COLUMBIA

ACCIDENT INVESTIGATION BOARD

Note: Volumes II – VI contain a number of conclusions and recommendations, several of which were adopted by the Board in Volume I. The other conclusions and recommendations drawn in Volumes II – VI do not necessarily reflect the opinion of the Board, but are included for the record. When there is conflict, Volume I takes precedence.

Report Volume II
October 2003

On the Front Cover

This was the crew patch for STS-107. The central element of the patch was the microgravity symbol, µg, flowing into the rays of the Astronaut symbol. The orbital inclination was portrayed by the 39-degree angle of the Earth's horizon to the Astronaut symbol. The sunrise was representative of the numerous science experiments that were the dawn of a new era for continued microgravity research on the International Space Station and beyond. The breadth of science conducted on this mission had widespread benefits to life on Earth and the continued exploration of space, illustrated by the Earth and stars. The constellation Columba (the dove) was chosen to symbolize peace on Earth and the Space Shuttle Columbia. In addition, the seven stars represent the STS-107 crew members, as well as honoring the original Mercury 7 astronauts who paved the way to make research in space possible. The Israeli flag represented the first person from that country to fly on the Space Shuttle.

On the Back Cover

This emblem memorializes the three U.S. human space flight accidents – Apollo 1, Challenger, and Columbia. The words across the top translate to: "To The Stars, Despite Adversity – Always Explore"

The Board would like to acknowledge the hard work and effort of the following individuals in the production of Volumes II – VI.

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VOLUME I

VOLUME II

CAIB TECHNICAL DOCUMENTS CITED IN THE REPORT

Reader's Guide to Volume II

Volume II of the Report contains appendices that were cited in Volume I. The Columbia Accident Investigation Board produced many of these appendices as working papers during the investigation into the February 1, 2003 destruction of the Space Shuttle *Columbia*. Other appendices were produced by other organizations (mainly NASA) in support of the Board investigation. In the case of documents that have been published by others, they are included here in the interest of establishing a complete record, but often at less than full page size. Full-size versions of these reports are contained on the DVD disc in the back of Volume VI, or hard copies of the documents may be requested through the organizations that originally produced them.

D.a Supplement to the Report

This supplement is presented to augment the Board Report and its condensed list of recommendations. It outlines concerns to prevent the next accident.

D.b Corrections to Volume I of the Report

Volume I of the Columbia Accident Investigation Board report contained minor errors that are detailed here. None of the errors affected the substance of the report.

D.1 STS-107 Training Investigation

The Board conducted a thorough review of all training activities that were performed in preparation for STS-107, including training conducted for the crew, launch controllers, and mission controllers. An analysis of STS-107 Orbiter and payload training requirements was conducted, as well as a complete review of all training records, schedules, instructor logbooks, and related documentation for the crew, flight controller, and launch controller training. Interviews and discussions were held with STS-107 training and operational personnel at both Johnson and Kennedy Space Centers to investigate the STS-107 training process, the effects of launch slips, the performance of the crew, flight controllers, and launch controllers, and the flight readiness of all for the STS-107 mission. Although several issues were identified as a result of this investigation, none were considered causal in the loss of *Columbia*.

The investigator who wrote this report proposed four recommendations, one of which was adopted by the Board for inclusion in the final report. The conclusions drawn in this report do not necessarily reflect the conclusions of the Board; when there is a conflict, the statements in Volume I of the Columbia Accident Investigation Board Report take precedence.

D.2 Payload Checklist

This appendix is a reproduction of the Payload Operations Checklist used by the STS-107 crew during on-orbit operations. It is reproduced here – at smaller than normal page size – to show the level of detailed instruction provided to the crew during on-orbit payload operations.

This is a NASA document and is published here as written, without editing by the Columbia Accident Investigation Board. The conclusions drawn in this report do not necessarily reflect the conclusions of the Board; when there is a conflict, the statements in Volume I of the Columbia Accident Investigation Board Report take precedence.

D.3 Fault Tree Closure Summary

The NASA Accident Investigation Team examined the accident using "fault trees," a common organizational tool in systems engineering. Fault trees are graphical representations of every conceivable sequence of events that could cause a system to fail. The fault tree's uppermost level illustrates the events that could have directly caused the loss of *Columbia* by aerodynamic breakup during re-entry. Subsequent levels comprise all individual elements or factors that could cause the failure described immediately above it. In this way, all potential chains of causation that could have ultimately led to the loss of *Columbia* can be diagrammed, and the behavior of every subsystem that was not a precipitating cause can be eliminated from consideration.

NASA chartered six teams to develop fault trees, one for each of the Shuttle's major components: the Orbiter, Space Shuttle Main Engine, Reusable Solid Rocket Motor, Solid Rocket Booster, External Tank, and Payload. A seventh "systems integration" fault tree team analyzed failure scenarios involving two or more Shuttle components. These interdisciplinary teams included NASA and contractor personnel, as well as outside experts. Some of the fault trees are very large and intricate. For instance, the Orbiter fault tree, which only considers events on the Orbiter that could have led to the accident, includes 234 elements. In contrast, the Systems Integration fault tree, which deals with interactions among parts of the Shuttle, includes 295 unique multi-element integration faults, 128 Orbiter multi-element faults, and 221 connections to other Shuttle components.

This appendix provides a listing of fault tree elements that were investigated by the Board and closed during the *Columbia* investigation. Some of the elements in this appendix were open at the time the investigation concluded, but are expected to be closed before the Return to Flight. Items marked "Open due to lower element" remained open because a lower level fault tree had yet to be closed; for the most part, the lower-level fault trees are contained in Appendix D.4.

D.4 Fault Tree Elements – Not Closed

This appendix contains fault tree elements that were not closed or could not be completely closed by the end of the *Columbia* investigation. In some cases, a fault tree element may never be closed since neither analysis nor data is available to rule that element out as a potential cause. In some cases, the lower-level fault trees contained in this appendix will cause a higher-level fault tree in Appendix D.3 to remain open as well (annotated as "Open due to lower element" in Appendix D.3).

D.5 Space Weather Conditions

This appendix provides a detailed discussion of space weather (the action of highly energetic particles, primarily from the Sun, in the outer layer of the Earth's atmosphere) and the potential effects of space weather on the Orbiter on February 1, 2003. This investigation was originally prompted by public reports of unusually active space weather conditions during the mission and by a photograph that was claimed to show a lightning bolt striking *Columbia* at an altitude of 230,000 feet over California during re-entry. The report concludes that space weather was unlikely to have played a role in the loss of *Columbia*.

This is a document commissioned by the Columbia Accident Investigation Board and is published here as written, without editing. The conclusions drawn in this report do not necessarily reflect the conclusions of the Board; when there is a conflict, the statements in Volume I of the Columbia Accident Investigation Board Report take precedence.

