the potential – although reduced – for foam and ice to cause critical damage to the Orbiter.

The Task Group believes that the Space Shuttle Program should continue their program to eliminate critical debris by aggressively working off the limitations documented in NSTS 60555, *Verification Limitations for the External Tank Thermal Protection System.*

The Task Group also notes that the processes for manual application of foam insulation on the ET have changed to include greater process control and quality inspection. These processes are costly, but the Task Group feels that these processes should be maintained over time.

3.1.6 RTF TG Minority Opinion

The ET Project and Space Shuttle Program have initiated an aggressive program to eliminate ET debris and, within the exceptions and limitations as documented in NSTS 60555, *Verification Limitations for the External Tank Thermal Protection System*, and the Technical Panel believes that NASA met the intent of CAIB recommendation 3.2-1.

3.2 CAIB Recommendation 3.3-1 – Reinforced Carbon-Carbon Non-Destructive Inspection

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.

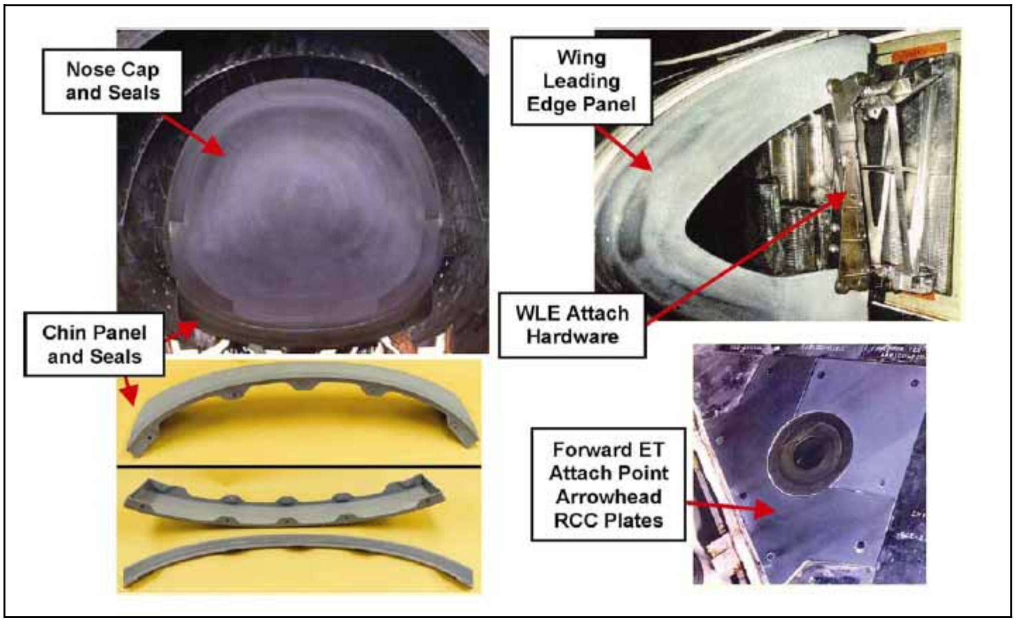
3.2.1 RTF TG Interpretation

Rebaseline the reinforced carbon-carbon components by recycling through the original inspection process, and also using advanced technology as appropriate.

3.2.2 Background

The *Columbia* accident clearly demonstrated that the Orbiter Thermal Protection System, including the reinforced carbon-carbon (RCC) panels and acreage tiles, was vulnerable to impact damage from the existing debris environment. As a result, the Columbia Accident Investigation Board (CAIB) issued recommendations to eliminate debris (R3.2-1), determine the structural integrity of the RCC (R3.3-1), harden the Orbiter (R3.3-2) against impacts, and to develop on-orbit repair capabilities (R6.4-1)

An advanced composite called reinforced carbon-carbon (RCC) is used on the Orbiter wing leading edge, nosecap, chin panel, and forward ET attach point. RCC is a graphite-impregnated rayon fabric laminate, further impregnated with phenolic resin and layered, one ply at a time, in a unique mold for each part, then cured, rough-trimmed, drilled, and inspected. The part is then packed in calcined coke and fired in a furnace to convert it to carbon and is made denser by three cycles of furfuryl alcohol vacuum impregnation and firing.



There are four areas of each Orbiter protected by RCC – the nosecap, the wing leading edges, chin panel, and the forward ET attach point. Damage to one RCC panel on the wing leading edge led to the destruction of *Columbia*.

To mitigate oxidation, the outer layers of the carbon substrate are converted into a 0.02-to-0.04-inch-thick layer of silicon carbide in a chamber filled with argon at temperatures up to 3,000 degrees Fahrenheit. As the silicon carbide cools, “craze cracks” form because the thermal expansion rates of the silicon carbide and the carbon substrate differ. The part is then repeatedly vacuum-impregnated with tetraethyl orthosilicate to fill the pores in the substrate, and the craze cracks are filled with a sealant.

The development of RCC by Ling-Temco-Vought (now Lockheed Martin Missiles and Fire Control) was key to meeting the wing leading edge requirements for the Orbiter Thermal Protection System. Each wing leading edge consists of 22 RCC panels, numbered from 1 to 22 moving outward on the wing (the nomenclature is “5-left” or “5-right” to differentiate, for example, the two number 5 panels). Because the shape of the wing changes from inboard to outboard, each panel is unique.

The rate of oxidation is the most important variable in determining the mission life of RCC components. Oxidation of the carbon substrate results when oxygen penetrates the microscopic pores or fissures of the silicon carbide protective coating. The subsequent loss of mass due to oxidation reduces the load the structure can carry and is the basis for establishing a mission life limit. The oxidation rate is a function of temperature, pressure, time, and the type of heating. Repeated exposure to the Orbiter’s normal flight environment degrades the protective coating and accelerates the loss of mass. Currently, the mass loss of flown RCC components cannot be directly measured. Instead, mass loss is predicted analytically using a methodology based on rates experimentally derived from simulated entry environments. This approach then uses derived entry temperature-time profiles of various portions of RCC components to estimate the actual entry mass loss.

The accident board determined that the on-vehicle inspection techniques in use at the time of the *Columbia* accident were inadequate to assess the structural integrity of the RCC components and attachment hardware. There were two aspects to the problem: (1) how NASA assessed the structural integrity of RCC components and attach hardware throughout their service life, and (2) how NASA verified that the flight-to-flight RCC mass loss caused by aging did not exceed established criteria. Structural integrity was thought to be ensured by wide design margins, and at the time, comprehensive non-destructive inspection was conducted only when the component was manufactured. Mass loss was monitored through a destructive test program that periodically sacrificed flown RCC panels to verify that the actual material properties of the panels were within the predictions of the mission life model.

3.2.3 NASA Implementation

After the *Columbia* accident, the Space Shuttle Program conducted an initial assessment of commercially-available equipment capable of verifying the structural integrity of RCC hardware while it is on the vehicle. A technical interchange meeting held in May 2003 included experts from across the country. A variety of non-destructive inspection technologies with potential for near-term operational deployment were presented to the Program Requirements Control Board (PRCB) in January 2004: (1) flash thermography, (2) ultrasound (wet and dry), (3) advanced eddy current, (4) shearography, and (5) radiography.

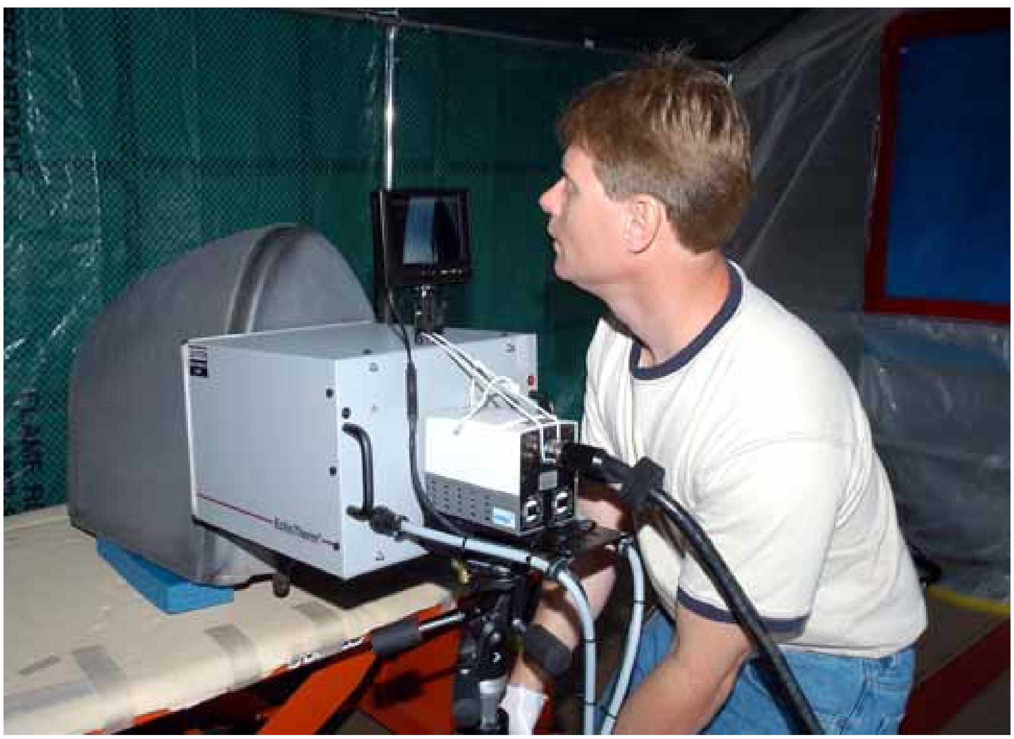
Thermography, contact ultrasonics, eddy current, and radiography were selected as the most promising techniques that could be developed in less than 12 months to be used for on-vehicle inspection. The PRCB approved the budget for the development of these techniques. Ultimately, contact ultrasonics was deemed less promising than the other techniques and its development was discontinued. The remaining techniques will continue to be developed and fielded at the Kennedy Space Center. The data they produce will complement and enhance the protection against abnormal flight and processing damage offered by current inspections.

The normal RCC post-flight inspection requirements now consist of visual, tactile, and infrared thermography on the installed (i.e., *in-situ*) RCC components (wing leading edge panels, nosecap, and chin panel). Contingency inspections (eddy current, ultrasonic, radiography) will be performed if there are any suspicions of impact damage to the RCC by virtue of instrumentation, photographic, thermography, or visual post-flight inspection.

