3.9 CAIB Recommendation 4.2-5 – KSC Foreign Object Debris Definition

Kennedy Space Center Quality Assurance and United Space Alliance must return to straightforward, industry-standard definition of "Foreign Object Debris" and eliminate any alternate or statistically deceptive definitions like "processing debris."

3.9.1 RTF TG Interpretation

During their investigation and interviews with personnel involved with processing the Space Shuttle for flight, the Columbia Accident Investigation Board (CAIB) determined that during January 2001 the Kennedy Space Center (KSC) generated new and non-standard definitions for Foreign Object Debris (FOD) which were fully implemented at KSC in June 2002. The term "processing debris" was applied to debris found during the routine processing of the flight hardware. The term FOD applied only to debris found in flight hardware after final closeout inspections. These definitions were unique to the Space Shuttle Program at the KSC. Because debris of any kind has critical safety implications, these definitions are important. Accordingly, the CAIB wanted the standard, industry-wide definitions reestablished for FOD.

3.9.2 Background

Problems with the Kennedy Space Center and United Space Alliance (USA) Foreign Object Damage Prevention Program, which in the Department of Defense and aviation industry typically falls under the auspices of Quality Assurance, were related to changes made during 2001. In that year, Kennedy Space Center and United Space Alliance redefined the single term "Foreign Object Damage" – an industry-standard term – into two categories: "Processing Debris" and "Foreign Object Debris."

Processing Debris:

> *Any material, product, substance, tool or aid generally used during the processing of flight hardware that remains in the work area when not directly in use, or that is left unattended in the work area for any length of time during the processing of tasks, or that is left remaining or forgotten in the work area after the completion of a task or at the end of a work shift. Also any item, material or substance in the work area that should be found and removed as part of standard housekeeping, Hazard Recognition and Inspection Program (HRIP) "walk-downs", or as part of "Clean As You Go" practices.*

Foreign Object Debris:

> *Processing debris becomes FOD when it poses a potential risk to the Shuttle or any of its components, and only occurs when the debris is found during or subsequent to a final/flight Closeout Inspection, or subsequent to OMI S0007 ET Load SAF/FAC "walk-down."*

These definitions were inconsistent with those of other NASA Centers, the Department of Defense, commercial aviation, and National Aerospace FOD Prevention, Inc., guidelines. Because debris of any kind has critical safety implications, the CAIB believed these definitions were important.

3.9.3 NASA Implementation

The Kennedy Space Center and United Space Alliance have changed work procedures to consider all debris equally important and preventable. Rigorous definitions of FOD that are the industry standard have been adopted. These new definitions adopted from National Aerospace FOD Prevention, Inc. guidelines and industry standards include Foreign Object Debris, Foreign Object Damage, and Clean-As-You-Go. FOD is redefined as “a substance, debris or article alien to a vehicle or system which would potentially cause damage.”

The new FOD program is anchored in three fundamental areas of emphasis. First, it eliminates various categories of FOD, including “processing debris,” and treats all FOD as preventable and with equal importance. Second, it reemphasizes the responsibility and authority for FOD prevention at the operations level. FOD prevention and elimination are stressed and the work force is encouraged to report any and all FOD found by entering the data in the FOD database. This activity is performed with the knowledge that finding and reporting FOD is the goal of the Program and employees will not be penalized for their findings. Third, it elevates the importance of comprehensive independent monitoring by both contractors and the Government.

United Space Alliance has also developed and implemented new work practices and strengthened existing practices. This new rigor will reduce the possibility for temporary worksite items or debris to migrate to an out-of-sight or inaccessible area, and it serves an important psychological purpose in eliminating visible breaches in FOD prevention discipline.

The new FOD program has a meaningful set of metrics to measure effectiveness and to guide improvements. FOD walkdown findings will be tracked in the Integrated Quality Support Database. This database will also track FOD found during closeouts, launch countdowns, post-launch pad turnarounds, landing operations, and NASA quality assurance audits. “Stumble-on” FOD findings will also be tracked, as they offer an important metric of program effectiveness independent of planned FOD program activities. For all metrics, the types of FOD and their locations will be recorded and analyzed for trends to identify particular areas for improvement. Monthly metrics reporting to management will highlight the top five FOD types, locations, and observed workforce behaviors, along with the prior months’ trends. Continual improvement will be a hallmark of the revitalized FOD program.

The implementation of the new program began on July 1, 2004, although many aspects of the plan existed in the previous FOD prevention program in place at KSC. Assessment audits by NASA and United Space Alliance were conducted beginning in October 2004. Corrective Action Plans have been established to address the findings and observations identified during the two audits. Schedules for the verification of the actions taken and for verifying the effectiveness of the corrective actions have been established to ensure the ongoing effectiveness of the FOD prevention program. Continual improvement will be vigorously pursued for the remainder of the life of the Space Shuttle.

3.9.4 RTF TG Assessment

The FOD Program at the Kennedy Space Center was very effective in the past. When the definitions were modified during 2001 to create multiple categories of debris, the workforce was not sufficiently trained to understand the implications. This confusion was expressed to the CAIB members during their interviews with KSC personnel; in response to the CAIB recommendation, KSC reevaluated the entire program. The Task Group concluded fact-finding during a technical interchange meeting at KSC in May 2004. This complemented previous meetings with KSC quality assurance and United Space Alliance personnel in late 2003 and early 2004.

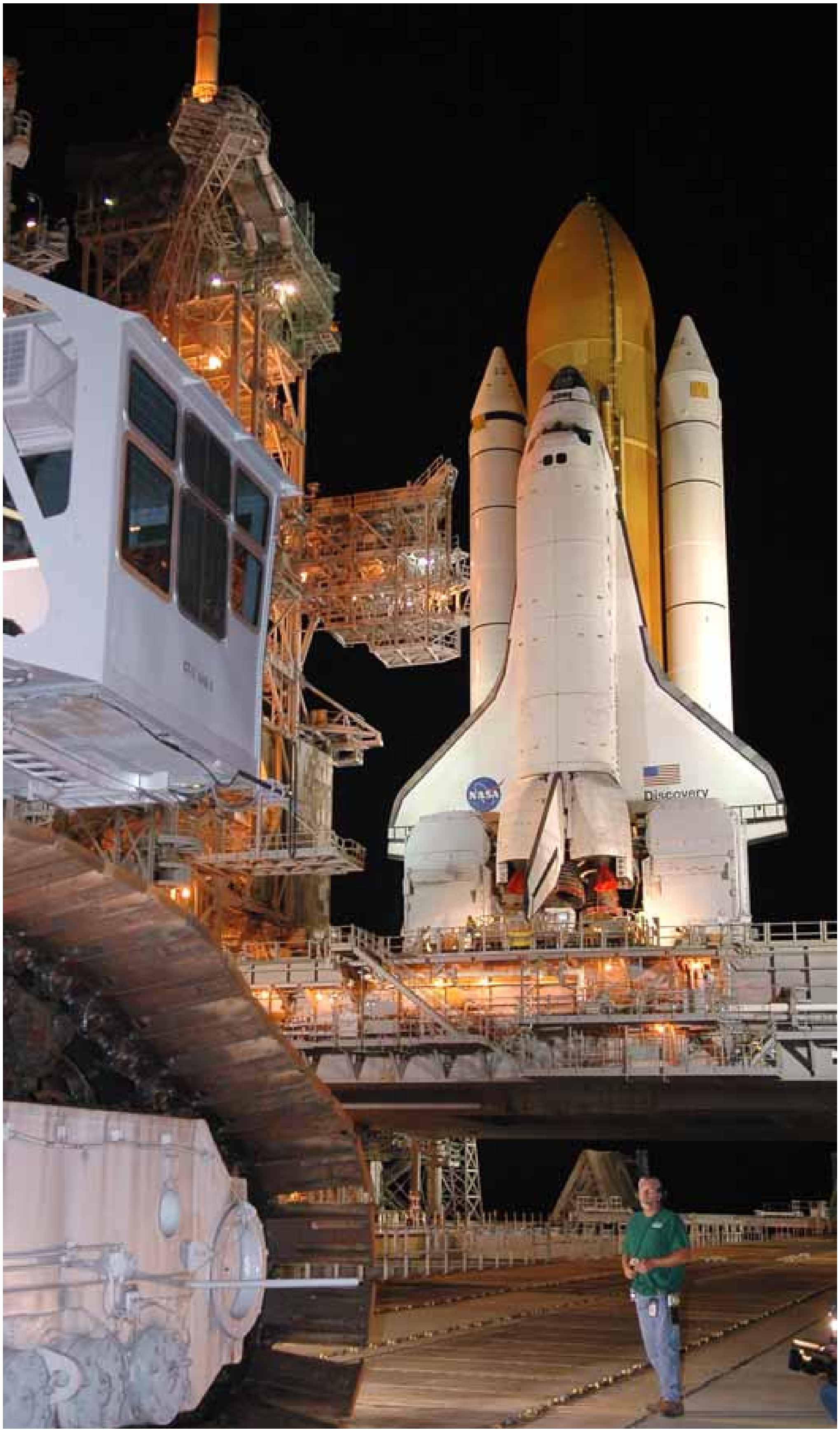
The Kennedy Space Center and United Space Alliance have changed the definition of "Foreign Object Debris" to be consistent with the recognized and accepted industry standard. Further, they have removed the misleading category of processing debris that caused concern. They have improved the training of the workforce, and obtained buy-in at all levels for both NASA and all contractors. The revised program has implemented several improvements above and beyond the expectations defined in the CAIB recommendation. The FOD database has been made significantly more robust and captures a higher level of reporting detail than existed previously. NASA management has demonstrated their buy-in with participation in "walk-downs" to inspect for FOD.

The RTF TG initial assessment of NASA's actions was completed at the July 22, 2004, teleconference plenary where the assessment was conditionally closed. After receiving audit results and specified corrective actions from NASA, the assessment was closed at the December 16, 2004, meeting. The intent of CAIB Recommendation 4.2-5 has been met.

3.9.5 RTF TG Observation

It is very important for NASA management to provide positive incentives for the reporting of FOD and to avoid negative sanctions for those who self-report. The Task Group believes management is sufficiently sensitive to this need and will provide the proper positive and negative feedback to the workforce. Metrics defined and tracked by NASA will assure continued compliance with the new improved FOD program.

Discovery during early processing for STS-114. The reinforced carbon-carbon nosecap had been removed and returned to the vendor for testing. Note the open nose landing gear door at the bottom left.



The Crawler-Transporter drives away after delivering *Discovery* on her Mobile Launch Platform to Launch Complex 39B.

3.10 CAIB Recommendation 6.2-1 – Consistency with Resources

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

3.10.1 RTF TG Interpretation

The Columbia Accident Investigation Board (CAIB) explicitly recognized the legitimate use of schedules to drive a process. They were concerned, however, that the line between "beneficial" schedule pressures and those that become detrimental, cannot be easily defined or measured. In the case of *Columbia*, the CAIB discovered that pressure on the Space Shuttle Program was created by the schedule for construction of the International Space Station. Indeed, the planned February 2004 completion of Node 2 of the International Space Station was being touted as a measure of NASA's ability to maintain a schedule.

The CAIB further observed that budget constraints inherently intensify the conflicts between schedule and safety. The meaning of the first sentence of the CAIB recommendation is clear: adjust the schedule to fit the available resources.

3.10.2 Background

During the course of the *Columbia* investigation, the CAIB received several unsolicited comments from NASA personnel regarding pressure. Oddly, the pressure was to meet a date more than a year after the launch of STS-107 that seemed etched in stone: February 19, 2004, the scheduled launch of STS-120. This flight was a milestone in the minds of NASA management since it would carry a section of the International Space Station called "Node 2" that would signal "U.S. Core Complete."

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

Meeting U.S. Core Complete by February 19, 2004 – a date the CAIB found was promised by NASA management to the White House and Congress – would require launching 10 Space Shuttle missions in less than 16 months. With the focus on retaining political support for the International Space Station Program, little attention was paid to the effects the aggressive Node 2 launch date would have on the Space Shuttle Program. After years of downsizing and budget cuts, this mandate introduced elements of risk, and the high-pressure environments created by NASA Headquarters unquestionably affected *Columbia*, even though it was not flying to the International Space Station.

After considering what they had uncovered during their investigation, the CAIB concluded:

> "The agency's commitment to hold firm to a February 19, 2004, launch date for Node 2 influenced many of decisions in the months leading up to the launch of STS-107, and may well have subtly influenced the way managers handled the STS-112 foam strike and *Columbia*'s as well.
>
> "When a program agrees to spend less money or accelerate a schedule beyond what the engineers and program managers think is reasonable, a small amount of overall

risk is added. These little pieces of risk add up until managers are no longer aware of the total program risk, and are, in fact, gambling. Little by little, NASA was accepting more and more risk in order to stay on schedule."

3.10.3 NASA Implementation

NASA has strengthened a risk management system that it believes balances technical, schedule, and resource risks to achieve safe and reliable operations. Under this system, safety is ensured by first focusing on the technical risks and taking the time and financial resources necessary to properly resolve them. Once technical risks are reduced to an acceptable level, program managers turn to the management of schedule and resource risks to preserve safety.

Among the activities NASA plans to undertake are more routinely assessing schedule risk, incorporating additional margin into the schedule and manifest to accommodate changes, and revising databases so schedule and risk indicators can be assessed by managers in real-time. KSC and United Space Alliance management use the Equivalent Flow Model (EFM) to plan resources that are consistent with the Space Shuttle flight schedule and available workforce needed to meet the technical requirements. The EFM is a computerized tool that uses a planned manifest and past performance to calculate processing resource requirements. The workforce, a primary input to the EFM tool, comprises fixed resources, supporting core daily operations, and variable resources that fluctuate depending on the manifest. Using past mission timelines and actual hours worked, an "equivalent flow" is developed to establish the required processing hours for a processing flow.

To assess and manage the manifest, NASA has developed a process called the Manifest Assessment System that incorporates all manifest constraints and influences, and allows adequate margin to accommodate a normalized amount of changes. This process entails building in launch margin, cargo and logistics margin, and crew timeline margin while preserving the technical element needed for safe and reliable operations. United Space Alliance is using the Manifest Assessment System to assess the feasibility of proposed technical and manifest changes to determine how changes to facility availability, schedule, or duration of flight production activities affect the overall manifest schedule. This capability enables a more useful way to implement realistic, achievable schedules while successfully balancing technical, schedule, and resource risks to maintain safe and reliable operations.

Policies are also in place to ensure the workforce health at KSC in the face of schedule deadlines. The Maximum Work Time Policy, found in KSC Handbook (KHB) 1710.2, section 3.4 includes daily, weekly, monthly, yearly, and consecutive hours worked limitations. Deviations require senior management approval up to the KSC Center Director and independent of the Space Shuttle Program. KSC work time safeguards ensure that when available resource capacity is approached, the schedule is adjusted to safely accommodate the added work. When possible, launches are planned on Wednesdays or Thursdays to minimize weekend hours and associated costs; repeated launch attempts are scheduled to reduce crew and test team fatigue. Overtime hours and safety hazard data are continually monitored by KSC and Space Shuttle Program management for indications of workforce stress.

3.10.4 RTF TG Assessment

The CAIB explored a number of root causes for the *Columbia* accident; one of these was the desire to maintain a schedule for achieving U.S. Core Complete during construction of the International Space Station. The ISS Program had a long history of cost and schedule overruns and had been the subject of numerous Congressional hearings and independent commissions. NASA was determined to complete construction with as few additional budgetary resources as possible. In this environment, there was a reluctance to expend the resources to investigate obvious problems with the Space Shuttle, among them the shedding of foam from the External Tank (ET). Damage to a Solid Rocket Booster – caused by foam from the ET – two flights before *Columbia*, prompted a study into the anomaly, but even this was not enough to cause anyone to waiver from the schedule.

Thus CAIB recommended that NASA "Adopt and maintain a Space Shuttle flight schedule that is consistent with available resources…" Recognizing the ongoing nature of this recommendation, the Task Group believes it will take vigilance in the future to maintain the "appropriate" pressure necessary to maintain a schedule for such a complex system without the pressure becoming, for any reason, "undue."

Recognizing the difficulty in assessing this recommendation, the Task Group undertook several activities in an attempt to evaluate the presence of "undue" schedule pressure and the general availability of resources. The Task Group consistently explored the question of adequacy of resources in virtually every meeting with NASA personnel – from Headquarters staff to the workforce on the floor of the Kennedy Space Center. The answer has always been the same: "…there are sufficient budgetary resources for return to flight."

Recognizing that any assessment is a snapshot, the Task Group also requested data on overtime and other work rule exceptions. The RTF TG looked at reports on sick leave, employee assistance visits, accidents, and near-accidents (close-calls or "diving catches"), as well as reports of problems with the quality of workmanship being performed. Altogether, these data, compared with previous intervals prior to launch, showed no unusual patterns suggestive of substantial adverse pressure.