D.6 Payload and Payload Integration

The Board conducted a thorough review of the STS-107 payload and the payload integration in preparation for the mission. This appendix contains the results of that investigation, which identified several anomalies, but none were determined to be causal in the loss of *Columbia*.

D.7 Working Scenario

The Working Scenario was the result of a joint effort between the Columbia Accident Investigation Board (CAIB) and the NASA Accident Investigation Team (NAIT). The report was written beginning early in the investigation to track the current understanding of the events that led to the loss of *Columbia*. As such, the report evolved over time as facts became known, theories were developed or disproved, and NASA and the Board gained knowledge of the accident sequence.

The report was written to document the collection of known facts, events, timelines, and historical information of particular interest to the final flight of *Columbia*. The Columbia Accident Investigation Board released the final version of the Working Scenario to the public on July 8, 2003. The version contained here has been reformatted to match the overall style of the first volume and has had a few minor editorial corrections, but none affect the substance of the report.

The Working Scenario includes information from numerous analyses, tests, and simulations related to the *Columbia* investigation that had been completed, or were ongoing at the time that this report was completed, i.e., up to and including July 8, 2003.

This effort compiles and documents the principal facts related to specific vehicle element events, timelines, and data. It also includes pertinent historical data surrounding some of the key vehicle element considerations in the investigation. The scenario addresses the chronology of vehicle events from prelaunch, launch countdown, launch/ascent, orbit, and re-entry, as well as specific information for the External Tank and the left wing, including aspects of the Reinforced Carbon-Carbon (RCC) and attachment hardware. Vehicle processing and significant preflight events and milestones are also discussed. The scenario addresses technical aspects only, and does not address management practices or philosophies, or other organizational considerations.

D.8 Debris Transport Analysis

This appendix contains the debris transport analysis used to determine information about the dimensions of the External Tank bipod foam ramp and the conditions in which the foam struck the Orbiter. This data provided inputs into the foam testing conducted at Southwest Research Institute for the foam impact testing.

This is a NASA document and is published here as written, without editing by the Columbia Accident Investigation Board. The conclusions drawn in this report do not necessarily reflect the opinion of the Board; when there is a conflict, the statements in Volume I of the Columbia Accident Investigation Board Report take precedence. While the report contains many recommendations to improve the data used in this type of analysis for future missions, the Board did not adopt every recommendation into the Columbia Accident Investigation Board Report.

D.9 Data Review and Timeline Reconstruction Report

This appendix contains the basic timeline data that was used to reconstruct the final minutes of *Columbia*'s re-entry on February 1, 2003. The version in this appendix contains all of the timeline events, but in condensed form.

The timeline organized the re-entry data. As such, this appendix contains no conclusions or recommendations. A visual presentation of the timeline has also been included on the DVD that contains this appendix. It shows the timeline laid over a map of the United States along the ground track that *Columbia* flew during the re-entry.

D.10 Debris Recovery

The *Columbia* accident initiated the largest debris search in history. The evidence collected during the effort was instrumental in confirming the working hypothesis that had been developed by the Columbia Accident Investigation Board and the NASA Accident Investigation Team. The Board is very indebted to the thousands of individuals, companies, and organizations that responded to the call to service. We sincerely apologize to anybody inadvertently omitted from this appendix.

D.11 STS-107 Columbia Resconstruction Report

This appendix contains the STS-107 Columbia Reconstruction Report – reproduced at smaller than normal size – written by NASA during the investigation. While the Board investigation eventually focused on the left wing and the forensics evidence from that area, this report looked at Orbiter damage over the entire vehicle.

The Board's conclusions about debris evidence in Chapter 3 of Volume I were based on this report and independent analysis and investigation by Board investigators.

This is a NASA document and is published here as written, without editing by the Columbia Accident Investigation Board. The conclusions drawn in this report do not necessarily reflect the opinion of the Board; when there is a conflict, the statements in Volume I of the Columbia Accident Investigation Board Report take precedence. While the report contains many recommendations to improve the data used in this type of analysis for future missions, the Board did not adopt every recommendation into the Columbia Accident Investigation Board Report.

D.12 Impact Modeling

This appendix contains the independent analysis of the foam impact with the left wing conducted by Southwest Research Institute in support of the Columbia Accident Investigation Board. In addition to the analysis performed by NASA during the investigation, the Board called for a second independent analysis of the foam impact data. This report examines the foam impact data as it might have affected both thermal tiles and the RCC. The results of this analysis were used to predict damage to the RCC and tile and to set conditions for the foam impact testing program.

The conclusions drawn in this report do not necessarily reflect the conclusions of the Board; when there is a conflict, the statements in Volume I of the Columbia Accident Investigation Board Report take precedence.

D.13 STS-107 In-Flight Options Assessment

During the course of the investigation, the Board heard several NASA officials say there was nothing that could have been done to save *Columbia*'s crew, even if they had known about the damage. The Board therefore directed NASA to determine whether that opinion was valid. NASA was to design hypothetical on-orbit repair and rescue scenarios based on the premise that the wing damage events during launch were recognized early during the mission. The scenarios were to assume that a decision to repair or rescue the *Columbia* crew would be made quickly, with no regard to risk. These ground rules were not necessarily "real world," but allowed the analysis to proceed without regard to political or managerial considerations. This report is the full result of that analysis; a summary was presented in Volume I of the report.

This is a NASA document and is published here as written, without editing by the Columbia Accident Investigation Board. The conclusions drawn in this report do not necessarily reflect the conclusions of the Board; when there is a conflict, the statements in Volume I of the Columbia Accident Investigation Board Report take precedence.

D.14 Orbiter Major Modification Review

Investigation Group I of the Columbia Accident Investigation Board conducted a review of the policies and procedures used by NASA during Orbiter Major Modifications (OMM) and Orbiter Maintenance Down Periods (OMPD). As part of this effort, the U.S. Air Force was invited to conduct an independent review. The results of these efforts are documented in this appendix.

The investigators who conducted this review proposed a number of recommendations, several of which were adopted by the Board for inclusion in the final report. The conclusions drawn in this review do not necessarily reflect the conclusions of the Board; when there is a conflict, the statements in Volume I of the Columbia Accident Investigation Board Report take precedence.

D.15 Maintenance and Sustainment Review

Investigation Group I of the Columbia Accident Investigation Board examined maintenance procedures and sustainment policies relevant to the Space Shuttle Program. Since the remaining Orbiters have all been in service for nearly 20 years, the review included "aging aircraft" issues similar to those faced by military and commercial aviation.

