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 V
APPENDICES G.1 - G.9
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.

Maj. Gen. John L. Barry
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THE ACCIDENT

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Chapter 2	Columbia's Final Flight
Chapter 3	Accident Analysis
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Part Two	WHY THE ACCIDENT OCCURRED
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Reader's Guide to Volume V

Volume V of the Report contains appendices that were not cited in Volume I. These consist of documents produced by NASA and other organizations, which were provided to the Columbia Accident Investigation Board in support of its inquiry into the February 1, 2003 destruction of the Space Shuttle *Columbia*. The documents are compiled in this volume in the interest of establishing a complete record, but they do not necessarily represent the views of the Board. Volume I contains the Board's findings, analysis, and recommendations. The documents in Volume V are also contained in their original color format on the DVD disc in the back of Volume II.



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Volume V Appendix G.1

Requirements and Procedures for Certification of Flight Readiness

This Appendix contains NASA NSTS 08117 Revision L, December 13, 1995 document <u>Space Shuttle</u>, <u>Requirements and Procedures for Certification of Flight Readiness</u>.



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NSTS 08117 REVISION L DECEMBER 13, 1995

Lyndon B. Johnson Space Center Houston, Texas 77058

SPACE SHUTTLE

REQUIREMENTS AND PROCEDURES FOR CERTIFICATION OF FLIGHT READINESS



FOREWORD

Efficient management of the Space Shuttle Program (SSP) dictates that effective control of program activities be established. Requirements, directives, procedures, interface agreements, and system capabilities shall be documented, baselined, and subsequently controlled by SSP management.

Program requirements controlled by the Manager, Space Shuttle Program, are documented in, attached to, or referenced from Volumes I through XVIII of NSTS 07700. NSTS 08117, Requirements and Procedures for Certification of Flight Readiness Requirements, establishes a standard approach to be used jointly by contractors and NASA to incrementally review flight preparation of the Space Shuttle Vehicle (SSV). The requirements and procedures herein provide a means for assuring a uniform flight readiness assessment of all SSV elements.

All elements of the SSP must adhere to these baselined requirements. When it is considered by the Space Shuttle Program/Project Managers to be in the best interest of the SSP to change, waive, or deviate from these requirements, an SSP Change Request (CR) shall be submitted to the Program Requirements Control Board (PRCB) Secretary. The CR must include a complete description of the change, waiver, or deviation and the rationale to justify its consideration. All such requests will be processed in accordance with NSTS 07700, Volume IV, and dispositioned by the Manager, Space Shuttle Program, on a Space Shuttle PRCB Directive (PRCBD).

Loren J. Shriver

Manager, Launch Integration, KSC

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1.0 INTRODUCTION

1.1 PURPOSE

The purpose of this document is to define the Space Shuttle Program (SSP) Flight Preparation Process (FPP). It defines the procedures for the Project Milestone Reviews, the Program Milestone Reviews and the Flight Readiness Review (FRR). It also defines the endorsement documentation required at the completion of the FRR which provides the Certification of Flight Readiness (CoFR) for a specific flight.

1.2 SCOPE

This document is applicable to JSC, KSC, MSFC, Stennis Space Center (SSC), and SSP NASA and contractor organizations and personnel involved in the conduct of Space Shuttle operations. The FPP consists of the required preparations for a Space Shuttle mission, from the baselining of the processing requirements to acceptance of the major hardware elements through processing, mating, launch, and ferry when required. The major elements of the FPP are the Project Milestone Reviews, three Program Milestone Reviews, and the FRR where the CoFR endorsement is signed. Reviews of the activities that support the FPP are considered part of the CoFR process.

This Revision L identifies the processes and requirements for all milestone reviews and the FRR for STS–78 and subsequent flights. Revision K applies to prior flights.

1.3 PROCESS DESCRIPTION

The FPP is structured to baseline a set of processing requirements through a series of requirements reviews and to incrementally review and status progress towards readiness for flight (reference Figure 1). It represents a commitment by each of the SSP element and project managers (NASA and contractor) certifying that their organizations have satisfactorily completed the requirements and their respective portions of the effort required to safely support each flight. The FPP is incrementally implemented through milestone reviews and an FRR which ensures the readiness of all organizations for the operational phase following each review. The FPP consists of Project Milestone Reviews, three Program Milestone Reviews and the FRR. The Project Milestone Reviews are the DD 250/1149-Element Acceptance Reviews, the Payload Readiness Review (PRR), the Software Readiness Review (SRR), and the organizational Pre-FRR Reviews. The three Program Milestone Reviews are the Pre-Mate Milestone Reviews, consisting of the External Tank (ET)/Solid Rocket Booster (SRB) Mate Milestone Review and the Orbiter Rollout/ET Mate Milestone Review, and a Ferry Flight Readiness Milestone Review which is conducted when a ferry is required. The CoFR endorsement is signed at the FRR. A Prelaunch Mission Management Team (PMMT) Review will be conducted on the Launch Minus Two (L-2) Day or Launch

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Minus One (L-1) Day when the Mission Management Team (MMT) is activated to status the launch countdown and address any issues remaining from the FRR (reference Figure 2). (Reference NSTS 07700 Volume III, Flight Definition and Requirements Directive; NSTS 07700, Volume IV, Configuration Management Requirements; and NSTS 07700, Volume VIII, Operations, Appendix D.)

1.4 RESPONSIBILITIES

The Manager, Launch Integration shall manage the FPP. SSP organizations and their respective contractors are responsible for implementing the FPPs as outlined in the appendices of this document. The implementation will be done by certifying that the required work under their purview, as defined in the Flight Preparation Process Plans (FPPPs) for each certifying organization, has been satisfactorily completed and will safely support the specified flight.

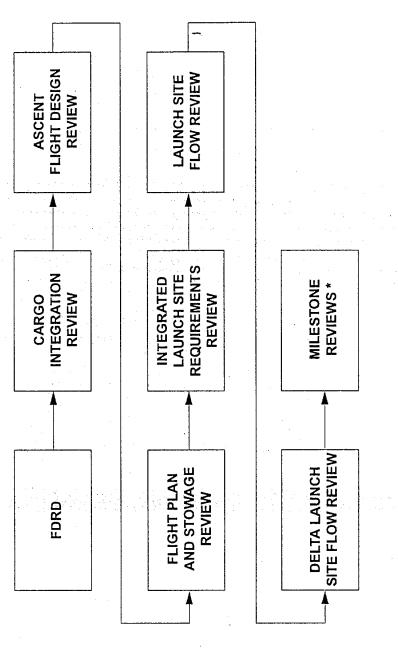
The review secretariat function for Program Milestone Reviews and the FRR shall be the responsibility of the Space Flight Operations Contract (SFOC) Program Integration Office at KSC. The secretariat function for the Project Milestone Reviews, shall be the responsibility of the review Chair.

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FIGURE 1

FLIGHT PREPARATION PROCESS



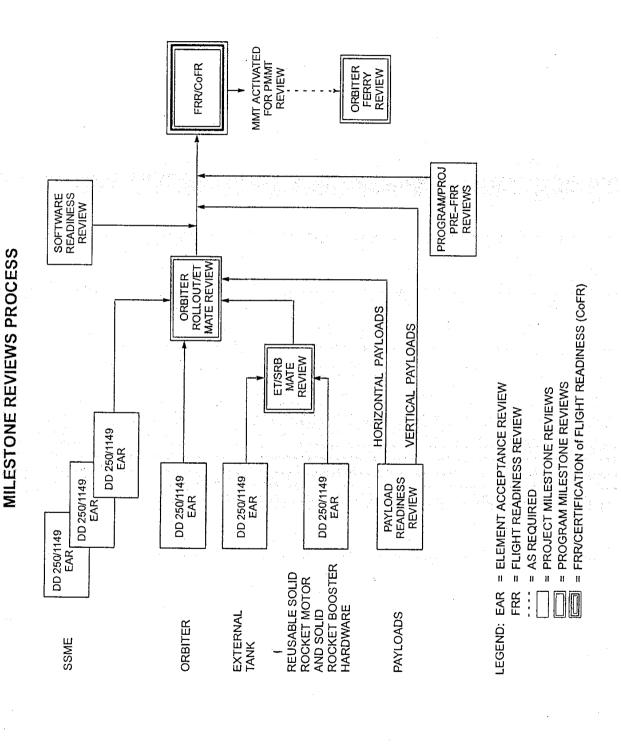
*NOTE: See Figure 2 for expansion.

NOTE: For specific timeline information, see JSC 25187, Flight Production Generic Template, Appendix A.

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FIGURE 2



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8.0 FLIGHT READINESS REVIEW (FRR)

Approximately two weeks prior to launch, a FRR will be conducted that will determine the readiness of the SSV, flight crew, and payloads. At the review, organizations identified in Paragraph 8.7b will certify the completion of all tasks and planned work required to prepare the flight/ground hardware/software, support facilities, and operations personnel to safely support a specific mission. Readiness for flight shall be determined through the review of necessary data to ensure satisfactory closeout of all FRR certification requirements, exceptions, and launch constraints, and be in sufficient detail to provide the Associate Administrator (AA), Office of Space Flight with the information needed to make a decision as to flight readiness.

8.1 POLICY

The FRR is an integrated senior management review chaired by the AA, Office of Space Flight who is supported by a review board. It is the policy of the AA, Office of Space Flight to make an assessment of mission readiness prior to each flight. This will be accomplished by a comprehensive review of all activities/elements necessary for the safe and successful conduct of all operations from prelaunch through post—landing and recovery operations. Government and contractor representatives will certify readiness in their areas of responsibility.

8.2 CERTIFICATION REQUIREMENTS

The CoFR endorsement certifies all organizations (NASA and contractor) have successfully completed their FPPs and products per their Flight Preparation Process Plans (FPPPs). During the transition period for the SFOC contract the transition plans and PDPs document the transfer of responsibilities from NASA to the contractor and should be referenced for complete CoFR accountability.

8.2.1 Flight Preparation Process Plans

Each organization's FPPP defines the processes and products the organization will complete for a each mission. The FPPP ensures the successful assembly, launch and completion of the flight. As applicable for each organization, the process plans shall encompass all major and critical operations, design, certification, analyses, testing, documentation, and requirements definition required for the each mission. The major processes involved are as follows:

- a. Vehicle processing
- b. Payload processing
- c. Configuration management/requirements definition

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- d. Flight certification (including Launch Commit Criteria [LCC], flight rules, etc.)
- e. Facility/equipment/GSE certification
- f. Personnel certification
- g. Special testing/analyses
- h. Material review
- i. Hazard analyses
- j. Failure Modes and Effects Analysis/Critical Items List (FMEA/CIL)
- k. Crew training/medical certification
- I. Validation that external inputs are appropriate for this specific flight

In addition, the following products and processes which organizations participate in, but are not their unique responsibilities, shall be completed in support to external organizations:

- a. Develop/validate/deliver products requested by external organizations
- b. Delivery of hardware or software and support data
- Operations and Maintenance Requirements and Specifications Document (OMRSD)/LCC requirements definition
- d. Configuration drawings
- e. Anomaly/discrepancy resolution
- f. Flight rules requirements
- g. Crew procedures requirements
- h. Flight design definition
- i. Flight constraints definition
- j. Ferry requirements
- k. Time, cycle, age life, interval inspection, and maintenance requirements
- I. Flight Data File (FDF) requirements

8.3 FLIGHT READINESS REVIEW PREPARATION

Each organization shall be responsible for conducting a Pre–FRR in preparation for the SSP FRR which ensures their project FPPPs are satisfied. The program/projects shall

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FIGURE 3 CoFR ENDORSEMENT

STSCOFR ENDORSEMENT				
ELEMENT	SERIAL NUMBER	PAYLOAD		
ORBITER	- .			
ET				
RSRM				
SSME				
SRB				
Projects having exceptions to	this CoFR document are as follows (see			
and the Analysis of the Ages				

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STS-	CoFR	ENDO	RSEMENT
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The Flight Preparation Process Plans documented in NSTS 08117, Requirements and Procedures for Certification of Flight Readiness, have been satisfied. Required products and other responsibilities for each project (NSTS 08117, Section 8) have been or will be produced or completed.

- a. Certified flight hardware elements have been delivered to the SFOC at the Kennedy Space Center.
- Required hardware element processing specifications and requirements have been delivered to the SFOC.
- All identified "out-of-family" events that occurred after delivery of hardware for launch processing/ assembly/testing have been resolved.
- d. For "out-of-family" conditions detected during manufacturing, testing, or post-mission tear down and analysis, notification to the Space Shuttle Program has been made, and corrective action, if any, identified.
- e. The as-built flight element configuration satisfies the released requirements and engineering, based on data compiled and reviewed by SFOC.
- f. For the Space Shuttle Main Engine Project: Certified main engine controller software has been delivered for this mission.

	CONTRACTOR		NASA	
SSME (8.5.3.1, 8.5.3.2, Apx. C)	PROGRAM MANAGER, ROCKETDYNE	DATE	MANAGER, SSME PROJECT, MSFC	DATE
ET (8.5.4.1, 8.5.4.2, Apx. D)	PROGRAM MANAGER, LMMSS	DATE	MANAGER, ET PROJECT, MSFC	DATE
RSRM (8.5.5.1, 8.5.5.2, Apx. E)	PROGRAM MANAGER, THIOKOL	DATE	MANAGER, RSRM PROJECT, MSFC	DATE
-	CONC	URRENC	E	
MSFC SHUTTLE PROJECTS	N/A		MANAGER, MSFC SHUTTLE PROJECTS	DATE

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STS- Cofr ENDORSEMENT

The Flight Preparation Process Plans documented in NSTS 08117, Requirements and Procedures for Certification of Flight Readiness, have been satisfied. Required products and other responsibilities for each organization (NSTS 08117, Section 8) have been or will be produced or completed.

- a. For Payload Processing: Flight and ground requirements, payload logistics, and configuration requirements provided by the flight projects, have been maintained, performed, or are planned to be performed per approved TOPs.
- b. For EVA project: Audit, insight, and surveillance of SFOC activities have been completed or are planned for completion, and all discrepancies have been resolved. Oversight functions have been conducted in conjunction with Hamilton Sundstrand.

NASA

FLIGHT CREW DIRECTOR, FLIGHT CREW OPERATIONS DATE **OPERATIONS** (8.5.11.1, 8.5.11.2, Арх. К) DATE FERRY FERRY OPERATIONS MANAGER **OPERATIONS** (8.5.16.1, 8.5.16.2, Apx. P) DATE SPACE AND LIFE DIRECTOR, SPACE AND LIFE SCIENCES SCIENCES (8.5.15.1, 8.5.15.2, Apx. O) DATE SPACE SHUTTLE MANAGER, SPACE SHUTTLE SR&QA SR&QA (8.5.17.1, 8.5.17.2, Apx. Q) **NASA** CONTRACTOR DIRECTOR OF ISS/PAYLOAD DATE PAYLOAD PROGRAM MANAGER, CAPPS DATE BOEING, KSC PROCESSING PROCESSING (8.5.10.1, 8.5.10.2, Apx. J) DATE DATE MANAGER. EVA PROGRAM MANAGER.

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Revision L

(8.5.2.1, 8.5.2.2, Apx. B)

HAMILTON SUNDSTRAND

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EVA PROJECT OFFICE

CHANGE NO. 71

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ST	'S-	CoFR	ENDO	DRSE	MENT
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The Flight Preparation Process Plans documented in NSTS 08117, Requirements and Procedures for Certification of Flight Readiness, have been satisfied. Required products and other responsibilities (shared or independent) for each organization (NSTS 08117, Section 8) have been or will be produced or completed.

 The following NASA organizations have completed or plan to complete audit, insight, and surveillance of contractor activities, and have resolved all discrepancies.

$\theta(x_1) \oplus (x_2) = (x_1^{k_1} \otimes \cdots \otimes x_{k_2}^{k_2}) \otimes (x_{k_2} $	and a company of the commence of the same of the commence of t	
CUSTOMER AND FLIGHT INTEGRATION (8.5.14.1, 8.5.14.2, Apx. N)	MANAGER, SPACE SHUTTLE CUSTOMER AND FLIGHT INTEGRATION	DATE
KSC INTEGRATION (8.5.12.1, 8.5.12.2, Apx. L)	MANAGER, SPACE SHUTTLE KSC INTEGRATION	DATE
SHUTTLE PROCESSING (8.5.8.1, 8.5.8.2, Apx. H)	DIRECTOR OF SHUTTLE PROCESSING, KSC	DATE
MISSION OPERATIONS (8.5.7.1, 8.5.7.2, Apx. G)	DIRECTOR, MISSION OPERATIONS	DATE
SRB (8.5.6.1, 8.5.6.2, Apx. F)	MANAGER, SRB PROJECT, MSFC	DATE
SSP S&MA	MANAGER, SSP S&MA	DATE
SYSTEMS INTEGRATION (8.5.13.1, 8.5.13.2, Apx. M)	MANAGER, SPACE SHUTTLE SYSTEMS INTEGRATION	DATE
VEHICLE ENGINEERING (8.5.1.1, 8.5.1.2, Apx. A)	MANAGER, SPACE SHUTTLE VEHICLE ENGINEERING	DATE

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	STSCOFR ENDORSEMENT	· · · · · · · · · · · · · · · · · · ·
NSTS 0811 satisfied. F	Shuttle Flight Preparation Process Plans (shared or independent) documented in 17, Requirements and Procedures for Certification of Flight Readiness, have been Required products and other responsibilities (shared or independent) for the SFOC 17, Section 8) have been or will be produced or completed.	
a. All out	of-family conditions have been identified and resolved with the NASA.	
l .	SV has been processed in accordance with requirements and policies baselined SSP.	
	UNITED SPACE ALLIANCE	
SFOC SQ&MA CONCURRENCE	VICE PRESIDENT, SAFETY, QUALITY AND MISSION ASSURANCE, SFOC	DATE
SFOC	SSP, PROGRAM MANAGER, SFOC	DATE
(8.5.18.1, 8.5.18.2, Apx. R)		
Implement flight. Any resolved or	dorses that the requirements for CoFR documented in SSP 50108 and the Boeing Flig ation Plan have been satisfied in accordance with the Boeing specific responsibilities f issues that have arisen since the Stage Operations Readiness Review (SORR) have r have been presented at the Flight Readiness Review. This certification is subject to iS 15-10000 (for ISS Missions).	or this been
	BOEING	
ISS PRIME CONCURRENCE	VICE PRESIDENT AND PROGRAM MANAGER, ISS, BOEING	DATE
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STS-	COFR ENDORSEMENT
NASA	A SSP READINESS
reviewed. All required processes, products	am and Project organizations for this mission has been s, and responsibilities are complete or will be completed waivers have been reviewed and will be dispositioned by the The Space Shuttle Program is ready to proceed with the
	$(A_{ij},A_{ij}$
MANAGER, SPACE SHUTTLE PROGRAM INTEGRATION	DATE
MANAGER, LAUNCH INTEGRATION	DATE
MANAGER, SPACE SHUTTLE PROGRAM	DATE
NASA ISS	PROGRAM READINESS
are planned. All deviations, waivers, and e	the flight, stage and increment have been accomplished or exceptions have been reviewed and satisfactorily dispositioned. It is ready to proceed with launch and on-orbit operations. Any lave been resolved or have been presented at the Flight DATE
· · · · · · · · · · · · · · · · · · ·	CONCURRENCE
I concur that the Space Shuttle Program at are ready to proceed with this mission.	nd the International Space Station Program (for ISS Missions)
DEPUTY ASSOCIATE ADMINISTRATOR FOR INTERNATIONAL SPACE STATION AND SPACE SHUTTLE PROGRAMS	OR DATE
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STS Cofr ENDORSEMENT				
CONCURRENCE				
As a member of the FRR Board, I concur that, pending comple Program and International Space Station Program (for ISS Mis	tion of planned work, the Space Shuttle sions) are ready to execute this mission.			
DIRECTOR, JOHNSON SPACE CENTER	DATE			
DIRECTOR, KENNEDY SPACE CENTER	DATE			
DIRECTOR, MARSHALL SPACE FLIGHT CENTER	DATE			
DIRECTOR, STENNIS SPACE CENTER	DATE			
PRIME MISSION NASA S&MA has reviewed the status of preparations for this n assessment of the readiness of the Space Shuttle Program for readiness of the International Space Station for launch and on in concurrence with proceeding with this mission.	the conduct of this mission, and the			
ASSOCIATE ADMINISTRATOR, SAFETY AND MISSION ASSURANCE	DATE			
APPROVAL				
The FRR Board has conducted a comprehensive assessment systems and supporting personnel. For ISS missions, the FRF comprehensive assessment of the readiness of the Launch Pa hardware/software support facilities and personnel to support t readiness of the on-orbit stage to accept the LP/CE and return has been endorsed by each program element. I have conclud that pending completion of planned work, the Space Shuttle Pthe International Space Station Program is ready for launch and ASSOCIATE ADMINISTRATOR, OFFICE OF SPACE FLIGHT	R Board has also conducted a ackage/Cargo Element (LP/CE), ground the flight, stage and increment including the items. The Certificate of Flight Readiness ed, with the concurrence of the FRR Board, rogram is ready to execute this mission and			
(CHAIR, FRR BOARD) SP Form 4042 (Rev Oct 02)	Page 7 of 7			

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Volume V Appendix G.2

Appendix R, Space Shuttle Program Contingency Action Plan

This Appendix contains NASA NSTS 07700, Volume VIII, Revision E, Appendix R; <u>Space Shuttle Program Contingency Action Plan</u>.