During the middle of 2004, press reports claimed NASA personnel were concerned about resources and the possibility of workforce reductions. The RTF TG was not able to confirm these reports and notes most were made prior to the finalization of the Fiscal Year 2005 NASA budget, during a time when exercises were being conducted to assess the impacts of various alternative levels of spending. NASA was one of the few federal agencies to receive full funding, although funding for aeronautics programs was severely cut to fund space initiatives, particularly the Vision for Space Exploration.

The Task Group also had the opportunity to assess the outcome of NASA's budget requests over the last two years. Last year (FY05), Congress actually added funds to the request to augment return-to-flight activities, and this year has taken actions to help protect resources for NASA in the future. And while NASA has somewhat reduced funding for the Headquarters Office of Safety and Mission Assurance, the Task Group has been assured these reductions will have no effect on return-to-flight activities.

The RTF TG assessment of NASA's actions was completed at the June 8, 2005, meeting. The intent of CAIB Recommendation 6.2-1 has been met.

3.10.5 RTF TG Observations

Resource sufficiency is also tied to the scheduled retirement date for the Space Shuttle, and any evaluation of whether to keep Space Shuttle in service past 2010 should include a reassessment of actions and upgrades not undertaken, and any long term items already deleted from work and acquisition cycles, including the Service Life Extension Program.

The Task Group also observes that resource constraints will likely pressure future programs, such as the Vision for Space Exploration. There will always be pressure for under-funding and overly-aggressive scheduling that must be recognized and mitigated by senior leadership. Along these lines, NASA must address the size and mixture of its future workforce to accomplish its new missions.

As new NASA space flight programs evolve, the Space Shuttle could well be caught between competing goals (e.g., the 2010 retirement date, Hubble SM4, and the delays in fielding a new vehicle). NASA will need to exercise great rigor to ensure that competing budgetary requirements do not affect the safety and reliability of Space Shuttle.

Discovery at the beginning of her slow trip to Launch Complex 39B, as seen from inside the Vehicle Assembly Building.

3.11 CAIB Recommendation 6.3-1 – Mission Management Team Improvements

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

3.11.1 RTF TG Interpretation

Mission Management Team (MMT) activities during the flight of *Columbia* have been widely criticized. Many of the additional capabilities embedded in other recommendations from the Columbia Accident Investigation Board (CAIB), such as imagery from various sources, are intended to support MMT activities for the next and subsequent flights. In addition to enhanced training for participants in the MMT, the Agency will need to exercise these many new sources of data and information.

3.11.2 Background

The CAIB report was very clear on the importance the accident investigation board placed on correcting the organizational behaviors which led to the multiple STS-107 MMT decision making failures they identified. Indeed, the CAIB issued 29 findings related to these failures, ranging from lapses in MMT leadership and communication, to the passivity of MMT safety representatives, to the lack of reliance on solid analysis and engineering data, to the absence of effective mechanisms for expressions of concern or dissent.

According to NSTS 07700, Volume VIII, Appendix D, the MMT is "the program decision-making body responsible for making programmatic trades and decisions associated with launch countdown and in-flight activities … outside the responsibility or authority of the Launch Director or Flight Director." Throughout STS-107, the CAIB found that the MMT (and its processes and procedures) failed to support or result in timely, informed, or effective critical decisions. In short, the MMT failed in the performance of its mission.

During Space Shuttle missions, the Mission Management Team is responsible for oversight of the launch and flight operations teams. The countdown and flight operations are conducted to rules and procedures approved by program management and are documented in NSTS 07700, Volume VIII. The MMT provides guidance to the operations teams during situations that fall outside normal operations; the MMT also redefines programmatic priorities when in-flight anomalies or off-nominal conditions result in conflicting priorities.

The MMT responsibilities for a specific Space Shuttle mission begin with a scheduled meeting two days prior to a scheduled launch (L-2). The MMT Chair, supported by the entire MMT, is responsible for the final GO/NO-GO decision for launch. MMT activities at the Kennedy Space Center continue through launch and terminate upon the declaration by the Flight Director of "Go for On-Orbit Operations," approximately 2 hours after launch. At that time, MMT activities transfer to the Johnson Space Center. The flight MMT meets daily during the subsequent on-orbit, entry, and landing phases, and terminates with crew egress from the Orbiter. When the MMT is not in session, all members are on-call and required to support emergency meetings convened because of anomalies or changing flight conditions.

As exhibited during STS-107, the MMT had become somewhat *ad hoc* and informal in nature; there was no clear method to formally present issues in an official forum. Therefore, the concerns of individual engineers, the quality of risk assessments, and the pedigree of engineering assessments were sometimes poorly understood by senior management. In retrospect, this approach did not adequately sensitize NASA management in general – and the MMT, in particular – to actively seek out potential concerns and issues raised by individuals, support teams, and working groups.

3.11.3 NASA Implementation

As a result of the CAIB findings and recommendations, the Space Shuttle Program began to identify necessary changes to the MMT in May 2003. A Space Shuttle Program Requirements Change Board on September 11, 2003, reviewed the proposed changes and presented a slightly modified set to the Space Flight Leadership Council on November 21, 2003. The changes included expanding the MMT membership, better defining member responsibilities, making the flight MMT meetings more formal, establishing a time reporting process, and establishing a rigorous process for the review and disposition of mission anomalies and issues. In addition, NASA contracted with several external evaluators (experts in training and critical decision making) and several past flight directors, including Gene Kranz and Glynn Lunney, to study the MMT processes and make recommendations to improve communications, decision-making, and operational processes.

NASA established a process for the review and resolution of off-nominal mission events to ensure that all such issues are identified to and resolved by the flight MMT. The Space Shuttle Systems Engineering and Integration Office will maintain and provide an integrated anomaly list at each MMT meeting. All anomalies will be assigned a formal office of primary responsibility (OPR) for technical evaluation and will be subject to an independent risk assessment by Safety and Mission Assurance (SMA). The MMT has one Space Shuttle Program SMA core member and three institutional SMA advisory members from JSC, KSC, and MSFC. In addition, the MMT has added the Space Shuttle System Technical Warrant Holder as a core member; this person represents the NASA Independent Technical Authority as a voting member. The NASA Engineering and Safety Center (NESC) also serves as a formal advisor to the MMT.

The MMT secretary will maintain an action tracking log to ensure all members are adequately informed of the status of all anomalies. Closure of actions associated with each anomaly will require a formal written request that includes a description of the issue (observation and potential consequences), technical analysis details (including databases, employed models, and methodologies), recommended actions and associated mission impacts, and flight closure rationale, if applicable. These steps are designed to eliminate the possibility of critical missteps by the MMT due to incomplete or un-communicated information. NASA has documented these changes in a new Mission Evaluation Room console handbook that includes MMT reporting requirements, a flight MMT reporting process for on-orbit vehicle inspection findings, and MMT meeting support procedures.

Additional improvements were made to MMT internal processes and procedures, including more clearly defining requirements for MMT meeting frequency and the process for requesting an emergency MMT meeting. The MMT will hold meetings daily beginning at L-2 or L-1 day, depending on the scheduled time of launch. The membership and organization of the preflight and flight MMT are standardized. In addition, the Space Shuttle Program Deputy Manager now chairs both phases of the MMT, preflight and flight.

The MMT member's responsibilities have been clearly defined, and MMT membership and training status for each mission is established by each participating organization in writing at the Flight Readiness Review (FRR). Each MMT member also has clearly defined processes for MMT support and problem reporting.

Procedures for flight MMT meetings are standardized through the use of predefined templates for agenda formats, presentations, action item assignments, and readiness polls. This ensures that the communication and resolution of issues are performed in a consistent, rigorous manner. Existing Space Shuttle Program meeting support infrastructure and a collaboration tool are used to ensure that critical data are distributed before scheduled meetings and that MMT meeting minutes are quickly distributed following each meeting. In addition, NASA established formal processes for the review of findings from ascent and on-orbit imagery analyses, post-launch hardware inspections, ascent reconstruction, and all other flight data reviews to ensure timely, effective reviews of key data by the MMT.

Using recognized techniques for improving communications for critical decision making, NASA refurbished the Mission Management Team's working space to provide increased seating and improved communications. Other enhancements include a video-teleconferencing capability, a multi-user collaboration tool, and a larger room to allow more subject matter experts and MMT members. A large C-shaped table now seats all members of the MMT and encourages open communication by eliminating a hierarchical seating arrangement. The MMT Command Center has been operational since the November 2004 MMT simulation to give the team time to adapt and learn how to use all of the new tools.

The MMT conference room was refurbished with the addition of a large C-shaped table and multimedia capabilities to better facilitate communications between members.

3.11.3.1 __Training__

All MMT members, except those serving exclusively in an advisory capacity and the Department of Defense Mission Support representative, are required to complete a minimum set of training requirements to attain initial qualification prior to performing MMT responsibilities. MMT members must also participate in an ongoing training program to maintain qualification status, which is renewed annually. Training records are maintained to ensure compliance with the new requirements.

In addition, to ensure adequate backup personnel are available, at least two people will be trained to fill each MMT core position prior to return to flight. This will protect the integrity of the integrated MMT process against individuals' inability to perform their role for any reason. Verification of each flight specific team will be presented at the appropriate FRR.

The Space Shuttle Program published a formal MMT training plan (NSTS 07700, Volume II, Program Structure and Responsibilities, Book 2, Space Shuttle Program Directive 150) that defines the generic training requirements for MMT certification. This plan is comprised of three basic types of training: courses and workshops, MMT simulations, and self-instruction. Courses, workshops, and self-instruction materials were selected to strengthen individual expertise in human factors, critical decision making, and risk management of high-reliability systems. MMT training activities are well under way with several courses/workshops held at various NASA centers and 13 simulations completed, including an end-to-end contingency simulation and a simulation to address MMT actions related to Contingency Shuttle Crew Support (see Section 3.16, SSP-3). These simulations brought together the flight crew, flight control team, launch control team, engineering staff, outside agencies, and ISS and Space Shuttle MMT members to improve communication and teach better problem-recognition and decision-making skills.

Quality assurance processes have been established to help monitor that MMT training requirements are met, sustained, and improved over time. Numerous channels have been opened to allow the real-time expression of concerns or dissent. The support teams, including contractors, have revised their processes to better serve the MMT and have trained to these new processes. Formal training objectives, evaluation processes, metrics, and a closed-loop lessons-learned system are now a part of MMT training. Independent external evaluators will continue to challenge the integrity of MMT training. The International Space Station and Space Shuttle MMTs have cross-trained and are improving the standardization of processes and communications. The development of NSTS 60540, *STS-114 Operations Integration Plan for Thermal Protection System Assessment* has greatly improved the real-time decision-making process concerning potential Orbiter Thermal Protection System damage (see Section 2.2 of this report for a further discussion of the OIP).

Risk management is now a major consideration at each MMT meeting. Each identified hazard is required to have a clear risk assessment performed and presented to the MMT so the appropriate risk-versus-risk tradeoffs can be discussed and decided upon. Supporting analyses, assumptions, issues, and ramifications are a part of this discussion.

3.11.4 RTF TG Assessment

Because of the central role played by the MMT during the last flight of *Columbia*, the Task Group conducted a great deal of fact-finding regarding this recommendation. Members attended the first "live" simulation on December 3-5, 2003, and additional sims on February 11, 2004, April 2, 2004, November 16-19, 2004, February 28 through March 7, 2005, and May 4, 2005. A variety of meetings, classroom training, assessed evaluations, and training exercises were also attended by the Task Group members and staff. NASA submitted a closure package in November 2004, but after review the Task Group requested additional data and simulations, especially one that exercised consideration of Contingency Shuttle Crew Support. A revised closure package was submitted to the Task Group on March 7, 2005. The Task Group again requested to witness a simulation that demonstrated the complex risk-versus-risk trades involved with the possibility of invoking the CSCS capability; this sim was finally held on May 4, 2005.

NASA has developed a new training plan for the MMT. With the passage of time, the Task Group has been able to witness the implementation of most aspects of the plan. There have also been numerous simulations conducted to date including more than ten involving live, face-to-face exercises of various parts of the next mission.

Some of the training protocols were initially developed without clear objectives and techniques to assess the quality of training. Similarly, the first simulations lacked clear objectives and evaluation criteria. Further, lessons learned from prior simulations were not incorporated in subsequent exercises. With a maturing training program, many of the earlier deficiencies have been corrected and the MMT Training Plan has been updated to reflect formal evaluation requirements. However, not all aspects of the enhanced role of the MMT have been exercised completely, such as the potential use of the CSCS option and a launch-on-need rescue mission (STS-300) and the incorporation of all new sources of data and imagery. The MMT held a special simulation (sim #13) that included consideration of invoking the CSCS capability; most Task Group members in attendance were satisfied with the results.

The various delays in launching STS-114 have allowed the MMT to further refine its procedures and have resulted in continual improvement. The Mission Management Team has made notable progress in addressing the accident board's concerns, and NASA has demonstrated a commitment to continual MMT improvement.

The RTF TG assessment of NASA's actions was completed at the June 8, 2005, meeting. The intent of CAIB Recommendation 6.3-1 has been met.

3.11.5 RTF TG Observations

The Task Group recognizes that the notable MMT improvements made to-date are a journey, not an end, and MMT processes and member training need to continue to grow and mature through the remaining missions of the Space Shuttle Program. In addition, NASA needs to ensure that the MMT and its support teams understand and have confidence in their ability to incorporate the latest analytical and engineering information available to them, to include the totally integrated risk assessment of the Space Shuttle system and its knowns, unknowns, limitations, uncertainties, and assumptions. Specific observations of areas that need continual improvement include:

- NASA needs to continually grow and improve a systematic MMT training evaluation system which ensures that MMT training focuses on value, required knowledge, and the "science of learning." The course content, simulation design and delivery, and self-instruction requirements must be continuously assessed and quality assurance plans rigorously applied. NASA should also consider formal MMT training on new and emerging capabilities, such as inspection, imagery, and CSCS.

- Just as the MMT needs to adjust and improve with each "learning experience" (training or live), all of the documents supporting the MMT need to be continually updated and refined based on experience, need, and the evolving MMT decision-making capabilities.

- The MMT needs to continue to improve and mature their integrated risk-versus-risk identification, assessment, decision making, and trades capabilities based on the latest available information and systems integration capabilities to guide them in their time-sensitive critical decisions. This includes the certainties and uncertainties that exist in the various analytical tools and models used by the MMT. Existing linear (i.e., non-integrated) decision making frameworks and the existing meeting agenda format need to be continually assessed and revised to meet the MMT's needs.

- In terms of the new, more rigorous training requirements, NASA also should recognize the opportunity to capitalize on the broader test and validation potentials of MMT simulations for other technical and operational capabilities beyond just the training of MMT members.

- Post-*Columbia*, NASA senior leadership have new responsibilities in terms of MMT decision making and, during future MMT simulations need to ensure that MMT processes fully support their new Headquarters roles for time critical decisions and risk-versus-risk trades and periodically exercise them. Specific areas where NASA Headquarters senior leaders have new responsibilities include Safety and Mission Assurance, the Independent Technical Authority, and the potential decision to declare the need to implement the Contingency Shuttle Crew Support capability and its resulting launch-on-need rescue mission.

- As a senior critical decision-making team, the MMT will continue to have unique insight into areas where there are critical information gaps, seams, unknowns, and uncertainties. The MMT can further serve NASA and the program by helping to point out these areas and prioritize them for focused closure.

- Finally, the Task Group observes that NASA should consider formalizing periodic, independent oversight of the MMT to help sustain it as a "continuously

> learning" entity for the remainder of the Space Shuttle Program. On at least an annual basis, an external entity should observe, evaluate (audit), and challenge the MMT's ability to continuously improve, as well as evaluate MMT member certifications and training.

While the Agency's implementation of this recommendation has been serious and comprehensive, it will, by its very nature, remain a "work in progress" for the remaining missions of the Space Shuttle Program. Many lessons have been learned from the *Columbia* accident over the past 29 months, but with each mission many other lessons will also be learned. As stated previously, the fulfillment of R6.3-1 is a journey, not an end.

The Vehicle Assembly Building (VAB) at the Kennedy Space Center is one of the largest enclosed spaces in the world. The building was originally constructed as part of the Apollo moon program, and is currently used to stack the Space Shuttle vehicle.

3.12 CAIB Recommendation 6.3-2 – National Imagery and Mapping Agency Memorandum of Agreement

Modify the Memorandum of Agreement with the National Imagery and Mapping Agency to make the imaging of each Shuttle flight while on orbit a standard requirement.

3.12.1 RTF TG Interpretation

There was considerable public discussion of the decision during the flight of *Columbia* to forego requesting the assistance of other federal agencies in assessing the condition of the Orbiter. The Columbia Accident Investigation Board (CAIB) wanted the Space Shuttle Program to have the procedures in place to get all possible data to investigate a potential problem. This included having the proper personnel maintain the appropriate security clearances to access data from National assets.