RCC structural integrity and mass loss estimates were validated by off-vehicle non-destructive inspection of RCC components and destructive testing of flown wing leading edge panels. All wing leading edge panels, seals, nosecaps, and chin panels were removed from *Discovery*, *Atlantis*, and *Endeavour* and returned to the Lockheed Martin facility in Dallas, Texas, for comprehensive non-destructive inspection. Inspections included a mix of ultrasonic, X-ray, and eddy current techniques. In addition, NASA has introduced off-vehicle flash thermography for all wing leading edge panels and accessible nosecap and chin panel surfaces; any questionable components are subjected to a CAT scan. This data will be used to support development of future *in-situ* non-destructive inspection techniques.

In addition, three flown RCC panels with 15, 19, and 27 missions, respectively, have been destructively tested to determine actual loss of strength due to oxidation. The testing of this flown hardware to date confirms the conservativeness of the RCC material values used for design and projected mission life.

The RCC Problem Resolution Team was also given approval for a plan to evaluate attach hardware through non-destructive inspection and destructive testing. Detailed hardware non-destructive inspection (dye penetrant, eddy current) to address environmental degradation (corrosion and embrittlement) and fatigue damage concerns have been performed on selected OV-103/104 WLE panels in the high heat and fatigue areas. No degradation or fatigue damage concerns were found.



Jim Landy, a specialist with United Space Alliance, examines a wing leading edge reinforced carbon-carbon panel using flash thermography. A relatively new procedure at KSC, thermography uses high intensity light to heat areas of the panels. The panels are then immediately scanned with an infrared camera. As the panels cool, any internal flaws are revealed.

3.2.4 RTF TG Assessment

Members of the RTF TG conducted fact-finding at the Kennedy Space Center on September 24, 2003. NASA submitted a closure package on April 7, 2004, and sufficient progress had been made for the Task Group to conditionally close this assessment at the April 16, 2004, public meeting. There were four conditions on the closure: an updated version of the Operations and Maintenance Requirements and Specifications Document, File 3, Volume 9, to include the inspection of the RCC panels, the closure of all Material Review and Problem Reports from the *Discovery* and *Atlantis* RCC non-destructive inspections, the receipt of PRCB Directive S064002 closing the NASA review of non-destructive inspection techniques, and the closure of the remaining RTG TG requests for information regarding impact test data.

As of December 2004, the RTF TG had received two of the items required for closure; the PRCB Directive and the RCC impact test data. The Operations and Maintenance Requirements and Specifications Document updated for inspection of RCC panels and closure packages for all MR/PRs from detailed RCC non-destructive inspection were delivered on February 2, 2005.

One other item of concern to the Task Group, an anomaly discovered in the nosecap from *Endeavour*, was satisfactorily explained by NASA. The damage occurred during a sealant refurbishment process; other RCC had previously been subjected to the same process without incident. It was concluded that the nosecap had a latent manufacturing flaw and was not cause for concern about any of the RCC on *Discovery*.

The RTF TG assessment of NASA's actions was completed at the February 17, 2005 teleconference meeting. The intent of CAIB Recommendation 3.3-1 has been met.

3.2.5 RTF TG Observation

The Task Group stresses that these inspections only verified the RCC against its original "as-built" manufacturing specifications and did not materially change the RCC or its impact resistance; this recommendation did not call for any change to the material. The original manufacturing specifications for RCC never envisioned the need for repair, nor were they written with the knowledge of the actual debris environment. This makes the elimination of debris shedding (R3.2-1) and Orbiter hardening (R3.3-2) all the more important. The Task Group also strongly endorses the continuation of non-destructive inspections of the RCC for the remainder of the Space Shuttle Program, the documentation of flight-to-flight inspections in the OMRSD, and the documentation of non-destructive inspection standards for RCC.

Billy Witt, a midbody shop mechanic with United Space Alliance, checks a part used for installation of a reinforced carbon-carbon panel to the leading edge of the wing of an Orbiter. Note the insulation between the RCC panel and the wing spar.

3.3 CAIB Recommendation 3.3-2 – Orbiter Hardening

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.

3.3.1 RTF TG Interpretation

Develop a detailed plan for an Orbiter hardening program including testing and modeling to determine the impact resistance of the Thermal Protection System. For the first Orbiter returning to flight, the actual impact resistance of installed material and the effect of likely debris strikes should be known. Implement hardware changes as defined in the hardening program.

3.3.2 Background

The *Columbia* accident clearly demonstrated that the Orbiter Thermal Protection System, including the reinforced carbon-carbon (RCC) panels and acreage tiles, was vulnerable to impact damage from the existing debris environment. As a result, the Columbia Accident Investigation Board (CAIB) issued recommendations to eliminate debris (R3.2-1), determine the structural integrity of the RCC (R3.3-1), harden the Orbiter (R3.3-2) against impacts, and to develop on-orbit repair capabilities (R6.4-1).

The development of RCC by Ling-Temco-Vought (now Lockheed Martin Missiles and Fire Control) was key to meeting the wing leading edge requirements for the Orbiter Thermal Protection System. Each wing leading edge consists of 22 RCC panels, numbered from 1 to 22 moving outward on the wing (the nomenclature is "5-left" or "5-right" to differentiate, for example, the two number 5 panels). Because the shape of the wing changes from inboard to outboard, each panel is unique.

It had always been known that the impact resistance of the acreage tiles that cover the majority of the Orbiter was limited, but flight experience indicated the tiles could tolerate some damage. The reinforced carbon-carbon used on the nose and wing leading edges was thought to have better impact resistance and damage tolerance. The *Columbia* accident and subsequent testing revealed that the impact tolerances for both RCC and acreage tiles were lower than believed. In addition, careful examination of flight data revealed that the debris environment was somewhat worse than had been thought, with both foam and ice from the External Tank frequently impacting the Orbiter during ascent.

3.3.3 NASA Implementation

NASA selected 17 hardening options to be implemented in three phases. Based primarily on maturity and schedule, four projects were identified as Phase I options for implementation before return to flight: front spar "sneak flow" protection for the most vulnerable and critical RCC panels 5 through 13; main landing gear corner void elimination; forward Reaction Control System carrier panel redesign to eliminate bonded studs; and installing thicker outer thermal panes in side windows 1 and 6.

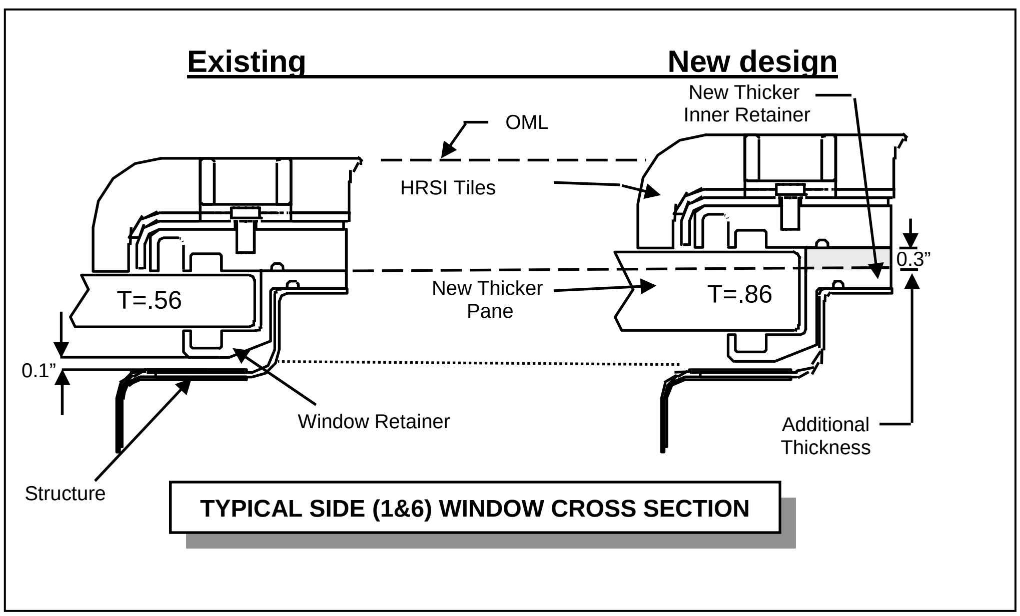
NASA also selected two Phase II options for implementation after return to flight: "sneak flow" front spar protection for the remaining RCC panels 1 through 4 and 14 through 22, and the main landing gear door perimeter tile material change. Both of these Phase II projects are in the final design phase and will be executed during Orbiter Major Modification periods or during extended between-mission flows.

Since the Phase II and Phase III efforts are not directly related to the return to flight of STS-114, they are not covered in any more detail in this report. Further details of these efforts may be found in the *NASA Implementation Plan*.

The 17 projects examined for Orbiter hardening, along with the associated phase for each and its status when this assessment was made.

Family	Redesign Proposal	Phase	Status
WLESS	"Sneak Flow" Front Spar Protection (RCC #5 – 13)	I	Installed/final cert approval pending
	"Sneak Flow" Front Spar Protection (RCC #1 – 4, 4 - 22)	II	Final cert approval pending
	Lower Access Panel Redesign/BRI 18 Tile Implementation	III	BRI-18 tile continues to be in qual & cert
	Insulator Redesign	III	On hold for higher priority arc-jet testing
	Robust RCC	III	Schedule and cost of implementing this option is not in sych with Agency's vision to retire Shuttle in 2010
Landing Gear and ET Door Thermal Barriers	Main Landing Gear Door Corner Void	I	Installed/final cert approval pending
	Main Landing Gear Door Perimeter Tile Material Change	II	In Final Design phase
	Nose Landing Gear Door Thermal Barrier Material Change	III	In Assessment/lower priority to RTF
	External Tank Door Thermal Barrier Redesign	III	In Assessment/lower priority to RTF
Vehicle Carrier Panels – Bonded Stud Elimination	Forward RCS Carrier Panel Redesign – Bonded Stud Elimination	I	Installed/ final cert approval pending
Side Windows	Thicken Windows #1 and #6	I	Windows installed on OV-103 and OV-104/final cert approval pending
Tougher Lower Surface Tiles	Tougher Periphery (BRI 18) Tiles around MLGD, NLGD, ETD, Window Frames, Elevon Leading Edge and Wing Trailing Edge.	III	Qual & Cert in work. BRI 18 tile has been authorized for installation on all three Orbiters
	Tougher Acreage (BRI 8) Tiles and Ballistics SIP on Lower Surface.	III	Qual & Cert in work
Instrumentation	TPS Instrumentation	III	On-hold until post RTF
Elevon Cove	Elevon Leading Edge Carrier Panel Redesign	III	In Assessment/lower priority to RTF
Tougher Upper Surface Tiles	Tougher Upper Surface Tiles.	III	Development complete/ authorization pending for qual & cert
Vertical Tail	Vertical Tail AFSI High Emittance Coating	III	This option will be eliminated since it only increases the Orbiter's capability in the event of an abort during ascent. Trajectory can be designed to minimize vertical tail temperature.