This report contains a large spreadsheet containing production data on every External Tank built to date. This table is not reproduced in the report because of its size, but it is included as a PDF file on the DVD included in Volume VI.

The investigators who conducted this review proposed a number of recommendations, several of which were adopted by the Board for inclusion in the final report. The conclusions drawn in this review do not necessarily reflect the conclusions of the Board; when there is a conflict, the statements in Volume I of the Columbia Accident Investigation Board Report take precedence.

D.16 Public Safety Analysis

After *Columbia* disintegrated in flight, many expressed surprise and relief that no one on the ground was injured by falling debris. During the Board's investigation, it became clear that no one had ever assessed the potential for loss of life on the ground if a re-entry mishap ever occurred. The results of this analysis indicated that the *Columbia* accident was not likely to have produced casualties on the ground.

The conclusions drawn in this report do not necessarily reflect the conclusions of the Board; when there is a conflict, the statements in Volume I of the Columbia Accident Investigation Board Report take precedence.

D.17 MER Manager's Tiger Team Checklists

This appendix contains the Mission Evaluation Room Manager's Tiger Team Checklist referenced in Volume I, Chapter 6. The checklist is reproduced at smaller than normal page size.

D.18 Past Reports Review

This appendix is a listing of relevant findings and recommendations concerning the Space Shuttle program issued by various independent review boards over a two-decade period. The list also includes the NASA responses to the findings or recommendations whenever such responses could be found. Although it was the intent of the Board to present this list in Volume II, its size precluded doing this and the list is actually contained in Volume V.

D.19 Qualification and Interpretation of Sensor Data from STS-107

This appendix provides a thorough review of the Modular Auxiliary Data System (MADS) recorder and sensor operation and an analysis of the data that was gathered from the MADS system and used during the investigation.

This appendix also contains several draft recommendations that were reviewed by the Board. Several of these were adopted and are included in their final form in Volume I. The conclusions drawn in this report do not necessarily reflect the conclusions of the Board; when there is a conflict, the statements in Volume I of the Columbia Accident Investigation Board Report take precedence.

D.20 Bolt Catcher Debris Analysis

This appendix contains – reproduced at smaller than normal size – the study of radar returns from past Space Shuttle launches to determine whether the Solid Rocket Booster bolt catchers may have failed during the flight of STS-107. The report concluded that there was the possibility that one of the debris items seen on radar during that flight could have been part of a bolt catcher.

This appendix has no recommendations, but the Board did make recommendations related to the bolt catcher issue in Volume I. The conclusions drawn in this report do not necessarily reflect the conclusions of the Board; when there is a conflict, the statements in Volume I of the Columbia Accident Investigation Board Report take precedence.

APPENDIX D.a

Supplement to the Report

by Brigadier General Duane W. Deal, Board Member

With appreciation to Dr. James N. Hallock, Dr. John M. Logsdon, Dr. Douglas D. Osheroff, and Dr. Sally K. Ride for their valuable inputs and editing.

Err on the side of providing too much rather than too little information in the aftermath of a mistake or failure.

–Strock, Reagan on Leadership[1]

FOREWORD: PREVENTING "THE NEXT ACCIDENT"

The Columbia Accident Investigation Board report is a powerful document. It goes far beyond any previous accident report in the scope and manner with which it tackles a multitude of complex and daunting subjects previously unaddressed. In extensive detail and often in blunt language, it conveys the intricacies of the physical cause of the *Columbia* accident, and places equal weight on the organizational cause. The Board and its staff of professional investigators who produced this landmark report represent the best our nation has to offer – dedicated men and women brought together from many walks of life by an international tragedy, united with a common purpose, and driven to produce a product of substance and worth to the human space flight program. Additionally, its lessons go far beyond the Space Shuttle Program; indeed, the lessons learned are applicable to any large organization, particularly to those operating complex, risky, or aging systems.

This supplement is not written to refute any portion of that report. The Board report contains data, analysis, and conclusions which combine to write a prescription for NASA to recover not only in returning the Space Shuttle safely to the vacuum of space, but also to address NASA's sporadic organizational morass. If NASA will accept this prescription and take the "medicine" prescribed, we may be optimistic regarding the program's future; if, however, NASA settles back into its previous mindset of saying, "Thanks for your contribution to human space flight," summarily ignoring what it chooses to ignore, the outlook is bleak for the future of the program.

The Board report already contains many findings and recommendations. We have confidence that the recommendations carrying a "Return to Flight" annotation will be addressed and fixed prior to the Shuttle launching again. My confidence diminishes somewhat with recommendations that stand alone, not annotated as return-to-flight. In light of the reaction to past studies – even those following the *Challenger* accident – my confidence disappears when we offer NASA items only as "observations" – when Board members and investigators considered them significant – and trust NASA to address each one of them. History shows that NASA often ignores strong recommendations; without a culture change, it is overly optimistic to believe NASA will tackle something relegated to an "observation" when it has a record of ignoring recommendations.

When the original members of the Board first spoke via teleconference on February 1, hours after the accident, and when we first assembled at Barksdale Air Force Base the evening of February 2, we were presented with the original Board charter. While that charter and the Board itself have expanded since then, the basic charge to the original Board was to (1) determine the cause of the loss of the *Columbia* and her crew, and (2) prevent recurrences – what we termed "the next accident" waiting to happen.

The Board report goes into great depth examining the physical cause of the accident – "the foam did it." Poorly designed, inconsistently manufactured, and inadequately tested, the foam is no longer an accident waiting to happen. The report then goes into a fascinating look at NASA's organizational culture and the pattern of breakdowns that have cost the lives of 14 astronauts.

With the preceding in mind, this supplement is presented to augment the Board report and its condensed list of recommendations. It is written from the perspective of someone who has presided or participated in the investigation of a dozen space and aircraft accidents, who fears the report has bypassed some items that could prevent "the next accident" from occurring – the "next" O-ring or the "next" bipod ramp.

As much or more than that rationale, this comes from the perspective of one who in the course of the investigation has interviewed those in high/medium/low management levels, and also those with hands on equipment "getting their hands dirty." If *they* express concerns, and those concerns are consistent throughout the workforce, those concerns regarding what could cause the next accident if not fixed *must* be heeded.

> *A primary task in taking a company from good to great is to create a culture wherein people have a tremendous opportunity to be heard and, ultimately, for the truth to be heard.*
>
> –Collins, Good to Great[2]

> *In this view [of adaptive leadership], getting people to clarify what matters most, in what balance, with what trade-offs, becomes a central task.*
>
> –Heifetz, Leadership Without Easy Answers[3]

Because of our conviction in the course of the investigation that we should do our very best to prevent the next accident, we must not miss an opportunity to fix something we know about that could cause that next accident and possibly deaths; indeed, we would be negligent to not do so.