3.12.2 Background

The National Imagery and Mapping Agency (NIMA) was created in 1996 by combining the mapping and imagery analysis efforts of the Central Intelligence Agency (CIA) and Department of Defense (DoD). On November 24, 2003, NIMA changed their name to the National Geospatial-Intelligence Agency (NGA) as dictated by the 2003 Defense Authorization Bill.

National assets were available that potentially could have revealed the damage to *Columbia* while on orbit, but these assets were not used during the flight. NASA has previously used National assets to support the Space Shuttle Program, but the process and procedures to do so were overly complex and obscure.

The CAIB found that the relationships between NASA and other Government agencies that could provide the assessment capabilities needed to be formalized and strengthened. Additionally, they recommended that such assessments should become a part of the standard mission requirements for each Space Shuttle flight, that all decision-makers within the Space Shuttle Program be made aware of the available capabilities, and that a small set of personnel maintain the appropriate security clearances and briefings.

3.12.3 NASA Implementation

The Memorandum of Agreement (MoA) with the National Imagery and Mapping Agency was modified in July 2003 as recommended by the CAIB. NASA has since worked with the full range of supporting agencies to develop an Interface Operations Agreement that maximized the use of available National assets to assist in on-orbit assessments. The NASA Standard Operating Procedures for requesting support from appropriate federal agencies were completed in December 2003 and have been exercised successfully. The capabilities have been, and will continue to be, demonstrated during MMT simulations.

In order to fully comply with the CAIB recommendation, NASA has identified the positions that require access to classified data and will ensure that all NASA personnel involved in human space flight are familiar with the general capabilities available for on-orbit vehicle assessments and the procedures to request and process such assessments. NASA has also put in place secure data transmission systems and procedures for the dissemination of classified information to the NASA Space Operations Mission Directorate field centers.

Final implementation details have been worked out in a lower level memorandum of understanding. Since this action may involve receipt and handling of classified information, the appropriate security safeguards will be observed during its implementation.

Although these actions address the recommendation found in CAIB R6.3-2, NASA has taken additional appropriate actions with other federal agencies to maximize use of National assets for all flight segments. NASA has teamed with the Department of Defense and the intelligence community to develop new agreements and operating procedures to obtain support from the partnering agencies.

3.12.4 RTF TG Assessment

Fact-finding meetings were attended by the Task Group on December 8, 2003, and February 18-19, 2004, where the Memorandum of Agreement with the NGA was discussed. The next lower-level Interface Operating Agreement that details the methods for NASA to obtain information, and how that classified information would be handled within NASA were also discussed. The detailed plans and agreements themselves are classified due to the nature of National assets they discuss.

The Task Group's initial evaluation of NASA's actions was completed at the April 16, 2004, teleconference plenary where the assessment was conditionally closed. The conditions required that NASA present the results of an integrated simulation that exercised the NGA MoA for assessment by the RTF TG. After receiving additional information from NASA, the assessment was closed at the December 16, 2004, plenary meeting. The intent of CAIB Recommendation 6.3-2 has been met.

3.12.5 RTF TG Observations

The Task Group believes that NASA should periodically review the Memorandum of Agreement with the National Geospatial-Intelligence Agency, assess the capabilities of the NGA and other agencies, and ensure that the appropriate security clearances are maintained within NASA to exploit these capabilities as necessary. In addition, this capability should also be periodically exercised during MMT simulations.

Discovery in the Vehicle Assembly Building transfer aisle, ready to be lifted to the vertical position in preparation for mating with the External Tank and Solid Rocket Boosters.

3.13 CAIB Recommendation 6.4-1 – Thermal Protection System Inspection and Repair

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

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

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

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

3.13.1 RTF TG Interpretation

Based on a majority opinion of the members, the Task Group revised its interpretation of this CAIB recommendation at the June 27, 2005 meeting. The interpretation that the final assessment was based on follows:

> CAIB Recommendation 6.4-1 consists of four separate provisions. Although the entire recommendation is labeled Return to Flight, the second and fourth provisions do not apply to STS-114. These provisions are not being considered by NASA or the Task Group. If a non-ISS mission, such as Hubble Space Telescope (HST) Service Mission 4, is added to the flight manifest, the ASAP should review this recommendation.
>
> NASA must define any damage to tile and RCC that poses an unacceptable hazard to the Orbiter and crew during entry, and be able to detect the location and extent of such damage. Assessment of NASA's on-orbit TPS inspection capability is covered in Recommendation 3.4-3
>
> Each of the repair options in the suite of options that constitutes the repair capability must be have completed formal design reviews, ground verification testing, procedure development and an integrated Design Certification Review such that NASA could implement it in an emergency situation with confidence that it would behave as expected

3.13.2 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 concept of a "tile repair kit" is hardly new. Such a kit was originally intended to be flown aboard STS-1 and work was undertaken by NASA and its contractors, particularly Martin Marietta. However, as the launch of STS-1 approached, the development effort was cancelled due to a variety of technical problems and a renewed confidence in the tiles themselves. At the time, the RCC was considered particularly resilient and there was little thought given to a repair capability; as later events demonstrated, this assumption was incorrect.

3.13.3 NASA Implementation

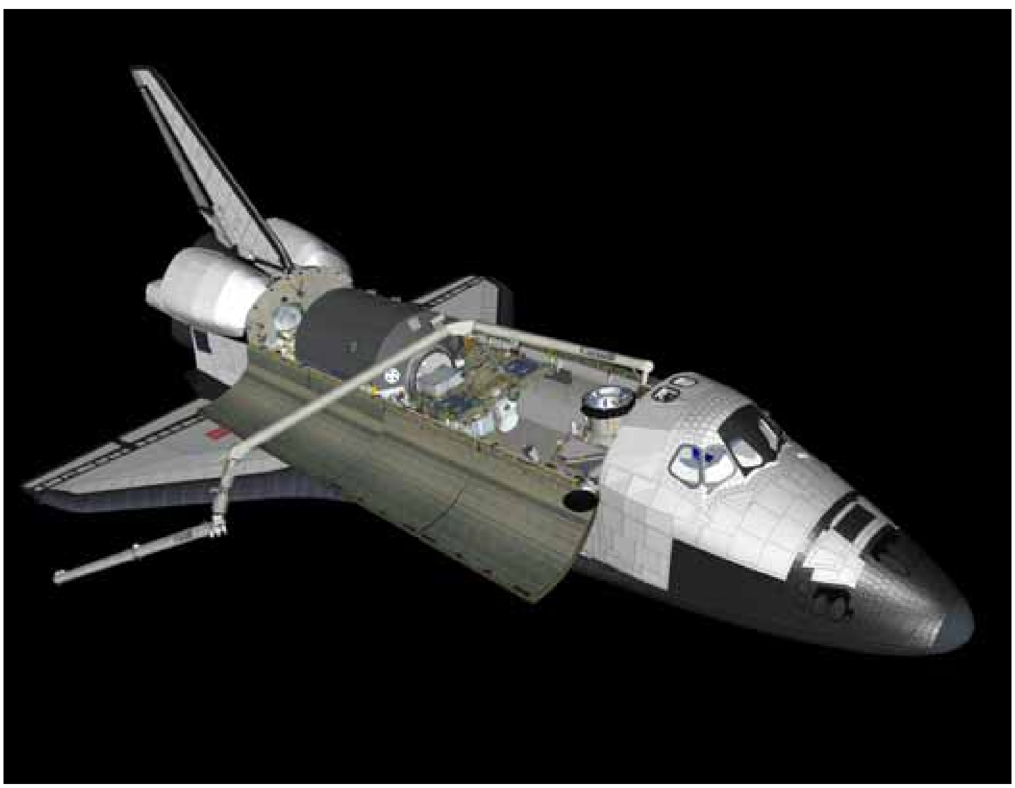
Note: *This section refers to inspection and repair during missions to the ISS.*

NASA has expanded the capabilities to detect debris liberated during ascent, to locate where debris may have originated, and to identify impact sites on the Orbiter Thermal Protection System for detailed evaluation. Methods to access the Orbiter for possible repair have been evaluated and procedures developed and trained. In addition, five repair techniques have been selected to be carried on STS-114.

These capabilities, paired with NASA's improved insight into the impact and damage tolerance of the Orbiter, will allow the Mission Management Team (MMT) to make informed decisions about whether any impacts sustained represent a threat to mission success or the safety of the crew and the vehicle. They will also help to determine whether any repairs that are attempted are successful.

3.13.3.1 <u>Inspection</u>

NASA will use a combination of Space Shuttle and International Space Station assets to evaluate the Orbiter Thermal Protection System and identify and characterize whether damage was sustained during ascent. These inspection assets and methods include the Orbiter Boom Sensor System (OBSS), the R-Bar Pitch Maneuver, the Shuttle Remote Manipulator System (SRMS), the Space Station Remote Manipulator System (SSRMS), and an experimental wing leading edge impact detection system. Each inspection method provides a piece of information to improve insight into the conditions of the Orbiter Thermal Protection System.



A computer-generated image of the OBSS in operation while attached to the Shuttle Remote Manipulator System. The OBSS is capable of inspecting all of the RCC on the Orbiter, as well as the majority of the tiles on the underside of the vehicle.

3.13.3.1.1 Orbiter Boom Sensor System

The OBSS is an imaging system that consists of two sensor packages on the end of a 50-foot-long boom structure. The boom is carried on the starboard sill of the Orbiter payload bay (which had originally been configured to carry a second remote manipulator system arm if needed) and is used in conjunction with the Shuttle Remote Manipulator System (SRMS) carried on the port sill. The OBSS carries a laser camera system (LCS) and a laser dynamic range imager (LDRI) that downlink data via the Orbiter communications system. The data will be processed and analyzed on the ground as part of the Thermal Protection System assessment process. The OBSS is the primary system used to inspect the wing leading edge and nosecap RCC, and also to obtain detailed depth measurements of damaged areas. In addition, the OBSS has the capability to support a crewmember in foot restraints if needed to perform inspection or repair during extra-vehicular activities (EVA).

On flight day 2, prior to docking with the ISS, the crew will use the OBSS to inspect the nosecap and the underside and apex of the 22 leading edge RCC panels on each wing. If any evidence of a debris strike exists, the OBSS instruments will be used during flight day 4 for more detailed inspections of specific areas.

3.13.3.1.2 ISS Imagery during the R-bar Pitch Maneuver

The primary method of inspecting the acreage tile on the bottom of the Orbiter consists of imagery taken by the ISS crew as the Orbiter approaches for docking. This approach, called the R-Bar Pitch Maneuver, has been practiced by Space Shuttle flight crews in the simulator. When the Orbiter is 600 feet away from the ISS, it will pause its approach and pitch-over to present its underside to the station. The ISS crew will take overlapping high-resolution digital still images of the acreage tiles and downlink them to the ground. Areas of concern will be re-inspected for more detail (such as damage depth) while the Orbiter is docked to the ISS.

The cameras used during the R-Bar Pitch Maneuver have the capability to detect critical damage in all areas of the Orbiter Thermal Protection System tile. Analysis indicates that the photos taken with a 400mm lens have an analytical resolution of 3 inches on normal surfaces; the 800mm lens provides a 1-inch analytical resolution.

3.13.3.1.3 Other Imagery Assets

Other imagery assets include the cameras on SRMS, the SSRMS, and digital camera assets on board the Orbiter or the ISS. The SRMS and SSRMS can inspect areas of the Orbiter Thermal Protection System within their reach, such as the crew cabin area, forward lower surface, and vertical tail, using their closed circuit television camera systems. Other assets include the still cameras available to EVA crewmembers in the event an EVA inspection is required to do focused inspection of areas that may have suspected damage. These alternate inspection methods are not pre-planned, and will be used as a backup for the other inspection methods.

3.13.3.1.4 Wing Leading Edge Impact Detection System

The wing leading edge impact detection system was developed from an existing technology that had been previously flown as an experiment in the Orbiter aft fuselage. Initially, NASA hoped to include the wing leading edge sensors as a key element to detect damage. However, this system has not been flight-tested in this environment, so its actual capability is yet to be determined. For STS-114, these sensors will be used primarily to “point” to areas of the wing leading edge needing further inspection by the OBSS.

The wing leading edge impact detection system is composed of accelerometer and temperature sensors attached to the wing spar behind the reinforced carbon-carbon panels.

These battery-powered sensors transmit data via RF to receivers in the Orbiter. The data are collected during ascent and downlinked to the ground via the Orbiter communications system once on-orbit to help identify possible debris impact areas on the wing leading edge RCC panels. In the event an impact is detected, engineers can determine the location of the sensor(s) that measured the impact and, through the TPS assessment process, recommend a more focused inspection of the suspect area later in the mission. Due to the limited battery life in the current implementation, there is a finite period of time for collection and transfer of impact data using this system. In the future, the power source will be changed from batteries to the Orbiter's main electrical systems, allowing the sensor system to provide impact detection throughout the mission.

3.13.3.2 Repair

Despite extensive efforts to develop TPS materials and techniques, the state-of-the-art in this area has yielded little technology to support the concept. As a result, continued effort does not hold promise of significant capabilities beyond those in hand. While a vehicle-wide TPS repair capability is not a constraint to the return to flight, STS-114 will carry a limited number of experimental materials and tools to repair minor tile damage and small- to medium-sized RCC damage in an emergency.

A variety of special tools are being carried aboard STS-114 and future flights in case repairs to the reinforced carbon-carbon panels becomes necessary.

To effect repairs, the EVA crew will use either the SRMS or the SSRMS to gain access to locations on the Orbiter; when necessary, they may also use the OBSS. NASA has also developed a combined SRMS and SSRMS "flip around" operation, called the Orbiter Repair Maneuver (ORM), to allow TPS repairs while the Orbiter is docked to the ISS. The ORM involves turning the Orbiter into a belly-up position that allows the SSRMS to position an EVA crewmember to reach any TPS surface needing repair. The procedure is feasible until later flights when the ISS grapple fixture required to support this maneuver will be blocked, and new TPS repair access techniques will need to be developed.

3.13.3.2.1 *RCC Repair*

NASA has evaluated RCC repair concepts with participation from six NASA Centers, 11 contractors, and the United States Air Force Research Laboratory. The main challenges to repairing RCC are maintaining a bond to the RCC coating during entry heating and meeting stringent aerodynamic requirements for repair patches and fills. NASA is investigating two complementary repair concepts – plug and crack – that together could, in the future, allow the emergency repair of limited RCC damage. Both concepts have limitations in terms of damage characteristics, damage location, and amount of testing and analysis completed to-date.

NOAX

Non-Oxide Adhesive eXperimental sealant (NOAX) is a pre-ceramic polymer sealant intended to repair cracks up to 0.065-inch-wide by 9-inches-long, and small areas (1-inch at the outer mold line and 2-inches at the inner mold line) of coating loss on any Orbiter RCC panel. Curing NOAX requires a heater, adding significant complication to its use on-orbit; however, uncured NOAX has recently passed arc-jet tests, leading to a decision not to use the heater to cure the material. NOAX has been shown to be successful in repairing cracks in ground tests but process controls will be more challenging in the EVA environment. At this time, there is uncertainty concerning the microgravity behavior of the material, and there is limited ground testing on real RCC substrate with realistic damage. This technology will be tested during an EVA development test objective (DTO) on STS-114.

Plug Repair

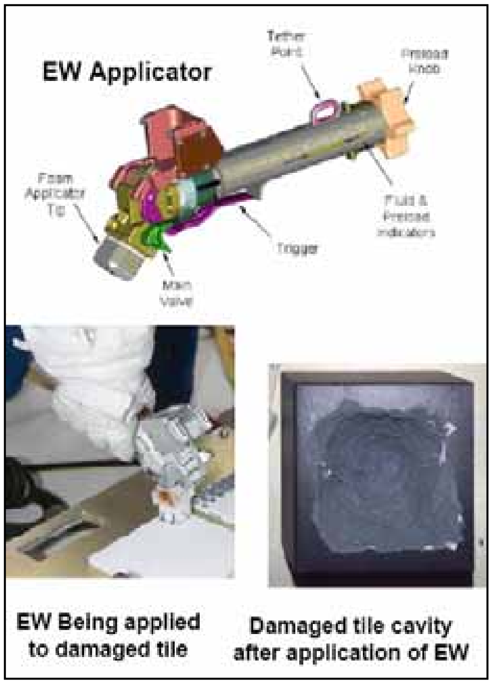
The plug repair is intended for small to medium-size holes in some areas of the wing leading edge RCC. A flexible carbon-silicon carbide (C-SiC) cover plate is held in place with a SiC-coated TZM toggle bolt and sealed around the edges with NOAX. Each plug cover plate might repair up to a 4-inch-diameter hole (major dimension) with a 1-inch surrounding spalled area. If the existing hole is less than 1-inch diameter, a drill will be used to enlarge the hole in order to insert the toggle bolt. A dozen different cover plates with various curvatures are available and provide coverage for 62-percent of the wing leading edge RCC areas. Although arc-jet testing indicates that the material can withstand entry, there are concerns about the bolt fracturing if the SiC coating is scratched. There are also concerns about drilling through RCC to insert the plug, especially if there is not a preexisting hole. A middeck DTO on the mechanical function of this repair capability, excluding drilling, will be performed on STS-114.