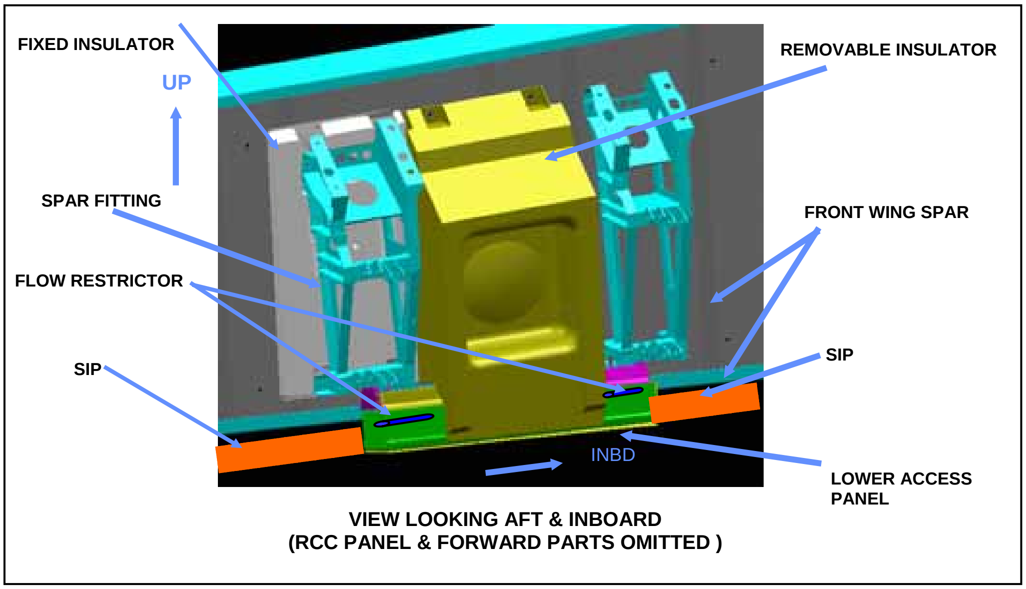
The new outer thermal panes installed in windows 1 and 6 are 0.30-inch thicker than the original panes. This necessitated changing the Thermal Protection System tiles surrounding the windows.



3.3.3.1 Impact and Damage Tolerance

Using both test and analysis, the Orbiter Damage Impact Assessment Team determined the impact and damage tolerance of tile, RCC, and the Orbiter windows to External Tank foam, ice, and ablator debris. Impact tolerance is the ability of the Orbiter Thermal Protection System materials to withstand impacts before damage occurs. Damage tolerance is defined as the level of damage from a debris strike that can be tolerated while still safely completing the mission, especially entry.

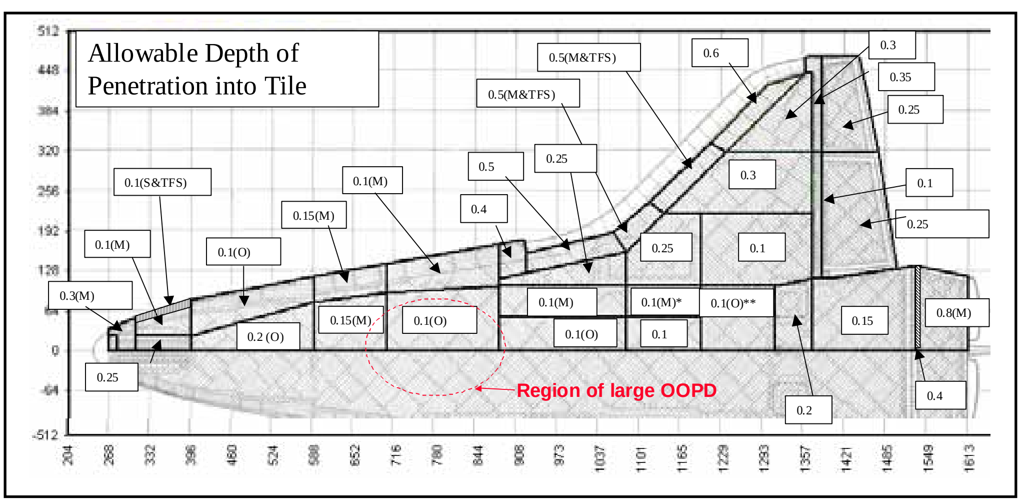
Preliminary impact tolerance data was used as the basis for the ET Project's work to certify the ET for foam debris generation. Subsequent test and analysis confirmed that the worst-on-worst damage tolerance of the tile and RCC was less than the ET certification limit.



Flow restrictors and additional insulation were added behind wing leading edge RCC panels 5 through 13; the other panels will receive similar modifications after the return to flight.

3.3.3.2 *Tile Impact and Damage Tolerance*

Tests to determine TPS tile impact tolerance – using foam, ice, and ablator projectiles – have been completed at several field centers and other test facilities using both acreage and special configuration tiles, and both new and aged tiles. These tests indicated that, although tile is not very resistant to impact, it tolerates entry heating well even with damage. Overall, testing shows tile to be tolerant to moderate levels of impact damage; tile damage tolerance depends on tile thickness among other factors, which varies by location. As a result, certain areas of reduced thickness, such as those tiles adjacent to the main landing gear doors, are more susceptible to critical damage. Based on tests and on flight history, NASA developed and certified zone and cavity definitions for tile with similar structural and thermal characteristics to determine the depth of allowable damage penetration into the tile before critical damage occurs and repair is necessary. These zones take into account aerodynamic heating, impact angle, and tile thickness, but assume rectangular damage where the length and width dimensions are a function of depth.



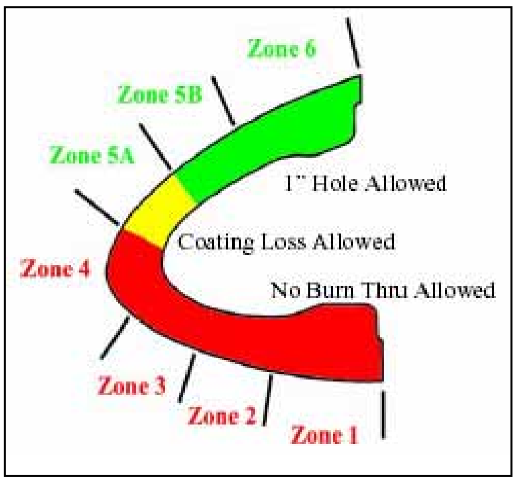
Since the heating loads vary across the Orbiter, the amount of damage that can be tolerated also varies. This chart shows the allowable depth of penetration into areas of acreage tiles that has been certified as safely tolerable. The red outline shows the region of large out of plane deflection (OOPD).

In addition, analysis of the Space Shuttle's flight history indicated that tile damage fell into three impact classes: (1) numerous, shallow impacts primarily on the forward chine and fuselage; (2) fewer, deeper impacts primarily on the lower surface; and (3) umbilical area impacts. The majority of historical damage fell into the first category, and was likely caused by foam popcorning rather than large foam divots; increased ET intertank venting is expected to reduce popcorning masses in the ET foam. The second category of damage, with fewer deeper impacts, was most likely the result of ice from the ET bellows and brackets and ET foam divots; this category of damage is the most likely to require repair. Finally, the umbilical area had a mixture of both small and large impacts from a unique subset of sources including ET umbilical ice, baggies, Kapton tape, and ET fire detection paper. Debris transport analysis suggests that most of the impacts came from "local" sources rather than from the forward ET. As a result, NASA expects little change to the damage in the umbilical area.

3.3.3.3 RCC Impact and Damage Tolerance

Impact and damage tolerance testing on the RCC was performed at several NASA field centers and other test facilities, using both RCC "coupons" (small samples of material) and full-scale RCC panels. It was found that RCC is impact tolerant but not damage tolerant, since even minor cracks or coating loss can be critical and prevent safe entry. Structural and thermal testing of damaged RCC samples established how much damage can be tolerated and still allow a safe return for the crew and vehicle. Test-verified models established impact tolerance thresholds for foam and ice against tile and RCC. These impact tolerance thresholds are the levels at which detectable damage begins to occur.

Arc-jet testing showed that the RCC cannot tolerate any significant loss of coating from the front surface in areas that experience full heating on entry. This is of concern because impacts can create subsurface delamination of the RCC that is undetectable through imaging scans. Testing indicates that loss of front-side coating in areas that are hot enough to oxidize and/or promote full heating of the damaged substrate can cause unacceptable erosion damage in the delaminated areas. However, for subsurface delamination to be a concern there needs to be front-side damage, thus eliminating the concern of "hidden" damage. Further testing and modeling have shown that, although the hottest areas on the wing leading edge (the bottom and apex surfaces) cannot tolerate any significant coating loss, other cooler areas (such as the top surface of the wing leading edge) can tolerate some amount of coating loss and subsurface delamination. Testing and model development work has produced a map of the damage tolerance capabilities of the wing leading edge RCC depending on panel and location (top, apex, or bottom surface).



Each RCC panel was split into seven zones, and the level of damage that could be tolerated was evaluated for each zone. The zones on the bottom of the panel and the apex cannot tolerate any substantial damage due to the thermal environment these areas are subjected to during entry.

Testing is also complete on window impact from debris, including butcher paper, ablator material, foam, Tyvek®, aluminum oxide, and small/fast ogive foam. NASA's debris transport analysis suggests that very small ogive foam has the potential to impact the Orbiter windows, but impact tolerance tests indicate that the windows can withstand these impacts without sustaining critical damage. Testing also indicated that butcher paper – used to cover the forward reaction control system thrusters at the launch pad – caused unacceptable damage to the windows. As a result, NASA replaced butcher paper covers with Tyvek covers (similar to what large FedEx® envelopes are made of) that will not cause critical damage.

3.3.3.4 Orbiter Hardening

NASA has completed implementation of the four Phase I Orbiter hardening tasks. Beyond the return to flight, NASA will continue to pursue Phase II and III hardening options and will implement those that are feasible at the earliest possible opportunity.

3.3.3.5 Risk Assessment

NASA identified, categorized, and assessed all known potential debris sources in order to assess the risk to the vehicle of debris. Most debris sources could be determined to be no threat to the Orbiter either because the debris was liberated before it gained enough velocity and kinetic energy to damage the Orbiter, was too small to be of concern (0.0002 lbm or less), or the transport analysis showed there was no path to take the debris from the source to any Orbiter structure. This left only a handful of debris sources of concern to be scrutinized and assessed for the potential to liberate debris that could cause critical damage to the Orbiter.

The program's "worst-on-worst" analysis of three of the remaining debris sources – acreage foam from the LH2 tank, LO2 tank and the intertank – showed they would not shed foam that could cause more damage than the Orbiter could safely enter with.