Addressing Items Already In The Report ... Why?

Why suggest modifications to items already present in the Board report? History reveals NASA has repeatedly demonstrated a lack of regard for outside studies and their findings. Chapter 5 of the Board report contains a 2-page chart conveying that during the course of the Board investigation, more than 50 separate post-Challenger reports were examined for various topics; Appendix D.18 recounts what was found, what was recommended, and NASA's response to findings and recommendations – if any. Board members had these findings and responses available as a benchmark for their lines of investigation to compare to NASA's current programs. Additionally, Dennis R. Jenkins, a Board Investigator and noted space and aviation author, compiled an exhaustive 300-page study of every Aerospace Safety Advisory Panel report; that study is also in Appendix D.18.

Despite this extensive look at the past, many items in the report were characterized as less than recommendations. The introduction to Chapter 10 of the Board report, "Other Significant Observations," says:

> *The significant issues listed in this chapter are potentially serious matters that should be addressed by NASA because they fall into the category of "weak signals" that could be indications of future problems.*

In my view, given the reality of NASA's past record with such issues, a sterner and more effective wording would have been:

> *The significant issues listed in this chapter are serious matters that must be addressed by NASA because they fall into the category of "strong signals" that are indications of present and future problems.*

While much of the following is contained in the Board report, it is repeated here together with related views that were not included in the body of the report.

These portions of the report are included to reflect the concern that the Board report addresses micrometeorites that we cannot predict or prevent with a Board recommendation, but allows things we can see and can prevent – and can predict an outcome – to remain as "NASA-ignorable observations." Items such as corrosion, the Solid Rocket Booster-External Tank attach rings, the Solid Rocket Booster hold-down cable, and the Kennedy Space Center quality assurance program deserve focused attention, as do ATK Thiokol security, the Michoud Assembly Facility quality program, Michoud security, crew cabin insulation, and other findings/recommendations. In my view, we have not done our best to "prevent the next accident" regarding things we've seen with our own eyes, and that individuals ranging from technicians to engineers have conveyed to us directly and via interviews and documentation.

Quality Assurance

Part of preventing the next accident lies in a strong quality assurance program; while you can't inspect quality into a product, the Shuttle Independent Assessment Team, an internal Kennedy Space Center report, and other past reports spotlight what a weak program can potentially cost. Also, as human error has been implicated in 60 to 80 percent of accidents in aviation and other complex systems, a solid quality assurance program may be the last measure of checks and balances in a complex system such as the Space Shuttle.[4]

Unresponsive Management

> *You need an established system for ongoing checks designed to spot expected as well as unexpected safety problems … Non-HROs [Non-High Reliability Organizations] reject early warning signs of quality degradation.*
>
> –Roberts, "High Reliability Organizations"[5]

Interviews and documentation provided by technicians, inspectors, and engineers revealed that when Quality Assurance Specialist inputs are made to improve processes or equipment, regarding issues from safety to discrepancies of out-of-specification items, Kennedy's quality management support is inconsistent.

Quality Assurance Specialists have found they must occasionally go around their management and elevate concerns using the NASA Safety Reporting System. In turn, the NASA Safety Reporting System has been responsive and validated concerns that local management would not. The KSC quality program management is perceived as unresponsive to inspector concerns and inputs toward improvement.

Staffing Levels

Maintaining adequate staffing levels remains a concern expressed by today's workforce and previous reports, including a February 17, 1999, letter to multiple levels of NASA management from John Young, dean of the astronaut corps. NASA Mission Assurance leadership reported that while the number of Quality Assurance Specialists may be adequate, with additional staff, workers would not have to wait for an inspector to close out a job, and would be available for additional quality-related pursuits. One of the more common reasons that quality engineers cited for declining to add government inspections at Kennedy Space Center was indeed inadequate personnel – a poor excuse for not adding inspections deemed necessary. Likewise, Marshall's Mission Assurance staff and the Michoud Defense Contract Management Agency (DCMA) staff also appear short of people for their workload. Columbia Accident Investigation Board recommendations to evaluate Quality Program Requirements Documents should drive decisions on additional staffing; in the interim, staffing to current authorizations with qualified people should be expedited.

Grade Levels

Grade levels also enter the equation, in two respects. First, the KSC Mission Assurance chiefs are at a lower grade than the Chief Engineer or Launch Director. This organizational structure may cause pressure in resolving conflicting priorities between respective organizations. KSC should review the position descriptions and make adjustments to establish parity in leadership and influence. Second, a review of other NASA center quality assurance specialist staffing and grades revealed that Kennedy is the only NASA center evaluated that has Quality Assurance Specialist grades set at GS-11 – other centers have Quality Assurance Specialist grades set at GS-12. An evaluation of this disparity should determine whether those grades are appropriate.

Inspector Qualifications

Examples surfaced where individuals with no previous aviation, space, technical, or inspection background had been selected as Quality Assurance Specialists and were making NASA final inspections. While most inspectors had extensive aviation and/or related military experience, such hiring practices indicate a need to consistently specify and stringently observe job qualifications for new hires that spell out proper criteria.

Employee Training

Workers expressed concerns over the type and amount of training they received. A common theme expressed by 67 percent of those interviewed regards the lack of formal training, particularly for quality engineers, process analysts, and quality assurance specialists of both NASA and DCMA. Instead of formal training, most is simply on-the-job training. Where available, some training is provided in classrooms conducted by and for contractor employees, and numerous examples were provided where a contractor technician had to provide training to the inspector who would be evaluating the technician's work. Quality Program management must work with the rest of NASA (and perhaps with the Department of Defense) to develop training programs for its quality program personnel. These views were expressed predominantly at KSC and the Michoud Assembly Facility. (Note: Board report observation O10.4-3 addresses Kennedy training, but not Michoud or NASA-wide interest.)

Providing Necessary Tools

Irritants preventing inspectors from performing undistracted were discovered at Kennedy: Quality inspectors experienced difficulty and delays in attaining the tools they needed to do their work per specifications. Some purchased their own equipment, leading to concerns about configuration management of the equipment used in final inspections.

Government Inspections

The existing list of NASA Mission Assurance oversight inspections was based on a point-in-time engineering risk assessment with limited application of quality analysis and sampling techniques to determine the scope and frequency of inspections. Tasks were retained for government oversight on the basis of criticality, not process or quality assurance. By comparison, Marshall Mission Assurance retained government oversight options during its government inspections reduction by moving all the former Government Mandatory Inspection Points (GMIPs) into a new category, Surveillance Opportunities. These Surveillance Opportunities are no longer considered mandatory inspection points, but remain an optional area for Mission Assurance inspection. The MSFC Mission Assurance system includes feedback and closed loop systems to use in trend analysis and in development of future Mission Assurance tasks designed to improve quality. Mission Assurance-observed events that result in a Verbal Corrective Action Report are included in this tracking system, and are used to tailor surveillance or government inspections. ATK Thiokol goes further and calls the Mission Assurance office with a 15-minute warning when a Surveillance Opportunity is occurring, but by agreement, will not wait for the inspector in order to maintain job flow.