The plug repair starts with either a pre-existing hole in an RCC panel, or with the astronaut drilling a hole. A toggle bolt is inserted through the hole to hold the carbon-silicone carbide cover in place. NOAX is used around the edge as a sealant.

3.13.3.2.2 Tile Repair

A limited tile repair capability will be ready for on-orbit testing on STS-114. On this flight, NASA plans to demonstrate the emittance wash technique during an EVA, fly two Cure-In-Place Ablator (CIPA) applicators (that will not be demonstrated) that could repair tile damage, and fly a mechanical overlay (also not demonstrated) that could potentially repair larger areas of damage in the acreage tiles.

A hand-held extrusion gun is used to apply the emmitance wash.

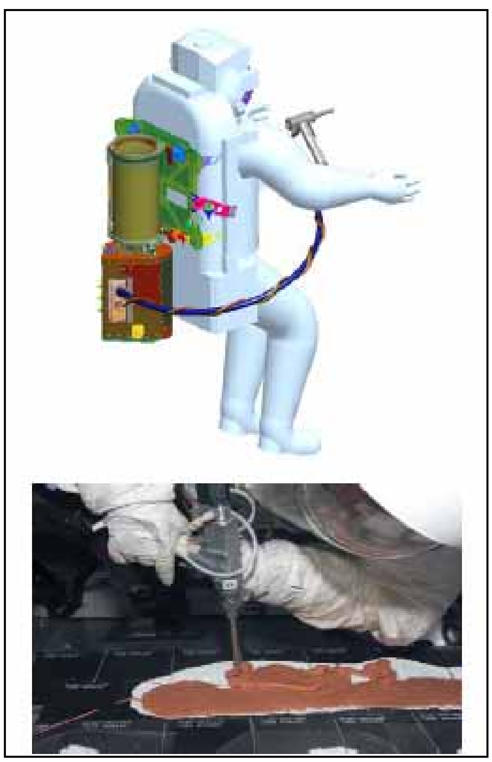


Emittance Wash

Emittance wash, a silicon carbide (SiC) material mixed with a carrier, is expected to be effective for shallow tile damage on any black tile surface. While initially developed as a surface preparation for the CIPA technique, NASA determined the material has a stand-alone repair potential. Emittance wash partially restores the emissivity of damaged tile surface to increase heat rejection through radiation, and is used to prevent small gouges in the tile from becoming deeper holes. The material is applied using an extrusion gun. Arc-jet tests are continuing to gather data on the thermal performance of a repair using this technique; however, thermal performance testing will be limited before STS-114.

Cure-in-Place Ablator (CIPA)

Two CIPA applicators will be carried aboard STS-114, potentially allowing repair of tile damage sites anywhere on the Orbiter except a small number of LI-2200 tiles. The CIPA material, called STA-54, is a two-part room temperature material that is applied with a pneumatic dispenser gun that mixes the two parts within the dispenser. Ancillary tools include emittance wash to prime the surface, gel and foam brushes to clean the surface, stamps to shape the material, a contour gage to measure the material surface relative to the outer mold line, and a durometer to test hardness. The CIPA "goo" is intended for use in deeper tile damage in areas up to 10 by 20 inches. If a CIPA repair is attempted, a second EVA will be required to inspect the repair and test the hardness. This information along with photographs of a dissected "test bead" created at the same time as the repair are required to assess the integrity of the repair for entry. The quality of the repair appears to be highly operator dependent.



The CIPA hardware is much more involved, with most components contained on a backpack that fits over the EVA suit.

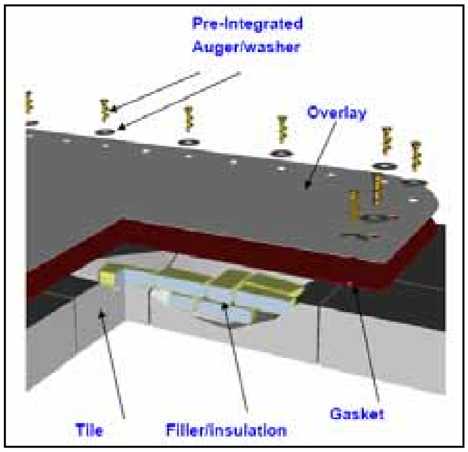
There have been multiple technical difficulties in the development of the CIPA materials and application tools. Most significant of these is recurrent bubbling in the STA-54. NASA has been unable to determine the root cause of the bubbling, or to adequately and consistently characterize its severity. Additionally, there remain several areas of uncertainty about the material properties of STS-54, including its ability to cure during the thermal cycling of Earth orbit and its adhesion to tile during entry, since tile and STA-54 have different thermal expansion coefficients.

Though somewhat unpredictable, bubbling of the material has been shown in arc-jet testing to be less important in the ability to protect the Orbiter than originally thought, but testing in the actual on-orbit environment is necessary to confirm this finding. Analytical models for CIPA repair assessment are uncorrelated with test data, and if the material is used as an emergency repair on STS-114, formal validation testing to material performance requirements will be limited to real time arc-jets test.

Another issue concerns the level of toxicity of one of the STA-54 components prior to mixing and dispensing. At this time the program is pursuing a triple level of containment – a common toxicity mitigation technique – for STA-54 stowage and is assessing the crew risk during EVA use for the STS-121 development test objective or if needed for tile repair.

Tile Overlay

The mechanical overlay repair is performed by filling the damaged tile cavity with a Saffil batting insulation, then placing a thin C-SiC cover plate and high-temperature gasket seal over the damaged tile area. SiC-coated ceramic augers (screws) with accompanying SiC-coated ceramic washers are screwed into undamaged tiles to attach the overlay. The 12-inch by 25-inch overlay is capable of covering a 10-inch by 20-inch damage area. While this technology is being carried as a contingency on STS-114, its testing is very immature at this time. However, development testing is on a fast track and NASA believes this option appears to be promising.



The tile overlay repair is a metallic sheet that is screwed in place over the damaged tiles after the cavity is filled with Saffil batting insulation.

3.13.3.3 <u>TPS Damage Assessment</u>

The Space Shuttle Program has developed a substantial knowledge-base of the vulnerabilities of both tile and RCC, and the level of damage that testing to date indicates could be sustained without unacceptable risk during entry. This knowledge is essential for decision-making in the event that on-orbit inspection reveals damage to the TPS. Critical damage size has been defined and is highly location dependent. NASA has incorporated the experimental data gleaned over the last year to create a “critical damage map” that reflects the best understanding to date. For RCC, critical damage in the most vulnerable areas is a 0.020-inch-wide crack or a 0.08-inch (major dimension) coating loss. A 1-inch (major dimension) gouge around the main landing gear door seals or ET umbilical door seals, or a 3-inch gouge in acreage tile represents critical tile damage. If damage exceeding these dimensions is detected, reducing Orbiter weight, altering the entry profile, reducing landing sink rate, and other options will be considered, along with or in lieu of repair, to achieve an acceptable condition for entry. The decision to land an Orbiter with an untested repair will require a difficult decision based on models, experimental runs in the arc-jet, and flight history of the thermal environment during the entry. The OIP companion document, NSTS 60540-ANX1 *Orbiter Damage Assessment Process Annex*, describes the teams, tools, and processes that will be used to transform data from the TPS assessment teams into information that can be used about the condition of the TPS at multiple milestones during flight by program leadership to make a timely entry readiness, repair, or Contingency Shuttle Crew Support determination.

3.13.4 RTF TG Assessment

The Orbiter Thermal Protection System was never intended to be repaired on-orbit. Various repair capabilities were explored early during Space Shuttle development and again more recently, but it is highly unlikely that a comprehensive repair capability for all possible damage will become available for the remaining flights of the Space Shuttle Program. Tile and RCC repair have proven to be far more challenging than either the CAIB or NASA understood two years ago. Enormous effort has been expended in search of effective and operationally feasible repair capabilities, and far more is known today than before about the capabilities and vulnerabilities of the Orbiter Thermal Protection System. Nevertheless, the program is far from having a certifiable capability. Several innovative repair solutions for a limited range of potential damage are aggressively being pursued. Five such limited repair options will be carried on STS-114; however, much more testing and evaluation remain to be done. The options proposed by NASA have not yet achieved a level of maturity that the Task Group considers necessary to be defined as a capability and thus the intent of this recommendation has not been met.

3.13.4.1 Inspection

The two primary methods to be used on-orbit for critical inspection of Orbiter Thermal Protection System, the OBSS sensor suite and R-Bar Pitch Maneuver have been assessed as part the Task Group's evaluation of CAIB Recommendation 3.4-3, High-Resolution Imagery of Orbiter. That recommendation was closed on June 8, 2005 (see Section 3.6 of this report). Data from the wing leading edge impact detection system will be used as corroborating evidence with imagery data to provide focus for on-orbit inspection. The limited data that will be available due to short battery life, together with the experimental nature of this system, mandate that no critical decisions be based on the data from this system.

The Task Group supports use of numerous other sources of ground and airborne imagery during launch and ascent to provide views of the External Tanks and Orbiter which serve as pointers for focused inspection of the Orbiter by the OBSS. All these capabilities together should assure a comprehensive and successful inspection.

3.13.4.2 Repair Technologies

Although NASA has determined, and accepted the risk, that the repair capability called for in CAIB Recommendation 6.4-1 is not a constraint to launch of STS-114, the Space Shuttle Program intends to provide the STS-114 crew with the best available options. An enormous amount of work on both tile and RCC repair has resulted in five experimental repair techniques. None of these techniques will be certified for STS-114; some may never be certified because they are too operator dependent. As NASA stated in the May 2005 version of the *Integrated Risk Acceptance Approach for Return to Flight* – "Until a verifiable, reliable Thermal Protection System repair technique for tile and reinforced carbon-carbon components is in hand, we will have limited, best effort capabilities to apply when needed."

While it is prudent to manifest repair materials and hardware on STS-114 to be used only if the Orbiter cannot otherwise make a safe entry, extreme caution must be exercised when use of these materials and hardware might further exacerbate the risk to Orbiter and crew beyond the risk due to the initial Thermal Protection System damage. In particular, the RCC plug and tile overlay repairs require additional holes to be bored into the Thermal Protection System, and CIPA and NOAX can each create an additional hazard if the material expands beyond the Orbiter outer mold line. Each option carries its own risks. For STS-114, should a damage situation require use of any repair technique, the Mission Management Team and NASA leadership will confront extremely complex and difficult risk-versus-risk trades given the unknowns and uncertainties within and between inspection, repair, and rescue options.

3.13.4.3 TPS Damage Assessment

The Task Group believes that it is just as important to be able to decide when not to repair as it is when to attempt a repair, especially when the repair capabilities are unproven. The "critical damage maps," although certified for preflight, continue to evolve to reduce the likelihood of making unnecessary repairs. The NASA Engineering Safety Center (NESC) peer review of critical tile damage models is an important milestone to be achieved prior to STS-114; a preliminary draft was available to the Task Group during this assessment. The addition of the peer review provides added confidence in the accuracy of these models.

The Mission Operations Directorate has defined several alternate scenarios to minimize entry heating that will be available should they be required. A number of procedures in various stages of maturity can be uplinked so that the crew can make these adjustments.

Because they will be collecting significant volumes of data on the condition of the TPS, much of which will be new to the ground operations team, the Task Group fully supports the development of NSTS 6054, *STS-114 Operations Integration Plan for Thermal Protection System Assessment* (the OIP) and it associated *Damage Assessment Annex* to govern the use of all these data in the decision-making process on the health of the Orbiter Thermal Protection System and the potential need to repair damage, execute other operational risk reduction strategies, or fly home with the expectation that the damage is not large enough to be considered critical. See Section 2.2 of this report for a further discussion of the OIP.

3.13.4.4 Conclusion

In the May 2005 *Integrated Risk Assessment Approach for Return to Flight,* NASA acknowledges that External Tank debris allowables currently do not protect against catastrophic damage to the Orbiter Thermal Protection System. Therefore the goal of demonstrating that the Orbiter Thermal Protection System can withstand impact from any debris which may be released from the External Tank or other flight elements has not been met. Nor can the repair options manifested on STS-114, even if they were certified, repair the range of damage that could occur. There is a gap between possible debris liberation and the ability of Orbiter Thermal protection System to withstand impact and to repair damage.

The Task Group has reached the conclusion that the five experimental repair options manifested on STS-114 show promise for future flights, but are contingency measures rather than practicable repair capabilities at this time. Even though all Orbiter Thermal Protection System repair techniques being considered are only for emergency use and cover a limited range of potential damage, they can and should go through a rigorous design and certification process; to date, none of the tile or RCC repair techniques have gone through this process. Therefore, the Task Group does not consider tile and RCC repair techniques sufficiently mature to be a practicable repair capability for STS-114.

As assessed in Section 3.6 (R3.4-3), the inspection techniques planned for STS-114 provide high resolution capability and significantly enhance the ability to view possible damage. Resources available via National assets (R6.3-2) add to this capability. Therefore, NASA has satisfied the inspection portion of this recommendation.

The RTF TG assessment of NASA's actions was completed at the June 27, 2005, meeting. Despite extensive efforts on the part of the Tile Repair Project and RCC Repair Project to develop a practicable Thermal Protection System repair capability, the majority of the Task Group believes that the intent of CAIB Recommendation 6.4-1 has not been met.

3.13.5 RTF TG Observation

The RTF TG believes that the repair portion of R6.4-1 presented an extreme technical challenge to NASA given the physical characteristics of the Orbiter Thermal Protection System. Repairs to TPS damage of the magnitude suffered by *Columbia* are not considered feasible with current technology; however, modifications to the External Tank should preclude that type of damage from occurring in the future.

3.13.6 RTF TG Minority Opinion on CAIB Recommendation 6.4-1

Much of the discussion among Task Group members has centered on the definition of the words "practicable capability." While Task Group members agree that a practicable capability must be "feasible, able to be accomplished," we cannot agree on the level to which a task must be developed before it becomes a "capability." The minority opinion of the Task Group is that a repair technique is a capability if it can actually be performed on orbit and has been shown to be able to withstand the heat of entry, which is its intended purpose.

There has been further discussion around the accident board's intent when they used the words "widest possible range of damage." Multiple conversations with several members of the CAIB, including those most closely associated with the writing of this recommendation indicate a clear intent of those words to be "to the widest possible damage that NASA can accomplish." Thus, the fact that NASA does not yet have coverage for 100 percent of the Orbiter Thermal Protection System does not preclude compliance with the intent of the recommendation.

While much more testing is necessary to increase the confidence in the repairs and to certify them, the repair capabilities are a far cry from the notion outlined for the CAIB that amounted to stuffing tools and water-filled baggies into the wing leading edge while dangling from a ladder hanging from the payload bay doors (CAIB, Vol. I, p. 173). The use of the crew in the development of the operations associated with the repair techniques, coupled with multiple training sessions using the standard environments to prepare for EVA operations, have resulted in repair techniques that can be put into practice should the need arise. MMT and component simulations have shown a willingness of the community to attempt a repair should one be deemed necessary, and upon successful completion of that repair, evaluated using set criteria, a willingness to bring the Orbiter and crew home rather than commit to a CSCS and attempt to launch a second vehicle.

The minority opinion of the RTF TG is that this is what the CAIB intended when writing Recommendation 6.4-1. Therefore, it is the minority opinion of the Task Group that the intent of CAIB Recommendation 6.4-1 has been met.

Discovery, with Earth as a backdrop, performs the R-bar Pitch Maneuver as she approaches the International Space Station. The crew of the ISS takes high-resolution photographs of the Orbiter during this maneuver to allow ground-based analysts to determine if there is any damage to the Orbiter Thermal Protection System.

3.14 CAIB Recommendation 9.1-1 – Detailed Plan for Organizational Change

Prepare a detailed plan for defining, establishing, transitioning, and implementing an independent Technical Engineering Authority, independent safety program, and a reorganized Space Shuttle Integration Office as described in R7.5-1, R7.5-2, and R7.5-3. In addition, NASA should submit annual reports to Congress, as part of the budget review process, on its implementation activities.

