AUDIT REPORT **IG-05-023**

SPACE SHUTTLE ORBITER WIRING INSPECTION

July 14, 2005

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Evelyn R. Klemstine
Assistant Inspector General for Auditing

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Executive Summary

The NASA Office of Inspector General initiated an audit with an overall objective of determining whether Agency actions regarding inspections of orbiter wiring were responsive to Columbia Accident Investigation Board (CAIB) Recommendation 4.2-2. The specific objectives were to determine whether (1) planned operational changes would make visual inspection more effective and (2) plans would enable the Agency to identify and test state-of-the-art evaluation technology and make tested technology available for the orbiter.

Background. In its August 2003 report, the CAIB recommended that "NASA should, as part of the Shuttle Service Life Extension Program and potential 40-year life, develop a state-of-the-art means to inspect all orbiter wiring, including that which is inaccessible." A significant amount of orbiter wiring (140 to 157 miles) is insulated with Kapton, a polyimide film used as electrical insulation. Kapton has been widely used in aircraft and spacecraft for more than 30 years because it is lightweight, nonflammable, has a wide operating temperature range, and resists damage. However, Kapton insulation can break down or become damaged with age, with mishandling, and from moisture. Since the CAIB recommendation, NASA has adopted the President's Vision for Space Exploration, which calls for the Space Shuttle retirement in 2010.

Results. To address Kapton concerns, the Space Shuttle Program modified visual inspection procedures for orbiter wiring. However, the Space Shuttle Program has not formally assessed the risk of aging and damaged wiring in accordance with NASA Procedural Requirements (NPR) 8000.4, "Risk Assessment Procedures," or developed a risk mitigation plan based on such an assessment. NASA has a well thought-out risk management policy. When NASA elects to bypass its risk management requirements, it is turning away from the safety and management principles built into the policy and is engaging in "decision-making processes that operate outside the organization's rules," which was cited in the CAIB report's executive summary. Without following the systematic risk management approach prescribed by NPR 8000.4, the Space Shuttle Program cannot ensure it has effectively managed the risks of aging and damaged orbiter wiring to increase the likelihood of flight safety.

Additionally, the Space Shuttle Program cancelled plans to develop and test state-of-the-art technology for evaluating orbiter wiring. As for whether CAIB Recommendation 4.2-2 has been met, we conclude that the recommendation has been overtaken by new events. The recommendation presumed that the Space Shuttle Program would continue to at least 2020; the President's Vision for Space Exploration reoriented NASA toward retiring the Shuttle in 2010, which removed the basis for the recommendation. However, it is important to note from a risk standpoint that without the new evaluation technology that was at the heart of Recommendation 4.2-2, the inability to detect problems with inaccessible wiring will continue to be a safety risk for the orbiter. Additionally, since there is no commitment to develop the

new evaluation techniques, any next generation space vehicle is likely to face challenges in evaluating damage to inaccessible wires.

Summary of Recommendations. We recommend that the Associate Administrator for the Space Operations Mission Directorate formally assess the risk of aging and damaged orbiter wiring in accordance with NPR 8000.4 and develop a risk mitigation plan based on the risk assessment. Additionally, the Associate Administrator for the Exploration Systems Mission Directorate and the Associate Administrator for the Space Operations Mission Directorate should establish a formal procedure that shares lessons learned on development of new nondestructive evaluation technology for wiring inspection of the Space Shuttle orbiter and/or next generation space vehicles.

Management Comments. Management concurred with our recommendations and is taking or has taken appropriate corrective actions. In response to our first recommendation, NASA's Associate Administrator for the Space Operations Mission Directorate agreed to initiate the process of formalizing wiring risk assessments to comply with NPR 8000.4. In response to our second recommendation, NASA's Associate Administrator for the Exploration Systems Mission Directorate and the Associate Administrator for the Space Operations Mission Directorate have begun to formally exchange information and lessons learned on new nondestructive wiring evaluation technology.

The complete text of management's response is in Appendix D.

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Acronyms Used in the Report

AFRL	Air Force Research Laboratory
CAIB	Columbia Accident Investigation Board
FY	Fiscal Year
NPR	NASA Procedural Requirements
PRCB	Program Requirements Control Board

SPACE SHUTTLE ORBITER WIRING INSPECTION

Objectives

The NASA Office of Inspector General initiated an audit with an overall objective of determining whether Agency actions regarding inspections of orbiter wiring were responsive to Columbia Accident Investigation Board (CAIB) Recommendation 4.2-2. The specific objectives were to determine whether (1) planned operational changes would make visual inspection more effective and (2) plans would enable the Agency to identify and test state-of-the-art evaluation technology and make tested technology available for the orbiter.