A Monte Carlo probabilistic analysis was done for five foam areas (LO2/intertank ice/frost ramps, LO2 tank to intertank flange, LH2 tank to intertank flange, LO2 PAL ramp, and bipod closeout) and four ice locations (mid and aft feedline bellows, and forward and mid feedline brackets). There were two independent approaches for the Monte Carlo analysis: one for foam debris, which used physics-based models for foam liberation, and another for ice debris, which had to rely on engineered distributions based on a very limited set of test data for ice liberation. It is the Agency's opinion that there is a great deal of conservatism in both approaches, but NASA has not been able to drive out the conservatisms from the models, mostly due to modeling limitations, a lack of time to generate ice-specific damage maps for tile, and limited test data not matching flight data. Each of the resulting probabilities for critical damage to RCC due to foam or ice liberation is less than 1 in 10,000; for tile, the probabilities range from 1 in 100 to 1 in 10,000. The four highest probabilities for critical damage to tile are for ice from the mid feedline bellows and second feedline bracket locations, and foam from the LO2 ice/frost ramps and the LO2 tank to intertank flange.

NASA determined that the residual risk to several of the remaining areas was enveloped by the probabilistic assessments: the LH2 ice/frost ramp foam residual risk was enveloped by the LO2/intertank ice/frost ramps, the LH2 PAL ramp by the LO2 PAL ramp, and the three aft-most feedline bracket locations by the forward and mid feedline brackets. The potential for ice on the forward feedline bellows location was greatly reduced by the addition of a heater in that area, and the remaining ice that could form in that location will be controlled by launch commit criteria, documented in NSTS 08303, *Ice/Debris Inspection Criteria*.

One debris source, ice around the umbilical doors, could not be shown by any means other than flight history to be an acceptable risk. NASA's rationale for accepting this risk was that there is no transport mechanism to RCC or the windows and flight history showed that while there is a moderate amount of damage on most flights in this area, none has been severe.

3.3.4 RTF TG Assessment

members of the RTF TG conducted the first fact-finding trip for this recommendation on October 28-30, 2003, a trip to Southwest Research Institute (SwRI) to witness a foam "shoot" against an RCC wing leading edge panel. Additional fact-finding during 2004 included numerous Debris Summits, and the Task Group attended the Orbiter Design Certification Review on February 7-11, 2005. Members of the Task Group also attended a series of System

Design Certification Reviews and Design Verification Reviews for Debris from February through June, 2005, culminating in the (final) Debris DVR Board on June 24, 2005. Members also attended the Delta System DCR on June 23, 2005.

This recommendation had two primary parts, Orbiter hardening and determining the impact resistance and the effect of likely debris strikes on the Orbiter TPS. Out of the Agency's effort in the area of Orbiter hardening, a hardware program was initiated that provided some minor improvements that supported return to flight. The STS-114 improvements include thicker thermal panes for side windows 1 and 6, limited "sneak flow" front spar protection, main landing gear door corner void elimination, and modifications to the forward RCS carrier panel; additional items will be incorporated on later flights. A long-term program to provide robust RCC was dropped due to the decision to retire the Space Shuttle by 2010.

The other part of this recommendation was a program to characterize the effects of debris strikes on the Orbiter Thermal Protection System. NASA embarked on a major effort toward that end. A program to determine the impact resistance of the TPS was performed and supported by a significant level of testing and analysis with independent peer reviews. Results from early testing and analysis were used to define ET debris allowable and Space Shuttle inspection criteria. As the testing and analysis effort matured, these early results were found to overestimate the impact and damage tolerances of the Orbiter TPS and a risk acceptance rationale had to be developed by the Space Shuttle Program.

An extensive effort was made to model the effects of debris impacts and validate them against the available test data. These models will be used to assess damage sustained during flight. The foam assessments are reasonably well understood; however the Space Shuttle Program is struggling with understanding the effects of ice debris and had not finalized this effort when the Task Group's assessment was completed. The NASA Engineering and Safety Center (NESC) stated at the June 24, 2005 Debris Verification Review Board, "Based on the available test data and analysis results, the NESC has concluded that the feedline brackets, bellows, and ET umbilical ice debris environment is not sufficiently characterized or understood to assign the level of risk. To establish the flight rationale for STS-114, additional work is required to develop adequate controls for ice."

The Orbiter is still vulnerable to the debris environment created by the External Tank. The Space Shuttle Program has acknowledged the possibility of critical debris damage and has accepted the remaining risk.

The RTF TG concluded at the June 27, 2005, meeting that NASA did not meet the intent of CAIB Recommendation 3.3-2, in spite of tremendous effort by NASA and its contractors. Two reasons were cited: the present lack of a long-term approach to RCC hardening – an early long-term plan for Orbiter hardening was abandoned after the National Policy decision to retire the Space Shuttle fleet no later than 2010 – and the amount of remaining non-standard open work on ice debris, risk analysis, and verification of damage models.

3.3.5 RTF TG Observation

Although the Space Shuttle Program has performed an extensive effort to reduce debris for return to flight, there still is the potential – although reduced – for foam and ice to cause critical damage to the Orbiter; NASA will need to continue to reassess their accepted risk rationale flight-to-flight.

3.3.6 RTF TG Minority Opinion

The Technical Panel believes that, with the completion of the documented open work, the Space Shuttle Program met the intent of the CAIB recommendation.

3.4 CAIB Recommendation 3.4-1 – Ground-Based Imagery

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.

3.4.1 RTF TG Interpretation

The *Columbia* post-accident investigation was hampered by the lack of high-resolution imagery of the vehicle during ascent. The existing ground-based camera locations were a legacy of earlier programs and their locations were not optimized for the ascent trajectory of recent Space Shuttle missions. Further, due to equipment problems and a lack of clear requirements to maintain this equipment, imagery was not always usable, as was the case for the STS-107 launch. The Columbia Accident Investigation Board (CAIB) was concerned about the need to have an adequate number of appropriately-located cameras that operated properly to provide photographic coverage from more than one view of the Space Shuttle from launch through separation of the Solid Rocket Boosters.

3.4.2 Background

Of the dozen ground-based camera sites used to obtain images of the Space Shuttle during ascent, five were normally used to track the vehicle from liftoff until it was out of view. Due to view angles and atmospheric limitations, two sites did not capture the STS-107 debris event. Of the remaining three sites positioned to "see" at least a portion of the event, none provided a clear view of the actual debris impact to the wing. The first site lost track of *Columbia* during ascent, the second site was out of focus – because of an improperly maintained lens – and the third site captured only a view of the upper side of the left wing. The CAIB noted that camera problems had also hindered the *Challenger* investigation 17 years earlier. Although the initial debris strike during STS-107 was discovered via image analysis, NASA's post-launch evaluation of the impact was hampered by the lack of multiple views from high-resolution, high-speed ground cameras. The CAIB also found the quality of existing imagery – of all recent Space Shuttle launches – to be less than ideal.

Long-range tracking camera (E-207) photo of STS-95 in October 1998 at SRB separation shows the resolution limitations of ground tracking.

Multiple views of launch and ascent from varying angles provide important data for engineering assessment and the detection of unexpected anomalies. Images may also be used to assess debris shedding in flight, including the origin, size, and trajectory of the objects. Because of resolution limitations, however, this imagery is not intended to pinpoint the exact nature of potential damage to the vehicle. Finally, in keeping with the CAIB view that the Space Shuttle should be treated as a developmental flight vehicle, imagery assets should be used to measure its performance for the duration of the Space Shuttle Program.

3.4.3 NASA Implementation

A suite of improved ground-based and airborne cameras has been deployed to provide the ability to capture three complementary views of the Space Shuttle during launch and ascent. This will allow a better understanding of the ascent environment and the performance of the vehicle within this environment. Ground imagery may also allow the detection of ascent debris and identify potential damage locations on the Orbiter for detailed on-orbit assessment. There are four types of imagery that NASA will acquire from the ground cameras:

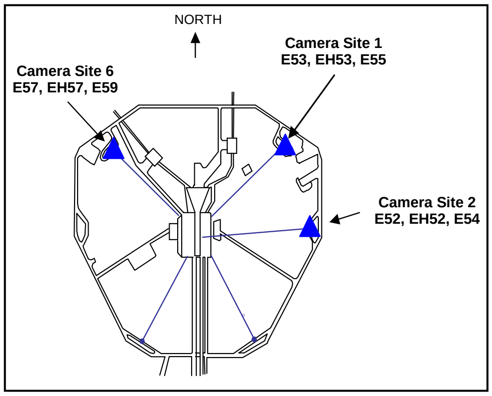
- Primary imagery – film images used as the primary analysis tools for launch and ascent operations;
- Fall-back imagery – back-up imagery (primarily 35mm and 16mm motion pictures) for use when the primary imagery is unavailable;
- Quick-look imagery – digital imagery (primarily HDTV and SDTV) provided to the image analysis groups shortly after launch for initial assessments; and
- Tracker imagery – imagery used to guide the camera tracking mounts and for analysis when needed.

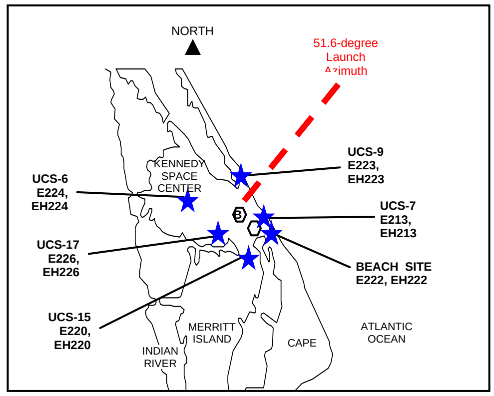
Although ground cameras provide important engineering data for the Space Shuttle, they are not intended to provide the resolution to identify the exact nature of any potential damage to the Orbiter. No real-time repair decisions will be directly based on this ascent imagery data. Instead, any anomalies identified using ground-based imagery assessments will be used to optimize the on-orbit inspections described in Section 3.13 (Recommendation 6.4-1).

For the STS-114 launch, NASA has three short-range camera sites around the perimeter of the launch pad, seven medium-range camera sites, and nine long-range camera sites. Each of the medium- and long-range tracking cameras is independent, ensuring that no single failure can disable all of the trackers. Further, each of the film cameras on the trackers has a backup (fall-back), so no single camera failure eliminates a particular view. The locations of the new cameras and trackers are optimized for 51.6-degree-inclination launches since most, if not all, future Space Shuttle launches will be to the International Space Station. Previously, camera coverage was limited by a generic configuration originally designed for the full range of possible launch inclinations and ascent tracks envisioned early in the Space Shuttle program.