Quality Program Surveillance

> *Discovering these vulnerabilities and making them visible to the organization is crucial if we are to anticipate future failures and institute change to head them off.*
>
> –Woods and Cook,
> "Nine Steps to Move Forward from Error"[6]

In contrast to other NASA and contractor locations – where inspectors conduct unscheduled evaluations and observations – Quality Assurance Specialist surveillance is essentially nonexistent at Kennedy, despite reports that document organizational inconsistency within the NASA quality assurance construct. For example, the 2000 Space Shuttle Independent Assessment Team report echoed the Rogers Commission report with a lengthy discussion of the need for organizational independence and a strong presence. [7] "The Shuttle Independent Assessment Team believes strongly that an independent, visible Safety and Mission Assurance function is vital to the safe operation and maintenance of the Shuttle. The Shuttle program and its "one strike and you're out" environment is unlike most other defense or commercial industries. As a consequence, it is believed the industry trend toward reducing Safety and Mission Assurance oversight and functions is inappropriate for the Shuttle."[8] Among the Assessment Team's recommendations was a strong suggestion to restore surveillance.[9] This is consistent with the testimony of numerous Mission Assurance inspectors, technicians, and engineers to the Columbia Accident Investigation Board. Further, this surveillance should include concurrent inspections (for oversight of the contractor Mission Assurance function), and sequential or no-notice evaluations to improve "oversight by spontaneity."

> *Over the years, these organizations [HROs] have learned that there are particular kinds of error, often quite minor, that can escalate rapidly into major, system-threatening failures.*

–Reason, Managing the Risks of Organizational Accidents[10]

> *In discussing such reliable organizations, it's emphasized that, "The people in these organizations … are driven to use a proactive, preventive decision making strategy. Analysis and search come before as well as after errors … [and] encourage:*
> - *initiative to identify flaws in SOPs and nominate and validate changes in those that prove to be inadequate;*
> - *error avoidance without stifling initiative or (creating) operator rigidity ….*

–LaPorte and Consolini, in Reason's Managing the Risks of Organizational Accidents[11]

The Mission Assurance function of United Space Alliance (and other NASA contractors) samples a large amount of its workload and processes. The relatively minimal Kennedy Mission Assurance samples of United Space Alliance work is informal, and results are currently documented only in the Safety & Mission Assurance Reporting Tool database, which is used as a quality problem-tracking tool to help Mission Assurance identify trends and focus its approach to oversight and insight. Problems revealed by the sampling inspections or from the informal Reporting Tool database can be communicated to United Space Alliance through its Quality Control Assessment Tool (QCAT) system, but there is no contractual requirement for United Space Alliance to respond or even take corrective action. The Space Shuttle Processing Independent Assessment Report of 2001 noted succinctly: "Process surveillance as it exists today is not accomplishing its desired goals nor is it a true measure of the health of the work processes, as was its original stated objective."[12] Even in 2003, the Board found this is still true. To achieve greater effectiveness, sample-based inspections should include all aspects of production, and emphasis should go beyond "command performance" (announced and scheduled) inspections to validate United Space Alliance quality inspection results.

Kennedy Quality Assurance Specialist Position Descriptions – what the specialists are hired to do and tasks against which they are evaluated – actually require independent surveillance of contractor activity. However, Kennedy Quality Assurance Specialist surveillance is essentially nonexistent, as the Kennedy quality program manager actively discourages Quality Assurance Specialist unscheduled hardware surveillance. Testimony revealed that the manager actually threatened those who had conducted such activity, even after a Quality Assurance Specialist had found equipment marked "ground test only" installed on an Orbiter.

In an attempt to meet position description requirements and the basics of a solid surveillance program, a thorough surveillance program concept was developed by Kennedy Quality Assurance Specialists, presented, and accepted as "needed" by Space Shuttle Program management. However, rather than adapting it for Kennedy, this concept was never implemented, and Space Shuttle Program management was never informed of that decision. Ignoring surveillance – a Position Description requirement and a basic tenet of quality operations – is setting the stage for reliance upon "diving catches" referred to by the Space Shuttle Independent Assessment Team report.

> *Some HROs design in redundancy to ensure that there are several ways to catch problems before they become catastrophes. U.S. Navy aircraft carrier operations are characterized by much human redundancy in oversight of operations to make sure nothing is missed that can potentially turn into an accident.*

–Roberts and Brea, Must Accidents Happen? Lessons from High Reliability Organizations[13]

Findings:

- Kennedy Space Center's current government mandatory inspection process is both inadequate and difficult to expand even incrementally, inhibiting the ability of quality assurance to respond to an aging system, changing workforce dynamics, and process improvement initiatives.
- The Quality Planning Requirements Document, which defines inspection conditions, was originally well formulated; however, there is no requirement that it be routinely reviewed and updated as applicable.
- KSC has a separate Mission Assurance office working directly for each program, a separate Safety, Health, and Independent Assessment office under the center director, and separate quality engineers under each program. Integration of the quality program would be much better served if these were consolidated under one Mission Assurance office reporting to the center director.
- Past reports (such as the 1986 Rogers Commission, 2000 Shuttle Independent Assessment Team report, and 2003 internal Kennedy Tiger Team) affirmed the need for a strong and independent quality program, though the quality program management at Kennedy took an opposite tack.
- NASA's Kennedy Space Center Quality Assurance Program discrepancy-tracking program is inadequate