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APPENDIX R SPACE SHUTTLE PROGRAM CONTINGENCY ACTION PLAN

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APPENDIX R

SPACE SHUTTLE PROGRAM CONTINGENCY ACTION PLAN

1.0 INTRODUCTION

1.1 PURPOSE

The purpose of this document is to serve as an integrated plan to predetermine the program response in the event of a Space Shuttle contingency. This plan will be implemented in concert with the OSF SFO Contingency Action Plan, and field center contingency plans. It has been written to augment each of these by providing the anticipated, integrated timelines of the formalized program response.

1.2 SCOPE

The Manager, Launch Integration, KSC has overall responsibility for contingency planning during flight preparation, launch ascent, and post-landing operations. During ascent, this responsibility continues until the Shuttle is established in a stable orbit or until landing, should a stable orbit not be achieved. The Manager, Launch Integration will hold a Mishap Response Teleconference (MRT) approximately one hour and 30 minutes after the contingency where specific actions will be levied by the MMT. Normal program elements will execute those actions along with this plan. The Manager, Space Shuttle Program will determine when the MMT no longer has operational oversight for this plan. The Manager, Launch Integration, KSC will retain responsibility for contingency operations until a formal investigation board is established, and/or until the Orbiter is returned to KSC.

1.3 DEFINITION

For the purpose of this plan, a program contingency is defined as any SSP-related failure, accident, or incident (involving SSP-controlled flight or test hardware, support equipment, or facilities) that significantly delays or jeopardizes the SSP or a flight, prevents accomplishment of a major objective, or terminates a flight prematurely.

NPD 8621.1G, NASA Policy Directive on NASA Mishap Reporting and Investigating Policy, defines six mishaps/contingencies in which the AA-OSF may become involved. They include Type A, B, and C Mishaps, mission failures, incidents, and close calls, all of which are defined in Table 1. The AA-OSF or delegated agent is the final authority in determining if an actual or suspected mission failure, accident, or incident constitutes a SSP contingency. All probable contingency situations will be reported to the AA-OSF or delegated agent for a final decision.

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1.4 APPLICABILITY

This plan applies to any contingency situation during Space Shuttle operations where a multi-center response may be required. It applies to all SSP organizations and those agencies that support the SSP during a contingency operation. Use of this plan assumes the AA-OSF has declared, or will declare, an SSP contingency.

1.5 REFERENCED DOCUMENTS

This plan is intended to be consistent with the documents listed in Attachment 10 of this appendix.

1.6 NOTIFICATION

Those witnessing a potentially significant Shuttle Program incident will notify the appropriate element/project manager who in turn will notify the Manager, Space Shuttle Program. The Manager, Space Shuttle Program will be responsible for notifying the Deputy AA for International Space Station and Space Shuttle.

1.7 CONTINGENCY READINESS

Space Shuttle Program and Project personnel will participate in contingency response exercises that demonstrate the program's effective response. These will consist of exercises prescribed by NASA Headquarters' Office of Safety and Mission Assurance and as outlined in the OSF SFO Contingency Action Plan.

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TABLE R.1 CONTINGENCY CRITERIA SUMMARY

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Classes of	Damage to Property, Facilities,		
Unexpected Events	or Equipment and/or Personnel Injury/Death		Investigation/Analysis
Type A Mishap	Greater than \$1M	Death	AA-OSF appoints investigation board or Administrator chooses to appoint investigation board and board investigates mishap*
Type B Mishap	Equal to or greater than \$250K but less than \$1M	Permanent disability of 1 or more persons, or hospitalization of 3 or more persons.	AA-OSF or Deputy AA appoints investigation board and board investigates mishap*
Type C Mishap	Equal to or greater than \$25K but less than \$250K	Occupational injury or illness that results in a lost workday case.	Deputy AA appoints investigator or investigation team depending on significance of mishap*
Incident	Equal to or greater than \$1K but less than \$25K	Personal injury of less than Type C Mishap severity but more than first-aid severity.	Same as Type C mishap*
Mission Failure	A mishap of such severity that it prevents the achievement of primary NASA mission objectives as described in the Mission Operations Report or equivalent document.		An investigation board is required and Type A or B Mishap investigation procedures are followed*
Close Call**	No equipment/property damage equal to or greater than \$1K	No injury or significant interruption of productive work	Investigated in accordance with its potential*

^{*}If event involves more than one Center or has significant public interest, the AA-OSF, or delegated agent, may order an investigation board or recommend to the Administrator that the Space Shuttle Mishap Interagency Investigation Board be activated.

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^{**}Event which possesses high severity potential for any of the previous types of mishaps.

2.0 RESPONSIBILITIES

2.1 MANAGER, SPACE SHUTTLE PROGRAM

In accordance with the OSF SFO Contingency Action Plan, the Manager, Space Shuttle Program is responsible for ensuring that:

- a. SSP contingency response actions are included in the OSF centers contingency plans.
- b. The program is ready to manage appropriate actions to minimize losses, and preserve evidence, should a contingency occur.
- c. The program is prepared to manage the contingency situation until a formal investigation board is established.

2.2 MANAGER, LAUNCH INTEGRATION, KSC

The Manager, Launch Integration, KSC is directly responsible for management of contingency activities after a suspected launch or EOM landing contingency has been reported. Immediately following a suspected contingency, the Manager, Launch Integration, KSC will implement this plan anticipating that the AA-OSF will declare the incident a program contingency.

The Manager, Launch Integration, KSC, will chair the MRT within one hour and 30 minutes after a contingency has been reported. The MMT will provide direct support to the Manager, Launch Integration, KSC.

The Manager, Launch Integration, KSC appoints the Chair of the Mishap Investigation Team (MIT), and activates the MIT, as necessary, with the approval of the AA-OSF.

2.3 MANAGER, SPACE SHUTTLE PROGRAM INTEGRATION

The Manager, Space Shuttle Program Integration is responsible for chairing the MMT during on-orbit activities. If a suspected mission contingency occurs, it is the responsibility of the Manager, Space Shuttle Program Integration, to coordinate and chair the MRT from JSC, and to inform the MMT.

Immediately following a suspected mission contingency, the Manager, Space Shuttle Program Integration, JSC will implement this plan anticipating that the AA-OSF will declare the incident a program contingency.

Responsibility for contingency operations will be transitioned back to the Manager, Launch Integration, KSC, after landing has occurred.

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2.4 SPACE SHUTTLE PROGRAM ELEMENTS (MSFC PROJECTS/EVA/FCOD/PAYLOADS PROCESSING/SHUTTLE PROCESSING/SYSTEMS INTEGRATION/VEHICLE ENGINEERING)

In the event a failure, accident, or incident occurs involving SSP hardware or facilities, it is the responsibility of the respective element manager to take the following actions:

- a. Assure that all possible action is taken to prevent injury to personnel, and damage or loss of equipment;
- b. Notify, by the most expeditious means, the Manager, Space Shuttle Program; the respective Center Director; AA-OSF; and the Deputy AA-OSF;
- c. Assure that the scene is secured against action that could impair investigation;
- d. Protect records, logs, data books, film, etc.
- Initiate preliminary on-site assessment to determine scope of potential contingency;
- f. Initiate their respective center contingency action plans;
- g. Support investigations of SSP contingencies under its own direction or under the direction of the lead center, a Headquarters Mishap Investigation Board (MIB), or any board established by the NASA Administrator or the President of the United States; and
- h. Prevent sabotage and provide security.

2.5 MISSION OPERATIONS

When a potential contingency situation arises during mission operations, the Flight Director, as specified in JSC 12805, Flight Control Operations Handbook, will put contingency procedures into effect. All flight control and support personnel will be required to complete these procedures. Logs of each individual's equipment status prior to and at the time of the potential contingency will be completed. JSC Form 1441, Flight Director's Mission Log, will be used and completed as soon as possible after a mission contingency and prior to the release of the individual from the MCC or his/her support area. These logs will be collected by each area/specialty supervisor or lead flight controller, and forwarded to the Flight Director, who will provide the data to the MIB. A roster of all mission personnel will be provided in addition to the logs. At the time a contingency is suspected or declared, all personnel will immediately verify that their logs are up-to-date and will institute a "hands-off" policy with regard to switches, push-button indicators, knobs, recorders, etc., as is appropriate to continued flight safety. The MCC will remain active in support of the potential contingency until released by the AA-OSF

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or the Manager, Space Shuttle Program. Upon release of the MCC, its functions in support of the contingency will be transferred to the Technical Action Center.

3.0 REQUIREMENTS

3.1 PERSONNEL NOTIFICATION

All Space Shuttle program elements shall provide predefined notification lists within their respective center contingency action plans to address any failure, accident, or incident involving program resources. These predefined notification lists will be executed within 60 minutes of the suspected incident. The notification shall include a description of the potential contingency; its cause, if known; associated information leading up to the potential contingency; any actions that have been initiated or are planned; and recommendations for a course of action.

The manning of action centers and communication networks also shall be predefined to ensure an organized and timely response. Attachment 2 describes the NASA Action Centers at NASA HQ, MSFC, KSC, JSC, and SSC.

3.1.1 Launch Notification Sequence

The Manager, Launch Integration, KSC will notify the members of the MMT who, in turn, will notify their respective organizations. The Flight Director shall notify the JSC MCC, and the LSO shall notify specific NASA and other government personnel.

3.1.2 Mission Notification Sequence

During SSP mission activities, officials will be notified through normal missionmonitoring activities. The SSP Manager will notify the Deputy AA for International Space Station and Space Shuttle or delegated agent of the potential contingency.

3.2 TEAM NOMINATIONS

The Manager, Launch Integration, KSC, or his designee shall be responsible for publishing a list of the qualified personnel two weeks prior to the FRR for each flight. This includes membership of the NASA MRT, MIT, RRT, and the Crew Recovery Team (CRT). MIT personnel will be on alert to depart for the contingency scene as soon as a contingency has been declared. A list of the positions to be filled for each team is included in Attachment 1.

The travel of all NASA personnel to an overseas landing site shall be approved by the AA-OSF, with responsibility delegated to the Manager, Launch Integration, KSC. All personnel deployments and manifests will be provided to the Office of External Rela-

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tions at NASA HQs approximately two weeks prior to each mission to ensure timely visa requests.

3.2.1 Mishap Investigation Team

The MIT shall be responsible for immediately traveling to the contingency site to gather first-hand information, take witness statements, and preserve material, which could be valuable to the formal investigation board. The turnaround/ salvage teams shall not begin their operations until the Orbiter is released by the MIT. The MIT shall comply with NPD 8621.1G and the NASA Headquarters OSF SFO Contingency Action Plan. The MIT Chair is appointed by the Manager, Launch Integration, KSC and approved by the AA-OSF. Once deployed, all MIT members are considered on detail from their field centers and are responsible only to the Chair. If the Orbiter should land undamaged, a decision not to deploy the MIT may occur at the MRT. Reference Attachment 5 for the detailed MIT Operations Plan.

3.2.2 Rapid Response Team

KSC shall prepare a KSC Off-site Transportation Plan for TAL site deployment. The RRT will arrive at the contingency site within approximately 18 hours. These plans shall be modified realtime to reflect the actual condition of the Orbiter. The activation of the airlift shall begin when the LRD calls the DDMS Operations SOC to request airlift. The SOC shall then notify the Air Mobility Command (AMC) Tanker Airlift Control Center for actual aircraft deployment. KSC, in conjunction with the AMC Tanker Airlift Command Element (TALCE) (once in place), shall coordinate support for arriving aircraft at NASA and TAL facilities.

The RRT shall consist of personnel under the direction of the KSC GOM who will evaluate the condition of the Orbiter and determine any additional requirements to prepare the Orbiter for ferry. The RRT will modify existing contingency planning to accommodate the realities of the Orbiter configuration and landing site facilities. If Orbiter towing equipment is not available at the landing site, the RRT will transport towing equipment to the site, if possible. Most of the RRT shall be deployed from KSC. For a TAL, the aircraft will pick up personnel and equipment at the KSC SLF approximately six hours after the TAL declaration. Estimated deployment timelines are in Attachment 6 of this appendix.

a. Augmented Landing Site Rapid Response - Three landing sites in the European and African continents shall have personnel trained to participate in an Orbiter recovery. Personnel from the sites at which the Orbiter did not land will be utilized at the actual landing site. The aircraft used for transportation will be the SAR or MEDEVAC aircraft (C-130) stationed at the TAL sites. The KSC GOM shall identify the personnel, and the request for transportation will be coordinated with the DDMS and the DOD/SOC at PAFB.



b. Non-augmented Landing Site Rapid Response - Unscheduled Orbiter landings will likely occur at ALS where NASA and DOD personnel will be trained and equipped to take care of an Orbiter that has landed. However, the possibility remains that the landing of an Orbiter may occur at an airfield other than an ALS. If such a landing should occur, the capability may exist for equipment and personnel at the ALS to reach the Orbiter before any response aircraft from CONUS. The aircraft used will be the SAR or MEDEVAC aircraft stationed at Zaragoza Air Base (AB), Banjul, and/or Ben Guerir.

3.2.3 Crew Recovery Team

In the event of a non-CONUS landing, the JSC FCOD will send the KC-135 aircraft containing the CRT from JSC EFD to the location of the flight crew. The purpose of this aircraft is to return the flight crew to the U.S. Transportation of other JSC personnel on the KSC RRT will be provided to the KSC SLF. A DDMS provided aircraft will be used as a backup aircraft in the event that the NASA KC-135 is unavailable. The DOD, using available SAR/MEDEVAC aircraft, will provide evacuation for uninjured flight crew members to the nearest U.S. military base, if necessary. The estimated typical TAL timeline for the KC-135 deployment is in Attachment 6 of this appendix.

3.3 MISHAP RESPONSE TELECONFERENCE

A MRT will be established within one hour and 30 minutes after a suspected launch, onorbit, or EOM landing contingency occurs.

- a. Launch MRT The KSC Launch Integration Staff Office will be responsible for coordination and set-up of the teleconference in Room 1R29 of the Launch Control Center. The teleconference will be effected by MCI communications. The Chair shall be the Manager, Launch Integration, KSC. The teleconference shall cover a review of pertinent facts, statements of contingency actions, and a review of deployment schedules of response teams. Access to the MRT will be predefined, and approved by the Manager, Launch Integration, KSC prior to the prelaunch MMT review.
- b. Mission MRT Upon notification of a suspected contingency, the Manager, Space Shuttle Program Integration will chair the MRT from JSC. The Space Shuttle Customer and Flight Integration Office, JSC will coordinate the teleconference.

A complete description of the MRT is included in this appendix in Attachment 3.

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3.4 SEARCH AND RESCUE REQUIREMENTS

SAR capabilities will be provided through the DDMS on a per site basis. Given 24-hour advanced notice, Air MEDEVAC will be available at the primary CONUS EOM sites and the TAL sites. ELSs will have no prepositioned Shuttle support resources and the DOD SAR and MEDEVAC effort will be on a "best effort" basis.

3.4.1 Kennedy Space Center

KSC will have the following resources available for launch, RTLS, EOM, and near coastal bailout:

Required:

- a. DOD HH-60 helicopters on standby at the SLF
- b. One UH-1 NASA helicopter
- c. One DOD HC-130 positioned 175 nm downrange (excluding EOM support)
- d. One DOD HC-130 and KC-130 positioned at PAFB (excluding EOM support)

If available:

- a. One E-2C positioned at PAFB (excluding EOM support)
- b. One U.S. Navy ship with helicopter (excluding EOM support)
- c. One Coast Guard cutter with helicopter

Each DOD helicopter will carry one medical doctor and two pararescuemen and have the capability to transport two astronauts in litters. Each HC-130 will have two 3-man pararescue teams with motorized inflatable rafts.

3.4.2 Edwards Air Force Base

When given 24-hour advanced notice, EAFB will have DOD UH-60 or UH-1 MEDEVAC helicopters available for EOM landings. Each UH-60 helicopter will carry one medical doctor, three Emergency Medical Technicians (EMTs), and up to three flight crew members. Each UH-1 helicopter will carry one medical doctor, one EMT, and two flight crew members.

3.4.3 White Sands Space Harbor

WSSH will have UH-1 MEDEVAC helicopters available for EOM landings, given 24-hour notice. Each helicopter will carry one medical doctor, one EMT, and two flight crew members.

3.4.4 TAL Sites

TAL sites will have available the following SAR/MEDEVAC resources to support a landing:

- a. One DOD fixed-wing aircraft (C-130) at Banjul, The Gambia, for low inclination launches
- b. One DOD fixed-wing aircraft (C-130) at Ben Guerir, Morocco
- c. One DOD fixed-wing aircraft (C-130) at Zaragoza AB, Spain, for high inclination launches

The C-130 aircraft at Ben Guerir, Banjul, and Zaragoza will have two flight surgeons and nine pararescue specialists onboard. Each aircraft will be capable of transporting the entire flight crew. Fixed-wing assets along with equipment to support landing activities will be transported to Moron, Spain as needed.

3.5 EMERGENCY MEDICAL SERVICES

The Director, Space and Life Sciences Directorate, JSC has overall management responsibility for EMS operations. This will be implemented by the Medical Operations Branch through the FCR surgeon and through the respective site EMS coordinators. The on-scene physician is responsible for making realtime trauma treatment decisions until such times as the flight crew member is under the care of an Intermediate Medical Care Facility (IMCF) or Definitive Medical Care Facility (DMCF). Patient information will be relayed from the on-scene physician to the site EMS coordinator. EMS's are described more fully in Attachments 7 and 9 of this appendix.

3.6 COMMUNICATIONS

In the event of an unscheduled landing, all operational communications will remain in their landing support configuration until direction to do otherwise is obtained from the MMT or other appropriate site managers. Any other predefined communications in support of unscheduled landings will be activated after crew egress. It can be expected that the support role of some facilities will change to support this unscheduled event. For any unscheduled landings associated with the launch phase, the MMT will exercise its management role while still at the KSC LCC. Landings occurring after the MMT has arrived at JSC will be supported using the Action Center in the MCC. Landings at any non-CONUS bases with U.S. military presence will have telephone capability in place and active to either the tower or airport manager's facility. This phone line capability is provided by the DOD SOC. For landings at non-CONUS sites without U.S. military presence, the LSO in the MCC will utilize a hotline to the State Department. The State Department will contact the embassy in the country where the landing occurred. The

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embassy will contact to the airport tower or airport manager's office. Within three days of a landing at a TAL site or non-CONUS ELS, DDMS will provide a 24-channel voice communications capability to handle non-secure communications with the DOD SOC and KSC.