Space Shuttle ascent imagery acquisition is divided into three overlapping periods with different requirements that provide for steps in lens focal lengths to maintain image resolution as the vehicle moves away from each camera location:

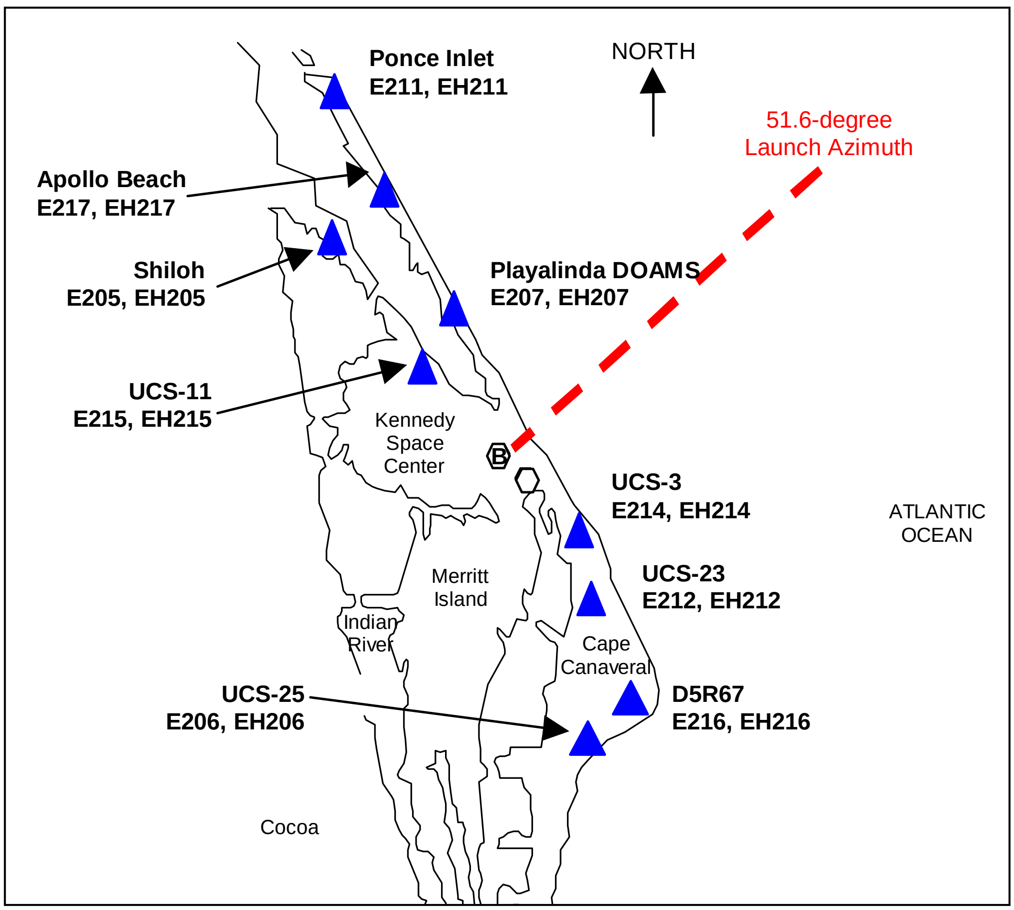
- Short-range images (T-10 seconds through T+57 seconds);
- Medium-range images (T-7 seconds through T+100 seconds); and
- Long-range trackers (T-7 seconds or vehicle acquisition through T+165 seconds).





Left: Three short-range tracking sites are located around each LC-39 launch pad.

Right: Medium-range tracking sites available for the Space Shuttle Program



Long-range tracking sites located around the Kennedy Space Center.

Currently, this capability nominally consists of 7.8-, 32-, 150-, and 400-inch focal length lenses. The theoretical limits of the optics under ideal conditions – assuming the object is not obscured by the exhaust plume and depending on orientation of vehicle to plane of film – provide:

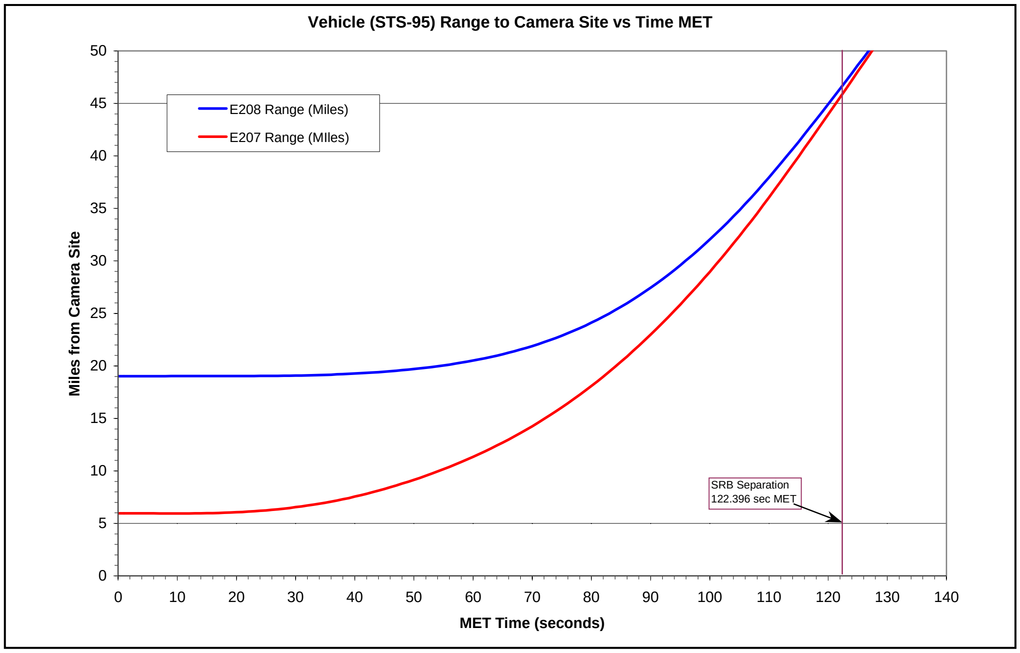
- Resolution to 1-inch size and 0.5-foot linear accuracy of debris source and impact location from lift-off to L+30 seconds along any expected azimuth;

- Resolution to 3-inch size and 1-foot linear accuracy of debris source and impact location from L+30 seconds to L+60 seconds along any expected azimuth;

- Resolution to 8-inch size and 3-foot linear accuracy of debris source and impact location from L+60 seconds to L+90 seconds along any expected azimuth;

- Resolution to 15-inch size and 5-foot linear accuracy of debris source and impact location from L+90 seconds to SRB separation (approximately 122 miles from the launch site) along any expected azimuth.

Range to target versus time for the two DOAMS long-range tracking sites. Only the Playalinda Beach DOAMS (E207) will be used for STS-114. The Cocoa Beach DOAMS (E208) is being moved to a new location at Patrick AFB and will not be used to support the first two launches.



These images will be acquired by a combination of mobile Kineto Tracking Mount (KTM), Intermediate Focal Length Optical Tracking (IFLOT), and Advanced Transportable Optical Tracking System (ATOTS) platforms that can be optimally positioned for each flight based on launch azimuth and other considerations. In addition, the fixed-position Distant Object Attitude Measurement System (DOAMS) site at Playalinda Beach, operated by the Air Force 45th Space Wing, will continue to be used for long-range observation. The "fuzzy" optics in the Cocoa Beach DOAMS noted by the CAIB has been corrected by the vendor, but the Air Force is in the process of moving this fixed installation several miles south to Patrick AFB to avoid high-rise condominiums that have been erected adjacent to the existing site, severely restricting the view of the launch areas; it will not be used to support STS-114.

A DOAMS long-range tracking site.

NASA is continuing to ship 14 existing trackers at the Kennedy Space Center to the White Sands Missile Range for refurbishment. This work will be ongoing until refurbishment of all trackers is complete in 2008. Trackers and optics will be borrowed from other ranges to support launches until the refurbished assets are redelivered. NASA is also procuring additional cameras to provide increased redundancy and refurbishing existing cameras. NASA has ordered 35 fixed camera lenses to supplement the existing inventory and has purchased two KTM Digital Signal Processing Amplifiers to improve KTM reliability and performance. In addition, NASA has received 24 HDTV cameras to improve quick-look capabilities. Funding has also been approved to procure additional spare mounts, as well as to fund studies on additional capability in the areas of infrared and ultraviolet imagery, adaptive optics, and high-speed digital video.

Long-range trackers at the Kennedy Space Center.

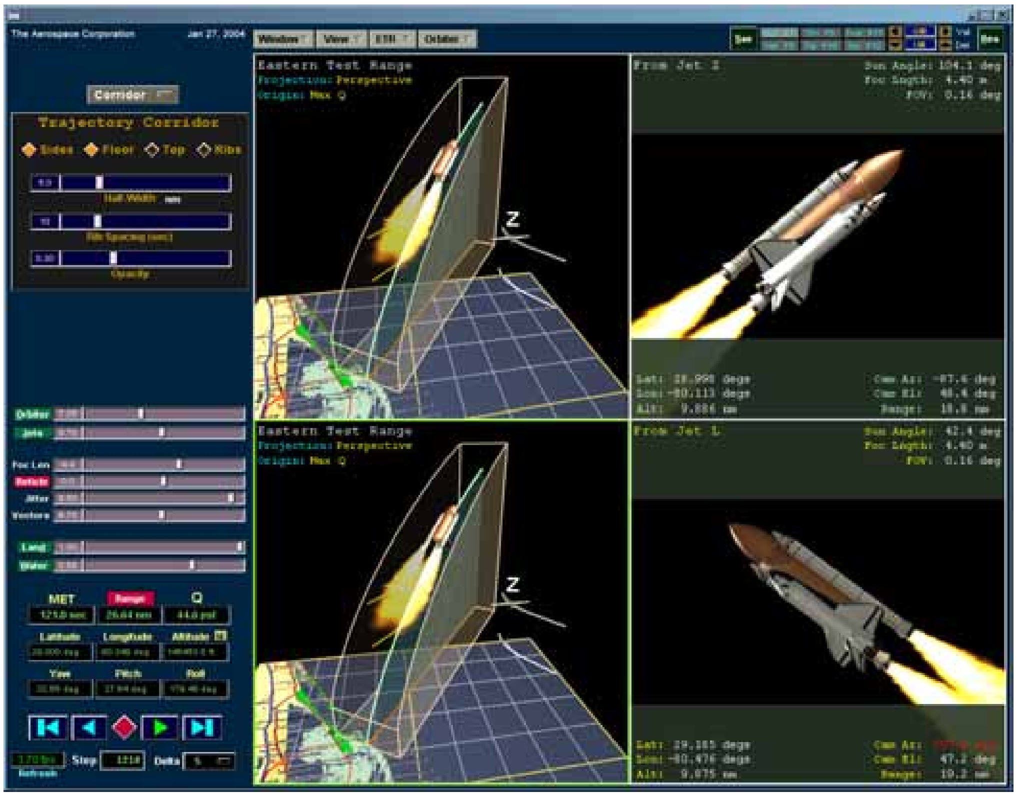
During, and subsequent to, the accident investigation, there was considerable interest in whether video technology had evolved far enough to replace film as the primary imagery for Space Shuttle launches. The NASA Intercenter Photo Working Group (IPWG) compared the image resolution of several different types of image gathering systems and determined their theoretical maximum performance.