to nonexistent. Robust as recently as three years ago, KSC no longer has a "closed loop" system, where discrepancies and their remedies make a full circle back to the person who detected the discrepancy, and in turn to others across the system who may help prevent or detect similar discrepancies.
- Efforts by Kennedy Space Center quality management to move its workforce toward a "hands-off, eyes-off" approach to quality assurance are cause for alarm.
- Evidence underscored the need to expand government inspections, the need for increased surveillance, and a lack of communication between NASA centers and contractors regarding the disposition of "ground test only" components.
- Witness testimony and documentation submitted by witnesses revealed items that had been annotated "Fly as is," without proper disposition by the Material Review Board prior to flight, leading to a concern about a growing acceptability of risk at the Center level.
- KSC quality management discourages inspectors from rejecting contractor work; instead, it insists on working with the contractor to fix things in the process of the work being accomplished, versus rejecting it and returning for a re-evaluation only after it is fixed.
- The NASA Safety Reporting System was viewed as credible, and was effectively used to validate concerns that local management would not.
- Though most inspectors had extensive aviation and/or related military experience, there are examples where some individuals with no previous aviation, space, technical, or inspection background had been selected as Quality Assurance Specialists, and were making NASA final inspections for human space flight components.
- Following the 2000 Shuttle Independent Assessment Team report, some 35 new inspectors were added at Kennedy Space Center; however, most of that increase has eroded through retirements, promotions, departures, and one death.
- A review of other NASA center Quality Assurance Specialist staffing and grades revealed that Kennedy Space Center is the only NASA center evaluated that has Quality Assurance Specialist grades set at GS-11 – other centers have Quality Assurance Specialist grades set at GS-12.
- No formal NASA Kennedy Space Center training exists in the quality program for its quality engineers, process analysts, and quality assurance specialists.
- NASA-KSC Quality Assurance Specialist Position Descriptions require independent surveillance of contractor activity. However, Quality Assurance Specialist surveillance is discouraged and essentially nonexistent at Kennedy Space Center.
- Through extensive interviews at the Michoud Assembly Facility (MAF) – technicians to managers – plus an extensive review of work documents, we conclude that the MAF Quality Program Requirements Document (alternatively, the Mandatory Inspection Points document) is in need of review, for few believe it covers all of the critical items that government inspectors should be reviewing, and that it may force redundant or non-value added inspections.

Recommendations:

- (Note: This item is currently Observation O10.4-1 in the Board report. Due to the potential gravity of this item, it is urged this become a return-to-flight Recommendation.) Perform an independently led, bottom-up review of the Kennedy Space Center Quality Planning Requirements Document to address the entire quality assurance program and its administration. This review should include development of a responsive system to add or delete government mandatory inspections. Suggested Government Mandatory Inspection Point (GMIP) additions should be treated by higher review levels as justifying why they should not be added, versus making the lower levels justify why they should be added. Any GMIPs suggested for removal need concurrence of those in the chain of approval, including responsible engineers.
- (Note: Like the preceding item, this item is currently a subset of Observation O10.4-1 in the Board report; while it is urged this become a Recommendation, it does not need to be characterized as a return-to-flight recommendation.) Kennedy Space Center must develop and institutionalize a responsive bottom-up system to add to or subtract from Government Inspections in the future, starting with an annual Quality Planning Requirements Document review to ensure the program reflects the evolving nature of the Shuttle system and mission flow changes. At a minimum, this process should document and consider equally inputs from engineering, technicians, inspectors, analysts, contractors, and Problem Reporting and Corrective Action to adapt the following year's program.
- NASA Safety and Mission Assurance should establish a process inspection program to provide a valid evaluation of contractor daily operations, while in process, using statistically-driven sampling. Inspections should include all aspects of production, including training records, worker certification, etc., as well as Foreign Object Damage prevention. NASA should also add all process inspection findings to its tracking programs.
- The Kennedy quality program must emphasize forecasting and filling personnel vacancies with qualified candidates to help reduce overtime and allow inspectors to accomplish their position description requirements (i.e., more than the inspectors performing government inspections only, to include expanding into completing surveillance inspections).
- Job qualifications for new quality program hires must spell out criteria for applicants, and must be closely screened to ensure the selected applicants have backgrounds that ensure that NASA can conduct the most professional and thorough inspections possible.
- Marshall Space Flight Center should perform an independently-led bottom-up review of the Michoud Quality Planning Requirements Document to address the quality program and its administration. This review should include development of a responsive system to add or delete government mandatory inspections. Suggested Government Mandatory Inspection Point (GMIP) additions should be treated by higher review levels as justifying why they should not be added, ver-

sus making the lower levels justify why they should be added. Any GMIPs suggested for removal should need concurrence of those in the chain of approval, including responsible engineers.

- Michoud should develop and institutionalize a responsive bottom-up system to add to or subtract from Government Inspections in the future, starting with an annual Quality Planning Requirements Document review to ensure the program reflects the evolving nature of the Shuttle system and mission flow changes. Defense Contract Management Agency manpower at Michoud should be refined as an outcome of the QPRD review.
- (Note: This item is currently Observation O10.4-4 in the Board report; however to avoid further diluting the quality program focus, it is urged this become a Recommendation.) Kennedy Space Center should examine which areas of ISO 9000/9001 truly apply to a 20-year-old research and development system like the Space Shuttle.

Observations:

- As an outcome of the Quality Program Requirements Document review, manpower refinements may be warranted (for example, should a substantial change in Government Inspections justify additional personnel, adjust the manpower accordingly). While Board recommendations to evaluate quality requirement documents should drive decisions on additional staffing, in the interim, staffing with qualified people to current civil service position allocations should be expedited.
- (Note: This item is currently Observation O10.4-3 in the Board report.) NASA-wide quality assurance management must work with the rest of NASA (and perhaps with the Department of Defense) to develop training programs for its quality program personnel.
- An evaluation of the disparity of Quality Assurance Specialist civilian grades at Kennedy Space Center compared to other NASA centers should be accomplished to determine whether the current grade levels are appropriate.

ORBITER CORROSION

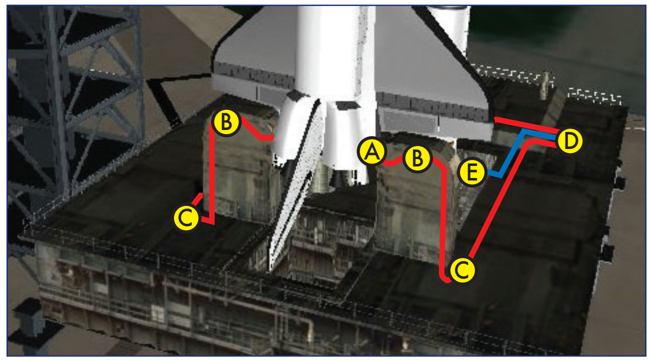
> *Dr. Gebman's draft [a RAND Corporation study's draft released to the New York Times] also says NASA has deferred inspections for corrosion, even though standing water had occasionally been found inside the* Atlantis *(which is still available to fly) and the* Columbia *after rainstorms. The* Columbia *and the* Discovery *have each had corrosion behind the crew cabin, a spot that is hard to inspect and hard to repair.*
>
> *At one time, NASA had a "corrosion control board," but the study said it apparently no longer exists.*
>
> –Wald, "Report Criticizes NASA and Predicts Further Fatal Accidents"[14]

Section 10.7 of the Board report does a great job of spelling out the dangers of and current NASA efforts to combat the effects of corrosion. The chapter also offers four observations to encourage NASA to continue to further its efforts. However, rather than remain an observation, O10.7-3 should be slightly reworded and become a recommendation:

Recommendation:

- Develop non-destructive evaluation inspections to detect and, as necessary, correct hidden corrosion.