Background

A significant amount of orbiter wiring (140 to 157 miles) is insulated with Kapton, a polyimide film used as electrical insulation. Kapton has been widely used in aircraft and spacecraft for more than 30 years because it is lightweight, nonflammable, has a wide operating temperature range, and resists damage. However, Kapton insulation can break down or become damaged with age, with mishandling, and from environmental stresses, particularly moisture. Appendix B contains a bibliography related to Kapton-insulated wiring.

During the July 1999 launch of Columbia, a short-circuit 5 seconds after liftoff caused two of the six main engine controller computers to lose power, which could have caused one or two of the three main engines to shut down. The short-circuit incident was investigated and found to be caused by damaged Kapton wiring. Subsequent to the incident, visual inspection procedures were revised to limit wire damage from mishandling. Revised procedures state that the inspection would examine the outer wires of wiring bundles and would not examine wires inside wiring bundles unless insulation damage was noted on outer wires. If wire damage was noted on outer wires, the wire harness would be opened up to perform further inspections to ensure no other damage existed. To minimize damage of wiring in high traffic areas, wire protection made from convoluted tubing was installed over the wiring. As an added control to prevent damage, the Space Shuttle Program issued a new requirement that personnel who require entry into orbiter areas must complete wire damage awareness training.

In addition to revised visual inspection criteria, additional insight into the health of orbiter wiring is obtained through standardized electrical functional tests. Such tests are routinely performed during visual inspection and expanded during orbiter maintenance periods. An expanded test example is an electrical connector test. A functional electrical test is performed every time an orbiter connector is demated (unplugged) to ensure that the electrical circuits contained within the connector are operational.

The CAIB initially targeted Kapton-insulated wiring as a possible cause of the February 2003 Columbia accident because of previous problems with its use in the Space Shuttle and its implications in aviation accidents. Ultimately, the CAIB found no evidence that Kapton wiring problems caused or contributed to the accident and made no related recommendation for action before returning the Space Shuttle to flight. Nevertheless, the CAIB made Recommendation 4.2-2 in its August 2003 report because visual inspection could not detect wiring damage in inaccessible areas. The CAIB recommended that "NASA should, as part of the Shuttle Service Life Extension Program and potential 40-year life, develop a state-of-the-art means to inspect all orbiter wiring, including that which is inaccessible."

Finding A: Formal Assessment of Wiring Risk

The Space Shuttle Program had not performed a formal risk assessment for aging and damaged wiring in conformance with NASA requirements or developed a risk mitigation plan based on such an assessment. The Space Shuttle Program did not perform a formal risk assessment because the program obtained a general assessment of wiring risk from an analysis of historical wiring damage and the visual inspection process. A formal risk assessment will initiate a systematic process that ensures wiring risk will be effectively managed by the Space Shuttle Program team and objectively communicated to the program's stakeholders.

NASA Requirements

NASA Procedural Requirements (NPR) 8000.4 establishes risk management processes and requirements that the program team must follow throughout the program life cycle. NPR 8000.4 defines the following six-step continuous process for managing risk and requires the program team to complete specific procedures and documented outputs during each step:

1. **Identification.** The program team must identify program risks, describe the undesirable event each risk presents, and state the consequences of the event to the program. Outputs are a risk statement for each identified risk and a comprehensive list of the risk statements.

2. **Analysis.** The program team must perform a risk analysis. Procedures include an assessment of the consequences of each risk, an estimate of the likelihood that an identified risk will occur, a prioritization of risks based on their consequences and likelihood of occurrence, and a timeframe for preventive action. Outputs are clear estimations of the risk consequences, likelihood, timeframe for preventive action, and risk priority.

3. **Planning.** The program team must plan mitigation actions and assign responsibilities. Procedures include establishing criteria for accepting risks and documenting the rationale and acceptance of risk. Outputs are assignments of responsibility, individual risk mitigation plans, and rationale for accepted risks.

4. **Tracking.** The program team must collect, update, and analyze risk data and report risk trends. Procedures include determining whether risks are decreasing, staying the same, or increasing over time. Outputs are risk status reports.

5. **Control.** The program team must reevaluate risk mitigation actions based on recent tracking information. Outputs are documented decisions made by the appropriate decision maker with respect to risk.

6. **Documentation and Communication.** The program team must maintain a formal documentation trail within the program team and with stakeholders. Outputs include the program plan, acquisition plan, risk management plan, statement of risk, and risk list.

Risk Assessment and Mitigation Documents

Space Shuttle Program officials provided two documents as evidence of the wiring risk assessment and mitigation plan. The first document, the "Fleet Wire Inspection and Repair Status Review," dated October 1999, reported observations of wire damage from vibration, wire routing, and physical impact. The second document, the "New Wire Insulation Study for Potential Orbiter Use," dated June 2000, evaluated characteristics of currently available wire insulation to recommend a possible new wire insulation type for orbiter use.