3.6.1 MCC Communications

Handover of the Orbiter from the JSC FCT to the KSC turnaround team occurs at flight crew egress. At this time, the FCT and communication lines are nominally released. If a contingency landing should occur, continuing communications between the flight crew and the MCC Capsule Communicator (CAPCOM) and Flight Director will be required. This may occur via telephone or by leaving the flight communication channels active. It is to be expected that all communication channels will remain active until the MMT convenes. For an unscheduled landing, the voice control element and the LSO would remain on console in the MCC to provide support to those elements, which are involved in evaluating the situation.

3.6.2 TAL Sites

The primary TAL sites will have three International Maritime Satellite (INMARSAT) terminals available for use prior to launch. These circuits will provide primary communications to the MCC and LCC. The channels are:

- a. Landing Field Prime 1
- b. Weather Observer, which is time-shared between voice and data transmissions. The following circuit reallocations will occur after the landing:
 - c. The Landing Field Prime 1 circuit will be left to its normal functions and additional JSC/DDMS coordination, as necessary.
 - d. The Weather Observer circuit will be reconfigured to the Convoy Commander net, to be used for local UHF communications with units around the TAL site.
 - e. The Weather Aircraft circuit will be used for initial MCC communications including medical status, flight crew debrief, flight crew family conversations, and recording the flight crew's statement. Should a bailout occur, this circuit would be used by DDMS to communicate with the SAR aircraft.

In addition, each flight crew member will have a PRC-112 UHF handheld radio in his flight suit, capable of transmitting and receiving on 282.8 MHz and 243.0 MHz. Attachment 8 describes the communications available at each TAL site.

3.6.3 Daily Status Teleconference

A daily status teleconference will be established from the landing site to KSC to report the progress of turnaround operations. The time will be established after the MRT.



Participants will vary according to the condition of the Orbiter and the recovery and turnaround progress.

3.7 AVAILABLE LANDING SITES

There are a variety of landing sites loaded into the Orbiter software available for flight crew selection during flight by item execution on the horizontal situation display. High and low inclination launches have different sites defined in the software. In addition, landing sites are defined as either (1) augmented, with Shuttle-specific landing aids and NASA personnel available or, (2) emergency, with 8,500 feet of available runway and a TACAN. The sites available are listed in NSTS 07700, Volume X - Book 3. Personnel at DOD ALS's and overseas ELS's have received rescue training. Attachment 6 of this appendix lists the types of landings that could occur and a nominal contingency response timeline for each site. Annex 1 to Appendix R will be published as a separate document for each mission to specify the configuration and operations for each landing site. This document will assist KSC and DDMS in planning and staffing for required support.

3.7.1 Return to Launch Site

The RTLS scenario will return the Orbiter to the SLF within 25 minutes. The RTLS may be declared between approximately T+2:30 and T+4:05 minutes. A convoy will be located at the SLF with purge, towing, fire, and rescue capabilities. Attachment 6, Table R6.1, of this appendix details an estimated RTLS timeline.

3.7.2 Transoceanic Abort Landing

A TAL may result in the Orbiter landing at the prime TAL sites of Ben Guerir, Morocco; Moron AB, Spain; Zaragoza AB, Spain; or Banjul, The Gambia. The TAL may be declared between approximately T+2:30 minutes and MECO. The primary TAL site will be manned by approximately 40 predeployed people to provide landing aids and weather operations. Fire and rescue capabilities will be present. The DOD MEDEVAC aircraft will evacuate the flight crew to Naval Station Rota, Spain if uninjured, or to appropriate medical facilities if injured. The flight crew will remain together unless medical circumstances dictate otherwise. The USA Transportation Office has developed airlift schedules for RRT personnel and equipment. All TAL sites are downgraded after launch day, with most of the personnel support released. If a TAL occurs, the NASA GOM will have a prepared press statement for release to the local media thanking the local government and explaining the nature of the landing.

Attachment 6, Table R6.3, of this appendix details a typical TAL timeline.

3.7.2.1 Support Requirements Available at Each TAL Site

Different TAL sites are governed by different international agreements and may have site-unique support personnel and facilities available. A synopsis of the support



provided is included in Attachment 8 of this appendix on those sites that have a high probability of a TAL occurring.

3.7.3 Abort Once Around

The AOA will result in a landing at either EAFB, California; WSSH, New Mexico; or KSC, Florida. It may be declared from MECO to approximately T+30 minutes. There will be personnel at each location to support convoy operations. This convoy does not allow the vehicle to remain powered up, but has adequate equipment for purge (excluding WSSH) as well as fire and rescue operations if needed. KSC ground operations personnel will be immediately dispatched for ground turnaround activities. The vehicle will remain on the runway until KSC personnel arrive if it is damaged; otherwise, the Orbiter will be secured and towed to the deservice area. Warm air purge (excluding WSSH) and around the clock surveillance will be provided until the turnaround team arrives. Attachment 6, Table R6.4, of this appendix describes a typical AOA timeline.

3.7.4 Emergency Landing Sites

3.7.4.1 Primary Landing Site (PLS)

Daily PLS's are identified for each mission. These are the sites that provide the best opportunity for an emergency deorbit to a NASA-supported facility (EAFB, WSSH, KSC). It is also possible to have a Rev 3 Deorbit if the Orbiter is not cleared to continue to orbit. These landings will have minimal convoy support including purge, (excluding WSSH), fire, and rescue. The Orbiter will not remain powered up. The flight crew will return to JSC on the STA as soon as possible.

3.7.4.2 Non-NASA Supported Facility

For an emergency landing at a CONUS site, KSC personnel will be airlifted and equipment will be loaded and shipped by rail or truck from EAFB and KSC. It is estimated to take at least 72 hours to begin equipment deployment. The flight crew will be picked up by the JSC STA, as soon as possible, and returned to JSC. The response timeline will be similar for the AOA up through the teleconference and press conference.

3.7.4.3 Emergency Landing at Non-CONUS Site

For an emergency landing situation where the Orbiter lacks sufficient time or energy to reach a PLS, the software loads onboard the Orbiter provide guidance to a variety of landing sites. These sites will not have personnel predeployed, and if they are non-DOD airfields, they may not have received any Shuttle-unique rescue training. Some non-U.S. sites may not have been notified by NASA that they are in the software loads.



The profiles of the facilities available at each local U.S. Embassy are available through the U.S. State Department. The Embassies have been sent an Airgram giving pertinent details of an Orbiter landing, and actual notification of an impending Orbiter landing will be accomplished by the State Department via a flash message and telephone call. In these instances, the flight crew will retain responsibility for the Orbiter until either (1) they are evacuated out or, (2) a U.S. citizen with a secret clearance arrives at the landing site. The flight crew will carry onboard letters of explanation to the local officials giving simple precautionary instructions and telephone contacts. In the timeline, a C-130 is shown arriving at the site at L+5H. This assumes a landing has occurred at a site that could be reached by the SAR or MEDEVAC C-130 from an ALS within two hours. This time could vary significantly depending on how close to the ELS a U.S. presence is and on the suitability of the airfield. The RRT will arrive in a minimum of 25 hours, assuming the Landing Operation Team is already deployed to DFRF. Aircraft support from the AMC will be best effort. A typical timeline is described in Attachment 6, Table R6.5, of this appendix.

3.8 BAILOUT

Preparations for flight crew bailout will be initiated by starting cabin depressurization to equalize cabin pressure with the altitude. A nominal bailout will begin at 20,000 feet taking approximately two minutes to egress all flight crew members. A bailout may be declared at any time when it is known that there is insufficient energy to reach a runway. The Commander may declare a bailout without MCC knowledge if there is a loss of communications. DOD SAR forces are prepositioned at KSC and TAL sites to locate and/or retrieve the flight crew as soon as possible. Initial DOD SAR forces are under the control of the DOD SOC at PAFB, FL. The progress of the SAR effort shall be reported to the DOD LSO. The LSO will report efforts to the Flight Director and appropriate officials. A typical timeline is described in Attachment 6, Table R6.6, of this appendix.

3.9 CREW CHECKLISTS

The flight crew will carry onboard the Orbiter a series of checklists to aid in post-landing operations after a contingency landing at a non-EOM site. These will be located in the Flight Data File Maps and Charts book. The Initial Flight Crew Response is included in this appendix as Attachment 7.

3.10 ORBITER TURNAROUND

After the RRT begins initial safing and towing of the Orbiter, approximately 400 more personnel will be deployed for turnaround operations. These operations will be controlled by the TAL Orbiter Recovery Plan, which describes the responsibilities for the



management and conduct of the preparation and return of an Orbiter from a TAL site. The detailed plan for TAL Orbiter Recovery is included in this document as Appendix S.

3.11 SALVAGE OPERATIONS

In the event that the Orbiter/payload cannot be returned to KSC via normal ground turnaround and ferry procedures, SFOC-GO-0014, KSC NSTS Salvage Plan, will be implemented. This plan establishes the structure of the Shuttle salvage organization, the assignment of responsibilities, and management procedures to be used in conducting Orbiter/payload salvage operations.

Salvage operations requirements under the direction of KSC Shuttle Processing are as follows:

- a. Develop, prepare, and implement the Space Transportation System (STS) Transportation and Salvage Plans.
- b. Provide the organization and staffing of KSC/contractor personnel for recovery and salvage operations.
- c. Coordinate with applicable government and commercial agencies for services, equipment, and personnel required to effect recovery and salvage operations.
- d. Identify support hardware and equipment required for recovery and salvage operations.
- e. Coordinate with and advise the Department of Defense (DOD) regarding the transportation of personnel and equipment and/or salvaged items of the Orbiter and its payload.

Salvage Operations will be conducted in support of and under the direction of the designated mishap investigation team or accident investigation board until the scene/hardware has been released from further investigation.

3.12 ACTING WORKING GROUPS

Activation - The MIB Chair will activate working groups appropriate to the contingency situation. The Manager, Space Shuttle Program, may also activate the working groups either prior to the appointment of a MIB Chair, or at the request of the AA-OSF or delegated agent or at the request of another Center Director. The appropriate center will provide personnel to support any working group established to evaluate the contingency including those specified in this plan.

As a basis for the selection of working groups for a specific contingency investigation, a description of various working groups is provided in the following paragraphs. Any or all



of the working groups may be activated. There is no limit to the number of specialized working groups that may be appointed.

The MIB Chair may rearrange the working group structures and define their roles as required. Maximum use should be made of government and contractor experts as consultants or advisors to the working groups and the MIB.

Responsibilities - Each activated working group is responsible to the MIB for performing the following functions within the scope of the group's assigned investigation activities:

- a. Take all possible action to prevent injury to personnel and damage or loss of equipment, property or data.
- b. Obtain and review contractor and NASA records pertaining to receipt, inspection, configuration control, assembly, reliability, quality control and checkout, as well as any other records pertinent to the investigation.
- c. Obtain and review contractor and NASA procedures associated with the activity taking place at the time the contingency occurred.
- d. Reconstruct the circumstances under which the contingency could have been initiated.
- e. Perform interviews and obtain witness statements as soon as practical after the occurrence of the contingency.
- f. Review all data, which may have a bearing on the contingency.
- g. Report progress to the MIB on a periodic basis (daily, weekly, etc.) as required by the Board Chair.
- h. Participate in MIB meetings when working groups of overlapping interest are reporting.
- i. Perform other services as directed by the Chair of the Board of Investigation.

3.12.1 Impoundment/Classified Data Working Group

The Impoundment/Classified Data Working Group will review all data, information and findings to determine if security classification guidance is applicable, and where applicable, will ensure proper classification handling is implemented. This group will also have the overall responsibility for ensuring proper data impoundment procedures are followed and impoundment records are maintained.

3.12.2 Systems Integration Working Group

The Systems Integration Working Group is responsible for the analysis of the integrated Space Shuttle Launch Vehicle data which includes the environment, aerodynamics, flight dynamics, and total vehicle loads.



3.12.3 Vehicle Engineering Working Group

The Vehicle Engineering Working Group is responsible for all of the Orbiter systems-associated instrumentation, prelaunch and post-launch data applying to those systems, and associated support not covered by the Facilities and Ground Support Working Group.

3.12.4 Propulsion and Power Working Group

The Propulsion and Power Working Group examines Orbiter propulsion and power subsystems such as reaction control subsystem, auxiliary power unit, orbital maneuvering subsystem, and hydraulics, pyrotechnics, fuel cells and power reactant storage and distribution subsystems. This group will also assess the integrated main propulsion system for conditions that may have contributed to the contingency.

3.12.5 Navigation, Control, and Aeronautics Working Group

The Navigation, Control, and Aeronautics Working Group will analyze and document the performance of the integrated avionics system, define requirements and compare these data to preflight predictions and post-flight history, and reconstruct flight dynamics, as required.

3.12.6 Avionics and Software Working Group

The Avionics and Software Working Group will analyze and document the performance of the integrated avionics system (includes all essential onboard electronics and software). Coordinate the retrieval and interpretation of data from recovered avionics units. The group will interface with the Navigation, Control, and Aeronautics Working Group as appropriate.

3.12.7 Structures and Mechanics Working Group

The Structures and Mechanics Working Group will analyze the Orbiter structural integrity, loads, structural dynamics, materials, thermal protection system, thermal control system and the purge, vent, and drain system. Orbiter mechanical systems, including interfaces between the Orbiter and External Tank, and their performance will also be reviewed.

3.12.8 Crew and Thermal Systems Working Group

The Crew and Thermal Systems Working Group will examine Shuttle environmental control and life support systems and EVA equipment.

3.12.9 Mission Operations Working Group

The Mission Operations Working Group is responsible for the MCC, network control center, network stations, and the associated data which may have a bearing on



the contingency. Responsibilities may include a review of the flight plan, MCC, NCC, and network configurations and procedures, flight control, communications with the launch site and flight vehicle, and commands (including spurious signals) to the SSV or attached payload. This working group is also responsible for reviewing the adequacy of all operating procedures and actions. Adequacy pertains to the adherence to and compliance with the procedures, the effectiveness of the procedures, and the flight controller training and certification processes.

3.12.10 Flight Crew Operations Working Group

The Flight Crew Operations Working Group is responsible for analyzing any flight crew procedures, training, or other factors involving crew participation which may have a bearing on the contingency.

3.12.11 Payloads/Cargo Working Group

The Payloads/Cargo Working Group is responsible for all payloads, including payload support equipment and consumables. This responsibility also includes examining prelaunch and post-launch data, payload integration, engineering, hardware safety, checkout and payload status at the time of the contingency.

3.12.12 Photographic and TV Analysis Working Group

The Photographic and TV Analysis Working Group is responsible for analyzing all available photographic and video data which may have a bearing on the contingency. This working group will also be responsible for processing, screening, and analyzing optical products. The working group will define and manage all imagery enhancement required and will perform the intercenter coordination required for all photographic investigation products.

3.12.13 Records and Witnesses Working Group

The Records and Witnesses Working Group is responsible for obtaining and reviewing contractor and NASA records pertinent to the contingency, including records on receipt, inspection, configuration control, assembly, reliability, quality control, checkout, and modification. Records may be impounded, if required. This group will accumulate and review statements of witnesses as soon as possible after the contingency.

3.12.14 Timeline Working Group

The Timeline Working Group will analyze all data (telemetry, photographic, etc.) concerning the contingency and will correlate the chronological timeline which will be used by other working groups in their analyses.



3.12.15 Public Affairs Working Group

The Public Affairs Working Group is responsible for the coordination and release of information in accordance with the NASA management instructions and the operational procedures outlined in the Center support plans. The PAO representative will develop and coordinate all public releases with the MIB Chair and will also effect coordination through normal PAO channels.

3.12.16 Fire, Explosives, and Radiological Working Group

The Fire, Explosives, and Radiological Working Group is responsible for locating, identifying, and plotting the position of any fire, explosive, or radiological hazard patterns and the associated debris. This working group is also responsible for reconstructing the circumstances under which such hazards could have been initiated.

3.12.17 Medical and Toxicological Working Group

The Medical and Toxicological Working Group will analyze all medical factors which may have a bearing on the contingency and assess any actual or potential health hazards or stress associated with the mission. In the formation of this working group, reference should be made to the Medical Contingency Action Working Group, defined in Paragraph 3.12.18, established immediately following the contingency.

3.12.18 Medical Contingency Action Working Group

The Medical Contingency Action Working Group responsibilities are to identify the relevant circumstances under which an injury or death occurred, considering those factors which may have led to the injury or death; review all relevant medical documents including autopsy reports; and formulate recommendations concerning corrective action as appropriate.

3.13 OTHER WORKING GROUPS

In addition to the working groups listed above, the lead center for the investigation will support the following working groups.

3.13.1 Facilities and Ground Support Working Group

The Facilities and Ground Support Working Group will evaluate launch and landing facilities, test support systems, and ground support equipment that includes servicing and deservicing equipment at the primary, backup, secondary and contingency landing sites and at ground test sites.

3.13.2 Launch, Landing, and Retrieval Operations Working Group

The Launch, Landing, and Retrieval Operations Working Group is responsible for reviewing all flight, ferry, launch, landing, and ground service operations associated with



the contingency. This includes landing operations and deservicing at secondary and contingency landing sites, and at ground test sites.

3.13.3 Search, Recovery, and Reconstruction Working Group

The Search, Recovery, and Reconstruction Working Group is responsible for performing the search for and recovery of critical vehicle flight components for determination of the exact cause of the contingency. Upon recovery of the hardware, the working group will take precautions to maximize the use of the recovered components for failure analysis. These steps will include photographic documentation, preservation and sampling.

3.14 CONSULTANTS

The following consultants should be assigned by the MIB Chair and approved by the Center Director:

- Counsel from the legal office will be available whenever witnesses are being questioned or when legal problems arise, or when legal advice is needed by the MIB.
- b. The PAO will provide advice and assistance regarding news releases or public information.
- c. A safety official; and
- d. Others as required.

3.15 SPECIALISTS

As many specialists as necessary will be appointed by the Chair of the MIB. Specialists will participate in the MIB meetings and be available, at the request of the Chair, to assist the working groups. These specialists can be selected from outside NASA; however, non-government employees or non-full-time government employees will not be voting members of the MIB.

4.0 INVESTIGATION GUIDELINES

4.1 GENERAL

The investigation is conducted to determine the cause of the contingency and to recommend steps to prevent recurrence of such a contingency. If the MIT is activated following the MRT, all evidence and data collected will be turned over to the formal MIB, once established. The MIB and each working group involved in the investigation will

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document their findings, determinations, conclusions, recommendations, and the procedural methods used during the investigation. Various guidelines for conducting an investigation are provided in the following paragraphs.

4.2 SUPPORT FACILITIES

The centers will support any investigation that may be required. Necessary resources to conduct the investigation - administrative, facilities, secretarial support, communications, data access and security systems - will be made available to the MIB. To the extent possible, the respective center will utilize existing facilities, organizations, and procedures for data handling and analysis.

4.3 SECURITY

Security, as it pertains to this plan, applies not only to classification of data, but also to restricting access to accident-sensitive areas to approved personnel only. NASA security regulations do not apply to the DOD supporting facilities, except for those specified instances where joint DOD/NASA agreements are available. Security coordination with contractor security services will be provided.

4.4 ACCIDENT SITE PRESERVATION

Those resources committed to support the SSP at the time of the contingency will be preserved in their operational state and configuration until released by the AA-OSF or MIT Chair. Space vehicle and launch or impact-site debris will be moved only as authorized by the AA-OSF or MIT Chair, except when mandatory for rescue personnel, firefighting, or removal of explosives. The DOD forces and equipment that are available for location and removal of salvageable components are responsible to the DOD for command and control. The AA-OSF or MIT Chair is responsible for requesting the DOD to utilize salvage equipment or move debris in the vicinity of KSC or adjacent shallow water areas, if required. The term vicinity applies to the Florida mainland and shallow waters of the Atlantic Ocean for which 45th Space Wing (45SW) agreements exist. The DOD Manager for Space Shuttle Support may be required to provide salvage/retrieval on a world-wide basis. Arrangements will be made to store damaged hardware, equipment, debris, etc., in controlled facilities, if necessary. Duties listed for the AA-OSF or MIT Chair in this paragraph will be assumed by the MIB Chair when investigation responsibility has been turned over to that board. Exceptions to this policy will be justified when equipment or actions are necessary to ensure personnel safety.