HOLD-DOWN POST CABLE ANOMALY



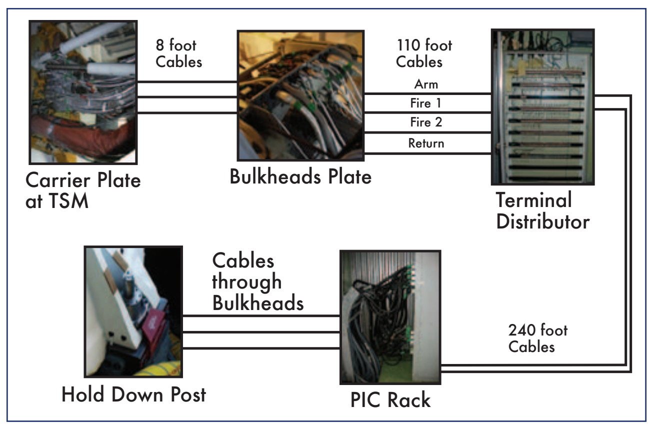


Figure S-1: Hold-Down Post/External Tank Vent Arm Systems diagram with nomenclature below (Note: This figure was not included in the final report Section 10.9; it is provided here for clarity.)

The signal to fire the HDP/ETVAS begins in the General Purpose Computers and goes to both of the Master Events Controllers (MECs). (See Figure S-1 for system routing.) MEC 1 communicates this signal to the A system cable, and MEC 2 feeds the B system. The cabling then goes through the Mobile Launch Platform mast to the Pyrotechnics Initiator Controllers (PICs; there are 16 PICs for A and B Hold-Down Posts, and 4 for A and B External Tank Vent Arm Systems); it then goes to each Solid Rocket Booster and Hold Down Post External Tank Vent Arm System. The A system is hard-wired to one of the initiators on each of the four nuts (eight total) that hold the Solid Rocket Booster to the Mobile Launch Platform. The B system cabling is hard-wired to the secondary initiator on each nut. The A and B systems also send a duplicate signal to the External Tank Vent Arm System. Either Master Events Controller will operate if the other or the intervening cabling fails. To verify cabling integrity, a continuity and ohms check is performed before each launch.

A post-launch review of STS-112 indicated that the A system Hold-Down Post and ETVAS PICs did not discharge. Initial troubleshooting revealed no malfunction, leading to the conclusion that the failure was intermittent. An extensive analysis was initiated, with some 25 different potential fault chains considered as the source of the A-system failure.

Recommendation:

- NASA should evaluate a redesign of the Hold-Down Post Cable, such as adding a cross-strapping cable or utilizing a laser initiator, and consider advanced testing to prevent intermittent failure.

Solid Rocket Booster External Tank Attach Ring

In Chapter 4, the Board noted how NASA's reliance on "analysis" to validate Shuttle components led to the use of flawed bolt catchers. NASA's use of this flawed "analysis" technique is endemic. The Board has found that such analysis was invoked, with potentially disastrous consequences, on the Solid Rocket Booster External Tank Attach Ring. Tests showed that the tensile strength of several of these rings was well below minimum safety requirements. This problem was brought to NASA's attention shortly before the launch of STS-107. To accommodate the launch schedule, the External Tanking Meeting Chair subsequently waived the minimum required safety factor of 1.4 for the Attach Rings (that is, able to withstand NASA-standard 1.4 times the maximum load ever expected in operations). Though NASA has formulated short- and long-term corrections, its long-term plan has not yet been approved by the Space Shuttle Program.

As a result of this finding, the Board issued an observation contained in Section 10.10 of the report. Due to the potential danger of this system experiencing a failure, this observation should become a recommendation.

Recommendation:

- NASA must reinstate a safety factor of 1.4 for the Attach Rings – which invalidates the use of ring serial numbers 15 and 16 in their present state – and replace all deficient material in the Attach Rings.

Other Issues

> *Leaders should listen and listen and listen. Only through listening can they find out what's really going on. If someone comes in to raise an issue with the leader and the leader does not allow the individual to state the full case and to get emotions out in the open, the leader is likely to understand only a piece of the story and the problem probably will not be solved.*
>
> –Smith, Taking Charge[15]

> *It's extremely important to see the smoke before the barn burns down.*
>
> -Creech, The Five Pillars of TQM[16]

Though discussed and submitted by various investigators, the observations that follow did not appear in the Board report. They are offered here to illuminate other aspects of the Space Shuttle Program observed during the course of the investigation.

Crew Survivability

The issues surrounding crew survivability are well covered in Chapter 3 and 10 of the Board report. However, only one observation came from that coverage, and no recommendations, instead deferring to NASA in its long-term evaluation of related issues through the work of the Crew Survivability Working Group. That Group is diligently pursuing improvements to future designs and to today's fleet. One example of a possible improvement to today's fleet is evidence presented to the Board that a small amount of additional insulation or ablative material adhering around the crew cabin (between the inner pressure vessel of the cabin and the outer shell of the Orbiter) might provide the thermal protection needed for the cabin to retain its structural integrity in certain extreme situations. Thus, it seems pertinent to offer a *recommendation* that NASA assess that and other near-term possibilities immediately.

Recommendation:

- To enhance the likelihood of crew survivability, NASA must evaluate the feasibility of improvements to protect the crew cabin of existing Orbiters.

Shiftwork And Overtime

In its Volume 2, Appendix G, on Human Factors Analysis, the Rogers Commission addressed the negative safety impacts of shiftwork and overtime. While Chapter 6 of our report addresses schedule pressure magnificently, it does not address directly issues of workforce morale resulting from that pressure. Workers, had they not been stressed by overtime, may have even highlighted items of concern such as foam fragility, and those concerns could have been acknowledged and potentially acted upon. Issues of excess overtime and staffing are worth including in this supplement, particularly as too much overtime is often indicative of too little manning. Indeed, there were some concerns expressed regarding overtime that provide evidence and resurrect "echoes of *Challenger*," making issues of excess overtime and manning worth including in this supplement:

Findings:

- Workers expressed concern over workflow scheduling. Workflow scheduling in some areas had become so challenging that 69 percent of interviewees related that overtime and its resultant family and workplace stress had become a significant factor in their work environment. Added to that stress, 75 percent related that overtime was not effectively scheduled, often being told on Friday afternoons that overtime would be required over the weekend.
- Workers expressed concern over staffing levels. Using excessive and unpredictable overtime as an indicator,

many employees remained convinced that achieving adequate staffing levels would not only allow adaptation to workflow schedules, but also prevent the stresses that accompany the excessive overtime they found themselves working.