The observations and evaluations in the documents would be useful inputs to identify and/or analyze risk but do not comply with the procedures or outputs that are required in NPR 8000.4. Specifically, the documents did not identify individual wiring risks, describe the undesirable events that the risk presents to the Space Shuttle, state the consequences of the events, estimate the likelihood that the consequences might occur, prioritize wiring risks based on their consequences and likelihood of occurrence, project a timeframe for preventive action, and state the actions that can be taken for each risk. The documents provided us showed no evidence of tracking or controlling the wiring risks that had been identified by the Space Shuttle Program. The documents were not outputs as described in NPR 8000.4.

Historical Damage and Visual Inspection

Space Shuttle Program officials stated that an analysis of wiring repairs on the orbiter showed that mishandling has historically caused wiring damage. Based on that analysis, program officials concluded that mishandling presented the greatest wiring risk. However, the officials reached that conclusion without formally assessing the risks associated with aging and damaged orbiter wiring.

Headquarters officials agreed that the Space Shuttle Program had not completed a formal risk assessment according to NPR 8000.4. Officials further stated that the Space Shuttle Program had a general assessment of wiring health and insight into wiring health through the visual inspection process without strictly following NASA risk assessment requirements.

Those officials cited additional measures taken by the Space Shuttle Program after the CAIB report to reduce wiring risk. For example, the Space Shuttle Program is separating redundant wires that are in the same wire bundle to minimize the risk of losing a critical system to which the wire bundle is attached. Redundant wires are designed to perform the same function and serve as a backup to each other should one of the wires fail during flight. Separation is completed on one orbiter and will be completed on the remaining two orbiters before the orbiters are returned to flight. The Space Shuttle Program also implemented a database that provides graphical images of wiring damage that show the severity and location of wiring damage. The Space Shuttle Program intends to use the images to pinpoint high damage locations so that a more thorough visual inspection can be conducted there.

Risks of Kapton-Insulated Wiring

Without following the systematic risk management approach prescribed by NPR 8000.4, the Space Shuttle Program cannot ensure it has effectively managed the risks of aging and damaged orbiter wiring to increase the likelihood of flight safety. Aging has been identified as a drawback of Kapton-insulated wiring and poses a potential risk for the Space Shuttle.

Aging and Environmental Effects on Kapton. Decades of use have revealed a significant defect with Kapton-insulated wiring that was not apparent during its development and initial use: Kapton insulation can break down or become damaged with age, with mishandling, and from moisture. The insulation damage that occurs is a condition referred to as aging. Wire that is aging is most susceptible to damage because the insulation becomes brittle and deteriorates over time. Minute insulation breaks can gradually occur.

To illustrate the vulnerability of Kapton insulation, the typical wiring bundle of an orbiter will experience extreme changes in heat, varying degrees of moisture, bending and contorting during installation, chaffing, and heavy vibrations. The Kapton insulation will begin to lose its elasticity because of the effects of time and harsh environmental elements—making it susceptible to becoming brittle. Such brittleness can cause radial and longitudinal breaks in the insulation. Insulation breaks or damage can potentially lead to a phenomenon known as arc tracking. Arc tracking takes place after carbon collects at the damaged area. After carbon deposits occur, Kapton becomes a conductor, leading to a "soft electrical short" that can cause systems to gradually fail or operate in a degraded fashion. For example, a soft electrical short in the wire system can cause a loss of critical functions in equipment, an unintended function of the equipment, or the loss of information regarding its operation. An electrical short in the wire system can lead to fire in an extreme case.

The useful life of a Kapton wire depends on the degree of deterioration of the polyimide insulation. A useful life for Kapton wire has not been established by research. Research has shown that the use of wiring over time is a factor in the deterioration of Kapton.

Age of Orbiter Wiring. Since the use of wiring over time has been associated with Kapton's deterioration, the age of wiring in the orbiters could indicate the potential for wiring deterioration. In calculating the age of the orbiter wiring, it was determined that the main wiring harnesses in the orbiters were manufactured 2 to 5 years before the orbiters were built. The following table identifies the remaining orbiters and shows that the main wiring harnesses have either reached or are nearing 25 years.

Age of Orbiter Wiring

Name of Orbiter Vehicle	Date Construction Began on Crew Module	Age of Wiring in Years
Discovery	August 1979	25+
Atlantis	March 1980	25+
Endeavor	February 1982	23+

Risk Should Be Assessed

In the near term, the Space Shuttle Program should formally assess and articulate the risks of aging and damaged orbiter wiring. A formal risk assessment ensures that wiring risk is not only identified and analyzed but effectively tracked, controlled, and communicated with the program team. A formal risk assessment also initiates a process that objectively documents and communicates risk management steps to the program's stakeholders. The Space Shuttle Program has implemented destructive evaluation of wiring removed during orbiter rework to determine the extent of wire aging. The destructive evaluation should provide data on wire aging that will serve as a first step in performing a formal wiring risk assessment.