4.5 NETWORK INSTRUMENTATION

The Flight Director will make timely recommendations to the Manager, Space Shuttle Program, regarding equipment and network instrumentation to be released from further



flight or test support. The Manager, Space Shuttle Program, should reach early agreement with the DOD Manager on the appropriate status of configuration control for any pertinent DOD equipment. GSFC will be kept informed through the Network Director of all decisions involving the network and recorded data requirements.

4.6 DATA HANDLING

4.6.1 General

Data designated in the implementing message, such as realtime recordings of telemetry, plotboard charts, trajectory data, tape recordings, weather reports, digital command system and tone command tapes, acquisition aid data, signal-strength records, photographs, etc., will be reduced into legible format as soon as possible and distributed as required to support the investigation. The MIB Chair may specify any special data requirements for use by the investigating authority. All other mission data may be processed in a normal manner on a noninterference basis with data in support of the investigation.

4.6.2 Records

The Director of Mission Operations, the Manager, Space Shuttle Program, the Manager, Launch Integration, and the Manager, Space Shuttle Vehicle Engineering, may impound applicable/appropriate records and protect NASA records pertinent to the contingency. These may include records of receipt, inspections, modifications, reliability and quality control, assembly and checkout, configuration control, and resolutions of significant technical problems. A custodian within each working group will be designated for these records and will retain the records for use by the MIB.

4.6.3 **Security of Data**

Data associated with the contingency will not be reclassified. To ensure all data are available to the MIB, the distribution of these data will be restricted and accorded special handling procedures as specified in this plan. Except for direct support of continued flight operations, and to the extent permitted by law, no information or data will be released to any person without a need-to-know, as designated by the Manager, Space Shuttle Program until such time as the MIB Chair is appointed. To the extent provided by law, access to the processed and reduced data associated with the investigation will be limited to personnel involved with the failure investigation until the data are released by the MIB Chair.

4.6.4 Public Release

Any public release of information relating to a contingency is the responsibility of the PAO. The Manager, Space Shuttle Program, in consultation with the AA-OSF or

designated agent, will provide guidance to the Manager, Launch Integration and the Director of Public Affairs, Flight Director, DOD Representative, and other appropriate personnel until a duly appointed MIB assumes investigative responsibilities.

4.7 REPORTS

The Mishap Investigation Board Report shall consist of five volumes which are entitled:

- a. Volume I: The Report
- b. Volume II: Appendices
- c. Volume III: Proposed Corrective Action Implementation Plan
- d. Volume IV: Lessons Learned Summary
- e. Volume V: Witness Statements/Recordings/Transcripts

The convening authority may also require the MIB to prepare intermediate reports. The MIB reports will be submitted to the convening authority and to other organizations as appropriate.

The working groups will report their progress periodically or at prearranged intervals as established by the MIB. Preliminary investigative reports will be reviewed at a time designated by the MIB Chair.

Time-lost reports will be filed for cases in which hospitalization for more than five days or death occurs.

The MIB will assemble lessons learned in the form of a summary of corrective actions.

4.7.1 Minority Reports

If a MIB member disagrees with the findings, conclusions, or recommendations of a majority of the MIB, a non-concurrence statement will be appended to the report and become a part of the report.



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Volume V Appendix G.3

CAIB Charter with Revisions

This Appendix contains the Columbia Accident Investigation Board Charter.



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National Aeronautics and Space Administration Office of the Administrator Washington, DC 20546-0001



February 2, 2003

Admiral Hal Gehman 3725 Lynnfield Drive Williamsburg, VA

Dear Admiral Gehman:

This letter is to advise you that, pursuant to 42 U.S.C. §2473 (c)(1), Section 203 (c)(1) of the National Aeronautics and Space Act of 1958, as amended, and as a result of the loss of the Space Shuttle Columbia, I have formally activated the Columbia Accident Investigation Board. I am appointing you to be Chairman of this Board.

I am requesting your immediate and full cooperation with the investigation of the STS-107 Space Shuttle mishap of February 1, 2003. As Chairman of the Board, you are charged with all activities and responsibilities described in but not limited to the Columbia Accident Investigation Board Charter.

Among other things, the Board shall independently determine the facts, as well as the actual or probable causes of the Shuttle accident and recommend preventative or other appropriate actions to preclude recurrence of a similar nature. Our regulations stipulate that the Board issue a final report within 60 days from this date. However, if you feel that you need additional time to arrive at a responsible conclusion, do not hesitate to request such additional time as you deem fit. You are free to pursue whatever avenue you deem appropriate. A copy of the Charter is attached for your reference.

I have designated Mr. David Lengyel and Mr. Steven Schmidt from my staff to be your key points of contact. We will also make other staff available to directly support the Board's activities.

I am grateful for your dedication and service to our country in this time or great need. I trust that you will be diligent, thorough, and unrelenting in your work to determine the cause and prevent the recurrence of this tragedy.

Respectfully,

Sean O'Keefe

Administrator



Columbia Accident Investigation Board Charter

1. GUIDELINES

In the case of a high-visibility, mission-related Shuttle mishap, the NASA Administrator may activate an International Space Station and Space Shuttle Mishap Interagency Investigation Board (the Board). Board activation is anticipated for events involving serious injury or loss of life, significant public interest, and other serious mishaps. The Board should consist of at least seven members, and be supported by the Office of Space Flight Headquarters and technical consultants as required.

2. ACTIVATION

The recommendation for the NASA Administrator to activate this Board will normally be made at either the Associate Administrator for the Office of Space Flight-directed Mishap Response Teleconference or as a decision at the Administrator's HCAT meeting and/or teleconference. For this case, the NASA Administrator has determined effective at 10:30 am February 1, 2003, to convene such a Board and to name it the Columbia Accident Investigation Board.

3. MEMBERSHIP

Chairman of the Board Admiral Hal Gehman, USN

Board Members

Commander, Naval Safety Center, Rear Admiral Stephen Turcotte
Director, Plans and Programs, Headquarters Air Force Materiel Command,
Major General John Barry

Commander, HQ USAF Chief of Safety, Major General Kenneth W. Hess Chief, Aviation Safety Division, Department of Transportation, Dr. James N. Hallock Director of Accident Investigation, Federal Aviation Administration, Mr. Steven B. Wallace Commander, 21st Space Wing, USAF, Brigadier General Duane Deal Director, NASA Ames Research Center, Mr. Scott Hubbard

4. BOARD SUPPORT

Standing Board Support Personnel

Ex-Officio Member: Mr. Bryan O'Connor, Associate Administrator for Safety and Mission Assurance

Executive Secretary: Mr. Theron Bradley, Jr., NASA Chief Engineer

Additional Support Personnel. The Board may designate consultants, experts, or other government or non-government individuals to support the Board as necessary.

Task Force Team Support. Within 72 hours of activation of the Interagency Board, the AA/OSF, the AA/SMA, the NASA Field Center Director or NASA Program Associate Administrator (Non-

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OSF or Non Mission Related), and the NASA Chief Engineer will meet to elect and recommend non Task Force Team members to the Mishap Board Chairman. Upon approval by the NASA Administrator, the Task Force Team members will convene and meet with the appropriate Working Group Team leads. The Task Force Team will support the Board and they will:

- 1. Be the formal interface between the Board and the activated Working Groups;
- 2. Monitor, collect, document, and file the reports of the Working Groups activated to support the mishap investigation;
- 3. Provide the Board members with requested information and reports from the Working Groups; and
- 4. Assist the Board in the preparation of interim and final reports as required.

5. BOARD RESPONSIBILITIES

The Board will:

- 1. Conduct activities in accordance with direction from the NASA Administrator and the provisions of applicable NASA management instructions.
- 2. Work with the NASA Administrator to schedule Board activities, interim Board reports, and submission of the final Board report.
- 3. Determine the facts, as well as the actual or probable causes of the Shuttle mishap in terms of primary cause(s), and potential cause(s) and recommend preventive and other appropriate actions to preclude recurrence of a similar mishap. The investigation will not be conducted or used to determine questions of culpability, legal liability, or disciplinary action.
- 4. Use the established NASA support structure of working groups, NASA Field Center support, and supporting facilities to conduct the investigations. This includes staff advisors as required for expertise in areas such as public affairs, legal, medical, safety, and security.
- 5. Activate the working groups appropriate to the mishap.
- 6. Obtain and analyze whatever facts, evidence, and opinions it considers relevant by relying upon reports of studies, findings, recommendations, and other actions by NASA officials and contractors or by conducting inquiries, hearings, tests, and other actions it deems appropriate. In so doing, it may take testimony and receive statements from witnesses. All elements of NASA will cooperate fully with the Board and provide any records, data, and other administrative or technical support and services that may be requested.
- 7. Impound property, equipment, and records to the extent that it considers necessary.
- 8. Document findings in terms of (a) the primary causes of the mishap; (b) contributing causes; (c) potential causes; and (d) pertinent observations.
- 9. Release mishap information and mishap investigation reports in accordance with applicable NASA policies.
- 10. Develop recommendations for preventative and other appropriate actions. A finding may warrant one or more recommendations or may stand alone.
- 11. Provide a final written report to the NASA Administrator not later than 60 days.

February 1, 2003



National Aeronautics and Space Administration Office of the Administrator Washington, DC 20546-0001



February 6, 2003

Admiral Hal Gehman 3725 Lynnfield Drive Williamsburg, VA 23081

Dear Admiral Gehman:

Please find, attached to this letter, a revised Charter for the Columbia Accident Investigation Board. I am pleased to make the changes you requested, which are incorporated in this new text. I thank you for your efforts, and those of the entire Board, as we all dedicate ourselves to determining the cause of the accident.

Respectfully,

Sean O 'Keefe Administrator

Enclosure

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Columbia Accident Investigation Board Charter

1. GUIDELINES

In the case of a high-visibility, mission-related Shuttle mishap, the NASA Administrator may activate an International Space Station and Space Shuttle Mishap Interagency Investigation Board (the Board). Board activation is anticipated for events involving serious injury or loss of life, significant public interest, and other serious mishaps. The Board should consist of at least seven members, and be supported by the Office of Space Flight Headquarters and technical consultants as required.

2. ACTIVATION

The recommendation for the NASA Administrator to activate this Board will normally be made at either the Associate Administrator for the Office of Space Flight-directed Mishap Response Teleconference or as a decision at the Administrator's HCAT meeting and/or teleconference. For this case, the NASA Administrator has determined effective at 10:30 am February 1, 2003, to convene such a Board and to name it the Columbia Accident Investigation Board.

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Board Members

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Director, Plans and Programs, Headquarters Air Force Materiel Command,
Maj. General John Barry
Commander, HQ USAF Chief of Safety, Major General Kenneth W. Hess
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Director of Accident Investigation, Federal Aviation Administration, Mr. Steven B. Wallace
Commander, 21st Space Wing, USAF, Brig. General Duane Deal
Director, NASA Ames Research Center, Mr. Scott Hubbard

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Standing Board Support Personnel

Ex-Officio Member: Mr. Bryan O'Connor, Associate Administrator for Safety and Mission Assurance

Executive Secretary: Mr. Theron Bradley, Jr., NASA Chief Engineer

Additional Support Personnel. The Board may designate consultants, experts, or other government or non-government individuals to support the Board as necessary.

Task Force Team Support. Within 72 hours of activation of the Interagency Board, the AA/OSF, the AA/SMA, the NASA Field Center Director or NASA Program Associate Administrator (Non-OSF or Non Mission Related), and the NASA Chief Engineer will meet to select and recommend

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Task Force Team members to the Mishap Board Chairman. Upon approval by the NASA Administrator, the Task Force Team members will convene and meet with the appropriate Working Group Team leads. The Task Force Team will support the Board and they will:

- 1. Be the formal interface between the Board and the activated Working Groups;
- 2. Monitor, collect, document, and file the reports of the Working Groups activated to support the mishap investigation;
- 3. Provide the Board members with requested information and reports from the Working Groups; and
- 4. Assist the Board in the preparation of interim and final reports as required.

5. COLUMBIA ACCIDENT INVESTIGATION BOARD RESPONSIBILITIES

The Independent Board will:

- 1. Conduct activities in accordance with the provisions of applicable NASA policies and procedures.
- 2. Schedule Board activities, interim Board reports, and submission of the final Board report in coordination with the NASA Administrator.
- 3. Determine the facts, as well as the actual or probable causes of the Shuttle mishap in terms of dominant and contributing root causes and significant observations and, recommend preventive and other appropriate actions to preclude recurrence of a similar mishap. The investigation will not be conducted or used to determine questions of culpability, legal liability, or disciplinary action.
- 4. Use the established NASA support structure of working groups, NASA Field Center support, and supporting facilities to conduct the investigations. This includes staff advisors as required for expertise in areas such as public affairs, legal, medical, safety, and security.
- 5. Activate the working groups appropriate to the mishap.
- 6. Obtain and analyze whatever facts, evidence, and opinions it considers relevant by relying upon reports of studies, findings, recommendations, and other actions by NASA officials and contractors or by conducting inquiries, hearings, tests, and other actions it deems appropriate. In so doing, it may take testimony and receive statements from witnesses. All elements of NASA will cooperate fully with the Board and provide any records, data, and other administrative or technical support and services that may be requested.
- 7. Impound property, equipment, and records to the extent that it considers necessary.
- 8. Release mishap information and mishap investigation reports in accordance with applicable NASA policies.
- 9. Develop recommendations for preventative and other appropriate actions. A finding may warrant one or more recommendations or may stand alone.
- 10. Provide a final written report to the NASA Administrator not later than 60 days.

February 1, 2003

Revised: February 6, 2003



National Aeronautics and Space Administration

Office of the Administrator Washington, DC 20546-0001



February 18, 2003

Admiral Hal Gehman, USN (Ret) Chairman Columbia Accident Investigation Board 16850 Saturn Lane Houston, Texas 77058

Dear Admiral Gehman,

Thank you for your comments on the charter changes proposed last week. Pursuant to your request, I have made further changes to the charter derived from our collective efforts to consult with Members of Congress. The enclosed charter reflects all revisions to this date.

The revised charter also reflects the appointments of Roger Tetrault and Sheila Widnall as members of the Board. You have advised that you are considering a recommendation to me for another appointment. In accord with our discussions, I am prepared to make such appointments you feel would contribute to the Board's work.

I am also in receipt of a copy of a letter addressed to you from NASA's Inspector General, Robert Cobb, on February 14, 2003, asking you to acknowledge your independence in certain respects. Please feel free to advise of any aspects of your charge you feel needs particular further emphasis. Of particular note relative to the Inspector General's views, you are charged in the charter to "obtain and analyze whatever facts, evidence, and opinions it (the Board) considers relevant" to "determine the facts, as well as the actual or probable causes of the Shuttle mishap... and recommend preventative and other actions to preclude recurrence of a similar mishap."

These charter provisions and others clearly demonstrate that your Board can and must act independently. Your Board is entitled to receive any information that NASA has. If there is any resistance, please let me know and we will assure cooperation. It is within your charter to determine causes, including whether NASA budget or management or any other factors created an environment which caused or contributed to the cause of this accident.

C0-000010 CAB031-0259



Page 2 Admiral Gehman February 18, 2003

For these and other factors we have discussed several times over the past two weeks, I find the Inspector General's views and advice to be completely consistent with our mutual understanding of the Board's responsibility and conduct of operations for this important investigation.

Cordially,

Sean O'Keefe Administrator

C0-000010 CAB031-0260



Columbia Accident Investigation Board Charter

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2. ACTIVATION

The recommendation for the NASA Administrator to activate this Board will normally be made at either the Associate Administrator for the Office of Space Flight-directed Mishap Response Teleconference or as a decision at the Administrator's HCAT meeting and/or teleconference. For this case, the NASA Administrator has determined effective at 10:30 am February 1, 2003, to convene such a Board and to name it the Columbia Accident Investigation Board.

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Chief, Aviation Safety Division, Department of Transportation, Dr. James N. Hallock

Director of Accident Investigation, Federal Aviation Administration, Mr. Steven B. Wallace Commander, 21st Space Wing, USAF, Brig. General Duane Deal

Director, NASA Ames Research Center, Mr. Scott Hubbard

Mr. Roger E. Tetrault

Dr. Sheila Widnall

4. BOARD SUPPORT

Standing Support Personnel Reporting to the Board

Ex-Officio Member: Mr. Bryan O'Connor, Associate Administrator for Safety and Mission Assurance

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Executive Secretary: Mr. Theron Bradley, Jr., NASA Chief Engineer

Additional Support Personnel. The Board may designate consultants, experts, or other government or non-government individuals to support the Board as necessary. In addition, the Board may substitute non-NASA personnel as Executive Secretary at the discretion of the Chairman.

Task Force Team Support. Within 72 hours of activation of the Interagency Board, the AA/OSF, the AA/SMA, the NASA Field Center Director or NASA Program Associate Administrator (Non-OSF or Non Mission Related), and the NASA Chief Engineer will meet to select and recommend Task Force Team members to the Columbia Accident Investigation Board Chairman. Upon approval by the Board and appointment by the NASA Administrator, the Task Force Team members will convene and meet with the appropriate Working Group Team leads. The Task Force Team may to the extent that the Board deems appropriate:

- 1. Be the formal interface between the Board and the activated Working Groups;
- 2. Monitor, collect, document, and file the reports of the Working Groups activated to support the mishap investigation;
- 3. Provide the Board members with requested information and reports from the Working Groups; and
- 4. Assist the Board in the preparation of interim and final reports.

5. COLUMBIA ACCIDENT INVESTIGATION BOARD RESPONSIBILITIES

The Independent Board will:

- Conduct activities in accordance with the policies and procedures adopted by the Board
- 2. Schedule Board activities, interim Board reports, and submission of the final Board report as the Board deems appropriate.
- 3. Determine the facts, as well as the actual or probable causes of the Shuttle mishap in terms of dominant and contributing root causes and significant observations and, recommend preventive and other appropriate actions to preclude recurrence of a similar mishap. The investigation will not be conducted or used to determine questions of culpability, legal liability, or disciplinary action.
- 4. Use the established NASA support structure of working groups, NASA Field Center support, and supporting facilities to conduct the investigations, as the Board deems appropriate. The Board may use non NASA support as it deems appropriate.
- 5. Activate the working groups appropriate to the mishap.
- 6. Obtain and analyze whatever facts, evidence, and opinions it considers relevant by relying upon reports of studies, findings, recommendations, and other actions by NASA officials and contractors or by conducting inquiries, hearings, tests, and other actions it deems appropriate. In so doing, it may take testimony and receive statements from witnesses. All elements of NASA will cooperate fully with the

C2-000031



- Board and provide any records, data, and other administrative or technical support and services that may be requested.
- 7. Impound property, equipment, and records to the extent that it considers necessary.
- 8. Release mishap information and mishap investigation reports, as the Board deems appropriate.
- 9. Develop recommendations for preventative and other appropriate actions. A finding may warrant one or more recommendations or may stand alone.
- 10. Provide a final written report at such time and in such manner as the Board deems appropriate which upon its completion will be immediately released to the public.

February 1, 2003

Revised: February 18, 2003

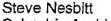
News Release

National Aeronautics and Space Administration

Washington, DC 20546 (202) 358-1600

Glenn Mahone/Bob Jacobs Headquarters, Washington (Phone: 202/358-1600)

For Release Feb. 18, 2003



Columbia Accident Investigation Board

(Phone: 713/301-9571)

NOTE TO EDITORS: N03-019

SPACE SHUTTLE ACCIDENT INVESTIGATION BOARD CHARTER AMENDED

The NASA charter for the independent panel in charge of the Space Shuttle Columbia accident investigation has been amended. The changes allow the Space Shuttle Accident Investigation Board additional flexibility in acquiring support staff and expertise outside of NASA.

NASA Administrator Sean O'Keefe has indicated the charter will continue to be updated as necessary to ensure the panel, which is known as the Gehman Board, remains independent during the course of the investigation.