RSRM Segments Shipping Security

The Columbia Accident Investigation Board examined security at NASA and its related facilities through a combination of employee interviews, site visits, briefing reviews, and discussions with security personnel. The Board focused primarily on reviewing the capability of unauthorized access to Shuttle system components. Facilities and programs examined for security and sabotage potential included ATK Thiokol in Utah and its Reusable Solid Rocket Motor production, the Michoud Assembly Facility in Louisiana and its External Tank production, and the Kennedy Space Center in Florida for its Orbiter and overall integration responsibilities. The Board also studied specific security preparations for STS-107, which, because the crew included an Israeli astronaut, were the most extensive in NASA history.

The Board visited the Boeing facility in Palmdale, California; Edwards Air Force Base in Edwards, California; Stennis Space Center in Bay St. Louis, Mississippi; Marshall Space Flight Center near Huntsville, Alabama; and Patrick Air Force Base at Cape Canaveral Air Force Station in Florida. These facilities exhibited a variety of security processes, according to each site's unique demands. At Kennedy, access to secure areas requires a series of identification card exchanges that electronically record each entry. The Michoud Assembly Facility employs similar measures, with additional security limiting access to a completed External Tank. The use of closed-circuit television systems complemented by security patrols is universal.

Employee screening and tracking measures appear solid across NASA and at the contractors examined by the Board. The agency relies on standard background and law enforcement checks to prevent the hiring of applicants with questionable records and the dismissal of those who may accrue such a record.

It is difficult for anyone to access critical Shuttle hardware alone or unobserved by a responsible NASA or contractor employee. With the exception of two processes when foam is applied to the External Tank at the Michoud Assembly Facility – and these are the subject of a Board processing recommendation – there are no known final closeouts of any Shuttle component that can be completed with fewer than two people. Most closeouts involve at least five to eight employees before the component is sealed and certified for flight. All payloads also undergo an extensive review to ensure proper processing and to verify that they pose no danger to the crew or the Orbiter.

The handling of redesigned Solid Rocket Motor segments in transit is a concern. Tight security surrounds the transport of completed segments from the ATK Thiokol plant to a Corrine, Utah, railhead, where they are loaded into hardened enclosures on flatbed rail cars. The segments are not loaded at once; it can take up to 12 days for all the segments to arrive at the rail yard. After the first segment is loaded onto a rail car, fences surrounding the railhead are locked, and ATK Thiokol uses occasional patrols and closed-circuit television to maintain security. Although stealing or destroying the segments would require heavy-lift equipment or a rail engine, this situation creates a vulnerability that should be addressed.

Findings:

- When ATK Thiokol completes an order, it transports completed segments to the Corrine, Utah, railhead. The segments are escorted by a host of vehicles on special transporters to the rail spur dedicated to ATK Thiokol that has no common access and is fenced off from public access.
- At the railhead, the segments are cross-loaded onto specially outfitted flatbed rail cars with a hardened enclosure for the booster. At this point the fences are closed and locked, and the booster is left to await delivery of the remaining segments to complete a SRB ship set. This wait time will typically approach 10-12 days.
- During this wait time, ATK Thiokol uses occasional patrols from the main compound and closed circuit TV to maintain vigilance. While theft or destruction of the booster would require heavy lift equipment or a rail engine, it appears to be an unnecessary vulnerability having such a component exposed without more stringent security.

Recommendation:

- NASA and ATK Thiokol perform a thorough security assessment of the RSRM segment security, from manufacturing to delivery to Kennedy Space Center, identifying vulnerabilities and identifying remedies for such vulnerabilities.

Michoud Assembly Facility Security

Findings:

- The Michoud Assembly Facility has a number of natural and manmade provisions to promote its security.
- Several gaps were noted that bear assessment, to include availability of 4-wheel drive vehicles, night vision goggles, and an assessment of security staffing for the large amount of property which must be covered in the manufacture and transport of the Shuttle External Tank.

Recommendation:

- NASA and Lockheed Martin complete an assessment of the Michoud Assembly Facility security, focusing on items to eliminate vulnerabilities in its current stance.

NOTE: ADDITIONAL SUPPLEMENTAL COMMENTS THAT CAN BE APPLIED TO PREVENTING THE NEXT ACCIDENT ARE AVAILABLE IN APPENDIX D.15.

ENDNOTES FOR THE APPENDIX D.a

The citations that contain a reference to "CAIB document" with CAB or CTF followed by seven to eleven digits, such as CAB001-0010, refer to a document in the Columbia Accident Investigation Board database maintained by the Department of Justice and archived at the National Archives.

1 James M. Strock, *Reagan on Leadership* (Roseville, CA: Forum, 1998), p. 104.

2 Jim Collins, *Good to Great* (New York: Harper Business, 2001), p. 88.

3 Ronald A. Heifetz, *Leadership Without Easy Answers* (Cambridge, MA: Harvard University Press, 1994), p. 22.

4 Douglas A. Wiegmann, Institute of Aviation of the University of Illinois, presentation before the Board, May 8, 2003. CAIB document CTF040-08750913.

5 Karlene H. Roberts, High Reliability Organizations, presentation before the Board, May 7, 2003. CAIB document CAB034-00430046.

6 D.D. Woods and R.I. Cook, "Nine Steps to Move Forward from Error," *Cognition, Technology, and Work* (2002), Vol 4, p. 140.

7 *Report of the Presidential Commission on the Space Shuttle Challenger Accident*, June 6, 1986, (Washington: Government Printing Office, 1986), Vol. I.

8 Space Shuttle Independent Assessment Team, Report to Associate Administrator, Oct.-Dec. 1999; March 7, 2001, p. 51.

9 Ibid.

10 James T. Reason, *Managing the Risks of Organizational Accidents* (Hampershire, England: Ashgate, 1997), pp. 214-215.

11 LaPorte and Consolini, as quoted in Reason, *Managing the Risks*, pp. 214-215.

12 Space Shuttle Independent Assessment Report for United Space Alliance, "Maintaining a National Treasure," April 23, 2001, p. 46. CAIB document CTF014-24802586.

13 Karlene H. Roberts and Robert Brea, "Must Accidents Happen? Lessons from High Reliability Organizations," *Academy of Management Executive*, 2001, Volume 15, No. 3, p 73.

14 Matthew L. Wald, "Report Criticizes NASA and Predicts Further Fatal Accidents," *New York Times*, July 15, 2003.

15 Perry M. Smith, *Taking Charge* (Garden City Park, NY: Avery, 1993), p. 89.

16 Bill Creech, *The Five Pillars of TQM* (New York: Truman Talley Books, 1994), p. 239.

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