Recommendation for Corrective Action

1. **The Associate Administrator for the Space Operations Mission Directorate should formally assess the risk of aging and damaged orbiter wiring in accordance with NPR 8000.4 and develop a risk mitigation plan based on the risk assessment.**

Management's Response. Management concurred and agreed to initiate the process of formalizing wiring risk assessments to comply with NPR 8000.4. In response to the lack of a comprehensive risk assessment conducted concerning orbiter wiring, the Associate Administrator for the Space Operations Mission Directorate stated that the Space Shuttle Program team has developed specific criteria for inspecting orbiter wiring and has refined wiring crimping techniques and specific criteria for inspecting orbiter wiring, to include baseline wire inspections. The team has implemented Critical 1[1] hardware wire separation and arc tracking modifications on all vehicles, significantly reducing the relative risk for loss of a crew or vehicle associated with a wiring event. The Associate Administrator noted that significant wire health assessments and improvements had been incorporated throughout the life of the Space Shuttle Program, to include refinement of wiring crimping techniques and inspection criteria, separation of wires performing criticality 1 functions, and additional wire protection modifications to minimize damage. He also stated that the orbiter wiring team maintains a comprehensive database of all wire damage identified across the fleet to assist in the management of potential wiring risk and to drive criteria for damage migration.

Evaluation of Management's Response. Management's actions are responsive to the recommendation. We consider the recommendation resolved, but the recommendation will remain open for reporting purposes pending completion of necessary corrective action. The complete text of management's response is in Appendix D.

[1] Items specified as Critical 1 are items that could cause the loss of crew, vehicle, or ground personnel, or could endanger the public, in the event of failure.

Finding B: Cancellation of Plan for New Evaluation Technology

The Space Shuttle Program Requirements Control Board (PRCB) cancelled development and testing of new technology for evaluating the condition of orbiter wiring. The PRCB decision was based on a conclusion that new technology would not be ready before 2010, a conclusion that developing new evaluation technology would not be cost effective because of the planned 2010 Shuttle retirement, and funding constraints. New evaluation technology could improve NASA's ability to detect damage to wiring not examined during visual inspections as well as enhance the safety of the orbiter and any next generation space vehicle that uses Kapton-insulated wiring.

CAIB Recommendation

In fall 2003, the Space Shuttle Program Office tasked the Wiring Working Group with developing a plan to respond to CAIB Recommendation 4.2-2. That recommendation stated, "NASA should, as part of the Shuttle Service Life Extension Program and potential 40-year life, develop a state-of-the-art means to inspect all orbiter wiring, including that which is inaccessible." The intent of the recommendation was for NASA to develop new nondestructive evaluation technology more advanced than technology used in visual inspection. The Working Group's plan, known as the Four-Prong Plan, contained four elements: (1) continue visual inspection, (2) develop nondestructive technology to evaluate wiring in the orbiters, (3) conduct destructive evaluation of damaged wiring removed from the orbiters, and (4) fund a study to determine feasibility of replacing orbiter wiring.

Decision on the Four-Prong Plan

Prongs 1, 3, and 4 of the Four-Prong Plan (visual inspection, destructive evaluation, and a feasibility study) did not relate to developing a state-of-the-art means of inspection. However, Prong 2 of the Four-Prong Plan involved developing new nondestructive evaluation technology that could automate wire damage detection as well as predict the remaining useful life of orbiter wiring. Prong 2 recommended three new nondestructive evaluation technologies (technology that could be used in the orbiter without removing wiring for testing): an insulation tester, age-life tester, and ultrasonic crimp joint tool. An insulation tester allows for detection of subtle defects in wiring insulation and shields. The tester would automate detection through software signal processing. Age-life testers could determine insulation degradation as a result of aging and the environment. The age-life testers considered several technologies, which included an ultrasonic tester, wire indenter, and infrared spectroscopy. An ultrasonic crimp joint tool could measure the integrity of a wire crimp when wires are spliced during maintenance or repair work.

In June 2004, the Wiring Working Group presented the Four-Prong Plan to the PRCB. The PRCB decided to continue visual inspection (Prong 1) and conduct destructive evaluation (Prong 3) and not to pursue development of new nondestructive evaluation technology (Prong 2) or the feasibility study on wiring replacement (Prong 4). The PRCB made the decision after consideration of the revised Space Shuttle service life, the readiness of new evaluation technology, and funding constraints.

Revised Shuttle Service Life. On January 14, 2004, the President announced a new vision for the Nation's space exploration program that would retire the Space Shuttle in 2010. The 2010 retirement would effectively reduce the Space Shuttle's planned service life from 40 years to less than 30 years. The PRCB concluded that the CAIB recommendation related to wiring was no longer feasible because flights would not continue after 2010 and the remaining service life of the Space Shuttle would be insufficient to develop and incorporate new evaluation technology.