Based on this analysis, NASA decided that the primary product for imagery analysis will continue to be film due to its resolution capability and dynamic range. The long-range tracking sites use 70mm cameras to track the Solid Rocket Boosters after separation and to provide “big sky” coverage of any major mishaps. All short- and medium-range tracking sites use 35mm cameras for optimum “resolution-on-media” as their primary imagery. Close-in fixed camera sites use high-speed (400 frames per second) 16mm film motion picture cameras. All short-, medium-, and long-range tracking sites use HDTV for a quick-look capability and as a backup to the primary 35mm or 70mm cameras. SDTV was not chosen as an analysis tool, but it will continue to be used by camera site operators for wide field-of-view target locating. SVHS demonstrated a poor resolution that made it unacceptable as an analysis tool, although budget constraints have forced its use in some limited instances.

In addition to ground cameras, NASA approved the development and implementation of an aircraft-based imaging system known as the WB-57 Ascent Video Experiment (WAVE) to provide both ascent and entry imagery.

The two NASA high-altitude WB-57F aircraft have been modified with cameras to photograph the Space Shuttle during ascent.

The use of an airborne imaging system will provide opportunities to better observe the vehicle during days of heavier cloud cover and in areas obscured from ground cameras by the exhaust plume following launch. The use of two aircraft flying at an altitude of 60,000 feet will allow a wide range of coverage with each airplane providing imagery over a 400-mile path. A 32-inch diameter ball turret in the nose of each WB-57F houses an optical bench that contains HDTV and infrared camera systems. The optics consists of a 4.2-meter fixed focal length lens that can be operated in both auto track and manual modes.



Computer model showing the views expected from the WB-57 WAVE aircraft.

The WAVE aircraft will be used on an experimental basis during the first two return-to-flight launches (STS-114 and STS-121). Based on an analysis of the system's performance and quality of the products obtained, NASA will make a decision on whether to continue use of this system on future flights. The Critical Design Review for the WAVE was completed on July 1, 2004 and the ball turrets were installed in early 2005. The HALO II Gulfstream aircraft operated for the Missile Defense Agency is available as a backup airborne tracking asset if needed.

NASA also has assessed using ground based radar for identifying and tracking potential debris sources, and new C-band radar on North Merritt Island will be used on STS-114 to complement information obtained from the camera systems.

In addition, NASA is revising the launch requirements and procedures to support an ability to capture three useful views of the Shuttle during ascent. Initially, NASA will limit launches to daylight hours in order to maximize the ability to capture the most useful ground ascent imagery. Camera and tracker operability and readiness to support launch will be supported by a new set of pre-launch equipment and data system checks. In addition to certification at the Flight Readiness Review, the status of the group imagery assets will be reviewed at the MMT Tanking Meeting (approximately L-11 hours) and within one hour of launch. The readiness of the camera sites will be reported to the Launch Director at T-20 minutes that will provide status to the MMT on the capability to capture three useful views.

3.4.4 RTF TG Assessment

The NASA approach to the CAIB recommendation was to provide an integrated package that tied together all three imagery recommendations (R3.4-1, Ground-Based Imagery; R3.4-2, High-Resolution Images of External Tank; and R3.4-3, High-Resolution Images of Orbiter), and moved the on-orbit inspection capabilities to R6.4-1, Thermal Protection System Inspection and Repair. Ultimately, the Task Group decided to consider R3.4-1 and R3.4-2 as standalone packages, while R3.4-3 and the inspection portion of R6.4-1 were tightly coupled and their final assessments were considered together.

NASA has made progress toward achieving an integrated suite of ground cameras to capture high-resolution images of the Space Shuttle during ascent and has significantly increased the number and capability of ground camera sites. Also, the Agency has arranged for airborne assets (WAVE) to mitigate the effects of cloud cover and improve higher altitude resolution, at least for the first two launches. From a hardware asset perspective, these changes should ensure an adequate capability to meet the CAIB intent for three useful views.

The RTF TG believes that NASA is aware of the limitations inherent in its approach to ground imagery. Although the ground cameras provide important engineering data for the Space Shuttle during launch and ascent, they do not have the resolution necessary to definitively establish that the Orbiter has not suffered ascent debris damage. NASA has stated that they will not make any real-time repair decisions directly based on ground imagery data. Rather, the comprehensive assessments of Orbiter impacts and damage necessary to ensure the safety of the vehicle and crew will be conducted using on-orbit inspection and analysis, but focused by ground and ascent imagery.

Numerous fact-finding activities were conducted by the Task Group beginning in October 2003 through the closure meeting on November 30, 2004. This final meeting led the Task Group to conditionally close their assessment during the December 2004 plenary. The conditions included the closure of two requests for information, completing the required safety documentation, complete systems testing and verification, training of the operators on the new cameras and mounts, incorporating the Ground Imagery Project Summary into the overall Program Design Certification Review, completing the Critical Design Review action closeout, and completing the standard readiness review process. In addition, prior to return to flight, NASA stated that they would add a redundant power source to the system that operates the launch pad cameras.

During a further fact-finding meeting held in January 2005, NASA, together with the 45th Space Wing, specified the participants and organizations responsible for certifying mission capability during the launch countdown, the reporting mechanisms to launch management for imagery asset status, and how the usability of imagery assets will be evaluated when weather obstructions exist. The relationship between the Kennedy Space Center and the 45th Space Wing on the Eastern Range was clarified, and the Task Group was satisfied that the correct agreements were in place between these organizations to ensure status reflecting the operability and readiness of assets during the launch countdown.

Despite the significant progress made in installing and refurbishing the cameras around the launch complex, not all of work was able to be completed prior to return-to-flight. NASA informed the Task Group that after the launch of STS-114 they will continue to refurbish the cameras and mounts per their existing plan, fly the WAVE aircraft in support of STS-121, and review the data from WAVE to determine if the concept should continue for future launches. Eventually, all borrowed assets will be replaced with planned procurements.

It should be noted that there is a difference between the NASA implementation and the wording of the CAIB recommendation in how the requirements for the camera systems are documented. The CAIB wrote that "*operational status of these assets should be included in* *the Launch Commit Criteria for future launches.*" NASA decided that including these systems in the Launch Commit Criteria document was inappropriate, and instead included the information in the Program Requirements Document with status reporting in the launch countdown procedure. While the Program Requirements Document includes launch support requirements, it, alone, does not require the MMT to consider the ground imagery assets as part of the launch decision process. A small part of the camera power system was included in the Launch Commit Criteria since its status affects multiple camera sites. The Task Group, while expressing some concerns, believed this approach was satisfactory.

The RTF TG assessment of NASA's actions was completed at the June 8, 2005, meeting. The intent of CAIB Recommendation 3.4-1 has been met.

3.4.5 RTF TG Observations

While the actions NASA has taken, for the most part, meet the letter of the CAIB recommendation, the RTF TG has the following observations:

1. The approach to documenting the requirements provides launch management awareness of the status of these assets. However, it does not require a Launch Commit Criteria waiver to proceed with less than three useful views.

2. The Shuttle should be treated as a developmental vehicle with its performance measured for all missions. Imagery has proven to be a useful tool for assessing the performance of the Space Shuttle during launch and ascent. Since a substantial amount of funds were expended to improve the capability to gather this imagery, NASA should retain these assets for the duration of the Space Shuttle Program.

Workers prepare a WB-57F aircraft at Patrick AFB, Florida. The WAVE provides both ascent and entry imagery and enables better observation of the Space Shuttle on days of heavier cloud cover and areas obscured from ground cameras by the launch exhaust plume. WAVE comprises a 32-inch-ball turret system mounted on the nose that houses an optical bench, providing installation of both HDTV and infrared cameras. The system can be operated in both auto track and manual modes.

3.5 CAIB Recommendation 3.4-2 – High-Resolution Images of External Tank

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

3.5.1 RTF TG Interpretation

Engineering quality imagery of the External Tank (ET) taken from *Columbia* after separation would have been of great significance in the accident investigation. High-resolution imagery of the External Tank should be obtained on each flight and downlinked to the ground as soon as practical after achieving orbit.

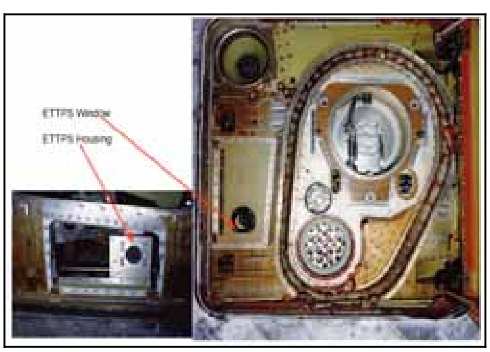
3.5.2 Background

At the time of the *Columbia* accident, the Orbiters had film cameras installed in each umbilical well to provide images of the External Tank following separation. Additionally, after ET separation, the Orbiter would be maneuvered into a position that permitted a crewmember to take images of the ET using a hand-held digital camera. Following landing, the film from the umbilical well cameras was removed and developed for evaluation; the hand-held digital camera was downloaded at the same time. These cameras provided images of sufficient quality and resolution to permit an engineering evaluation of the ET thermal protection system, including foam shedding. Unfortunately, none of these cameras were recovered from the *Columbia* debris. Therefore, no images of the External Tank were available to provide engineering insight into foam shedding and debris during the mission.

3.5.3 NASA Implementation

To provide the capability to downlink images of the External Tank after separation, NASA replaced the 35mm film camera in the Orbiter right umbilical well with a high-resolution digital still camera. This 6 megapixel camera uses a 35mm lens and provides a field-of-view only slightly smaller than the original film camera. Because of technical complexity and limited bandwidth during ascent, the images will not be downlinked in real-time. Rather, once the Orbiter is on-orbit and the laptop network is set up in the crew cabin, the images will be copied from the camera to a laptop computer then downlinked to the Mission Control Center using the existing Orbiter Ku-band link.

In addition, the flight crew will continue to use a handheld digital still camera with a telephoto lens. The Orbiter pitch-over maneuver has been modified to occur sooner after ET separation to provide better images from the crew camera. The location where the camera is stowed in the crew cabin has also been changed to allow easier access by the crew. The data from the digital camera will be transferred to a laptop in the crew cabin and downlinked to Mission Control in the same manner as the umbilical well camera images.



A digital still camera is being carried in the right umbilical well to photograph the External Tank as it separates.