On Saturday, Admiral Harold W. Gehman, Jr., announced the addition of Dr. Shelia Widnall of the Massachusetts Institute of Technology, Cambridge, Mass., to the panel. Dr. Widnall, former Secretary of the Air Force from 1993 to 1997, is a world-renowned expert in aircraft turbulence and spiraling airflows. She will begin meeting with the other members of the Gehman Board Thursday, Feb. 20, in Houston.

An updated copy of the board's charter and letter from the NASA Administrator is on the Internet at www.nasa.gov.

-end-

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Volume V Appendix G.4

Group 1 Matrix Brief on Maintenance, Material, and Management

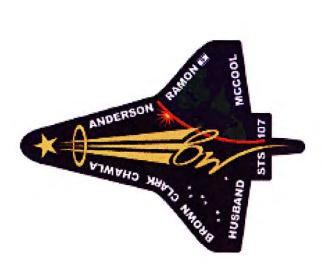
This Appendix contains a working matrix of slides on maintenance, material, and management. These slides were used by Group I in tasking NASA to respond to requests for information or specific issues. Each matrix subject addresses an action/issue, background/facts, findings, recommendations and source documentation. By using this tool, Group I was able to engage NASA on potential final report inclusions.



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Group 1

INVESTIGATION MATRIX



Group 1 Investigation Matrix



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8 (4) 11 (5) 14 (7) 9 (4) 12 (1) 15 (5) 16 (3)
12

FINAL Date CAIB/Group 1 Presenter

2 of 32

Slide

Reset Matrix

Design - Certification ET - Foam

ET Bipod Ramp Redesign

7

Geometry of LH2-IT Flange

44

Super Lightweight Tank Design Change

Presenter

Date CAIB/Group 1

FINAL

3 of 32 Slide

Matrix



ET - Foam **Design - Certification**

- Action / Issue: Redesign of Bipod Fitting Enclosure
- Background / Facts:
 - Complex bipod attachment designed to be structurally optimal TPS materials (incl. foam ramp) were incorporated into the design following structural optimization
 - Foam & SLA must be applied to a complex geometry
 - Combination of complex geometry and variable foam spraying techniques make current bipod foam ramp fabrication difficult
 - · Only 6 spray operators are trained for foam application in this area
 - Bipod foam ramp has been redesigned twice in past
 - Foam from bipod ramp lost during ascent on at least 7 occasions:
 - STS-7 (ET-6), STS-32 (ET-32R), STS-50 (ET-50), STS-52 (ET-55), STS-62 (ET-62), STS-112 (ET-115), STS-107 (ET-93)

Presenter M3/Material Date FINAL



ET - Foam **Design - Certification**

- · Findings:
 - Bipod fitting enclosure redesign efforts are already underway
 - · Effort was initiated after loss bipod ramp foam on STS-112
 - Lessons learned indicate use of SLA is not necessary
 - Five designs proposed
 - · All eliminate SLA
 - Two minimize size of sprayed-on foam ramp with metal (Ti) fitting
 - · One uses a bare metal (Ti) fitting
 - · Two use an Inconel housing to protect the metal fitting
 - Leading candidate (2a) is a bare metal fitting with no foam
 - Preliminary Design Review scheduled for 17-19 Jun 03
 - Critical Design Review planned for ~15 July 03

Presenter M3/Material Date FINAL

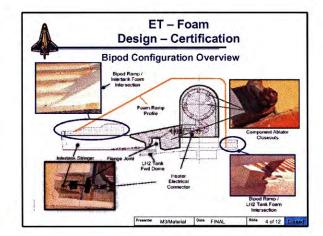


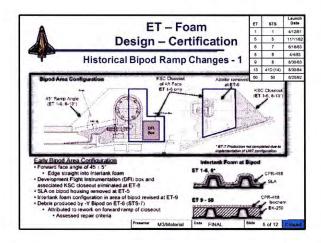
ET - Foam **Design - Certification**

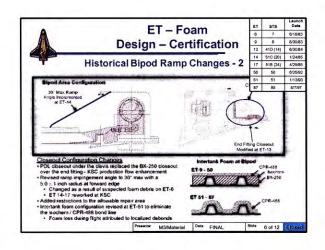
- Recommendations:

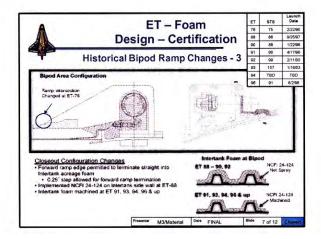
 - NASA efforts to redesign the bipod fitting enclosure must continue.
 Redesign efforts must include testing and analyses that account for the complex combination of aerodynamic loads, structural loads, aerodynamic heafing, cryogenic backface temperatures, and changes in atmospheric pressure.
 - Tests and analyses must be sufficient to ensure that the loss of foam or hardware from this region will not happen in the future.
 - The redesign of the bipod fitting enclosure will be a Return-To-Flight
 - If foam is still required on bipod fitting:
 - Tighten acceptable temperature & humidity spray envelope
 - · Standardize operator techniques
 - Consider use of robotics to fabricate bipod ramp
 - · Develop and validate NDE techniques to check for defects

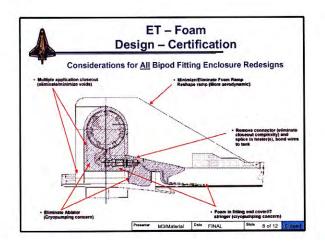
Presenter M3/Material Date FINAL Slide 3 of 12



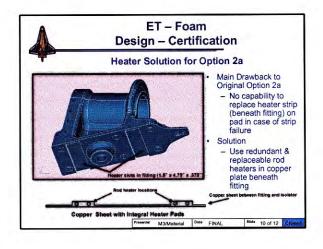


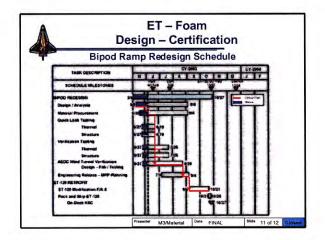
















ET – Foam Design – Certification

- Action / Issue: Geometry of the LH2-IT flange could contribute to foam loss
- · Background / Facts:
 - LH2-IT geometry provides several paths where LN2 can possibly get into the flange area
 - Solid N2 to GN2 state transitions could possibly contribute to foam loss
 - A "Y" joint is formed where the LH2-IT connection is made provide a reservoir where LN2 can collect

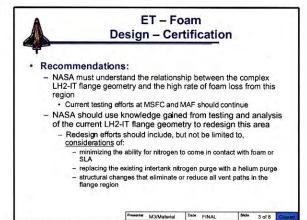
Presenter M3/Material Date FINAL Stide 1 of 8 Close

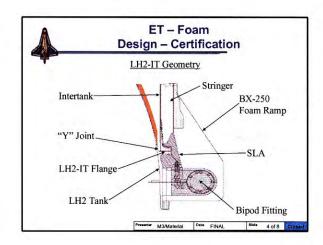


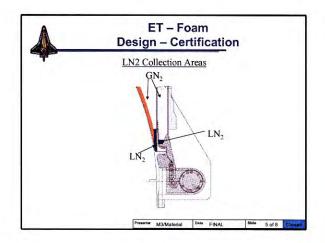
ET – Foam Design – Certification

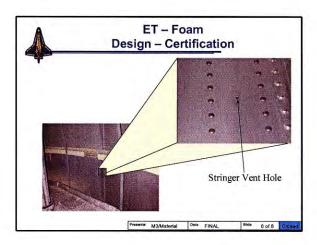
- · Findings:
 - Bolt holes, shim gaps and stringer venting could provide a path for LN2 to get behind the foam in the flange closeout area
 - During ascent, stresses in flange area change between tension and compression
 - LN2 path back to the IT could possibly be sealed leading to foam being "popped" off
 - Foam loss from the LH2-IT flange region has been observed on ~70% of missions where imagery was available

Presenter M3/Material Date FINAL Stade 2 of 8

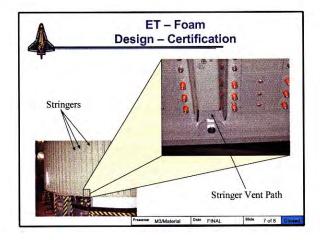


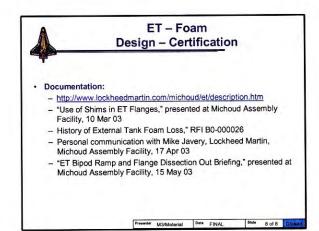






COLUMBIA ACCIDENT INVESTIGATION BOARD

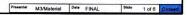






ET - Foam Design - Certification

- Action / Issue:
 - Stringer valley cracks have been documented as occurring on super lightweights more frequently than on other tanks
- Background / Facts:
 - Cracks in the valleys between stingers (external stiffening elements) on the intertank have been observed on several missions on all types of tanks
 - Standard weight [eg. ET-6]
 - Lightweight [eg. ET-29 & ET-35]
 - · SLWT
 - However, the occurrence of these cracks have been identified more often beginning with the first SLWT, ET-96, launched with mission STS-91 in June 1998





Findings:

- Subsequent to the change to super lightweight tanks, final inspection teams started seeing cracks in the intertank stringer valleys more frequently than on lightweight or standard tanks
 - It is believed these cracks form during tanking as a form of stress relief as the aluminum ET cools and contracts

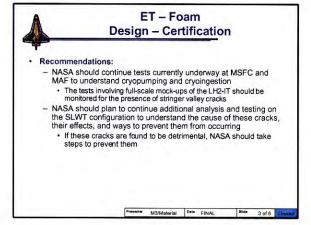
 Hypothesis: thinner, machined foam in these areas (part of the super lightweight design) is more susceptible to cracking

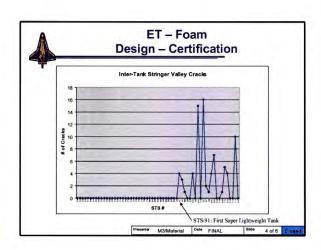
 Ice/Debris Team inspection & documentation procedures have not changed with respect to stringer valley cracks

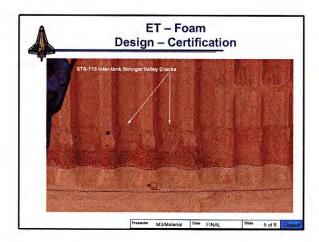
 Cracks are more difficult to spot in machined foam

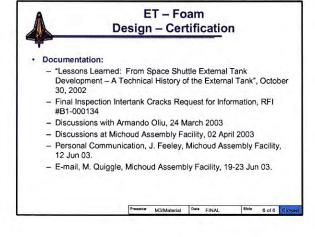
 - Thus, so the sudden increase in the numbers of cracks observed with the advent of the SLWT appears to be real.
- A comprehensive review of historical records has not been performed

 However a quick data search shows that these cracks were rarely recorded prior to the SLWT inception
- These cracks, if underneath the bipod ramp, could provide a possible reservoir for LN2











2-1	Blowing Agent Changes
2-2	Manual Spraying Operations
2-3	Processing Environment Controls for Foam Applications
2-4	NDE for ET During Production

CAIB/Group 1 Presenter

FINAL

Date

Matrix



Action / Issue:

Concerns exist about changes to blowing agents used in ET foams and their influence on foam properties

Background / Facts:

- 1978: US bans CFCs in aerosol sprays
- 1988: US Senate approves Montreal Protocol
- 1988: Martin Marietta initiates activities to screen CFC alternates
- 1990: Clean Air Act Amendment rules phase-out of CFCs by 2000
- 1991: Martin Marietta selects best CFC alternative (HCFC 141b)
- 1993: CFC 11 manufacture discontinued

NASA chooses not to pursue "Essential Use Exemption" for production of CFC 11 after remaining stockpile exhausted

- 1995: SS 1171 (HCFC 141b) chosen to replace BX 250 (CFC 11) CFC 11 stock secured by Martin Marietta to continue BX 250 production

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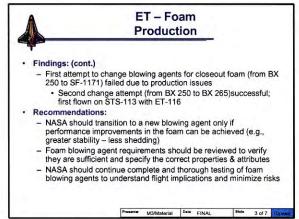
ET - Foam Production

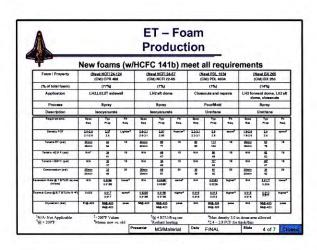
Background / Facts: (cont.)

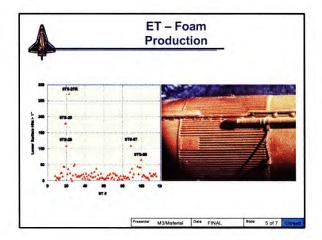
- 1998: Problems with SS 1171 force continued use of BX 250
- 2001: BX 265 (HCFC 141b) chosen to replace BX 250 (CFC 11)
- 2002: BX 265 implemented on ET-117 (MAF) & ET-116 (KSC)
- 2003: EPA phase-out of HCFC 141b production takes effect Waiver for continued HCFC 141b production approved for NASA

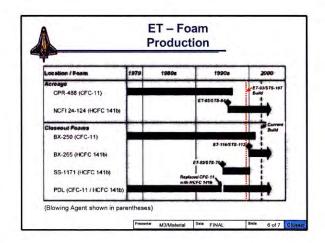
Findings:

- Thousands of tests conducted to develop & qualify each ET foam
- Change in blowing agents for acreage foam (from CPR 488 to NCFI 24-124) caused "popcorning" earlier in ascent profile
 - · Popcoming = small pieces lost from thrust panels
 - Popcoming earlier in ascent results in debris with higher energy
 - Early popcorning first observed on STS-84/ET-85
 - · Resulted in extensive tile damage on STS-87/ET-89













- Documentation:

 - Documentation:

 NASA's "Petition for Space Shuttle Program HCFC 141B Exemption Allowance," 4 Feb 03

 "Blowing Agent Info Splinter Meeting," presented @ MAF, 13 Mar 03

 CAIB Request for Information, "CAIB Cryoinsulation Report," B1-000121, 27 Mar 03

 "Foam Blowing Agent," presented @ MAF 2 Apr 03

 Public Hearing, "ET Cryoinsulation Report," 7 Apr 03



- · Action / Issue:
 - Manual spraying operations of complex and closeout areas are not sufficiently controlled
- · Background / Facts:
 - Operators must be qualified to hand spray foam
 - Each spraying operation is unique and is operator dependent
 - Control of spraying variables has been limited except in the flange closeout area
 - Special techniques with limited qualified operators are now used due to prior problems in the flange closeout area
 - Spraying operations can be either one or two people depending on the operator's preference
 - Complex shapes and access to the area being sprayed makes these operations even more difficult to control

Presenter M3/Material Date FINAL Slide 1 of 6 Cligated



ET - Foam Production

- · Findings:
 - Dissection of various bipod and flange closeout areas has revealed that defects are introduced during the spraying operation
 - Defects tend to occur in complex geometry regions or where there is limited access for operators during the spray evolution
 - Defects are random and unpredictable
 - There have been limited attempts to control spraying variables except in the flange closeout area
 - Summary: complexity of areas to be sprayed + variability in operator techniques = a unique product with insufficient/unknown foam quality

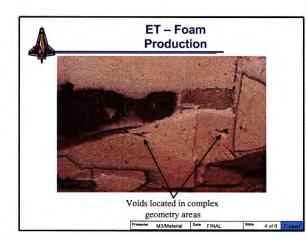
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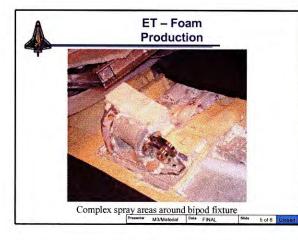


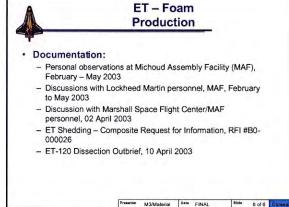
ET – Foam Production

- · Recommendations:
 - Efforts should be made to try and standardize (control) the hand spraying process as much as possible
 - If automated processes can be put in place to spray these areas, such as is currently done on the acreage foam, every effort should be made to make that transition
 - In areas where hand spraying must continue, operators should be qualified to spray all complex geometries
 - There should be no foam application processes requiring less than two people

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· Action / Issue:

 Process controls (especially those for temperature and humidity) may be insufficient to permit consistently high quality foam application.

· Background / Facts:

- Spraying operations must be within required environmental conditions
- Boundaries of the environmental conditions are considered to be conservative to guarantee proper foam performance
- Plug pulls are performed subsequent to spraying operations to verify proper material bonding and strength

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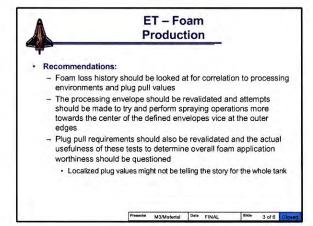


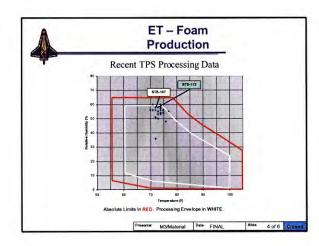
ET - Foam Production

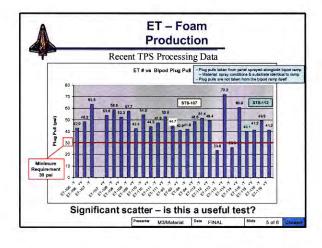
· Findings:

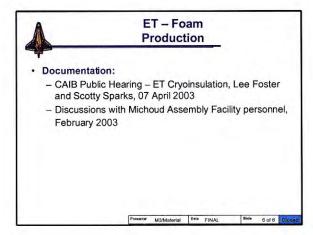
- Most spraying operations occur at or near the outer acceptable boundaries of the processing envelope
- Large variability in the response of the foam based on inherent randomness of foam cell structure
- Plug pulls, as a single indicator, might not be sufficient to verify the foam's bonding and strength properties

Presenter M3/Material Date FINAL Slide 2 of 6 Closed











- Action / Issue: No validated NDE techniques are available to identify subsurface damage within ET foam during or after production
- Background / Facts:
 - Extensive NDE is performed on welded aluminum sections of ET
 - No NDE performed on ET thermal protection system (TPS) except:
 - Visual checks during and after production
 - · Eddy current checks for thickness
 - · Preflight ice/debris inspections
 - · Plug puls & witness panels (destructive tests)
 - Previous efforts at MAF (1986-93) were unsuccessful in identifying NDE technologies that could be readily implemented
 - Boeing has had success using laser shearography on acreage foam of Delta-IV boosters, but
 - · Geometry is much less complex than that of ET
 - Inspection requirement is for larger defects



ET - Foam Production

Findings:

- Previous tests of laser shearography on flat foam panels indicated the technique had promise as a potential NDE technique for foam
 - · Some promise also seen on flat panels with intertank geometry
 - · Additional work is required to develop technique for production
- Production checks for foam quality are:
 - · Visual -or-
 - Require destructive testing (plug pulls) -or-
 - · Test representative foam sample rather than foam actually applied to tank ("witness panels")
- Dissections of bipod foam ramps on ET-94, ET-120, and ET-124 revealed that production defects in foam are common
 - Laser Shearography and X-ray NDE indications provided minimal correlation with physical observations

Presenter M3/Material Date FINAL



ET - Foam Production

- Findings: (cont.)
 - MAF and MSFC are actively pursuing development of an NDE technique to use on hand-sprayed closeouts
 - Candidate techniques include: X-ray (radiography), backscatter X-ray, shearography, microwave, and terahertz
 - Experts in field among are in Working Group All post-build & KSC processing inspections of the ET are visual
 - No NDE is used to confirm or size regions needing repair
 - · Visual examination relies on experienced personnel
 - Especially the Ice/Debris Team at KSC
 - LTI (John Newman) has estimated that 12-24 months is needed to develop shearography scanner hardware for the ET
 - Standards and procedures would also be required in addition to hardware