However, one CAIB investigator involved in the assessment of Kapton wiring issues stated that the intent of Recommendation 4.2-2 was that NASA should develop and implement new nondestructive evaluation technology for inspecting orbiter wiring regardless of the retirement date. In addition, the investigator stated that NASA should still pursue research and development of new evaluation technology because visual inspection alone would not detect wiring and insulation problems that could cause systems to gradually fail or operate in a degraded fashion.

Readiness of New Evaluation Technology. In deciding to cancel development of new nondestructive evaluation technology, the PRCB concluded that a proof of concept would occur during Fiscal Year (FY) 2005 but that the technology would not be operational until 2009 at the earliest. The PRCB concluded that because new nondestructive evaluation technology was unlikely to be made operational before 2009, the evaluation technology would benefit only Space Shuttle flights planned from 2009 through the new Space Shuttle retirement date of 2010. However, an official from the Air Force Research Laboratory (AFRL) who conducts research on aging aircraft wiring stated that a developmental test system might be available by the end of 2006.

The same AFRL official stated that, although not yet suitable for the orbiter, diagnostic systems for wiring are being used today on commercial and military aircraft to identify and locate wiring problems. A study that two AFRL researchers presented at the Joint Conference of Aging Aircraft in September 2002[2] projected that new technologies capable of diagnosing intermittent failures and damaged wiring might be available between 2004 and 2008.

Funding Constraints. Between January and July 2004, NASA estimated the cost to implement the 29 recommendations[3] that the CAIB made at $450 million to $760 million more than the $1.082 billion the Agency requested in its FY 2005 budget (see Appendix C for details of funded return-to-flight activities associated with the CAIB recommendations).

The Space Shuttle Program Office estimated that the Four-Prong Plan would cost $12.6 million—$12.0 million to develop new nondestructive evaluation technology and

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[2] "Aircraft Wiring System Integrity Initiatives – A Government and Industry Partnership," presented by George A. Slenski and Joseph S. Kuzniar of the Materials and Manufacturing Directorate, AFRL.

[3] The August 2003 report of the CAIB contained a total of 29 recommendations related to the physical and organizational/cultural causes of the accident. The CAIB identified 15 recommendations mostly related to the physical causes of the accident as "before return to flight" that must be addressed before the Space Shuttle returns to flight. The remaining 14 recommendations were viewed by the CAIB as "continuing to fly" recommendations that reflect the Board's views on what's needed to safely operate the Space Shuttle and future spacecraft in the mid- to long-term.

$600,000 to conduct destructive evaluation. The Four-Prong Plan did not identify costs for visual inspection and the wire replacement study in the $12.6-million estimate. Visual inspections would be funded from Shuttle operations funds because they are an ongoing part of operations, and a cost estimate had not been completed for the wire replacement study. In August 2004, the Space Shuttle Program prepared closeout plans for CAIB Recommendation 4.2-2, which showed no funding after FY 2004 for either new nondestructive evaluation technology or destructive evaluation.

Wiring Not Examined During Visual Inspection

Visual inspections of orbiter wiring involve examining the outer wires of a bundle and not the wires inside the bundle. Wires inside the bundle are inspected only when insulation damage is detected on the outer wires. The inspection then includes a 360-degree check of loose wires and the area of insulation damage. Figure 1 shows wiring bundles within the crew module of the orbiter Atlantis.

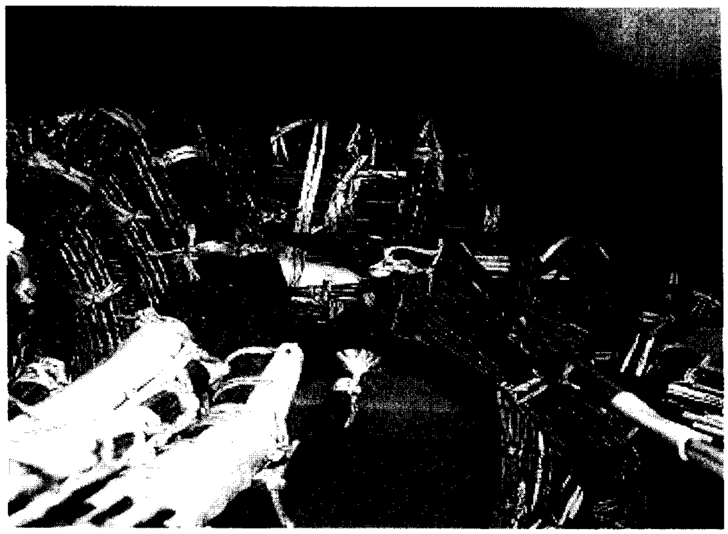

Figure 1. Wiring Bundles Within the Crew Module of Orbiter Atlantis

Visual inspection is limited because inaccessible wiring may not be examined for damage. Inaccessible wiring includes wire bundles in locations that are too constricted to permit the inspector to reach the wiring with inspection tools, which consist of a small magnifying lens and a flat metal spatula held behind the wiring. Also, wires inside a wire bundle are obscured from view by other wiring and not examined unless damage is noted on the outer wires in the bundle. More intrusive inspection of orbiter locations that are inaccessible to visual inspection would require the inspector to pull apart, pull down, or otherwise disturb wire bundles. Figure 2 shows a visual inspection of wiring in the payload bay of the orbiter Atlantis.