R7.5-1 *Establish an independent Technical Engineering Authority that is responsible for technical requirements and all waivers to them, and will build a disciplined, systematic approach to identifying, analyzing, and controlling hazards throughout the life cycle of the Shuttle System. The independent technical authority does the following as a minimum:*

- *Develop and maintain technical standards for all Space Shuttle Program projects and elements*
- *Be the sole waiver-granting authority for all technical standards*
- *Conduct trend and risk analysis at the sub-system, system, and enterprise levels*
- *Own the failure mode, effects analysis and hazard reporting systems*
- *Conduct integrated hazard analysis*
- *Decide what is and is not an anomalous event*
- *Independently verify launch readiness*
- *Approves the provisions of the recertification program called for in Recommendation R9.2-1*

The Technical Engineering Authority should be funded directly from NASA Headquarters and should have no connection to or responsibility for schedule or program cost.

R7.5-2 *NASA Headquarters Office of Safety and Mission Assurance should have direct line authority over the entire Space Shuttle Program safety organization and should be independently resourced.*

R7.5-3 *Reorganize the Space Shuttle Integration Office to make it capable of integrating all elements of the Space Shuttle Program, including the Orbiter.*

3.14.1 RTF TG Interpretation

The Columbia Accident Investigation Board (CAIB) expected NASA to return to flight relatively quickly, and did not want to restrict this activity by requiring major organizational changes. Instead, the CAIB wrote a separate recommendation that NASA produce a detailed plan on how the Agency would implement organizational changes embodied in three other recommendations (R7.5-1, Independent Technical Authority; R7.5-2, Safety and Mission Assurance; and R7.5-3, Systems Engineering and Integration).

However, preparations for the first return-to-flight mission took longer than initially expected, and NASA proceeded to implement the three specific organizational recommendations of the CAIB; the Task Group elected to evaluate the actual changes, although the final assessment was based only on the required plan.

The CAIB used the term “culture” throughout its report, although there was not a specific recommendation (RTF or otherwise) to change NASA culture. Nonetheless, numerous CAIB findings and observations strongly emphasize leadership, managerial, training, and organizational issues that require immediate and serious attention. Within the parameters of the RTF TG charter, the Task Group did not specifically address these CAIB “culture” concerns, and the Task Group did not assess the studies ongoing within NASA pertaining to culture issues. Nonetheless, NASA has elected to implement an Agency-wide response to R9.1-1 through a document entitled “NASA Plan for Implementing Safe and Reliable Operations” (referred to as the “9.1-1 Plan”).

Many of the CAIB organization observations are reflected in R7.5-1. The CAIB observed critical technical requirements were routinely waived and concluded the inherent conflicts of schedule, cost, and safety – the balance for which resided essentially with the Space Shuttle Program Manager – needed to be separated to provide an independent safety consideration.

In regards to R7.5-2, the CAIB observed various parts of NASA were nominally responsible for “safety;” each NASA Center has safety organizations; each NASA program, including the Space Shuttle Program, has designated individuals responsible for safety; and NASA has an Office of Safety and Mission Assurance at Headquarters. This recommendation was intended to create clear lines of authority, responsibility, and communication, and help ensure independence by moving funding from NASA Centers and programs to NASA Headquarters.

The CAIB found several aspects of Space Shuttle operations it believed to be suffering from incomplete integration, prompting them to write R7.5-3. Perhaps the most glaring was the apparent division of responsibility for addressing the separation of foam from the External Tank. Simplistically stated, the Orbiter Project thought it was up to those responsible for the tank to stop the shedding; the External Tank Project assumed the shedding occurring was not injurious to the Orbiter because no one told them otherwise.

3.14.2 Background

The accident board’s independent investigation revealed numerous areas in NASA’s organization and its operations requiring substantial improvement before returning the Space Shuttle to safe and reliable flight operations. The CAIB report specifically called for a detailed plan prior to the return to flight on three fundamental changes that NASA needed to make to improve the safety and reliability of its operations:

- Restore specific engineering technical authority, independent of programmatic decision-making.
- Increase authority, independence, and capability of the Safety and Mission Assurance (SMA) organizations.
- Expand the role of the Space Shuttle Integration Office to address the entire Space Shuttle system, not just propulsive elements.

3.14.3 NASA Implementation

Once a plan for CAIB Recommendation 9.1-1 had been developed, NASA proceeded toward implementation.

3.14.3.1 Independent Technical Authority (R7.5-1)

The NASA Chief Engineer, as the Independent Technical Authority, governs and is accountable for technical decisions affecting safe and reliable operations. The Independent Technical Authority provides technical decisions for safe and reliable operations in support of mission development activities and programs and projects that pose minimum reasonable risk to astronauts, the NASA workforce, and the public. Sound technical requirements necessary for safe and reliable operations will not be compromised by programmatic constraints, including cost and schedule.

The Independent Technical Authority is also working to strengthen the technical conscience throughout the engineering community, that is, personal responsibility to provide safe technical products coupled with an awareness of avenues available to raise and resolve technical concerns. Technical authority and technical conscience represent a renewed culture in NASA governing and upholding sound technical decision-making by personnel who are independent of programmatic processes. This change affects how technical requirements are established and maintained as well as how technical decisions are made, safety considerations being first and foremost in technical decision-making. Five key principles govern the Independent Technical Authority. This authority:

1. Resides in an individual, not an organization;
2. Is clear and unambiguous regarding authority, responsibility, and accountability;
3. Is independent of Program Management;
4. Is executed using credible personnel, technical requirements, and decision-making tools; and
5. Makes and influences technical decisions through prestige, visibility, and the strength of technical requirements and evaluations.

3.14.3.1.1 Warrant System

The Chief Engineer has put technical authority into practice through a system of governing warrants issued to individuals. These Technical Warrant Holders (TWH) are proven subject matter experts with mature judgment who are operating with an Independent Technical Authority budget that is separate from program budgets and program authority. This Independent Technical Authority budget covers the cost of the Technical Warrant Holders and their agents as they execute their responsibility for establishing and maintaining technical requirements, reviewing technical products, and preparing and administering technical processes and policies for disciplines and systems under their purview.

The warrant system provides a disciplined formal procedure that is standardized across the Agency, and a process that is recognized inside and outside NASA in the execution of Independent Technical Authority.

On November 23, 2004, the NASA Administrator issued the policy and requirements to implement Independent Technical Authority through a technical warrant process. This policy was issued under NPD 1240.4 NASA Technical Authority (draft) and NPR 1240.1 Technical Warrant System (draft), and is in accordance with the 9.1-1 Plan. The Chief Engineer has selected Technical Warrant Holders for many critical areas, including all major systems for the Space Shuttle. These Technical Warrant Holders are making technical decisions necessary for safe and reliable operations and are involved in return to flight activities for the Space Shuttle. NASA is selecting additional Technical Warrant Holders to span the full range of technical disciplines and systems needed across the Agency. The Chief Engineer issued several new warrants in March 2005, including one for Systems Safety Engineering which will help revitalize the conduct of safety analyses (failure mode and effects analysis – FMEA, hazards analysis, reliability engineering, etc.) as part of design and engineering. The Chief Engineer will continue to issue warrants as required.

3.14.3.1.2 Technical Conscience

Technical conscience is personal ownership of the technical product by the individual who is responsible for that product. Committee reviews, supervisory initials, etc., do not relieve these individuals of their obligation for a safe and reliable mission operation if their technical requirements are followed. Technical conscience is also the personal principle for individuals to raise concerns regarding situations that do not “sit right” with the Agency’s mandate for safe and reliable systems and operations. With adoption of the Independent Technical Authority and the warrant system, technical personnel have the means to address and adjudicate technical concerns according to the requirements of the situation. The Independent Technical Authority and Technical Warrant Holders provide the means for independent evaluation and adjudication of any concern raised in exercising technical conscience.

3.14.3.2 Safety and Mission Assurance (R7.5-2)

To address the authority issue raised by the accident board, NASA has strengthened the traditional policy oversight over NASA programs provided by the Office of Safety and Mission Assurance (OSMA) with explicit authority of the Administrator through the Deputy Administrator to enforce those policies. The Chief Safety and Mission Assurance Officer provides leadership, policy direction, functional oversight, assessment, and coordination for the safety, quality, and mission assurance disciplines across the Agency. Operational responsibility for meeting the requirements of these disciplines rests with the Agency’s program and line organizations as an integral part of the NASA mission. To increase OSMA’s “line authority” over field SMA activities, NASA has taken four important steps:

1. The Chief Safety and Mission Assurance Officer now has explicit authority over the selection, relief, and performance evaluation of all Center SMA Directors as well as the lead SMA managers for major programs – including Space Shuttle and International Space Station – and the Director of the Independent Verification and Validation (IV&V) Center.

2. The Chief Safety and Mission Assurance Officer will provide a formal “functional performance evaluation” for each Center Director to their Headquarters Center Executive each year.

3. “Suspension” authority is delegated to the Center Directors and their SMA Directors. This authority applies to any program, project, or operation conducted at the Center or under that Center’s SMA oversight regardless of whether the Center also has programmatic responsibility for that activity.

4. The Safety and Mission Assurance community, through their institutional chain of command up to the Deputy Administrator, now has authority to decide the level of SMA support for the project/program.

NASA safety and mission assurance support for the Space Shuttle Program consists of dedicated program office staff, technical support from the centers, and functional oversight from the Headquarters OSMA. The program’s SMA Manager reports directly to the Space Shuttle Program Manager and is responsible for execution of the safety and quality assurance requirements within the program. The program SMA Office integrates the safety and quality assurance activities performed by all Centers for various projects and program elements located at those Centers.

The Center SMA Directorates provide technical support to the program's SMA Manager. They also provide independent safety and quality assurance functions in the form of independent assessments, safety, and reliability panel reviews. Finally, they provide a cadre of personnel dedicated to the Headquarters OSMA Independent Assessment function.

3.14.3.2.1 SMA Independence

The CAIB recommendation requires that OSMA be independently funded. After the *Report of the Presidential Commission on the Space Shuttle Challenger Accident*, also known as the Rogers Commission Report, NASA created the Office of Safety, Reliability and Quality Assurance, later renamed OSMA, and specifically set up its reporting and funding to be separate from the Office of the Chief Engineer and any of the programs. At the time of the *Columbia* accident, all funding for OSMA was in the general and administrative (G&A) line, separate from all other program, institutional, and mission support and functional support office funding. All permanent OSMA personnel are dedicated to OSMA and, therefore, independent of program or other mission support and functional support offices. This plan retains independent reporting and funding approach consistent with the CAIB recommendation.

With respect to center-based civil servants and their support contractors performing safety, reliability, and quality assurance tasks, this plan calls for significant change. The 9.1-1 Plan establishes that the institution, not the program, decides SMA resource levels. Under the oversight of Headquarters Center Executives, centers will set up "directed service pools" to allow SMA labor to be applied to programs and projects in the areas and at levels deemed necessary by SMA Directors and their institutional chain of authority. The SMA Directors will pre-coordinate the use of their resources with the programs to foster understanding of how SMA labor will be used. This approach will guarantee both organizational and funding independence from the programs in a way that fully addresses the CAIB findings. Finally, the Headquarters OSMA will, for the first time, be a voting member of the Institutional Committee wherein institutional (including the directed service pool) budget decisions are made for the Agency.

The prior definition of independence focused on organizational independence, and the Space Shuttle program and project managers had approval authority for about 99 percent (based on FY03 estimates) of total SMA funding level for Space Shuttle (including all contractor and Center NASA and support contractor SMA resources). The remaining 1 percent consisted of Center SMA supervisor time (paid by center general and administrative funds) and approximately $2 million per year of Space Shuttle Independent Assessment activity paid for by Headquarters OSMA.

Under the new definition of independence, which now includes the directed service pool, the Space Shuttle Program has funding approval authority for only about 70 percent of the total SMA funding level. This funding pays for Space Shuttle prime and subcontractor SMA and for the small civil service SMA Management Office in the program. Remaining funding approval is accomplished through the directed service pool, and is therefore independent from the program.

3.14.3.2.2 SMA Capability

To address SMA capability, all centers have reviewed their safety and mission assurance skills and resources for adequacy and added positions as required. Headquarters OSMA has increased significantly its ability to provide functional oversight of all NASA safety and mission assurance programs. Staffing has been increased in the Headquarters office from 48 to 51 people, partly to accommodate increased liaison needs created by the addition of NASA Engineering and Safety Center (NESC), IV&V, and new assurance programs. At the time of the *Columbia* accident, OSMA had a budget of $6 million per year for Independent Assessments, its primary assurance tool. OSMA will continue to send Independent Assessment funding to the centers for use by SMA Directorates in performing center audits and supporting OSMA audits and assessment of resident programs.

The NASA Engineering and Safety Center (NESC), as a technical resource available to the SMA community, in coordination with the ITA, combined with IV&V and Independent Assessment capabilities, provides an unprecedented increase in the independent assessment, audit, and review capability. This will reinforce the SMA community's role in providing verification and assurance of compliance with technical requirements owned by the Independent Technical Authority, and in technical support for mishap investigations.

The Independent Technical Authority will own all technical requirements, including safety and reliability design and engineering standards and requirements. OSMA will continue to develop and improve generic safety, reliability, and quality process standards, including FMEA, risk, and hazards analysis processes; however, the Independent Technical Authority will specify and approve these analyses and their application in engineering technical products.

NASA is also improving its trend analysis, problem tracking, and lessons learned systems (CAIB Finding F7.4-9, -10, and -11), in a concerted effort to ensure the Independent Technical Authority invokes appropriate technical requirements. In order to improve OSMA insight and reduce the confusion cited in F7.4-13, NASA is formalizing its Prelaunch Assessment Review (PAR) process for the Space Shuttle and International Space Station, and the equivalent processes for expendable launch vehicles and experimental aerospace vehicle flight approvals, called Independent Mission Assurance Reviews (IMAR). Both processes have been standardized into a new NASA-wide review process called Safety and Mission Assurance Readiness Reviews (SMARR).

In addressing the CAIB concern about the lack of mainstreaming and visibility of the system safety discipline (F7.4-4), OSMA has taken two actions, one long term and the other completed. First, the audit plan includes the project and/or line engineering assessment of the OSMA system safety engineering per new NASA policy directives for program management and ITA. Secondly, for some years the senior system safety expert in the Agency was also the OSMA Requirements Division Chief (now Deputy Chief, OSMA). To respond to the CAIB concern, OSMA has brought on a full-time experienced system safety manager who is the Agency's dedicated senior system safety assurance policy expert. In addition, the Chief Engineer will select a Systems Safety Engineering Technical Warrant Holder who will be responsible for establishing systems safety engineering requirements.

The SMA Directorates supporting the Space Shuttle Program are staffed with a combination of civil service and support contractors providing system safety, reliability, and quality expertise and services. Their role is predominantly assurance in nature, providing the program with functional oversight of the compliance with requirements of the contractor engineering and operations. The civil service personnel assigned to work on Space Shuttle are functionally tied to their Center SMA organizations, and although some are collocated with their project or contractor element, their official supervisors are in the Center SMA organization.

The System Safety Review Panel (SSRP) process continues to evolve as the relationship between the ITA, SMA, and the Space Shuttle Program is defined and understood. This plan redefines the SSRP as the Engineering Risk Review Panels (ERRP). The ERRP is designed to improve engagement by the engineering community into the safety process, including the development and maintenance of documentation such as hazard reports.

The organizational structure of the ERRP will consist of Level II (Program) and Level III (Project/Element) functionality. The ERRP structure and process continues to evolve in a phased approach. Until return to flight, the Space Shuttle System Technical Warrant Holder will be represented at all ERRP levels through trusted agents who are assigned to support each ERRP. The trusted agents ensure that the engineering interests of the Independent Technical Authority are represented at all working levels of the ERRP and are reflected in the products resulting from these panels. After return to flight, the Shuttle System Technical Warrant Holder will reassess his/her role in all Space Shuttle Program panels and boards that deal with flight safety issues, including the ERRP.

The Level II Panel will ensure that the safety integration function remains at the Program level. It will have representation by all program elements as well as the Engineering Directorate, ITA, and SMA. The Lead ERRP Manager will also assure that Level III panels operate in accordance with safety program requirements. The Level II Panel exists to oversee and resolve integrated hazards, forwarding them to the System Integration Configuration Board (SICB), and finally to the ITA and the Space Shuttle Program Manager for approval.

The Level III ERRPs will consist of a Johnson Space Center (JSC) Panel dealing with the Orbiter, extravehicular activity, government-furnished equipment, and integration responsibility; a Marshall Space Flight Center (MSFC) Panel that handles the External Tank, Solid Rocket Booster, Reusable Solid Rocket Motor, and Space Shuttle Main Engine; and a Kennedy Space Center (KSC) Panel that deals with ground servicing equipment and ground operations. As presently defined, the Level III Panels will be chaired by the independent SMA Directorates at each center, again with representation by trusted agents at these panels.