Presenter M3/Material Date FINAL

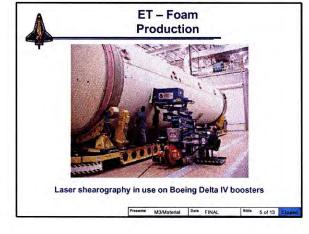
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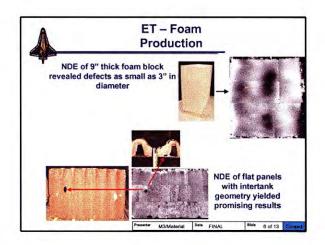


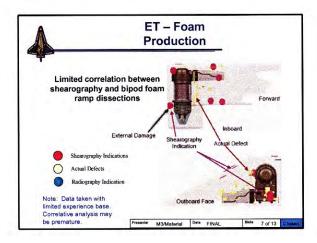
ET - Foam Production

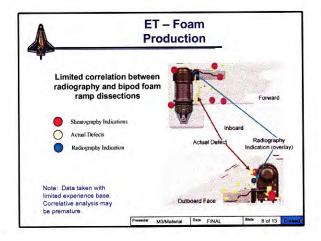
Recommendations:

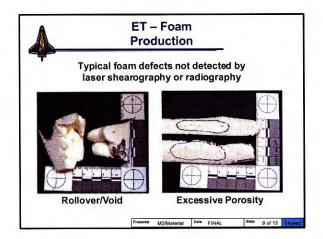
- Potential Return to Flight Recommendation: NASA should continue to pursue the development, validation, and implementation of NDE techniques that can be used to interrogate ET foam during production
- NASA should continue to pursue the development, validation, and implementation of NDE techniques that can be used to interrogate ET foam following production (i.e. at KSC prior to launch)

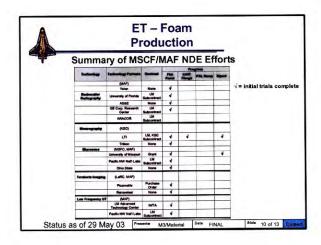


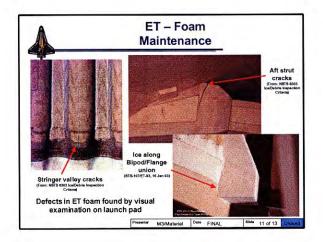


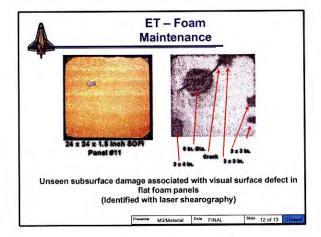
















Documentation:

- cumentation:

 NDT of Spray On Foam Insulation (SOFI), J. Newman, Laser Technologies Inc., 21 Feb 03

 Shearography NDE of Space Shuttle ET Spray On Foam Insulation (SOFI), J. Newman, Laser Technologies Inc., 21 Feb 03
- NSTS-8303, Rev. A, "Ice/Debris Inspection Criteria"
- (http://www-launchops.ksc.nasa.gov/msdinfo/et/8303/TABLE%20OF%20CONTENTS.htm)
- IS.ntm)
 CAIB Request for Information, "SoFI NDE Team: Approach, Progress & Plan." B1-000150
 MMC-ET-RA13, "ET Project-Nondestructive Evaluation Plan"
 MMC-ET-SE13, "ET Project-Fracture Control Requirements and Implementation Document"
 MMC-ET-SE16, "ET Project Materials and Process Control Plan"
 Empirity Noncomputer (Table) In Modific (CAIR) 40, lane 93.

- E-mail, J. Newman (LTI Inc.) to J. Wolfe (CAIB), 10 June 03

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CAIB/Group 1

Presenter

ET - Foam



ET Storage, Shipping, and Handling 3-2

Crushed Foam from Mate/De-Mate of ET-93

Matrix



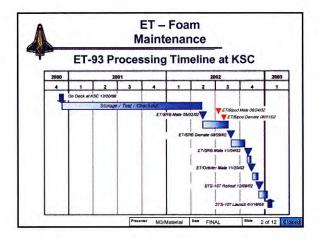
ET - Foam Maintenance

Action / Issue: Foam crushed beneath the -Y (left side) bipod strut clevis during pre-launch mating & demating with the bipod strut may have contributed to the loss of the -Y bipod foam ramp from ET-93 during STS-107.

Background / Facts:

- ET-93 mated to SRBs on 8 May 02 in VAB; de-mated on 28 Aug 02
- ET-93 mated to bipod on 24 Jun 02 in VAB; de-mated on 1 Aug 02
- Operations carried out in accordance with standard procedures
- Crushed foam seen after -Y strut removal (1.5" x 1.25" x 0.187")
- · Beneath -Y fitting-clevis joint after bipod struts removed
- Thickness of foam in this area: 2.187"
- Exposed crushed foam not permissible; Problem Report written
- Testing was performed @ MAF and KSC (on ET-117) to determine:
 - · If crushed foam on ET-93 could have caused loss of -Y bipod ramp
 - · If limits specified in PR procedures were sufficient

Presenter M3/Material Date FINAL



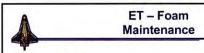


ET - Foam Maintenance

Findings:

- Crushed foam is always present at ET bipod attach points
 - · Specifically designed to be an "interference fit"
- KSC engineers decided to defer action on PR. Rationale:
 - · Crushed foam was contained beneath bipod strut clevis after mating to a new set of bipod struts
 - · Unexposed (i.e. contained) crushed foam is permissible
- Inspection of region after installation of bipod struts showed that crushed foam did not extend further than 0.75" beyond bipod fitting-clevis joint
 - · Within acceptable limits
- STS-107 launched with crushed foam contained behind -Y bipod strut clevis





Findings: (cont.)

- Three other mate-de-mate instances occurred on shuttle program; unknown link between mating/de-mating & foam loss
 - ET-13 used on STS-14(41D)
 - No imagery to confirm/deny foam loss
 ET-23 used on STS-27R
 - - Handheld video imagery; bipod ramps not visible, no other loss noted
 - Mated & de-mated during checkout of Vandenberg AFB facilities Extensive tile damage due to the loss of SRB ablator during launch
 ET-80 used on STS-80

 - Lost 2 divots on flange under bipod
 Lost one 10-inch diameter divot on intertank forward of -Y bipod ramp

Presenter M3/Material Data FINAL Slide 4 of 12 Clo



ET - Foam Maintenance

Findings: (cont.)

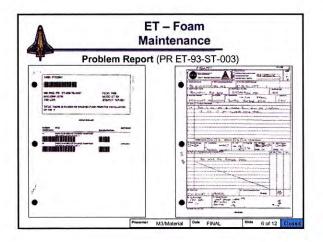
- Crushed foam testing conducted at MAF & KSC (on ET-117)
 - Red dye indicated extent of damage to be limited to a maximum of 0.5" beyond region visibly crushed with aid of dye Within acceptable limit

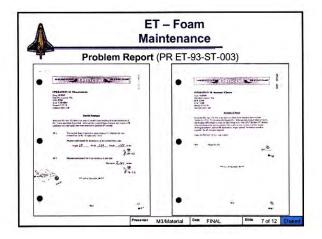
 - Receives little/no airflow with bipod strut installed
 - · Undamaged foam thickness was over 2" on ET-117
 - No ice/frost potential
 - · Localized damage would have no impact on performance of ramp
 - Results indicate no contribution from crushed foam to the loss of the bipod foam ramp on ET-93

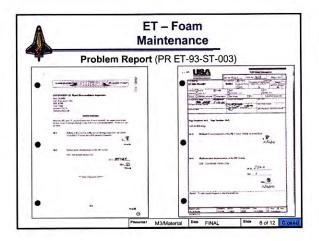
Recommendations:

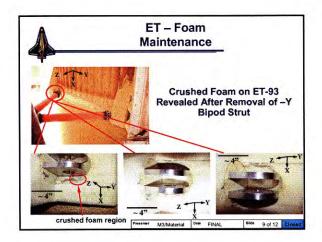
- None

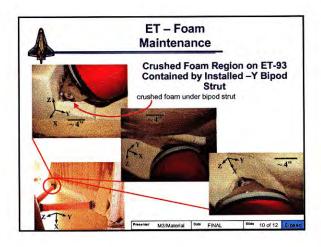
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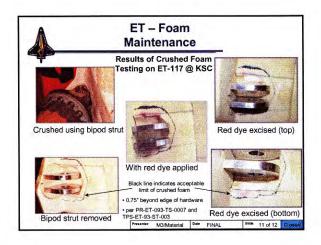


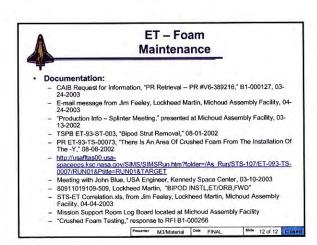














ET - Foam Maintenance

- Action / Issue: A concern existed that improper storage and handling of the ET between its completion and launch may have damaged foam and contributed to foam loss during the ascent of STS-107.
- · Background / Facts:
 - Post-build activities include storage at MAF, shipment to KSC, processing at KSC, and mating to SRBs and orbiter
- · Findings:
 - Extensive documentation governs steps taken to care for ET
 - Storage takes place in locked, limited-access facilities
 - Tanks are pressured with nitrogen or helium to 6.0 +/- 0.5 psi
 Pressure checked every 2 weeks at MAF, every week at KSC
 - Visual inspections performed every 90 days
 - ET is inspected 7 times between arrival at KSC and launch
 - · This does not count daily inspections when stack exists

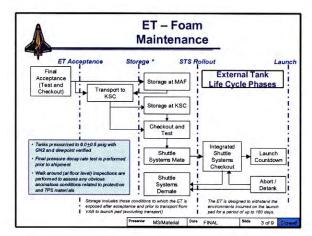
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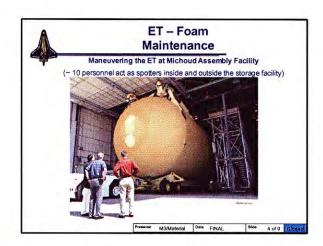


ET – Foam Maintenance

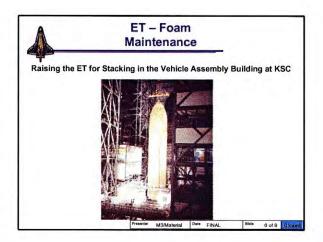
- · Findings (cont.):
 - Protective covers are used for 14 areas with historically significant potential rates of damage due to collateral operations
 - Repairs performed by KSC with assistance from MAF if needed
 - Repaired areas inspected for "collateral" damage after repairs made
 - Post STS-107 paper review by KSC examined 56,000 pages of documentation
 - · No contributing events identified
- · Recommendations:
 - None
 - Processes appear to be in place and followed to ensure that shipping and handling is performed in a manner that minimizes damage to the ET

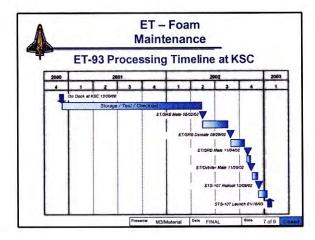
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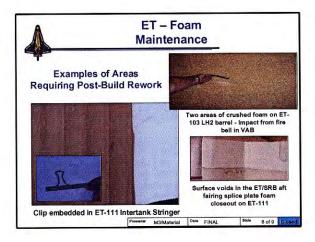


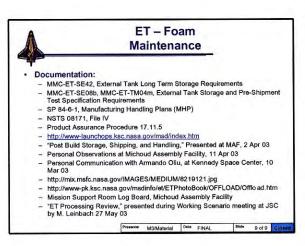












Launch - Ascent ET - Foam



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Presenter CAIB/Group 1

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Matrix



- Action / Issue: Cryopumping & Cryoingestion
- Background / Facts:
 - Cryoingestion: escape of N2 from intertank into SLA or foam
 - Gaseous N2 used to purge inner tank condenses to liquid on upper surface of LH2 tank
 - LN2 can leak through LH2-intertank flange shims, panel joints, and vent holes under stringers
 - . LN2 can then enter voids in foam or can be absorbed by SLA
 - Cryopumping: entry of ambient air through cracks in foam
 - Type (2) Ambient air condenses on surface of LO2 or LH2 tanks
 - · Air can come into contact with tank surface through cracks in foam
 - . Air can then enter voids or debonds at foam/substrate interface
 - Theory:
 - . Trapped liquid N2 or liquid air vaporizes during ascent as temp rises
 - · Lacking an escape path, vaporization causes a pressure build-up
 - · Pressure can force foam to shed off the ET

Presenter M3/Ma rials Date FI





ET - Foam Launch - Ascent

Findings:

- Recent dissections of bipod ramps and LH2-intertank flanges (ET-94, ET-120, ET-124) revealed flaws (voids, disbonds, FOD) potential cryoingestion/cryopumping sites
- Cracks in intertank stringer valleys & other areas may contribute to cryopumping
- No evidence exists of SLA having spalled off along with foam
- Test #6 at MSFC (cryoingestion) revealed:
 - When conditions were correct for cryoingestion and subsequent vaporization, foam failure mode was characterized by cracking
 - · Cracking relieved pressure permitting N2 to escape from beneath
 - . No spalling of foam was observed
 - · Test #6 conditions do not simulate the operational environment

Presenter M3/Materials Date FINAL





ET - Foam Launch - Ascent

Findings: (cont.)

- Test #2 at MSFC (combined thermo/cryo/vacuum environment) revealed:
 - · Conditions during tanking favor the formation of liquid and/or solid N2 in "Y" joint at intertank flange
 - · Conditions are not correct for vaporization of liquid/solid N2 during
- MSFC will continue to change parameters on Test #2 to determine if N2 vaporization can be artificially induced
- Bottom Line: Vaporization following ingestion of N2 from the intertank may be a contributing mechanism for foam loss but does not appear to be the sole driver

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ET - Foam Launch - Ascent

Findings: (cont.)

- Test #6 at MSFC (cryoingestion) revealed:
 - · When conditions were correct for cryoingestion and subsequent vaporization, foam failure mode was characterized by cracking
 - · Cracking relieved pressure permitting N2 to escape from beneath
 - · No spalling of foam was observed
 - · Test #6 conditions do not simulate the operational environment
 - Rapid warm up of the backface is not representative of flight environment
 Even with rapid warming, it takes approximately 3-5 minutes to build up enough pressure to crack foam, time far outside STS-107 bipod foam loss
- Bottom Line: Test #2 and Test #6 together show that vaporization following ingestion of N2 from the intertank is probably not a contributor to bipod ramp foam loss during

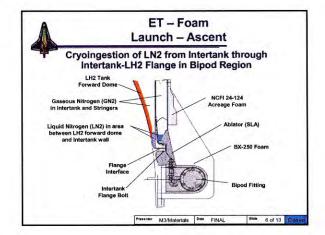
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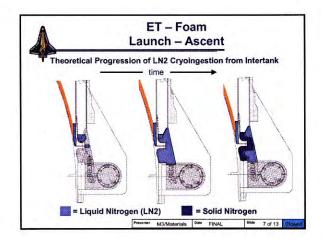


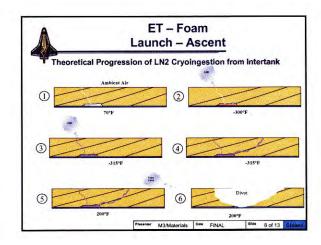
ET - Foam Launch - Ascent

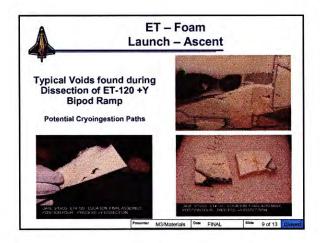
- NASA (MSFC) should continue with the series of tests planned to investigate the loss of the bipod foam ramp from ET-93 during STS-107
 - These tests will focus on understanding the cryopumping/ingestion issue and its effect on and relationship to other environmental conditions that the ET experiences during launch and ascent.
- NASA should perform independent (non-MSFC) testing to understand cryo-effects and other foam properties/behavior
- Lessons learned from these tests must be used in the redesign of the bipod fitting enclosure and also in the redesign of the LH2intertank flange area
- Cryopumping and cryoingestion must be eliminated as potential initiating events for foam loss from the ET.

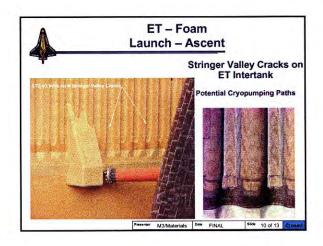
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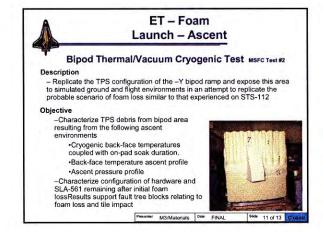


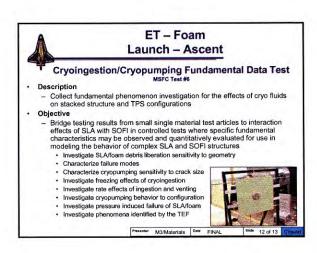
















- Documentation:
 - "External Tank Working Group Test Approval Request" presented to CAIB, 25 Feb 03

 - "Technical Exchange Forum on External Tank Nonmetallic Debris," MSFC, 3-4 Mar 03

 "External Tank Working Group Testing" presented at MAF, 14 Mar 03



- Action / Issue: The ET has shed foam since STS-01. Major events, such as the loss of portions of bipod foam ramps, have occurred periodically.
- Background / Facts:
 - Although tile damage is often used as the indicator of foam loss, no conclusive evidence exists linking tile damage with foam loss
 - Chemical sampling of tile damage sites for foam has been inconclusive
 - · Debris sources are not limited to the ET
 - Use of imagery from launch, ascent, and ET separation is necessary to confirm foam loss
 - All 113 STS missions have been reviewed to determine availability of launch/ascent imagery data
 - No imagery coverage available on 34 missions
 - 16 Night Launches & 18 Day Launches with no camera coverage
 - Bottom line: Presence or absence of foam loss can be visually confirmed on 79 of 113 missions at this time



ET - Foam Launch - Ascent

- Findings: Recall, visual imagery available on 79 of 113 missions
- 65 missions experienced visually confirmed foam loss
- Foam loss confirmed on 82% of missions for which imagery was available
- 55 experienced loss of foam from LH2-Intertank flange
- · 34 experienced loss of foam from Intertank acreage
- At least 7 experienced loss of a portion of a bipod ramp (all –Y [left])
- 12 experienced <u>confirmed</u> loss of foam from thrust panels ("popcorning")
- · 45 experienced loss of foam from other sites
- Of the 57 without a bipod ramp loss, 39 experienced losses "near bipod"
- Worst damage to orbiter tiles: STS-27R (OV-104)
- · Due to loss of SRB ablator material: not due to loss of ET foam
- Hits to orbiter: 644 lower surface (272 >1")

[707 total (298 > 1")]

- Most damage to tiles from ET foam loss: STS-87 (OV-102)
- · Thrust panel popcorning
- Hits to orbiter: 244 lower surface (109 >1")
 Present Apparent Deep Present Pr

[308 total (132 > 1")]



ET - Foam Launch - Ascent

- Findings (con't):
 - MSFC has taken actions on numerous occasions to eliminate or reduce foam loss from the ET
- Recommendations:
 - NASA must continue testing currently underway at MSFC and MAF to identify the root cause(s) for the generation of debris from the ET.
 - NASA must minimize the generation of debris from the ET.
 - NASA must establish programs to understand the possible damage resulting from debris impacts on other Space Shuttle elements.
 - NASA must institute a policy to provide (visual) imagery on 100% of launches to check for ET foam loss and other launch debris.