Figure 2. Visual Inspection of Wiring in the Payload Bay of Orbiter Atlantis

The CAIB reported that 1,700 feet of Kapton wiring was inaccessible but did not state whether the amount included wire bundles in inaccessible locations and/or wires inside wire bundles. Space Shuttle Program staff at Kennedy calculated that roughly 86 percent[4] of the orbiter's wiring is inaccessible and generally not examined during a visual inspection. The 86 percent calculation conservatively estimated the amount of inaccessible wiring since it did not consider wires inside wire bundles.

After NASA retires the Space Shuttle, any next generation space vehicle may use Kapton wiring and will need a way of inspecting inaccessible and unseen wiring. Wiring officials with the Space Shuttle Program confirmed that no good substitute has been developed to replace Kapton wiring in space vehicles.

New Evaluation Technology Should Be Developed

In the longer term, only state-of-the-art technology might substantially improve an inspection by evaluating the condition of unseen wiring. New nondestructive evaluation technology could detect minute damage that cannot be identified through a visual inspection. For example, the age-life tester could be used to predict when the Kapton insulation would begin to fail by determining its degradation caused by time and the environment. Although testing inaccessible wiring was not a requirement of the age-life tester, that approach was one of the methods the Space Shuttle Program designed to determine when or if the orbiter would require rewiring.

Because new nondestructive evaluation technology could benefit the next generation of space vehicles, NASA should take action to facilitate reestablishing plans for developing the technology. The Space Operations Mission Directorate oversees the Space Shuttle Program Office, which had identified and assessed new nondestructive evaluation technologies and prepared development plans. The Exploration Systems Mission Directorate oversees the programs for next generation space vehicles. The two Mission Directorates should establish a

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[4] The calculation was made by engineering staff of the Orbiter Electrical, Power, Distribution, and Control Group at Kennedy Space Center and is available on an internal Web site.

formal procedure to share lessons learned by the Space Shuttle Program during the planning of new technology development. Sharing of this information will facilitate the development of nondestructive evaluation technology for wiring inspection in the Shuttle and/or next generation space vehicles.

Recommendation for Corrective Action

2. **The Associate Administrator for the Exploration Systems Mission Directorate and the Associate Administrator for the Space Operations Mission Directorate should establish a formal procedure that shares lessons learned on development of new nondestructive evaluation technology for wiring inspection of the Space Shuttle orbiter and/or next generation space vehicles.**

Management's Response. Management concurred and stated that implementation of a formal procedure has begun. Implementation will include formal exchanges of information and lessons learned between the Space Operations Mission Directorate and the Crew Exploration Vehicle Team and subsequent Exploration Systems Mission Directorate programs and projects. The Space Operations and Exploration Systems Mission Directorates will continue to document and share lessons learned and determine the need for and scope of complex electrical system integrity and wire system nondestructive evaluation research.

Evaluation of Management's Response. Management's actions are responsive to the recommendation and we consider the recommendation closed for reporting purposes. However, we will continue to monitor the technical recommendations resulting from the exchange of information. The complete text of management's response is in Appendix D.

Appendix A. Scope and Methodology

Scope and Methodology

We interviewed personnel directly involved in CAIB Recommendation 4.2-2 and wiring visual inspection, which included personnel at the Space Shuttle Program Office, the Kennedy Space Center Quality Assurance Office, and two contractors. Specific personnel interviewed included the Wiring Project Manager, quality assurance officials and inspectors, Space Shuttle Program officials and engineers, and other management and contractor officials. We participated in meetings of the orbiter wiring project team. An official from AFRL provided information on Kapton and evaluation technologies. We also interviewed the leader of the CAIB team and a CAIB evaluator for orbiter wiring issues.

The audit team observed visual inspection procedures and reviewed inspection policies for the orbiter. The team reviewed technical studies on wire aging and inspection, including a report by the Government Accountability Office, "Aviation Safety, FAA and DoD Response to Similar Safety Concerns," GAO-02-77, dated January 2002. We reviewed the CAIB report; Space Shuttle Program plans for implementing CAIB Recommendation 4.2-2 (the Four-Prong Plan); notes from the June 2004 meeting of the PRCB; the closeout plan for CAIB Recommendation 4.2-2, dated August 2004; and pertinent sections of the "NASA Implementation Plan for Return to Flight and Beyond" (Implementation Plan), August and December 2004. Our review of those plans included an evaluation of planned actions and funding.