The Space Operations Mission Directorate Space Shuttle Certificate of Flight Readiness (CoFR) process is being updated to clearly show the new SMA, Integration, and Independent Technical Authority roles and responsibilities. Part of that will be a requirement for concurrence by the Chief Safety and Mission Assurance Officer on the flight readiness statement as a constraint to mission approval.

3.14.3.3 Integration of the New ITA and SMA (R7.5-1/R7.5-2)

In a practical sense, the people that perform the responsibilities of SMA and the ITA need to be involved within a program or project beginning in the early stages and continuing for the life of the program or project. CAIB Recommendation 7.5-1 defined what activities at the program level must be clearly controlled by the Independent Technical Authority. At the same time, Chapter 7 of the CAIB report makes it clear that the SMA organization must be independent of the program and technically capable to provide proper check-and-balance with the program. Finally, the SMA organization must be able to perform its assurance functions in support of but independent of both program and engineering organizations.

The Independent Technical Authority has delegated fully to responsible individuals who hold warrants for systems and engineering disciplines. Fundamentally, this concept brings a "balance of power" to program management such that the Independent Technical Authority sets technical requirements, the programs execute to that set of technical requirements, and the SMA organization assures the requirements are satisfied. This means that the Independent Technical Authority owns the technical requirements and will be the waiver-granting authority for them.

The principal effect of the foregoing is the clear assignment of responsibility for execution of design and engineering, including the safety functions (FMEA, hazards analysis, reliability engineering, etc.) to engineering with the Independent Technical Authority setting requirements and approving the resulting engineering products. In this context, SMA organizations have the responsibility for independently assuring that delivered products comply with requirements.

3.14.3.4 Systems Engineering and Integration (R7.5-3)

The CAIB found several deficiencies in the organizational approach to program-wide system engineering integration for the Space Shuttle Program. Their Recommendation 7.5-3 calls for a reorganization of the Space Shuttle Integration Office to "make it capable of integrating all elements of the Space Shuttle Program, including the Orbiter." The CAIB concluded, "…deficiencies in communication …were a foundation for the *Columbia* accident. These deficiencies are byproducts of a cumbersome, bureaucratic, and highly complex Shuttle Program structure and the absence of authority in two key program areas that are responsible for integrating information across all programs and elements in the Shuttle program."

3.14.3.4.1 Integration Definition

NASA defines integration as a system engineering function that combines the technical efforts of multiple system elements, functions, and disciplines to perform a higher-level system function in a manner that does not compromise the integrity of either the system or the individual elements. The integration function assesses, defines, and verifies the required characteristics of the interactions that exist between multiple system elements, functions, and disciplines, as these interactions converge to perform a higher-level function.

3.14.3.4.2 Restructured Space Shuttle Systems Engineering and Integration Office

NASA has restructured its Shuttle Integration Office into a Space Shuttle Systems Engineering and Integration Office (SEIO) to include the systems engineering and integration of all elements of the Space Shuttle system. The SEIO Manager now reports directly to the Space Shuttle Program Manager, thereby placing the SEIO at a level in the Space Shuttle organization that establishes the authority and accountability for integration of all Space Shuttle elements. The new SEIO charter clearly establishes that it is responsible for the systems engineering and integration of all Space Shuttle elements. The number of civil service personnel performing analytical and element systems engineering and integration in the SEIO was doubled by acquiring new personnel from the JSC Engineering and Mission Operations Directorates and from outside of NASA. The role of the System Integration Plan (SIP) and the Master Verification Plans (MVP) for all design changes with multi-element impact has been revitalized. The SEIO is now responsible for all SIPs and MVPs, including those developed for all major changes that impact multiple Space Shuttle elements.

3.14.3.4.3 Orbiter Project Office

The Space Shuttle Vehicle Engineering Office is now the Orbiter Project Office, and its charter is amended to clarify that SEIO is now responsible for integrating all flight elements. NASA reorganized and revitalized the Integration Control Board, with the Orbiter Project Office now a mandatory member. The Space Shuttle Flight Software organization was moved from the Orbiter Project into the SEIO. This reflects the fact that the Shuttle Flight Software Office manages multiple flight element software sources besides the Orbiter.

3.14.3.4.4 Integration of Engineering at Centers

All Space Shuttle Program integration functions at JSC, KSC, and MSFC are now coordinated through, and receive technical direction from, the SEIO. The former MSFC Propulsion Systems Integration office is now called the Propulsion Systems Engineering and Integration (PSE&I) office. Agreements between the PSE&I Project Office and the appropriate MSFC engineering organizations are being expanded to enhance anomaly resolution within the Space Shuttle Program.

3.14.3.4.5 Integrated Debris Environments/Certification

The SEIO is also responsible for generation of all natural and induced design environments analyses. Debris is now treated as an integrated induced environment that will result in element design requirements for generation limits and impact tolerance. All flight elements are being reevaluated as potential debris generators. Computations of debris trajectories under a wide variety of conditions define the induced environment due to debris. The risk associated with the Orbiter Thermal Protection System will be reassessed for this debris environment, as will the systems of all flight elements.

3.14.3.5 Summary

The reorganized SEIO now addresses all elements of the Space Shuttle system including the Orbiter. The SEIO manager located at JSC has oversight and control of matrix Systems Engineering and Integration support from KSC and MSFC. SEIO works in compliance with Independent Technical Authority requirements and the SMA organization. SEIO recognizes the Independent Technical Authority as the approval authority for variances to technical requirements, as documented in NSTS 07700, Volume IV. Additionally, SEIO will conduct integrated hazard analyses with the oversight of the Space Shuttle System Technical Warrant Holder. The results of these analyses will be accepted or rejected by the Space Shuttle System Technical Warrant Holder prior to use.

3.14.4 RTF TG Assessment

In support of our assessment of CAIB Recommendation 9.1-1, the RTF TG conducted fact-finding with several former CAIB members, representatives of the NASA-Navy Benchmarking Team, and various senior NASA officials on numerous occasions during the last two years.

CAIB required only a plan to implement the 7.5-series of recommendations before return to flight. The accident board, as did many of the Task Group, assumed that the return-to-flight would not be a two-plus-year endeavor and a plan was all that could be reasonably expected before the launch of STS-114. Thus, strictly speaking, NASA has largely complied with this recommendation.

With the passage of time, however, the NASA Administrator announced his desire to have the elements of R9.1.1 implemented, at least for the Space Shuttle Program, before the return to flight. The Task Group has therefore been able to monitor the implementation of at least some of the plan, gauge early effects, and evaluate whether the individual elements of the 7.5-series of recommendations meet the intent of the CAIB. On that basis, the results are mixed.

3.14.4.1 Recommendation 7.5-1: Independent Technical Authority

The CAIB was concerned with the conflict of interest inherent in the Space Shuttle Program Manager balancing resources, schedule, and safety. In that role, prior to the *Columbia* accident, the program manager was often called upon to approve waivers of technical requirements – waivers that could compromise program safety – sometimes in order to meet schedule or budget constraints.

The road to the current plan was neither straight nor smooth – there was a great deal of resistance from the safety community within NASA as well as from the various NASA centers. Some in the safety community view the current construct as a diminution of authority, with certain standards and waiver authority transferred to the ITA. The original assignment of NESC to SMA and its subsequent movement to the Chief Engineer was also viewed as a further relegation of authority. The NASA centers, maintaining their historical position, argued that the accident board's recommendation for Headquarters-level ITA was misguided – that centers are better able to manage technical authority.

The Agency's plan for implementing a new agency-wide Independent Technical Authority places waiver-approval in the hands of the Chief Engineer, who is independent of all programs. However, because of internal dissension, the final organizational structure of the Independent Technical Authority was only recently determined and full implementation has not yet been accomplished. The establishment of roles and responsibilities, in addition to technical waivers, is being determined in conjunction with the Office of Safety and Mission Assurance and the Systems Engineering and Integration Office.

The Chief Engineer has chosen to exercise this authority through delegation to a series of Technical Warrant Holders. Each warrant holder is considered to be among the foremost technical experts in his or her field employed by NASA. Warrant holders essentially own the technical standards specified in their warrant and possess the discretion to change the standards and grant waivers to them.

This construct is fully consistent with the intent of the CAIB. However, not all details of implementation have been worked out, especially the roles and responsibilities of the Independent Technical Authority relative to Office of Safety and Mission Assurance and the Systems Engineering and Integration Office. Further, while a number of warrant holders have been designated, not all will be in place before the return to flight.

There also remains resistance within NASA to the totality of the change implied by the Independent Technical Authority concept. Nevertheless, the Agency's implementation of this recommendation is viewed by many in Congress and the public as an indicator of the Agency's willingness to change. Further implementation of the Independent Technical Authority and its durability will be of continued interest long after the return to flight. Ultimately, the sustainability of the Independent Technical Authority will be one measure of NASA's willingness to change critical processes.

3.14.4.2 Recommendation 7.5-2: Safety and Mission Assurance

The CAIB viewed the organization of the Agency's Space Shuttle safety offices as a contributing factor to NASA not being appropriately attuned to minimizing risks. They recommended: "NASA Headquarters Office of Safety and Mission Assurance should have direct line authority over the entire Space Shuttle Program safety organization and should be independently resourced."

After review, NASA determined it is preferable to keep the Center Directors in the line of authority so they retain some responsibility for safety. Therefore, NASA has chosen not to completely comply with the CAIB recommendation. Instead, they have increased the authority of Headquarters, but are keeping the director of each NASA Center responsible for safety and mission assurance by continuing to have each center's SMA organizations report to the Center Director rather than the Chief Safety and Mission Assurance Officer at Headquarters. As part of these changes, NASA has strengthened the role Headquarters plays in employment and evaluation of safety personnel, and removed decisions for funding safety activities from the Space Shuttle Program.

The Task Group has also noted OSMA efforts to enhance its auditing role – making sure that safety-related processes are adequate and implemented. Expanded auditing can help ensure that the remaining center-centric aspect of managing the safety organizations is not detrimental to the overall agency adoption of adequate safety systems. Like R7.5-1, the success of the implementation of this recommendation will require consistent attention by NASA leadership to ensure survival.

3.14.4.3 Recommendation 7.5-3: Systems Engineering and Integration

The CAIB noted the apparent inability of the Space Shuttle Program to integrate across its various components. In the long history of NASA, integration has been the hallmark of both the challenges and successes of the Agency. In the particular case of the *Columbia* accident, foam from the External Tank inflicted catastrophic damage to the Orbiter. Previous instances of foam debris – including one just two flights prior to STS-107 – had not been taken sufficiently seriously by the managers of either the External Tank Project or the Orbiter Project. It appeared that no one was in charge of monitoring trends between and among flights, and data was generally unable to be shared between NASA Centers and program elements. The Agency's capabilities for system engineering had atrophied.

In response to the CAIB recommendation, NASA enhanced the reach and responsibilities of the SEIO operation within the Space Shuttle Program. Additional resources and personnel were added and new processes instituted. The integration function was improved and coordination between the program elements is more common. In addition, system analysis has improved; e.g., analytical modeling of debris flow. In strengthening system analysis and integration, the basic intent of R7.5-3 has been partially accomplished.

However, weaknesses remain in the system engineering function and related processes. In many cases unverified and unvalidated analytical modeling is replacing sound engineering rationale as the hallmark of establishing engineering standards, measuring the attainment of technical requirements, and assessing risk.

The Task Group and other outside observers (e.g., The Aerospace Corp. audit and NESC) have faulted NASA for inadequate documentation. Requirements have often been established long after design, testing, or hardware modifications have taken place; e.g., foam debris allowables, or repair material to be flown on the next flight manufactured prior to the completion of the establishment of requirements or formal design reviews. In some cases, such as ice debris from the External Tank, or software to control the bellows heaters, the requirements have yet to be established, as of the June 8, 2005 Task Group's public meeting.

Further, the SEIO management of the Design Certification Review/Design Verification Review (DCR/DVR) process for the return to flight has been inconsistent – each project has executed these critical processes in different manners, ranging from rigorous reviews to status reports. In many cases, minutes of the meetings were not published and required actions were not tracked. Information is therefore not systematically collected and may be lost or not easily accessible; e.g., the list of actions from the first Program DCR, conducted April 19, 2005, took over three weeks to assemble and consisted of different, non-collated lists contained in over half a dozen non-standardized files.

3.14.4.4 Conclusion

NASA has a mature plan to restructure the organization in response to the CAIB recommendation and therefore satisfies the letter of R9.1-1. Planned implementation of the Independent Technical Authority comports with CAIB intent – it will take some time to see if the process is robust enough to be sustainable. The planned response to R7.5-2 is intentionally not consistent with CAIB intent – NASA simply disagrees that the best organization for SMA is direct reporting to Headquarters. Implementation of R7.5-3 is uneven, with improved integration and system analysis but remaining gaps in system engineering capability.

The RTF TG assessment of NASA's actions was completed at the June 8, 2005 meeting. The intent of CAIB Recommendation 9.1-1 has been met.

3.14.5 RTF TG Observations

The Task Group observes that the R9.1-1 plan is a first iteration, and the implementations of the 7.5-x recommendations are works in progress. Constant senior leadership vigilance of the implementation will be required to ensure maturity and resolve potential areas of conflict or confusion in terms of roles and responsibilities. The Task Group suggests that the Aerospace Safety Advisory Panel (ASAP) continue to review the ongoing implementation of the 7.5-x recommendations.

Because of a lengthy NASA internal debate over the implementation of Recommendation R7.5-1, planning was not finalized until November 2004, resulting in a major organizational change to the program late in 2004. This resulted in confusion over roles and responsibilities and significant changes to program documentation immediately prior to the then-scheduled return-to-flight launch of STS-114. Of particular importance for NASA leadership is to ensure that the Independent Technical Authority implementation fulfills one of its stated key principles, specifically, "clear and unambiguous … authority, responsibility, and accountability."

Although not directly related to any CAIB recommendation, the Task Group applauds NASA's establishment of the NASA Engineering and Safety Center (NESC) and observed valuable work produced by NESC. Over time, NASA leadership needs to ensure clarity of the NESC role (and more importantly, the NESC authority) in decision making.

With respect to Recommendation R7.5-2, given the NASA alternative to "direct line reporting" and the history from *Challenger* to *Columbia*, the Task Group feels that significant NASA Headquarters leadership attention will be required to ensure SMA "independence" and appropriate authority. Enhancing Headquarters auditing capabilities and performance are critical to ensure this result. NASA Headquarters may wish to develop specific metrics and oversight to periodically ensure the independence and authority of critical SMA functions, including their performance in the Mission Management Team.

Since the Space Shuttle SMA Manager is the voting member of the MMT, constant vigilance will need to be maintained to ensure the independence of the safety function and that close communications are maintained with those SMA directors which possess "suspension authority."

In regards to recommendation R7.5-3, the Task Group expects that NASA will address the remaining identified weaknesses in the systems engineering function and processes; will demand rigorous documentation that sustains effective systems integration and engineering; and will require improvements in standards for (and standardization of) validation, verification, and certification requirements for the development and use of analytical models.

NASA further needs to assess the impact of its contractual relationships on effective systems engineering and integration. The Task Group was advised very shortly after its formation by Shuttle management that the Space Flight Operations Contract (SFOC) needed revitalization to ensure effective SEIO functions and/or those workforce capabilities reestablished in-house. The SSP needs to ensure that flight-to-flight verification and evolution of SEI databases are continuously updated, documented and appropriately provided for future flight and MMT decision making.

The Task Group also observes that a significant workforce challenge is facing NASA. The Space Shuttle Program long ago transitioned, largely, to an "operations and maintenance" organization, losing the skill set and talents required to do the developmental work that was required post-*Columbia*. The Space Shuttle will remain a "developmental" vehicle until its retirement, and will require a developmental mindset, skill set, and discipline at both the workforce and management levels.

3.15 CAIB Recommendation 10.3-1 – Digitize Closeout Photos

Develop an interim program of closeout photographs for all critical sub-systems that differ from engineering drawing. Digitize the closeout photograph system so that images are immediately available for on-orbit troubleshooting.

3.15.1 RTF TG Interpretation

During the investigation, the Columbia Accident Investigation Board (CAIB) encountered numerous engineering drawings that were inaccurate. Further, they discovered a large number of engineering change orders had not been incorporated into the drawings. Tied in with this, CAIB investigators were not able to access needed closeout photography for several weeks.

3.15.2 Background

Closeout photographs have been archived in a database at the Kennedy Space Center since the beginning of the program. (Closeout photos are pictures taken of Space Shuttle areas before they are sealed for flight.) This database was primarily used by the KSC engineering community and photos were filed based on the work authorization document that originally requested the photograph, making it difficult to search for particular images. A large number of non-standardized cameras were used resulting in arbitrary resolution of critical images. In addition, there were no clear requirements to photograph all critical closeout activities, or to record changes to the vehicle configuration.