These images will be used for quick-look analysis by the Mission Management Team to determine if any ET anomalies exist that require additional on-orbit inspections (see Section 3.13, Recommendation 6.4-1).

A feasibility study for the Orbiter umbilical well camera was initiated in September 2003 and the design reviews were completed in April 2004. Modifications to *Discovery* to support STS-114 began in May 2004, and the camera system function testing was completed in March 2005. The umbilical well camera was installed during Orbiter processing in early April 2005.

3.5.4 RTF TG Assessment

The NASA approach to the CAIB recommendation was to provide an integrated package that tied together all three imagery recommendations (R3.4-1, Ground-Based Imagery; R3.4-2, High-Resolution Images of External Tank; and 3.4-3, High-Resolution Images of Orbiter), and moved the on-orbit inspection capabilities to R6.4-1, Thermal Protection System Inspection and Repair. Ultimately, the Task Group decided to consider R3.4-1 and R3.4-2 as standalone packages, while R3.4-3 and the inspection portion of R6.4-1 were tightly coupled and their final assessments were considered together.

Fact finding was conducted by the Task Group on February 20, 2004, November 15, 2004, and during the closure meeting on November 30, 2004. This final meeting led the Task Group to close their assessment during the December 2004 plenary.

Appropriate cameras have been selected to obtain quality views of the External Tank using both the handheld camera from the Orbiter and the digital umbilical well camera. The STS-114 crew has been trained in use of the hardware, and the digital umbilical well camera was installed before OV-103 rolled-out to the launch pad.

The RTF TG assessment of NASA’s actions was completed at the December 16, 2004, meeting. The intent of CAIB Recommendation 3.4-2 has been met.

3.5.5 RTF TG Observation

It is our observation that the addition of the digital umbilical well camera to the overall suite of imagery planned for STS-114 was vital. This camera requires good lighting in order to provide high-quality images during separation. The views obtained from this imagery are, in our opinion, critical for evaluating the state of the modified External Tank.

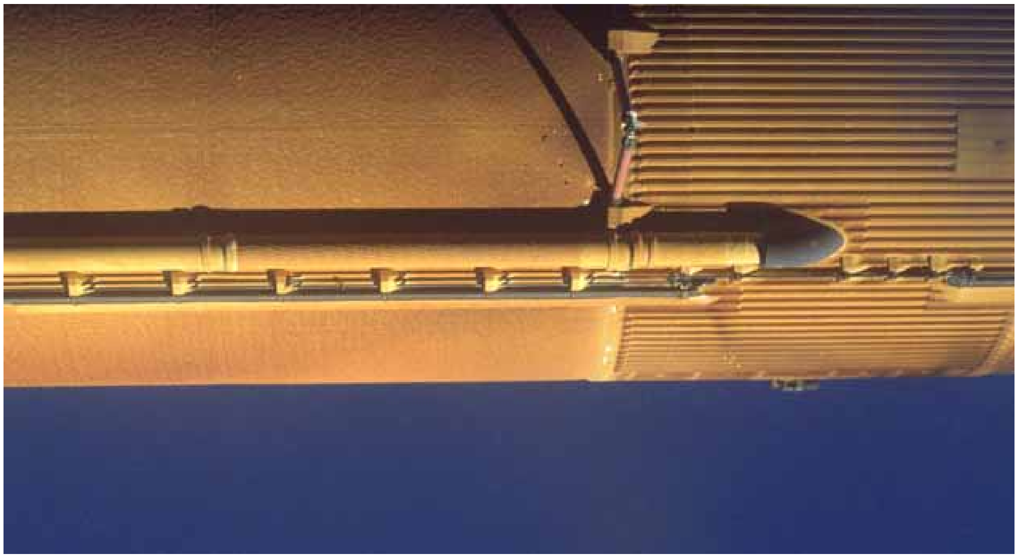


Image of the STS-106 External Tank taken by the umbilical well film camera after separation. NASA has replaced this camera with a digital camera so that images can be downlinked to the ground during the mission. The bipod ramps that used to be used on the ET are clearly visible.

3.6 CAIB Recommendation 3.4-3 – High-Resolution Images of Orbiter

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.

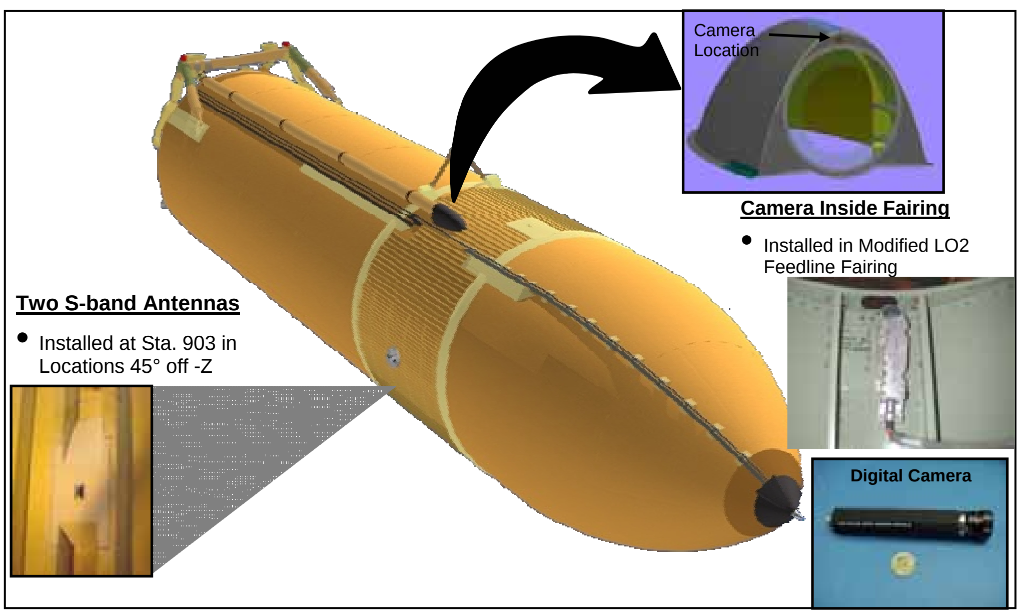
3.6.1 RTF TG Interpretation

The Columbia Accident Investigation Board (CAIB) investigation was hampered by the lack of high-resolution images of the launch ascent trajectory. The only images available were from ground cameras that were inadequate in number, placement, and resolution to permit a meaningful and timely engineering analysis of the External Tank (ET) thermal protection system performance.

3.6.2 Background

The damage to the left wing of *Columbia* occurred shortly after liftoff, but went undetected for the entire mission. Although there was photographic evidence from ground cameras of a debris impact to the wing, the quality of the imagery hampered a thorough analysis of the debris and its potential damage. There was no on-board imagery of the debris strike.

Many expendable launch vehicles carry cameras pointing toward various parts of the vehicle. Usually, these cameras monitor the separation of solid rocket motors, or provide public relations value only. Such a camera was mounted on the ET during STS-112 as an experiment (the so-called "ET-Cam"). The CAIB believed that this type of camera arrangement could provide valuable engineering data if aimed at areas of interest on the Orbiter, such as the main landing gear doors and wing leading edges.



A digital camera has been added to the External Tank LO2 feedline fairing.

3.6.3 NASA Implementation

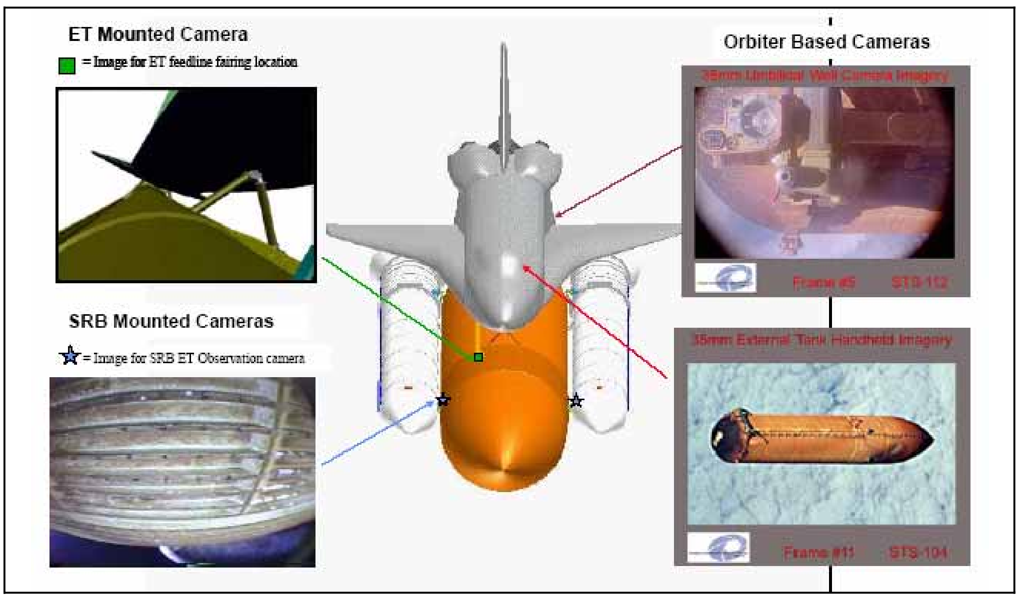
For the first few missions after return to flight, NASA will use primarily on-orbit inspections to meet the requirement to assess the health and status of the Orbiter Thermal Protection System. This is because the on-vehicle ascent imagery suite does not provide complete imagery of the underside of the Orbiter or guarantee detection of all potential impacts to the Orbiter. NASA's detailed implementation of high-resolution images of the Orbiter was presented with Recommendation 6.4-1. The two primary methods include Orbiter Boom Sensor System (OBSS) and the R-Bar Pitch Maneuver (RPM) imagery; see Section 3.13 (R6.4-1) for a further discussion.

In addition, NASA will have cameras on the External Tank liquid oxygen (LO2) feedline fairing and the forward skirt of each Solid Rocket Booster. The ET LO2 feedline fairing camera will take images of the ET bipod areas and the underside of the Orbiter fuselage and the right wing from liftoff through the first 15 minutes of flight. The new location of the ET camera will reduce the likelihood that its views will be obscured by the booster separation motor plume, a discrepancy observed on STS-112. These images will be transmitted to ground stations in real time.

The SRB forward skirt cameras will take images from 3 seconds to 350 seconds after liftoff. These two cameras will look sideways at the ET intertank. The images from this location will be stored on the Solid Rocket Boosters and will be available after the SRBs are recovered, approximately three days after launch.

Beginning with STS-115 (the third flight), NASA will introduce an additional complement of cameras on the SRBs: aft-looking cameras located on the SRB forward skirt and forward-looking cameras located on the SRB External Tank Attachment Ring. Together, these cameras will provide additional views of the underside of the Orbiter during ascent.