The audit team received technical assistance from an electrical engineer and an aerospace engineer technologist. Those employees researched properties of Kapton-insulated wiring used in the orbiter, identified best practices for inspections and new technologies for evaluation, reviewed studies of evaluation technologies, and evaluated the status of new technologies. The aerospace engineer technologist also reviewed the estimated percentage of inaccessible orbiter wiring that was calculated by Space Shuttle Program engineering staff at Kennedy Space Center. To verify the estimated percentages, the aerospace engineer technologist reviewed the methodology and supporting data and retraced calculations used to derive the estimated percentage.

Use of Computer-Processed Data

We did not assess the reliability of computer-processed data because we did not rely on it to achieve our objectives.

Management Controls

Specific management controls we reviewed were wiring risk mitigation procedures, actions taken in response to CAIB Recommendation 4.2-2, and procedures to communicate Space Shuttle Program Office plans for the recommendation in the Implementation Plan.

Audit Work

We performed audit field work from January 2004 through June 2005 at Johnson Space Center and Kennedy Space Center. We performed the audit in accordance with generally accepted government auditing standards.

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36. Space Shuttle Independent Assessment Team, Henry McDonald, Chair. Space Shuttle Independent Assessment Team Report to Associate Administrator, Office of Space Flight. March 7, 2000. http://history.nasa.gov/sait.pdf.

Appendix C. Funded Return-to-Flight Activities

As of December 2004, NASA had funded the following return-to-flight activities (listed in the Implementation Plan) that were associated with the 29 recommendations that the CAIB made:

Orbiter Reinforced Carbon-Carbon Inspections
On-orbit and Tile Repair
Orbiter Workforce
Orbiter Thermal Protection System Hardening
Orbiter Government-furnished Equipment
Orbiter Contingency
Orbiter Certification and Verification
External Tank Items (Camera and Bipod Ramp)
Solid Rocket Booster Items (Bolt Catcher, External Tank Assembly Ring, and Camera)
Ground Camera Ascent Imagery Upgrade
Kennedy Space Center Ground Operations Workforce
Other (Systems Integration, Full Cost Accounting, Additional Workforce)
Stafford-Covey Team (Return-to-Flight Task Group)

Appendix D. Management's Response

National Aeronautics and
Space Administration
Headquarters
Washington, DC 20546-0001

June 28, 2005

Reply to Attn of:

Space Operations Mission Directorate

TO: Inspector General

FROM: Associate Administrator, Space Operations Mission Directorate

SUBJECT: Draft Audit Report titled "Space Shuttle Orbiter Wiring Inspection" (Assignment number A-04-010-00)

Please find below the enclosed Space Operations Mission Directorate (SOMD) and Exploration Systems Mission Directorate (ESMD) comments and responses to the above NASA Office of Inspector General (OIG) audit report.

We acknowledge the hard work and professionalism of the NASA OIG in their recent audit of the Space Shuttle program's Orbiter wiring inspections efforts as they relate to the Columbia Accident Investigation Board's (CAIB) recommendation 4.2-2. We are always looking for opportunities to improve ourselves and our systems and appreciate your insights.

We concur with both of your recommendations and will initiate the process of formalizing our Orbiter wiring risk assessments as to comply with NPR 8000.4. Your recommendation to establish a formal exchange with the ESMD is already underway and valuable lessons learned are being transmitted.

As programs and projects evolve in ESMD, Systems Technical Warrant Holders (STWHs) will be selected per the NASA Technical Authority guidelines. Discipline Technical Warrant Holders (DTWHs) have already been involved in the review of ESMD requirements and acquisition documents. The DTWHs are responsible for:

- Approval of all new or updated NASA Preferred Standards (including nondestructive evaluation (NDE)) within their assigned disciplines,
- Interfacing with other warrant holders, promoting communication throughout the Agency's technical community to ensure that appropriate individuals and organizations are aware of technical issues, and
- Proactively communicating best practices, improving standards, providing technical recommendations, and monitoring the general health of their respective disciplines.

ESMD is in contact with the Shuttle STWH, Electrical Power Distribution and Control DTWH, Nondestructive Evaluation DTWH, and NASA Technical Standards Program to:

- Ensure we establish a dialog on this issue,
- Document specific lessons learned, and
- Determine the need for and scope of complex electrical system integrity and wire system NDE research.

This information will be shared with the Crew Exploration Vehicle Team and subsequent ESMD programs/projects as well as with SOMD. Within the ESMD risk management community, they will ensure that this effort is coordinated between the Exploration Systems Research and Technology Division and Constellation Systems organizations.