In the years since the Space Shuttle was designed, NASA has not updated many of its engineering drawings or converted to computer-aided drafting systems. The accident board's review of those engineering drawings revealed numerous inaccuracies; in particular, the drawings do not incorporate many engineering changes made in the last two decades. Equally troubling was the difficulty in obtaining the drawings, accurate or not: some took up to four weeks to receive. Although some close-out photography was available as a substitute, these images took up to six weeks to obtain. The Aerospace Safety Advisory Panel noted similar difficulties in its 2001 and 2002 reports.

3.15.3 NASA Implementation

The Space Shuttle Program formed a Photo Closeout Team consisting of members from the engineering, quality, and technical communities to identify and implement necessary upgrades to the processes and equipment involved in vehicle closeout photography. Kennedy Space Center (KSC) closeout photography includes the Orbiter, External Tank, Solid Rocket Boosters, and Space Shuttle Main Engines, based on project requirements. The Photo Closeout Team divided the CAIB recommendation into two main elements: (1) increasing the quantity and quality of closeout photographs, and (2) improving the retrieval process through a user-friendly web-based graphical interface system.

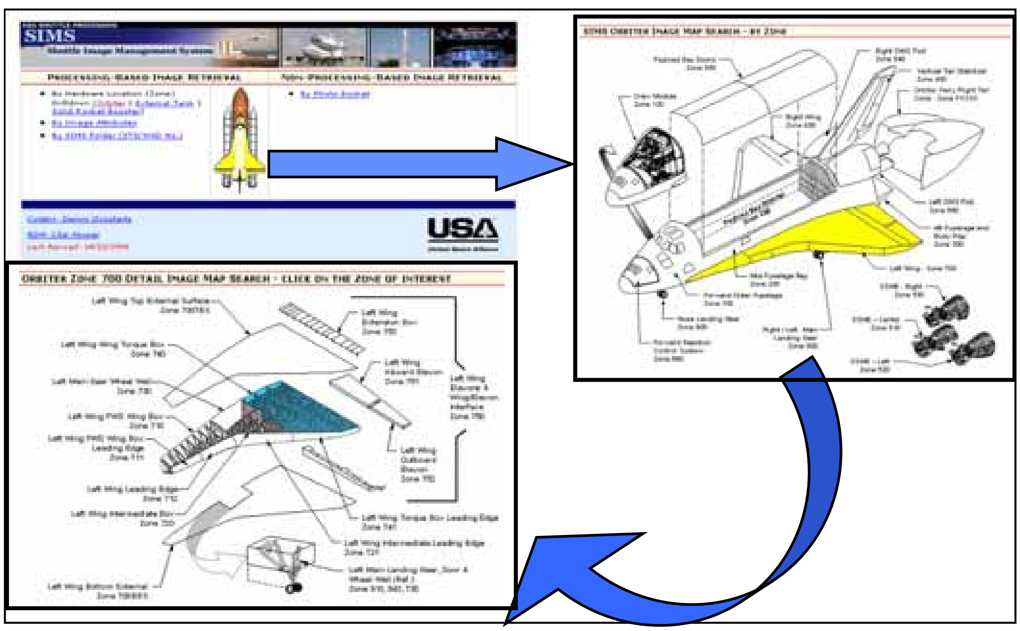
Led by the Photo Closeout Team, the Space Shuttle Program completed an extensive review of existing closeout photo requirements. This team systematically identified the deficiencies of the current system and assembled and prioritized improvements for all elements. These priorities were distilled into a set of revised requirements that has been incorporated into program documentation. NASA also added a formal photography step for KSC-generated documentation and mandated that photography of all Material Review Board (MRB) reports be archived in the Shuttle Image Management System (SIMS) database. These MRB problem reports provide formal documentation of known subsystem and component discrepancies, such as differences from engineering drawings.

To meet the new requirements and ensure a comprehensive and accurate database of photos, the Kennedy Space Center established a baseline for photographic equipment and quality standards, initiated a training and certification program to ensure all operators understand and can meet these requirements, and improved the SIMS. To verify the quality of photographs taken and archived, NASA has developed an ongoing process that calls for SIMS administrators to continually audit the photos being submitted for archiving in the SIMS. Photographers who fail to meet the photo requirements will lose their certification pending further training. Additionally, to ensure the robustness of the archive, poor-quality photos will not be archived.

The Nikon D100 digital camera provides a resolution of 6.1 megapixels.

NASA determined the minimum resolution for closeout photography should be 6.1 megapixels to provide the necessary clarity and detail. KSC has procured 36 Nikon D100 6.1 megapixel cameras and completed a test program in cooperation with Nikon to ensure the cameras meet the Agency's requirements.

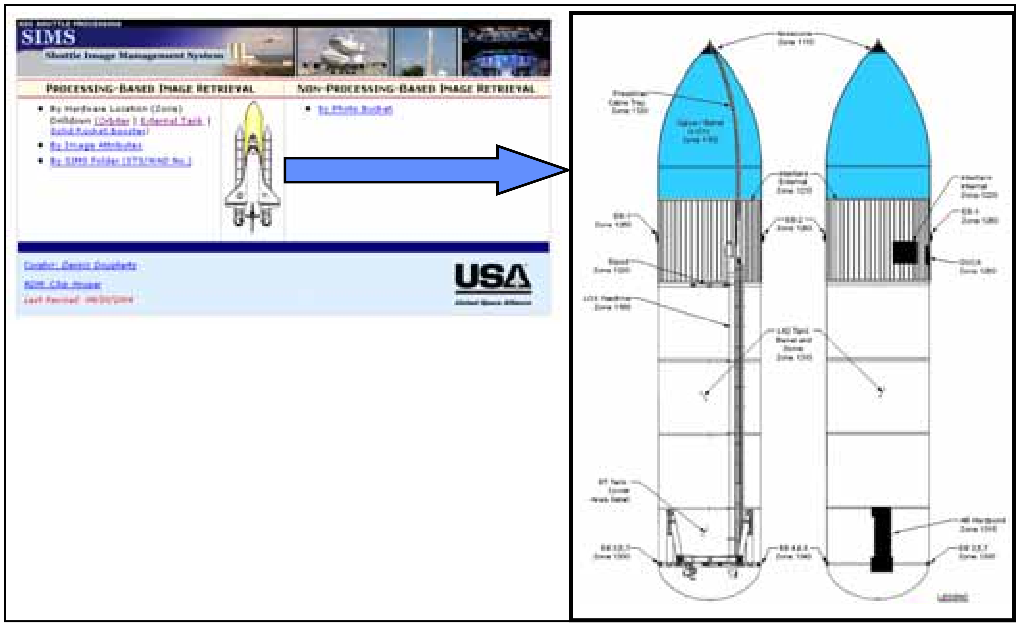
To improve the accessibility of the SIMS database, NASA developed a web-based graphical interface. Users can easily view the desired Space Shuttle elements and systems and quickly drill down to specific components, as well as select photos from specific Orbiters and missions. SIMS also includes hardware reference drawings to help users identify hardware locations by zones. These enhancements will enable Mission Evaluation Room and Mission Management Team personnel to quickly and intuitively access relevant photos without lengthy searches, improving their ability to respond to contingencies.



The Shuttle Image Management System (SIMS) database features a graphical interface.

NASA has revised the Operation and Maintenance Requirements System to mandate that general closeout photography be performed at the time of normal closeout inspection process and that digital photographs be archived in SIMS. Overlapping photographs will be taken to capture large areas. NSTS 07700, Volume IV and the KSC MRB Operating Procedure have also been updated to mandate photography of visible MRB conditions be entered into the

SIMS closeout photography database. This requirement ensures all known critical subsystem configurations that differ from Engineering Drawings are documented and available in SIMS to aid in engineering evaluation and on-orbit troubleshooting.



Each Space Shuttle element is represented in the SIMS database.

Training for critical personnel is complete, and will be ongoing to ensure the broadest possible dissemination within the user community. Photographer training is complete and associated classes are taught on a regular basis. SIMS computer-based training has been developed and released. Use of SIMS has been successfully demonstrated in a launch countdown simulation at KSC, which included participation from the KSC Launch Team, JSC Flight Control Team, Mission Evaluation Room, MSFC Huntsville Operations and Support Center, and the Systems Engineering and Integration Office.

3.15.4 RTF TG Assessment

The Task Group conducted numerous fact-finding activities during 2004 concerning closeout photography and the SIMS database. These efforts complemented earlier meetings with KSC staff and their contractors to review their response to the CAIB recommendation in December 2003. New standardized 6.1 megapixel cameras have been acquired and are now being used in closeout and configuration photography. Generic and return to flight-specific closeout photo requirements have been established by program elements and documented. Photography of areas already closed has been deemed adequate. NASA identified enhancements to the SIMS and the necessary upgrades are complete. Updated training material has been developed for users of the SIMS database and users have received training at the Kennedy Space Center, Johnson Space Center, and Marshall Space Flight Center from local trainers. Through several integrated launch countdown simulations, the Space Shuttle Program staff has confirmed that the modifications to the SIMS database satisfy their needs.

When the accident board wrote their recommendations, they assumed that the Space Shuttle Program would continue for the long term, and indicated digital photography could provide an interim solution pending the digitizing and updating of all Space Shuttle engineering drawings (R10.3-2). However, based on the National Policy decision to retire the Space Shuttle no later than 2010, the Task Group concurs with the NASA decision that it does not make economic sense to expend the resources to make major changes to the drawings. The digital closeout photography provides an adequate solution until the end of the program.

However, if the Space Shuttle Program is extended past 2010, or if a Shuttle-Derived Launch Vehicle (SDLV) is selected as a future booster, this decision should be reevaluated.

The RTF TG initial assessment of NASA's actions was completed at the July 22, 2004, teleconference plenary where the assessment was conditionally closed. After receiving additional information from NASA, the assessment was fully closed at the December 16, 2004, meeting. The intent of CAIB Recommendation 10.3-1 has been met.

3.15.5 RTF TG Observation

If the Space Shuttle Program is extended past 2010, or a Shuttle-Derived Launch Vehicle (SDLV) is selected as a future booster, the decision concerning updating the Space Shuttle engineering drawings should be reevaluated.

Actual photographs from the SIMS database of STS-114. On the left, a photo of the liquid oxygen feedline where it comes out of the External Tank; on the right, a shot of the inside of a piece of the reinforced carbon-carbon wing leading edge panel.

More photographs from SIMS. At left is a turbopump impeller on a Space Shuttle Main Engine; at right, the bolts around a field joint of a Solid Rocket Booster.

More from the SIMS database. At left, the forward Orbiter-External Tank attach point; at right, the left main landing gear of *Discovery*.

3.16 Raising the Bar Action SSP-3 – Contingency Shuttle Crew Support

NASA Implementation Plan: *NASA will evaluate the feasibility of providing contingency life support on board the International Space Station (ISS) to stranded Shuttle crew members until repair or rescue can be accomplished.*

3.16.1 RTF TG Interpretation

Space Shuttle Program Action 3 (SSP-3) addresses Contingency Shuttle Crew Support (CSCS), the capability to harbor Space Shuttle crewmembers aboard the International Space Station (ISS) until a damaged Orbiter can be repaired or the crew rescued. The Columbia Accident Investigation Board (CAIB) did not make a specific recommendation with regard to CSCS, but Section 9.1 of the CAIB report listed the exploration of "all options for survival, such as provisions for…safe havens" as one of several necessary measures for safe flight. Section 6.4 of the CAIB report also assesses the possibility of rescuing a crew by launching another Space Shuttle.

3.16.2 Background

In the aftermath of the *Columbia* accident, NASA responded with a set of corrective actions characterized as "raising the bar" – not required by the CAIB for returning to flight, but self-imposed by the Space Shuttle Program. These actions are documented in the *NASA Implementation Plan*. One of these actions resulted in NASA examining options for providing a capability to sustain a Space Shuttle crew on the ISS should the Orbiter become unfit for entry. NASA chose to pursue CSCS as a functional emergency capability that is not certified, similar to how NASA addresses other emergency plans. Thus CSCS is not intended to mitigate known but unacceptable risks; rather, it is a contingency plan of last resort with limited capability to sustain the crew on the ISS. Finally, NASA committed to ensuring that a rescue Space Shuttle will be available for at least its next two flights. In fact, NASA leadership committed to the delay launch of STS-114 and STS-121, if necessary, until a rescue vehicle can be ready within the projected CSCS window.

The Task Group chose to assess SSP-3 because NASA uses the CSCS capability as part of its launch rationale, and because NASA considers the ability to launch a rescue vehicle within estimated CSCS duration to be a constraint to launch for the first two return-to-flight missions. The CSCS capability bears on the safety and operational readiness of STS-114 and therefore falls within the purview of the Task Group to evaluate.

3.16.3 NASA Implementation

On June 9, 2004, the Space Flight Leadership Council approved pursuing the CSCS concept as an emergency capability for the first two return-to-flight missions, STS-114 and STS-121. NASA will revisit the feasibility and need for continued CSCS capability following STS-121.

The CSCS capability will not be fault tolerant, and imposes no additional requirements for fault tolerance other than those that already exist. The capability is built on the presumption that, if necessary, all ISS consumables and Orbiter reserves will be depleted to support the combined crews aboard the ISS until a rescue mission can be launched. In the most extreme CSCS scenarios, it is possible that the ISS crew will need to return to Earth following the rescue of the Space Shuttle crew until consumables margins can be reestablished and a favorable safety review is completed.

For the first two flights, NASA will ensure the capability to launch a rescue mission is available within the time period the International Space Station can reasonably sustain the combined crews of the ISS and the stricken Orbiter. This includes allowing sufficient time to evacuate the ISS following departure of the rescue Space Shuttle, if necessary. This time period, referred to as the International Space Station engineering estimate of supportable CSCS duration, represents a point between worst- and best-case scenarios based on operational experience and engineering judgment. The ISS Program will provide this estimate in advance of the first two return-to-flight missions as a part of the flight preparation process.

To arrive at the engineering estimate, the ISS Program analyzed the impacts of maintaining seven additional people on the ISS in the event of CSCS. Their analyses indicate that at current operating levels, and with conservative assumptions of system viability, the combined crews can be supported long enough to allow the launch of a rescue mission. As consumables aboard the International Space Station are used by the normal crew prior to the launch of STS-114, the CSCS engineering estimate will change. The engineering estimate will be updated at specific milestones during the STS-114 mission planning process.

As part of the CSCS concept, NASA will have a second Space Shuttle, designated STS-300 for STS-114 and STS-301 for STS-121, ready for launch on short notice. The Space Flight Leadership Council has directed the ability to launch a rescue mission within the ISS Program engineering estimate will be a constraint to launch for the first two missions.

Should a rescue mission become necessary, it would be subject to the same requirements as any other Space Shuttle mission, but processed on an accelerated schedule. The rescue Orbiter would be reconfigured with additional accommodations, including seating, for the crew of the stricken Orbiter.

The International Space Station (ISS) could provide a safe haven for the crew of a damaged Orbiter using the Contingency Shuttle Crew Support capability described in SSP-3.

The rescue Orbiter, *Atlantis* for STS-300 and *Discovery* for STS-301, would be crewed by four astronauts. Following launch, the rescue Orbiter would dock with the ISS using standard rendezvous and approach procedures. Any extra consumables would be transferred to the ISS. The stranded Orbiter crew would board the rescue Orbiter and return to Earth with the four rescue astronauts. If evacuation of ISS becomes necessary, the ISS crew would return to Earth via the Soyuz spacecraft docked at the ISS.

Since, as currently configured, the ISS can only dock one Orbiter at a time, the stricken Orbiter must be undocked prior to arrival of the rescue Orbiter. NASA has developed procedures for undocking an unmanned Orbiter from the station, separating to a safe distance, then conducting a deorbit burn that will cause the Orbiter to enter and burn-up over an uninhabited oceanic area. These procedures have been developed in detail through the ISS Safe Haven Joint Operations Panel, and have been simulated in a joint integrated simulation involving flight controllers and flight crews from both the International Space Station Program and the Space Shuttle Program.

The decision to implement CSCS would result in extremely serious consequences, including: exposure of the stricken Orbiter crew to a severe survival situation presenting the distinct possibility of loss of life; exposure of the rescue Orbiter crew to flying a vehicle possibly vulnerable to the same failure(s) that stranded the first Orbiter; the loss of an irreplaceable National asset (the stricken Orbiter); possible depletion of ISS resources to a level requiring evacuation of ISS; and the likely termination of all future Space Shuttle missions, significantly restricting the United State’s human access to space and utilization of the International Space Station.