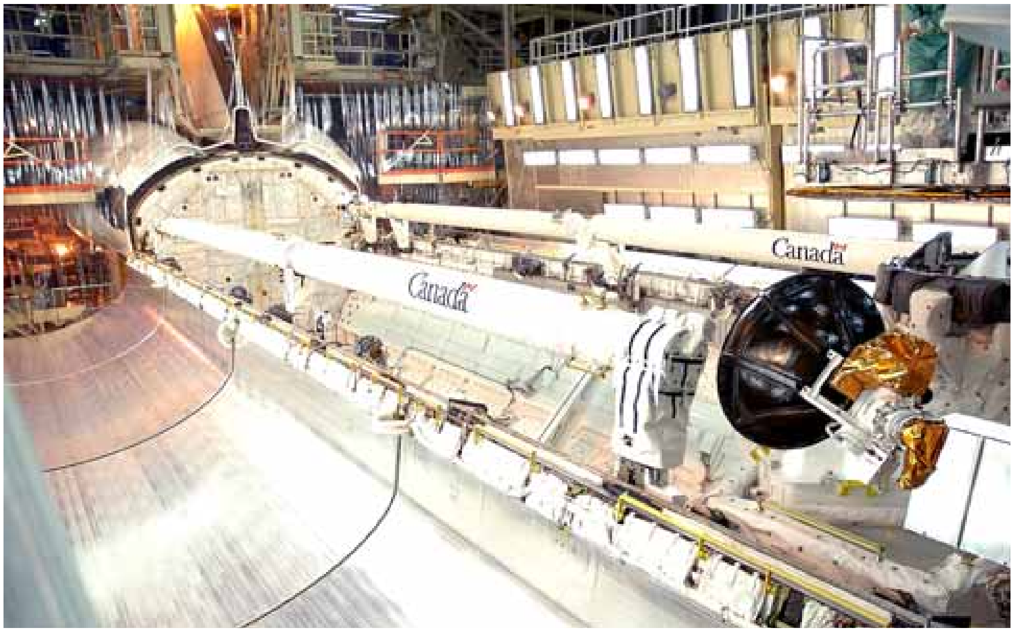
STS-114 and STS-121 will carry cameras in the forward skirt of each Solid Rocket Booster, in the External Tank LO2 feedline fairing, and in the Orbiter umbilical well. In addition, the crew will continue to use hand-held cameras to photograph the ET after separation.



3.6.4 RTF TG Assessment

The NASA approach to the CAIB recommendation was to provide an integrated package that tied together all three imagery recommendations (R3.4-1, Ground-Based Imagery; R3.4-2, High-Resolution Images of External Tank; and 3.4-3, High-Resolution Images of Orbiter), and moved the on-orbit inspection capabilities to R6.4-1, Thermal Protection System Inspection and Repair. Ultimately, the Task Group decided to consider R3.4-1 and R3.4-2 as standalone packages, while R3.4-3 and the inspection portion of R6.4-1 were tightly coupled and their final assessments were considered together.

NASA addressed the Orbiter Boom Sensor System (OBSS) and the R-Bar Pitch Maneuver (RPM) as part of CAIB Recommendation 6.4-1. However, these are the capabilities that provide evidence that this recommendation has been met and are assessed here.



Inside the Orbiter Processing Facility bay 3 at the Kennedy Space Center, *Discovery*'s payload bay doors are ready to be closed. Seen in the center (starboard side) and at right are the new Orbiter Boom Sensor System (OBSS) and the Shuttle Remote Manipulator System (SRMS). The black object in the foreground is the Ku-band antenna.

Numerous fact-finding activities were conducted between October 2003 and the closure meeting on November 30, 2004. NASA provided a partial closure package for R3.4-3 concurrently with R3.4-1 and R3.4-2, the other imagery recommendations, and the closure presentation covered all three recommendations. However, since NASA moved their implementation of the OBSS and the R-Bar Pitch Maneuver into R6.4-1, the Task Group did not feel it could close R3.4-3 until the closure package for R6.4-1 was received.

The closure package for R6.4-1 was received on May 26, 2005. Although the Task Group did not feel that the repair portion of the closure package were sufficient to deliberate R6.4-1, the portion of the package concerning inspection was complete and R3.4-3 was deliberated at the June 8, 2005, plenary meeting in Houston.

The closure package showed that the primary tool for imaging the wing leading edge on orbit will be with the Orbiter Boom Sensor System. There are two sensor packages on the OBSS: the laser dynamic range imager (LDRI), which will be used on the lower surface and apex of the wing leading edge, and the laser camera system (LCS), which will be used primarily on the nosecap. The LDRI has demonstrated, under laboratory conditions, the ability to resolve 0.25-inch holes and 0.015-inch cracks, while the LCS has shown the ability to resolve 0.125-inch holes and 0.25-inch coating loss. The Task Group questions whether these resolutions can actually be achieved on orbit, and they do not necessarily correspond to the smallest critical damage the RCC can withstand; nevertheless they are a significant capability.

There are some questions remaining regarding the Orbiter Boom Sensor System, which must be resolved operationally. These include the clearance between the OBSS and the Ku-band antenna in the retracted position, and analysis of LDRI cable clearance with the Orbiter radiator and CMG payload. NASA assures the Task Group that these items will not affect the operation of the OBSS during STS-114.

The primary method for imaging the acreage tiles on the bottom of the Orbiter and the surface insulation on top of the Orbiter will be via photography from the ISS during the R-Bar Pitch Maneuver while the Orbiter is approaching the station to dock. These images provide adequate resolution to initiate a more-focused inspection using the OBSS, if required.

The RTF TG assessment of NASA's actions was completed at the June 8, 2005, meeting.

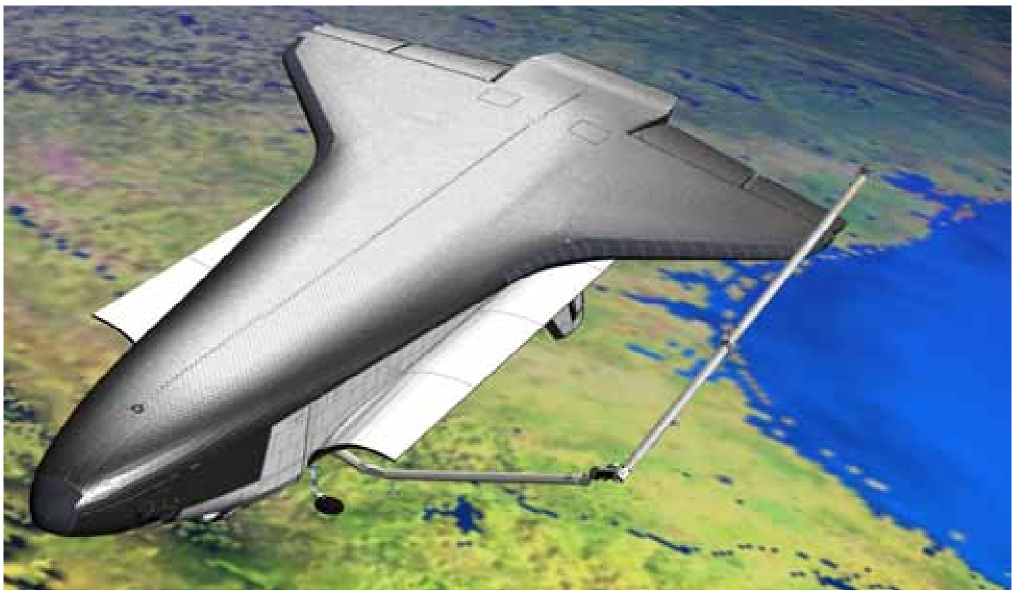
With the provision that the forward work, described previously, is completed, the Task Group feels that the intent of CAIB Recommendation 3.4-3 has been met.

3.6.5 RTF TG Observation

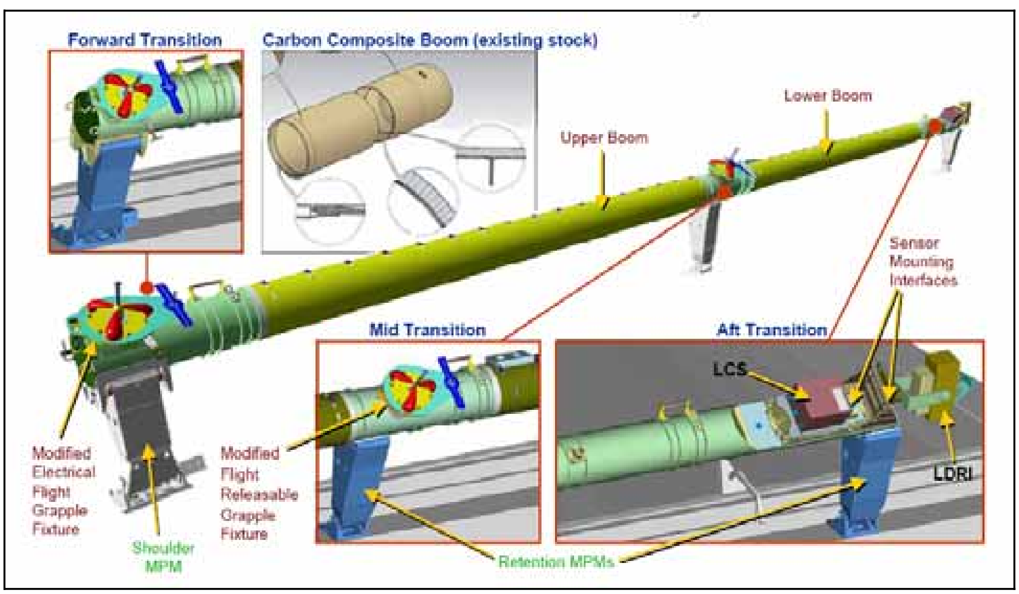
The Task Group believes that on-vehicle ascent imagery will be a valuable source of engineering, performance, and environment data and will be useful for understanding in-flight anomalies. The new location of the ET camera should reduce the likelihood that the camera will be obscured by the booster separation motor plume. The RTF TG cautions, however, that this on-vehicle ascent imagery suite does not provide complete imagery of the underside of the Orbiter or guarantee detection of all potential impacts to the Orbiter.

The certified resolution of the OBSS sensor suite does not meet critical damage size criteria.

NASA has committed to retain an on-orbit inspection capability after the OBSS can no longer be flown. The RTF TG strongly endorses that commitment.



The 50-foot long OBSS attaches to the end of the SRMS and provides the capability to inspect all of the RCC on the Orbiter as well as most of the underside tiles.



The OBSS boom is very similar to the standard Remote Manipulator System boom the Orbiter has carried on most of its missions. The RMS attaches to the OBSS and provides power and control to the new boom. Two new imaging systems are located at the end of the OBSS.