With the announcement of the Vision for Space Exploration in January 2004, the goals and objectives of the Space Shuttle Program (SSP) have dramatically changed. This change is felt particularly in the operational life of the Orbiter. Prior to the announcement, the SSP was planning on flying until at least 2020; now we are preparing for an Orbiter retirement in 2010. This is a significant variation and, as would be expected, has necessitated an alteration in our operations strategy.

The initial responses to the CAIB recommendation 4.2-2 were based on operating the Orbiter to 2020 and beyond. To adjust to the 2010 date, we have modified our approach and have reflected this in our most recent update to *NASA's Implementation Plan for Space Shuttle Return to Flight and Beyond*.

In response to the lack of a comprehensive risk assessment conducted concerning Orbiter wiring, the SSP team has developed specific criteria for inspecting Orbiter wiring (i.e., baseline wire inspections). Also, since we have implemented Critical 1 hardware wire separation and arc tracking modifications on all vehicles, the relative risk for loss of crew/vehicle associated with a wiring event has been significantly reduced. In addition, the Orbiter wiring team maintains a comprehensive database of all wire damage that is identified across the entire fleet. This tool assists in the management of potential areas of wiring risk and drives future criteria for damage mitigation. We are also continuing our destructive testing and analysis from which we will glean all available information to further advance our understanding of the lifetime characteristics of Kapton wiring.

It is noteworthy that significant wire health assessments and improvements have been incorporated throughout the life of the SSP. Most notable were those following the wiring concerns stemming from the STS-93 flight including:

- Refinement of wiring crimping techniques and inspection criteria.

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- Separation of wires performing criticality 1 functions (loss of which could lead to loss of crew/vehicle) needed to attenuate potential impacts to critical systems that might be affected during an arc tracking incident.

- Additional wire protection modifications to minimize potential wire damage.

As was stated in the *NASA Implementation Plan for Space Shuttle Return to Flight and Beyond*, the SSP has approved, after careful review, the implementation of option 1 (inspect and protect) and option 3 (perform destructive evaluations), as related to the initial four prong approach that was provided in response to the CAIB's recommendation 4.2-2. The decision not to go forward with option 2(develop NDE technology), does not suggest we have given up on a dedicated NDE tool. Throughout the life of the SSP, vendors have provided NASA with NDE type equipment for evaluation. We are currently evaluating a system now. If our engineers find that an NDE tool has value, we will pursue it. In regard to option 4 (evaluate Orbiter wire replacement), given the new Shuttle retirement date, it now becomes unrealistic to consider the replacement of *all* the Orbiter wiring. This time and effort is better spent on inspection and prevention. However, wire segments will be replaced where practical. This philosophy has been routinely implemented throughout the life of the program and is performed on a case by case basis where wire segment damage is considered to be extensive.

It should also be noted that a type of NDE is being performed on the wiring every time power is applied to the Orbiter. In addition, SSP regularly conducts numerous NDE type electrical system checks during scheduled Orbiter processing to validate the electrical paths provided by the wiring. These tests are performed by all onboard subsystems that use electrical power. As an added authentication, every time an Orbiter connector is demated / mated an electrical test is performed on each of its pins to ensure circuit integrity. This occurs hundreds of times during a standard Orbiter processing flow. In addition to these electrical validations, technicians, engineers and quality control personnel routinely perform visual wire inspections. As an added precaution, before an area within the Orbiter can be closed out for flight, an additional visual inspection is performed.

Periodically, each Orbiter is subjected to extensive maintenance down-time periods or Orbiter Major Modifications (OMM) in which modifications and more in-depth visual inspections are performed. These include inspecting areas that are normally inaccessible during a standard processing flow as well as re-inspecting areas that were done during normal processing, thus providing additional insight to the health of the wiring systems. Also, during an OMM period additional electrical validation tests are performed above and beyond those tests that are performed during a standard flow. We have completed the OV-103 OMM wiring inspections prior to STS-114. We are completing the OV-105 inspections during its current OMM, and we will follow up with the inspections on OV-104 in 2007.

Certain types of routinely performed wire repairs provide NDE type insight into wiring health. These repairs necessitate a circuit integrity test to verify that the repair was done correctly. This retest not only verifies the repair, it also provides additional insight to the

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health of the entire wire segment from source to load. And depending on the wire type and function, additional circuit integrity tests are performed above and beyond the normal electrical parameters that the wire segment would see during standard operation.

As your report details, the complexity of evaluating the miles of wire flowing through each Orbiter is very difficult to fully encompass. The need for diligent examination and testing of the wiring will continuously evolve within the framework of the Shuttle program. We are committed to this undertaking now and through our last flight.

Sincerely,

William Readdy

William F. Readdy

Appendix E. Report Distribution

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Major Contributors to the Report

Nora E. Thompson, Program Manager

Stephen D. DeVillo, Aerospace Technologist

Sandra Leibold, Auditor