Given these extreme consequences of implementing CSCS, the Space Flight Leadership Council has made it clear that the Mission Management Team (MMT) will be responsible for orchestrating a recommendation to implement CSCS only upon clear evidence of catastrophic Thermal Protection System damage that cannot be satisfactorily repaired. Such a recommendation would be accompanied by an assessment of the risk of repeating the failure(s) that damaged the first Orbiter. This would be aided by the enhancements to the ascent and on-orbit imagery collection and analysis made since the *Columbia* accident. The MMT would make its recommendation through the Deputy Associate Administrator for International Space Station and Space Shuttle Programs to the Associate Administrator for Space Operations. The final risk-versus-risk trade and decision to implement CSCS, or not, would be made at the Agency level with appropriate notification to National Authorities.

3.16.4 RTF TG Assessment

Since the CSCS capability was not a CAIB recommendation, the Task Group had no predefined criteria to evaluate the capability against. Instead, the RTF TG established five conditions that it believed constituted an adequate CSCS contingency capability:

1. Clear articulation of the role CSCS plays in NASA’s risk management framework for damage to the Orbiter Thermal Protection System from debris.

2. Development of a dynamic, rigorous analytic process for estimating the number of days the ISS could sustain the seven crew stranded by a damaged Orbiter in addition to its two crewmembers.

3. Development and demonstration of a robust plan for launching a rescue Orbiter, including safely undocking and de-orbiting a damaged Space Shuttle.

4. Integration of CSCS plans and estimates into the pre-launch decision process and relevant documents.

5. Integration of the CSCS capability into the Mission Management Team (MMT) decision-making process, including a demonstration of its ability to consider the risk-versus-risk trades inherent in invoking CSCS, to make informed decisions in the face of these risks, and to implement CSCS procedures.

This assessment is based on information that emerged from various fact-finding activities. Most prominent among these were a series of meetings between the RTF TG Operations Panel and NASA representatives, beginning on July 8, 2004. The objective of this meeting was to help the Operations Panel obtain a high-level understanding of the NASA Thermal Protection System risk reduction framework, the role of CSCS in that framework, and the extent to which NASA intended to develop the CSCS capability. The second meeting took place on August 10, 2004, to help understand the analytic approach by which NASA will estimate possible CSCS duration. Of particular concern was the health, stability, and resilience of the ISS habitat under the stress of nine people.

In March, 2005, the Task Group observed the performance of the MMT during a simulation (sim #12), the objectives of which included analysis of tile damage and decision-making with regard to repair and the possibility of CSCS. Subsequently, a third fact-finding meeting occurred on March 22, 2005, to discern the extent to which the MMT had exercised the CSCS decision process. The fourth fact-finding meeting was on April 7, 2005, primarily to ascertain the NASA simulation supervisors' assessment of the MMT ability to make decisions regarding CSCS, as demonstrated in various simulations. The fifth meeting took place on April 8 where the NASA simulation supervisors reviewed the training strategy for an additional MMT simulation (sim #13) targeted at the MMT decision-making process regarding repair, entry, and CSCS. Finally, on May 4, 2005, the Task Group observed the simulation in which the MMT was confronted with the choice between entry on an uncertified tile repair or the declaration of CSCS.

The outcomes of these meetings, coupled with additional discussions, review of documentation, and the responses NASA provided to thirteen requests for information, form the basis for the Task group's assessment of SSP-3. Overall, the RTF TG finds that NASA set a Raising the Bar action for themselves and exceeded it by a significant margin. The Task Group commends NASA for its excellent work on SSP-3. This conclusion is derived from the following assessments against the five conditions specified above for successful SSP-3 implementation.

3.16.4.1 Condition 1: Risk Reduction

The NASA return-to-flight approach is founded on a framework for TPS risk reduction that has five hierarchically interrelated components: elimination of critical debris, impact detection during ascent, on-orbit damage detection, TPS repair, and crew rescue.[1] The Agency's core risk management strategy has been to eliminate critical debris sources. Despite these efforts, there remains some probability that debris could cause catastrophic damage, although NASA expects to be able to generate an accepted risk rationale. To reduce this residual risk enough to accept it and provide adequate flight rationale, NASA intends to rely on a set of strategies and capabilities first to detect damage to the Orbiter through sensing, imaging, and on-orbit inspection, and then to either effect repair or rescue the crew with another Space Shuttle.

Each of these capabilities faces technical challenges that create uncertainty about its viability and utility. Crew rescue also involves uncertainties associated with providing life support for the Space Shuttle and Space Station crews aboard ISS, undocking and de-orbiting the damaged Orbiter, and the launch of a rescue vehicle into a risk environment where damage,

[1] This approach is documented in *The Integrated Risk Acceptance Approach for Return to Flight,* May 2005.

potentially from unknown or not-well-understood causes, has already occurred. Furthermore, CSCS itself exposes the crews aboard the ISS to the risks inherent in operating in a survival mode. Finally, CSCS may deplete ISS consumables and systems to the point that the ISS must be evacuated. In sum, a decision to invoke CSCS poses a severe threat to the future of the Space Shuttle Program and the International Space Station Program.

These concerns prompted the RTF TG to query NASA about assessments of these uncertainties and risks, and of other unintended consequences that may result from CSCS. NASA reports that the Space Flight Leadership Council (SFLC) has discussed these risks and consequences “at various forums,” although they did not provide documentation of those discussions. They admitted that “no formal preflight assessment has been performed,” and intend to make a real-time assessment of the risk of rescue versus the risk of repair versus the risk of entry, should TPS damage occur. It is the sense of the RTF TG that while NASA recognizes these risks and the magnitude of potential consequences, they have not systematically developed a mature appreciation of this trade space.

Nonetheless, it is conceivable the aggregate benefits of these capabilities to crew survival will outweigh these risks, therefore providing sufficient justification for NASA to accept the residual risk of damage to TPS that remains after mitigation of critical debris. NASA has appropriately developed CSCS as a viable but limited contingency capability to be invoked only under particular circumstances of extreme emergency. These circumstances are confined to Orbiter TPS anomalies only (and not to other system failures), and further to cases where Orbiter TPS has suffered damage that cannot be repaired adequately to permit safe entry, and therefore the lives of the Space Shuttle crew are in jeopardy. In other words, CSCS is a last resort in the event of a catastrophic damage scenario. Since most of the mitigation for risk associated with critical debris is based on the efforts to reduce the foam shedding of the External Tank, the major burden of risk mitigation is not required of the CSCS capability. Thus, NASA has chosen not to make CSCS a “certified” contingency. This is a choice that the RTF TG endorses, since it would require extreme efforts to balance logistic resources and manage ground-breaking international agreements – efforts disproportionate given the probability of a CSCS declaration. The CSCS capability is, nonetheless, an integral component of NASA’s TPS risk management strategy that, in conjunction with other capabilities, can help NASA accept the residual risk that remains despite efforts to mitigate all sources of critical debris. To be a viable component of overall risk reduction, though, CSCS must be a capability that can be reasonably executed in a survival mode, therefore a vigorous analysis is required to determine ISS duration estimates that exceed the time necessary to launch a rescue mission.

3.16.4.2 Condition 2: Engineering Analysis

The centerpiece of CSCS is an engineering analysis that supports ISS habitability for nine people for a predicted duration; therefore this analysis must thoroughly address issues such as consumables, ISS Environmental Control and Life Support System (ECLSS) functionality, systemic ISS biosphere stability, stowage, crew protocols for food and exercise, and impacts from changes to launch schedules and vehicle manifests. NASA understands this need, and has developed an excellent engineering assessment process that provides an estimate of possible CSCS duration.

The International Space Station Program completed a study of the ability to support a one fault tolerant CSCS capability, and presented these recommendations to the Space Flight Leadership Council on June 9, 2004. The ISS Program has defined the following ECLSS functions as critical: carbon dioxide (CO2) control and disposal, oxygen (O2) generation and supply, water supply and recovery, and waste management.[2] The ISS Program’s June study

[2] ISS Contingency Crew Support (in support of STS TPS Anomaly) Status presentation to the SFLC,

concluded the ISS will be unable to meet one-fault tolerance in several important areas. Thus the CSCS capability is considered zero-fault tolerant overall, although some systems (e.g. temperature/humidity control and trace contaminant control) are as much as two-fault tolerant. Nonetheless, CSCS will not be a certified capability, since the ISS is only certified for a crew of six on a temporary basis and a crew of three on a permanent basis (without Space Shuttle support). Also, NASA is assuming that "STS-114 will require no newly developed Shuttle or ISS performance capabilities to enable CSCS."[3]

It is also important to recognize that NASA is scoping CSCS possibilities "in-house," and will not coordinate formally with the Russian Federal Space Agency (FKA) to extend FKA commitments beyond their current levels. The FKA has explicitly stated that it does not endorse the CSCS concept. The basis of the FKA position is an operational philosophy – advanced by the United States – that rejects having any more crew aboard ISS than there are "lifeboat" seats available for. The FKA did not comment on the adequacy of ISS consumables to support the CSCS plan. Furthermore, through informal discussions, NASA analysts are aware that their Russians counterparts believe there is unexploited margin in the estimated performance of their systems.

NASA published an L-1-month assessment that included an estimated CSCS duration for STS-114 of 43 days, given a May 15, 2005 launch.[4] NASA will revise this analysis as the status of systems and consumables aboard the ISS, Progress schedules, and STS-114 launch date vary. The engineering duration estimate is not, however, a stable figure; it can fluctuate as a result of changes in several conditions to which it is particularly sensitive, including:

- Progress [Russian ISS supply vehicle] schedule, which directly affects the levels of consumables aboard the ISS;
- Space Shuttle launch schedule, which likewise drives consumable levels and requirements;
- Current operational status of all environmental systems aboard the ISS, and the occurrence of failures in these systems;
- Plans for and assumptions about crew consumption; and
- Plans for, and assumptions about, Space Shuttle manifests, particularly regarding spares and consumables.

The fluidity inherent in the engineering estimate is mitigated to some extent by the fact that the prediction rests as much as possible on U.S. systems, and makes very conservative estimates about the performance of Russian systems (or omits them from consideration altogether). Moreover, the duration estimate could likely be extended through power-downs, resource-saving measures, and additional supplies/spares. Regardless, the stability and validity of the engineering estimate depends on good coordination and information flow between the International Space Station Program and the Space Shuttle Program.

June 9, 2004.

[3] *NASA's Implementation Plan for Space Shuttle Return to Flight and Beyond*, (Tenth Edition, June 3, 2005, p. 2-6).

[4] According to NASA, "ISS ECLS engineering team has evaluated all of the critical ISS ECLS systems. Based on the current system status, past history, and current on-orbit consumables, the limiting system is oxygen supply, which can provide a 43-day CSCS TPS duration support." ("STS-114 (LF-1) L-1 Month Duration Report of the Environmental Control and Life Support Systems (ECLSS) Contingency Shuttle Crew Support (CSCS) for Thermal Protection System (TPS) Failure," March 2005, p. 24.)

Overall, the RTF TG believes that CSCS protocols must rest on a thorough engineering analysis that specifies the parameters under which CSCS is likely to be technically possible. It is our assessment that NASA has developed and demonstrated a sound approach to such an analysis.

3.16.4.3 Condition 3: Rescue Space Shuttle

Invocation of CSCS necessitates a rescue mission. For STS-114 and STS-121, the Space Flight Leadership Council has mandated that the Space Shuttle Program be able to launch a rescue mission within the ISS engineering estimate of CSCS duration. In the event of CSCS, NASA has developed a plan for launching a rescue Space Shuttle that would have a crew of four, and would return with the stranded Orbiter crew within the duration defined by the ISS Program. If evacuating the ISS becomes necessary as a result of depletion of ISS systems and consumables, the ISS crew would return via the Soyuz spacecraft already docked at the ISS.

Since only one Orbiter can dock to ISS, safe undock and de-orbit procedures for the damaged Orbiter are also necessary. The JSC Mission Operations Directorate has developed procedures for undocking an unmanned Orbiter from the ISS, separating to a safe distance, and then conducting a de-orbit burn to dispose the damaged Orbiter into an uninhabited oceanic area. These procedures have been exercised successfully in a joint integrated simulation involving flight controllers and flight crews from both the ISS Program and the Space Shuttle Program.

The Task Group’s assessment is that NASA understands these processes well, and the RTF TG has confidence in their capability to execute them. The prominent concern associated with the launch of a rescue Space Shuttle is that it requires exposing the rescue Orbiter to the same potential for sustaining damage as that which stranded the primary vehicle. NASA is aware of this risk, although, as noted above, no formal assessment of this risk can be performed until the specific cause of the damage to the primary vehicle has been determined.

3.16.4.4 Condition 4: Launch Decision Process

The requirement to launch a rescue Space Shuttle imposes a need for NASA to address CSCS in its launch decision process, because it will have to specify the timeframe within which STS-300 must be ready to launch and CSCS requires coordination between the Space Shuttle Program and the International Space Station Program. CSCS processes are documented in a Memorandum of Agreement between the programs, which jointly analyze and report CSCS capabilities at L-6 months, L-3 months, L-1 month, and the L-2 week Flight Readiness Review. Updates to the estimate will be provided at the L-2-day and L-1-day MMT meetings, the L-9 hour pre-tanking meeting, and final go/no-go poll during the T-9 minute hold. If failures are reported during any of these updates, the MMT will assess their impact, and decide whether to continue or scrub the launch. NASA does not intend to write launch commit criteria to automatically abort a launch for late ISS failures which might create a gap in CSCS capability.

It is the RTF TG’s assessment that the process for reporting and updating CSCS capability in the period before launch is appropriate.

3.16.4.5 Condition 5: MMT Capability

NASA asserts it will implement CSCS only upon clear evidence of catastrophic TPS damage that cannot be repaired. It has also determined that a CSCS decision will be made at the agency level, supported by MMT recommendations. The decision process by which the MMT would arrive at a CSCS recommendation is extremely difficult, and the potential consequences of CSCS implementation are momentous. Thus, invocation of CSCS requires complex risk-versus-risk assessments regarding whether to repair, entry, or launch a rescue

Space Shuttle that are fraught with uncertainty and ambiguity. To reduce uncertainty, these decisions will require the rapid assessment of data from multiple sources. To reduce ambiguity, these decisions will require close collaboration among MMT members to develop a common view of the severity of the risks.

Given how central these decisions about repair, entry, CSCS, and rescue are to the NASA risk architecture, and how challenging this decision process would be, the RTF TG believed that it was important for the MMT to exercise and demonstrate this decision-making and analytic process prior to flight. The RTF TG asked NASA to "demonstrate the MMT process to weigh and evaluate the risk of CSCS relative to other options in an integrated simulation; demonstrate how the MMT will build a rationale for launching the rescue vehicle; and demonstrate the MMT, MER, and FCT process to evaluate and consider unintended consequences resulting from calling CSCS."

NASA believed they had fulfilled the RTF TG request during an MMT simulation held in early March, 2005 (sim #12). According to the simulation supervisor, the objectives of the sim included analysis of tile damage and decision-making with regard to repair and the possibility of CSCS. The simulation supervisor was satisfied with the MMT performance relative to this stated intent. Likewise, the chair of the MMT believed the MMT thought carefully about the implications of repairing the TPS versus invoking CSCS. While MMT sim #12 was a very important exercise that did appear to enhance the capacity of the MMT overall, RTF TG observers present during the simulation witnessed little systematic discussion with regard to CSCS specifically, and believed that NASA failed to fully confront – and ultimately make – the central, difficult risk-risk choices given circumstances where damage cannot be fully assessed, repairs may not be reliable, and a rescue launch may sustain similar debilitating damage. The minutes from the MMT meetings during the simulation also revealed little such discussion. Furthermore, the RTF TG discovered that the ISS team contribution to the MMT sim #12 scenario was relatively static, so that little discussion of the impacts on CSCS of the extra consumables used during the planned tile repair was possible.

Based in part on these concerns, NASA subsequently added another MMT simulation (sim #13) to the schedule, with the objective of completing the scenario that was started in MMT sim #12. Making the critical choice of whether or not to ride a repair to the ground, and performing the risk-versus-risk analysis in the process, were the driving goals for this simulation. In the end, the MMT did review pertinent risk for the major options, and did a greatly improved job of evaluating the CSCS/LON option. Critical factors related to CSCS duration were discussed, and the view of CSCS as a last-resort option was appropriately held by the MMT members. In the end, the MMT unanimously decided to attempt the return from orbit with the uncertified tile repair, but the rationale for this decision was logically and thoroughly discussed.

3.16.4.6 Conclusion

While the RTF TG believes weaknesses remain in NASA's demonstration of their capacity to handle a CSCS decision, the MMT clearly has made important progress since the loss of *Columbia*, and its overall decision-making ability is much improved. The RTF TG believes the MMT is capable of addressing a CSCS decision appropriately.

The Task Group's assessment of NASA's actions was completed at the June 8, 2005, meeting. The RTF TG commends the Agency for its excellent work on SSP-3, and believes that NASA set a raising the bar goal for itself and exceeded that goal by a significant margin.

3.16.5 RTF TG Observation

RTF TG Observations concerning the MMT role in CSCS are provided in Section 3.11.