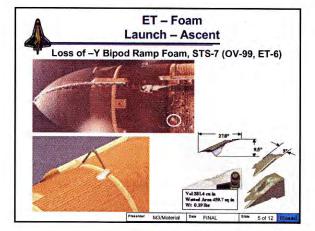
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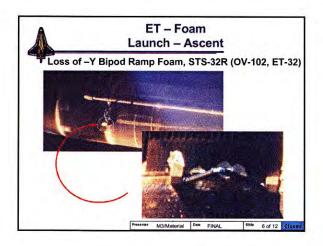


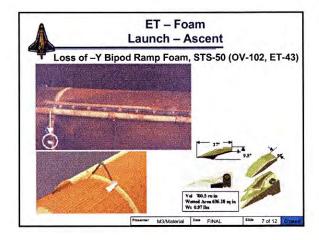
ET - Foam Launch - Ascent

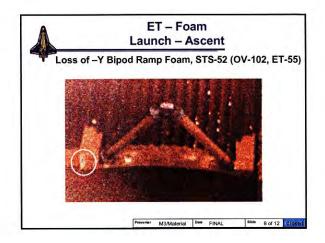
- Recommendations (con't):
 - NASA must harden each of the Space Shuttle elements (especially the orbiter) to maximize their impact damage tolerance.
 - NASA should take an integrated approach to address these recommendations
 - · All future efforts that minimize the debris generated by each Space Shuttle element and maximize each element's impact damage tolerance must be mutually compatible.
 - NASA should consider eliminating a foam-covered ET from the Space Transportation System

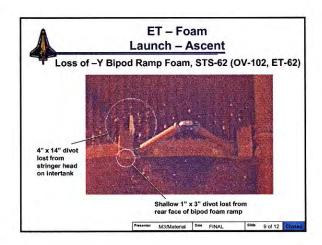
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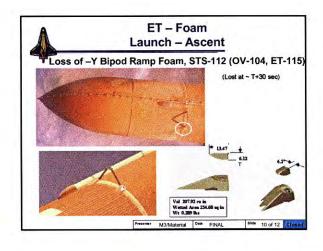


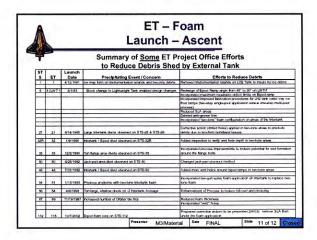


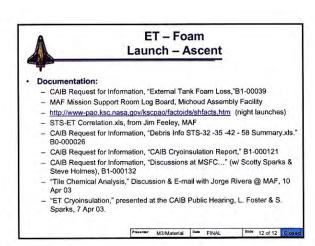














Ascent Debris Strike Other (ET/Foam)

- Action / Issue: Complex aerodynamic loads on ET-93's bipod foam ramp may have caused it to fail during the ascent of STS-107
- Background / Facts:
 - Bipod foam ramp shed at 81 sec (Mach 2.46, α = 2.08°)
 - Ascent environment is very severe; flow field is complex
 - · 3 intersecting shocks occur in bipod region
 - Airloads determined by numerous methods
 - · Wind tunnel testing of 3% scale model
 - · Computational Fluid Dynamics (CFD) analysis
 - · Analytical (Hoerner) analysis

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Ascent Debris Strike Other (ET/Foam)

· Findings:

- $-\,$ Early wind tunnel tests on flat-faced and 20° angle ramps confirmed
- a 1.1 safety factor against failure caused by aerodynamic loads
- · Additional analysis calculated a safety factor of 2.35
- Wind tunnel testing was not performed on the current bipod ramp geometry (22°-30°) nor on flight configuration articles (SLA, underlying bipod fitting, etc.)
- Wind tunnel testing was also performed on 3% scale model of Space Shuttle
 - Correlation between this testing and CFD/analytical models was good
 - MADS data from the OEX recorded recovered from STS-107 confirmed that CFD and analytical models were conservative
- No flight instrumentation was used on early ETs to investigate airloads on bipod ramps
 - · Instrumentation on early flights collected only bipod strut strains

Carry migrits concered only piped struct struct





Ascent Debris Strike Other (ET/Foam)

· Findings: (cont.)

- Aerodynamic loads predicted by CFD and analytical methods are significantly less than design requirements
 - Minimum safety factor is 1.4
- Vibroacoustic analysis calculated a safety factor of 1.64 against the formation of divots
- No finite element analysis was performed to determine the ability of the bipod foam ramps to withstand aerodynamic loads
 - Complexity of geometry and material makes such modeling difficult
 - Efforts are in place at MAF to develop a finite element modeling capability for foam protuberances

 The complex combined aero/thermo/vibro/vacuum/acoustic is
- extremely difficult to simulate, thus, combined testing was never performed
 - "Worst case" conditions were solved and superimposed to determine the integrity of the bipod foam ramps under these conditions

Presenter M3/Material Data FINAL Slide 3 of 15 Close



Ascent Debris Strike Other (ET/Foam)

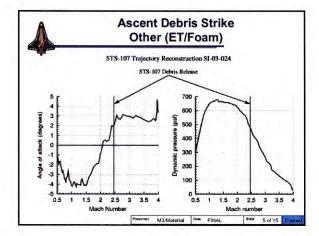
· Findings: (cont.)

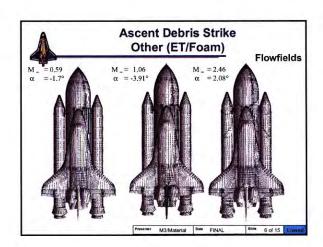
- No studies of the behavior of partially failed (i.e. cracked, etc.) bipod foam ramps was ever performed
- No evidence that aerodynamic loads, <u>alone</u>, caused bipod ramp to fail on ET-93 during STS-107
 - In fact, precited aero loads have a large radial load component (300 lb) forcing ramp to remain on ET

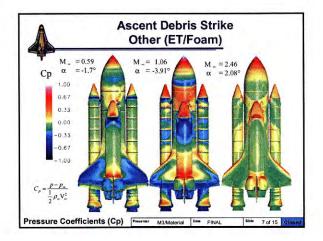
· Recommendations:

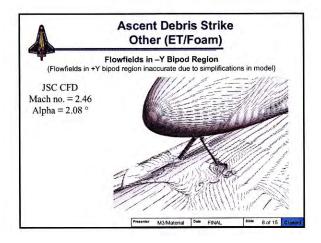
- NASA must continue to improve its capabilities to perform analytical and numerical simulations of the complex combined environments to which the the ET is exposed.
 - · These capabilities must be validated with test and/or flight data

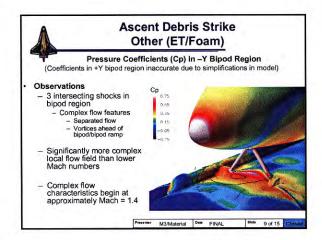
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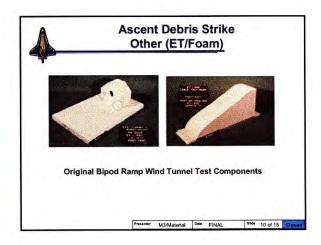


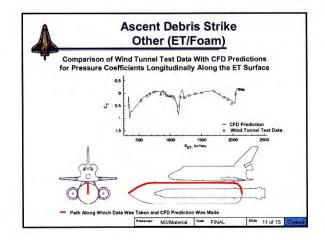


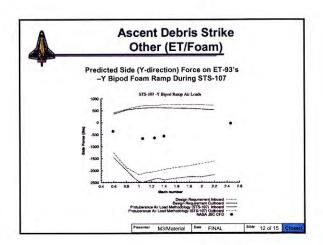




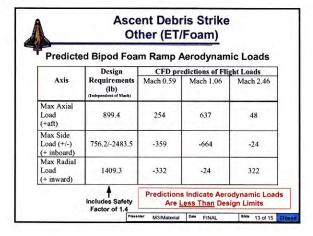


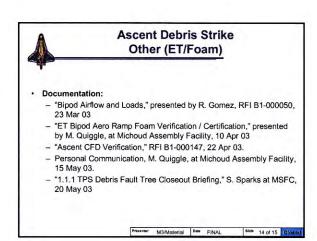


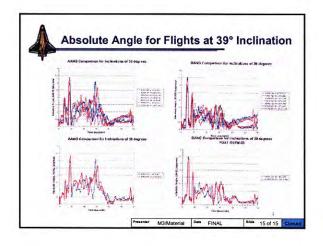












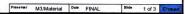




- · Action / Issue: Potential for Foam Loss to be Related to Weather
- Background / Facts:

 - Numerous suggestions (via PIAs and media) that foam loss is related to moisture absorption and/or ice formation

 Weather office at KSC has provided the following historical info for the time during which the shuttle was outside for each mission: 1) daily rainfall, 2) min/max daily temps, 3) min/max daily th, 4) min/max daily surface wind gusts & direction, 6) temp at start of tanking (fueling), 7) temp at launch
- Findings:
 - Average ET pre-launch exposure time for all missions is 38.5 days
 - ET-93 (used on STS-107) was on the pad for 39 days prior to launch
 No apparent trend linking pre-launch exposure time to foam loss
 No apparent trends linking foam loss with any weather variables analyzed



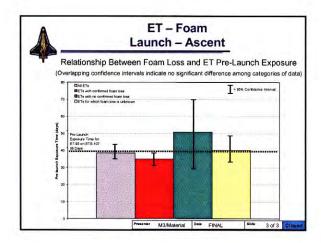


ET - Foam Launch - Ascent

- Recommendations:
 - NASA should continue to investigate moisture absorption by foam and relate any results to pre-launch exposure of the ET to the atmosphere.
 - NASA should continue analyzing weather data in search of correlations between weather variables and foam loss. Particular attention should be given to identifying the importance of combinations of variables that might contribute to foam loss.
- Documentation:

 - RFI B1-00145 "Historical Weather Data," 27 Mar 03 John Madura, KSC Weather Office, 321-867-0814, john.t.madura@nasa.gov







- Action / Issue: Moisture absorption by the External tank (ET) foam may have caused or exacerbated the foam loss event by increasing the mass of the piece shed from ET-93 during the ascent of STS-107
- Background / Facts:
 - PIA #644 cited a "review of publications" indicating closed-cell foam can absorb water and increase in mass by a factor of 10
 - B. Peterson (formerly of Texaco Chemical) cited experience with polyurethane foams that could absorb water at near-freezing temperatures if chemical constituents of foam were correct
 - Prof. L. Glicksman (M.I.T.) performed preliminary calculations
 - · Showed water vapor could be absorbed into foam at 68°F and 100% rh
 - 6-hour tanking would result in absorption of 0.001 lb/ft² of water
 - Moisture absorption by foam is a concern in the building industry PIA # 671 identified two commercially available codes designed to predict moisture absorption in foam
 - Incorrect analyses by media led to public misunderstandings



ET - Foam Launch - Ascent

- Findings:
 - ET foams do not have chemistry susceptible to moisture absorption
 - Peterson identified a specific EO/PO ratio (ethylene oxide / propylene oxide) that made foams absorptive near 32°F
 - · EO is the hydrophyllic component (attractive to water)
 - EO/PO ratio of ET foams is zero
 - Regardless of chemistry, unlikely that <u>closed-cell</u> foam can absorb liquid water
 - · Diffusional absorption of water vapor may be possible
 - Prof. Glicksman predicted ice and vaporization layers
 - Potential ice layer: thickness = 0.002 in, weight = 0.015 oz/ft²
 - Vaporization layer: thickness = 0.2 in, weight = 0.06 oz/ft²
 - Dr. Osheroff has performed simple experiments at Stanford
 - Immersion of foam in ice water suggests water permeates foam only to 0.004 in below surface
 - · Consistent with depth of single layer of open cells at surface

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ET - Foam Launch - Ascent

- Findings: (cont.)
 - MSFC previously performed water absorption tests under accelerated conditions (7 days at 125°F and 95% rh)
 - NCFI 24-124 acreage foam: 0.12% weight gain

 - BX 250 closeout foam: 0.16% weight gain
 SS 1171 feedline foam: 0.42% weight gain
 - PDL 1034 poured foam: 0.83% weight gain
 - · Both foams had machined surfaces (i.e. surface cells were open)
 - Recent additional tests conducted at MSFC (with Prof. Leon Glicksman of M.I.T. retained as a consultant)
 - Immersion of BX 250 & NCFI 24-124 in distilled, de-aired water at 125°F for over 60 hours
 - Water absorption equivalent to thickness of exposed surface laver of open cells Consistent with Dr. Glicksman's calculations and Dr. Osheroff's
 - experiments

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ET - Foam Launch - Ascent

Findings: (cont.)

- Recent additional tests conducted at MSFC (cont.)
 - · Vapor Phase Transmission through BX 250
 - Included thermal gradient of ~70°F to simulate tanking conditions

 - Level of transmission deemed insignificant (< 3 g/hr·m²)
 Especially in light of low moisture absorption & limited tanking times
- Bottom Line from recent tests at MSFC
 - · "Absorbed" water limited to open cells on surface
 - Any water absorbed deeper into foam does so through vapor transmission at a very low rate
 - Water ingress through voids/cracks open to surface and subsequent vaporization & crack formation or growth is a possibility
- Role of long voids, wormholes, knitlines may merit further testing
- Future research should integrate test results into a mechanistic, quantitative failure mode model

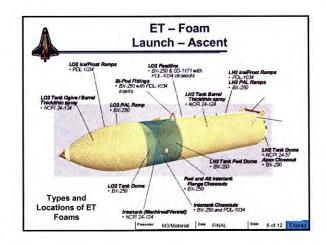
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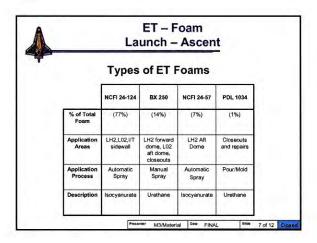


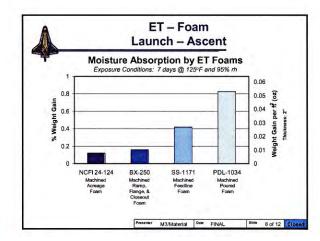


ET - Foam Launch - Ascent

- Group Recommendations:
 - NASA should consider continued testing per Dr. Glicksman's suggestion
 - Investigating water ingress through unique features (long voids, etc.)
 - Developing failure mode model incorporating test results









ET Foam Moisture Absorption Source: RFI B3-00060

NCFI 24-124

- Accelerated Exposure (7 days @ 125% and 95% humidity)
- 0.12% weight gain due to moisture absorption (machined foam)
- Outdoor Exposure (28 day variable daily relative humidity)
 - 0.70% maximum weight gain due to moisture absorption (after 6 days) - 0.04% moisture loss after 28 days

Vented NCFI 24-124

- Concern: Holes in vented foam will wick moisture if ET is exposed
- Test performed: 5 repeated exposures of heavy rain and extreme freezing conditions caused no deterioration of the foam tensile properties

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ET - Foam Launch - Ascent

ET Foam Moisture Absorption (cont.) Source: RFI B3-00060

BX-250

- Accelerated Exposure (7 days @ 125°F and 95% humidity)
 - 0.16% weight gain due to moisture absorption (machined foam)

- Accelerated Exposure (7 days @ 125°F and 95% humidity)
- 0.42% weight gain due to moisture absorption (machined foam)

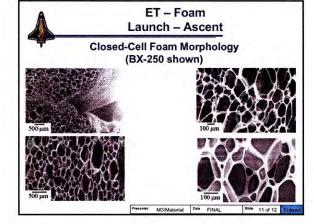
PDL-1034

- Accelerated Exposure (7 days @ 125°F and 95% humidity)
- 0.83% weight gain due to moisture absorption (machined foam) Conclusion
- ET foam materials absorb insignificant amount of moisture under

accelerated test conditions

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ET - Foam Launch - Ascent

Documentation:

- E-mail: Bruce Peterson to Johnny Wolfe, 27 Feb 03
- E-mail: Leon Glicksman to MG Barry, 9 Mar 03
- CAIB Request for Information, "External Tank Moisture Absorption," B3-00060
- CAIB Request for Information, "ET Cryoinsulations," B1-000121
- PIA 671 "Insulation & Moisture"
- PIA 644 "Closed Cell Foam Can Absorb Water"
- Discussion with Scotty Sparks (MSFC) at MAF, 16 Apr 03
- Discussion with Dr. Osheroff (CAIB/Stanford) at MAF, 21 Apr 03
- Response to RFI B1-000194 "ET Foam Moisture Absorption Testing," 1 Jun 03

Slide

FINAL

Date

CAIB/Group 1

Presenter

Design - Certification RCC



WLE Subsystem Design Requirements and Certification

RCC Impact Energy Requirements and Certification

5-2

5-1

Matrix

104



Wing Leading Edge Design & Certification

- Action / Issue: Determine adequacy of the WLE subsystem requirements, design and certification
- Background / Facts:
 - RCC is a critical component of the TPS (safety-of-flight)
 - Performance and design requirements documented in specification MJ070-0001-1E, 7 Nov 02
 - TPS impact energy design requirement is 0.006 foot-lbs (paragraph 3.3.1.8.11)
 - Orbiter not designed to withstand launch debris or ice (paragraph 3.3.1.8.16)

Presenter M3/Material Date FINAL Stide 1 of 26 Close



Wing Leading Edge Design & Certification

- Background / Facts :
 - Procurement specification MC621-0007, Rev E requirement more stringent than design requirement
 - Impact/ground handling damage resistance limits defined in figure 3.1
 - Impact energy limit ranges from 1 to 2.25 foot-pounds based on part thickness
 - TPS mission life requirement of 100 missions with scheduled maintenance and refurbishment (paragraph 3.4.3)

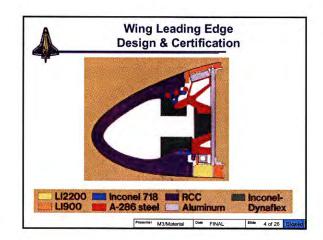
Presenter M3/Material Date FINAL Slide 2 of 26 Closed

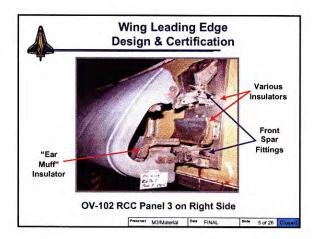


Wing Leading Edge Design & Certification

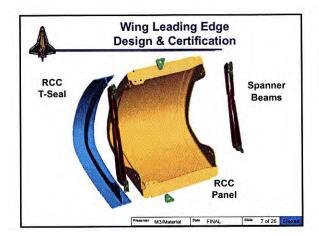
- · Background / Facts:
 - RCC system is mounted to the wing front spar using attach fittings bolted to the front spar
 - Wing front spar attach fittings redesigned from a 2-piece design using A-286 steel (OV-102) to a 1-piece design using Ti-6Al-4V titanium (subsequent orbiters)
 - The insulators used to protect the metallic components of the WLE have been redesigned to increase survivability against MMOD
 - Moment constraint fittings (spanner beams) were retrofitted on several OV-102 RCC panels as a result of an increase in the predicted loads
 - · OV-102 spanner beams installed on panels 5 through 19

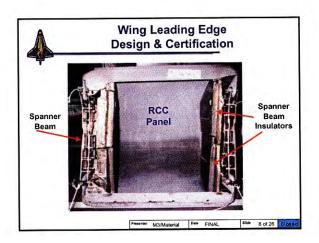
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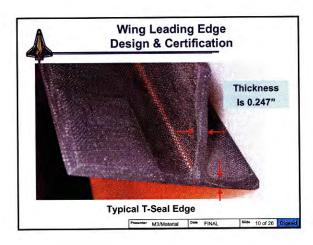




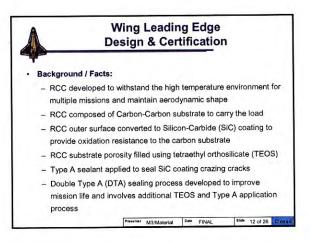




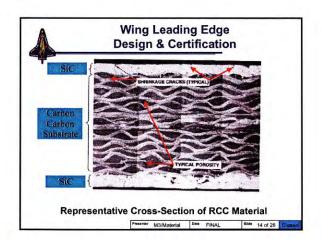




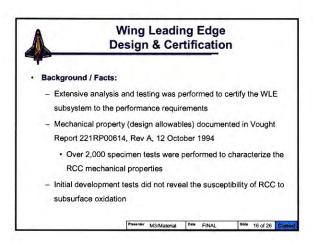


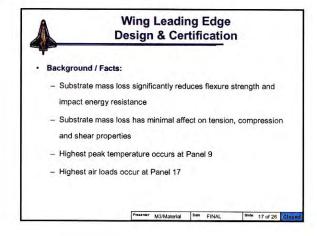


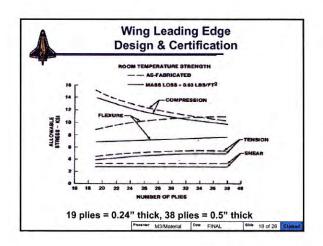


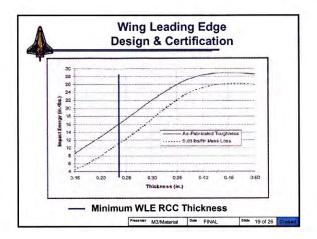


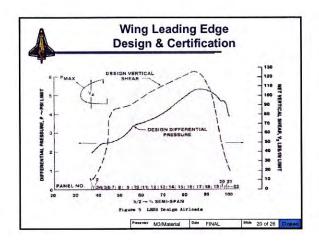


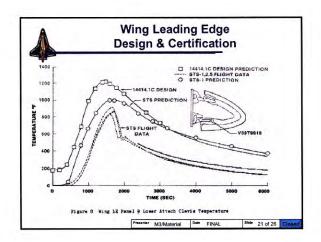
















Wing Leading Edge Design & Certification

- Recommendations (agreed to by Curry, Gordon, Grant):
 - Determine RCC component damage sources, frequency, and severity to include debris impact during ascent
 - Determine the damage tolerance capability for each damage type, location, and size ranges by calculating remaining service life and residual strength
 - Develop an NDE technique and capability to ensure damage limits have not been exceeded prior to each mission
 - Establish realistic service life duration expectation for remaining orbiters and revise operation and maintenance requirements accordingly

Presenter M3/Material Date FINAL Slide 23 of 26 Closed



Wing Leading Edge Design & Certification

- · Documentation:
 - Briefing by M. Gordon, "LESS/RCC Recovery and Reconstruction Data, OV-102 LESS/RCC Components Installed for STS-107", 1 March 2003
 - Boeing Specification MJ070-0001-1E, "Orbiter End Item Specification for the Space Shuttle Systems, Part 1, Performance and Design Requirements, 7 Nov 02
 - Briefing by D. Curry et al., "Orbiter RCC Design and Flight Experience", 28 July 1999

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Wing Leading Edge Design & Certification

· Documentation:

- Vought Report 221RP00614, Rev A, "Leading Edge Structural Subsystem Mechanical Design Allowables for Material with Improved Coating System", 12 October 1994
- Paper by D. Curry, "Space Shuttle Orbiter Thermal Protection System Design and Flight Experience", May 1993
- Paper by D. Curry, "Thermal Protection Systems Manned Spacecraft Flight Experience", February 1992
- Carbon-Carbon Materials Development and Flight Certification Experience From Space Shuttle*, September 1987
- AIAA Paper 86-0949-CP by D. curry et al., "Space Shuttle Orbiter: Leading Edge Structural Design/Analysis and Material Allowables", May 1986

Presenter M3/Material Date FINAL Slide 25 of 26 Close



Wing Leading Edge Design & Certification

· Documentation:

- AFFTC-TR-85-11, "Flight Test Results from the Entry and Landing of the Space Shuttle Orbiter for the First Twelve Orbital Flights", June
- Rockwell Procurement Specification MC621-0007, Leading Edge Structural Subsystem – Shuttle Orbiter", Rev E, 17 March 1983
- Paper by D. Curry et al., "Space Shuttle Orbiter Leading Edge Flight Performance Compared to Design Goals", March 1983
- Paper by R. Wakefield et al., "A Method for Determining Structural Properties of RCC Thermal Protection Material", May 1978
- Rockwell Report SD73-S11-0300B, "Orbiter Leading Edge Structural Subsystem Induced Environments", 9 April 1976

Presenter M3/Material Date FINAL Slide 26 of 26 Closed



RCC Impact Energy Requirements

- Action / Issue: Determine adequacy of RCC impact requirements and certification.
- · Background / Facts:
 - Performance and design requirements documented in specification MJ070-0001-1E, 7 Nov 02
 - TPS impact energy design requirement is 0.006 foot-lbs (paragraph 3.3.1.8.11)
 - Orbiter not designed to withstand launch debris or ice (paragraph 3.3.1.8.16)
 - Procurement specification MC621-0007, Rev E requirement more stringent than design requirement
 - Impact energy limit ranges from 1 to 2.25 foot-pounds based on part thickness

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Previous RCC Impact Testing

- · Background / Facts:
 - Hypervelocity impact testing performed
 - Reference NASA-LARC Report TMX-74039, June 1977
 - Nylon projectile resulted in front face damage at 2.2 foot-pounds and both front and back face damage at 8.1 foot-pounds
 - · Glass projectile resulted in front face damage at 0.2 foot-pounds
 - Hypervelocity impact testing performed in support of NRC MMOD study at JSC facility
 - · 15 shots using 2017-T4 aluminum
 - Projectile energy ranged from 53 to 213 foot-pounds
 - Minimum damage: front face = 0.65" and back face = 0.87"

Presenter M3/Material Date FINAL St



Previous RCC Impact Testing

- · Background / Facts :
 - Low velocity ice impact testing performed
 - Reference Boeing report STS-82-0615
 - · Specimen perforated at 132 foot-pounds normal to surface
 - Low velocity impact testing performed in an attempt to generate damage result seen on RCC panel 10R after STS-45 on OV-104-11
 - Aluminum projectile generated front face crater at 19.6 footpounds and front and rear face damage at 31.7 foot-pounds
 - Steel projectile generated front and rear face damage at 42.77 foot-pounds best match of STS-45 damage
 .22 short lead bullet did not damage specimen at 3.36 foot-
 - pounds
 - Steel BB damaged front and rear face at 1.23 foot-pounds

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WLE RCC Impact Fleet Experience Summary

Year	STS	ov	Flight #	Impact Location	Debris Type	Resulting Damage
1988	27R	104	3	T-Seal 7R	SRB Ablative	1 Dent, No SiC Loss
1992	45	104	11	Panel 10R	Man-Made Object	2 Dents with SIC Loss
1994	65	102	17	Panel 5L	MMOD	Small Crater
2003	107	102	28	Panel 5 to 10	ET Bi-Pod Foam	Under Evaluation

21 Flights Sampled, 43 Impacts Discovered due to Orbital Debris, Largest Damage = 0.2"

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WLE RCC Impact Fleet Experience Foam/Ablative

- Background / Facts:
 - OV-104-03 impact damage to right wing discovered after STS-27R in 1988
 - Reference TPS post-flight report KL0-89-001
 - "Some of the RCC panels and tee seals had streaks on the OML"
 - "Rib station #7 had a dent near the upper trailing edge"
 - Most probable cause is the right SRB nose cap ablative insulating material
 - OV-102-28 ET bi-pod ramp foam impact to left wing during STS-107 in 2003

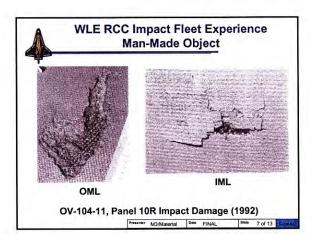
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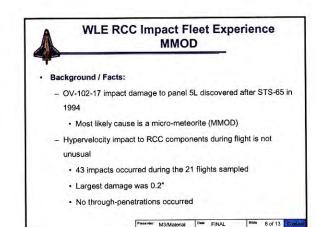


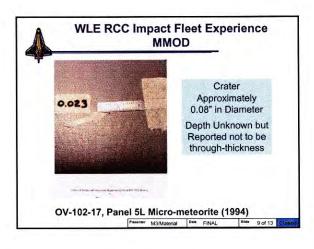
WLE RCC Impact Fleet Experience Man-Made Object

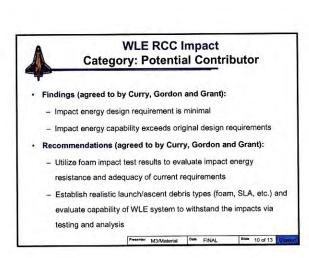
- Background / Facts:
 - OV-104-11 impact damage to panel 10R discovered after STS-45 in 1992
 - · Reference S. Christensen briefing
 - · Substrate was exposed and oxidized, panel scrapped
 - Failure analysis documented in LTR4088-2427
 - Impact was caused by a low velocity impact by a man-made object
 - · Impact occurred before reentry heating
 - Ascent encounter determined to be possible
 - On-orbit encounter determined to be remote possibility

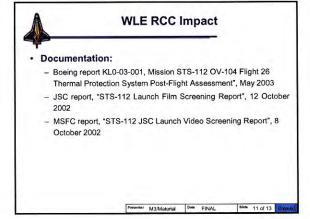
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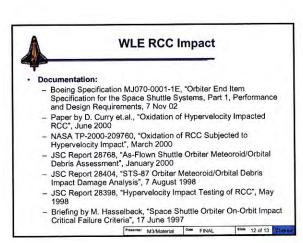
















WLE RCC Impact

Documentation:

- Documentation:

 Briefing by H. Sharifzadeh, "On-Orbit Impact Thermal Analysis Summary", 11 October 1996

 Rockwell Report LTR4088-2427, "Investigation of RCC R/H Panel #10 Wing Leading Edge Impact Damage STS-45 (OV-104), September 1992

 Rockwell briefing by S. Christensen, "Investigation Analyses of the RCC R/H Panel #10 Impact From STS 45 (OV-104), 2 July 1992

 Report KL0-89-001, "Mission STS-27R OV-104 Flight 3 Thermal Protection System Post Flight Assessment", February 1989

 Rockwell Report, "Evaluation of Flight Experience and Test Results for Ice Impact on Orbiter RCC and ACC Surfaces", 26 November 1984

 Rockwell Procurement Specification MC621-0007, Leading Edge

- Rockwell Procurement Specification MC621-0007, Leading Edge Structural Subsystem Shuttle Orbiter*, Rev E, 17 March 1983
 NASA-LARC Report TMX-74039, June 1977

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Date

CAIB/Group 1

Presenter

RCC Production

6-1

RCC Production Processes

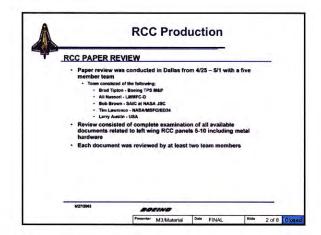
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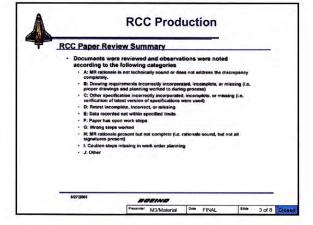


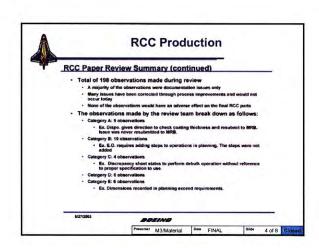
RCC Production

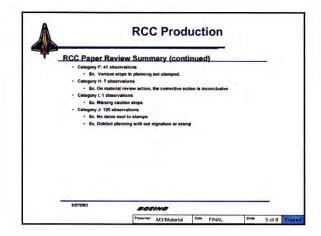
- · Action / Issue: Determine adequacy of RCC production process
- · Background / Facts:
 - Continuous production since 1973
 - RCC component manufacturing flow days = 6 months
 - Currently only limited production capacity exists due to low demand for pade
 - RCC part deliveries = 943 to date
 - Production of 7 T-Seals, 1 Chin Panel and 2 Panel/T-seal assemblies in work
 - NDI is performed after initial part cure and after the final pyrolysis cycle
 - Ultrasonic NDI is performed after the same processing steps and after the SiC coating process
 - Control panels are fabricated in parallel with RCC part production

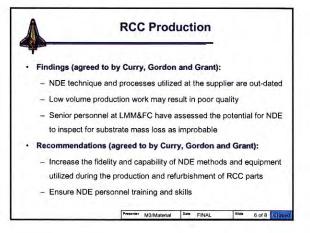
















RCC Production

· Documentation:

- CAIB Trip Report, "Report of a Trip to Lockheed Martin Missiles and Fire Control", 17-18 March 2003
- Lockheed Martin Specification 508-RCC-40A, "Process Specification for Fabrication of RCC Composites from Phenolic Impregnated Graphite Fiber", 26 November 2001
- Lockheed Martin Specification 508-RCC-122, "Process Specification for Double Type A Coating Enhancement", 29 March 2000
- Lockheed Martin Specification 508-RCC-42, "Process Specification for TEOS Impregnation", 29 March 2000

Presenter M3/Material Pate FINAL Blide 7 of 8



RCC Production

· Documentation:

- Lockheed Martin Specification 508-RCC-76, "Process Specification for Type A Coating Enhancement", 29 March 2000
- Boeing Report KLO-98-008, "Leading Edge Structural Subsystem and RCC Reference Manual", 19 October 1998
- Vought Specification 205-21-001C, "Acceptance Test Criteria for LESS Wing Panel Assemblies", 5 November 1981
- Vought Report 2-42211/6NDT-02, "Ultrasonic Decibel (dB)
 Measurement of LESS Components", 30 June 1976

Presenter M3/Material Date FINAL Side 8 of 8 Close

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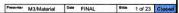
RCC Mission Life Capability

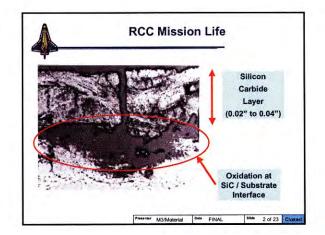
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RCC Mission Life

- Action / Issue: Determine adequacy of RCC mission life analysis methodology
- Background / Facts:
 - Oxidation rate is the most important parameter to determine mission life
 - · Function of temperature, pressure and heating time
 - · Resulting mass loss reduces part strength
 - Repeated exposure to the flight environment degrades the oxidation protection system and increases amount of mass loss
 - Mass loss rate characterized by laboratory testing



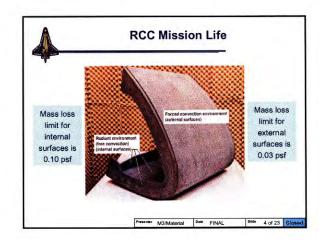




RCC Mission Life

- · Background / Facts:
 - Arc jet test at Ames and JSC in 1973 first revealed mass loss with no apparent dimensional changes
 - Database generated for non-TEOS material
 - Arc jet and radiant exposure tests at JSC, ARC, LARC and Rockwell
 - · Established strength reduction as a function of mass loss
 - Mass loss greater in plasma arc jet (convective) than radiant tests
 - Mass loss correlation (radiant/convective) developed from the test results (see charts 7 and 8 for convective heating results)
 - · Established need for improved coating system

Presenter M3/Material Date FINAL Side 3 of 23 Close





RCC Mission Life Material System Evolution

- Background / Facts:
 - TEOS infiltration system baselined for OV-102 in March 1976
 - Mass loss correlation for radiant and convective heating developed in 1978
 - Surface porosity effects on mission life discovered in December 1978
 - Type A sealant developed in 1980 to seal surface porosity
 - · Retrofitted onto OV-102 after 5th flight
 - Mass loss database developed in 1984
 - Double Type A (DTA) sealant developed to increase mission life
 - · Baseline for OV-105 and all new parts
 - Mass loss database developed in 1994

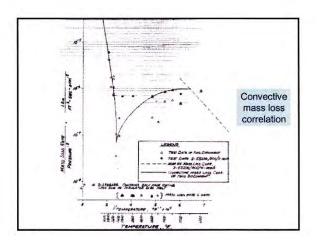


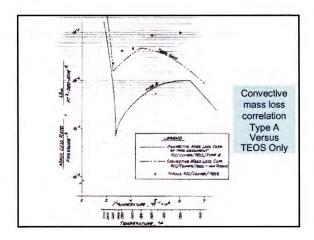


RCC Mission Life Convective Mass Loss Correlation

- Background / Facts:
 - RCC/SiC/TEOS/Type A material system plasma arc jet tests for convective mass loss conducted at JSC in 1984
 - 40 total specimens, 2 each at 20 combinations of temperature and pressure
 - Temperature ranged from 1000 to 3000 F
 - Pressure ranged from 0.01 to 0.05 atmospheres
 - Test results summary
 - SiC erosion occurred at temperatures at 2800 F and above
 - Specimens exposed to temperatures at 2700 F and below did not indicate a thickness change
 - · Mass loss rates increase rapidly above 2500 F
 - See next 2 charts for actual results

2 charts	for act	ual results					
	Presenter	M3/Material	Date	FINAL	Slide	6 of 23	Close







RCC Mission Life Determination

- Background / Facts:
 - Determination of mission lives due to operational aging includes both thermal and structural analysis results
 - · Thermal analysis determines mass loss based on certification mission profiles (closest match to each actual mission)
 - · Structural analysis determines strength based on air loads and thermal loads
 - Margin of safety is determined for longest possible mission life while preserving the required factor of safety = 1.4
 - Mission life limits are documented in NSTS 08171, Operations and Maintenance Requirements Specifications Document, File II, Volume 3

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RCC Mission Life Margin of Safety Versus Factor of Safety

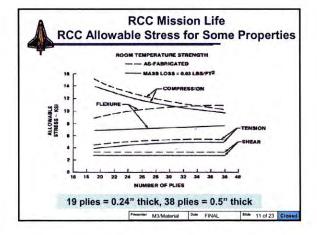
- Background / Facts:

 MS = (Allowable Stress / Applied Stress * FS) 1

 MS = Margin of Safety
 - · Required to be 0 or positive

 - Required to be 0 or positive
 FS = Factor of Safety
 Shuttle program uses 1.4
 USAF, USN, commercial aircraft use 1.5
 Allowable stress based on mechanical design allowables database generated from over 2000 RCC specimens (A-basis, 99% of material expected to exceed the value)
 Allowable stress for material expected for material at mass loss
 - Allowable stress for material generated for material at mass loss cut-off limits
 - When we hear that a location has a reduced "factor of safety" it really means a <u>negative</u> margin of safety (reduction of FS is typically not an option)
 SRB ETA ring is an example of a liberal allowance of a FS reduction issue only known for 24 hours prior to ET tanking
 - meeting

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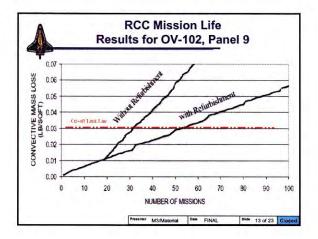


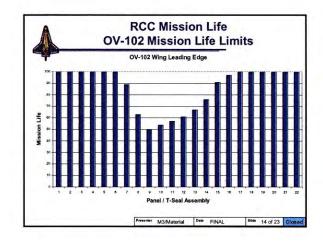
RCC Mission Life

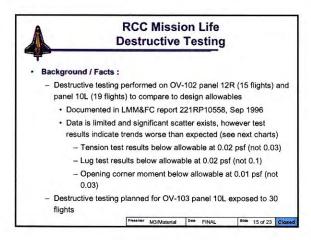
Background / Facts:

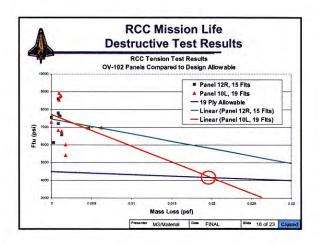
- OV-102 RCC components were not coated with Type A sealant for the first 5 missions - reduced mission lives from other orbiters
- RCC Refurbishment intervals established to replenish Type A sealant to achieve desired mission life
- Minor repair capability developed to allow for continued operation between scheduled OMM downtime
- Minimum predicted life for WLE RCC component on OV-102 is 50 missions for panel/seal 9 assembly

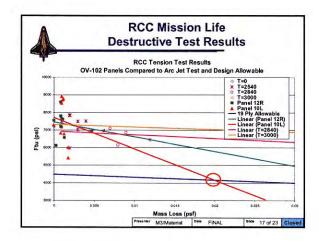
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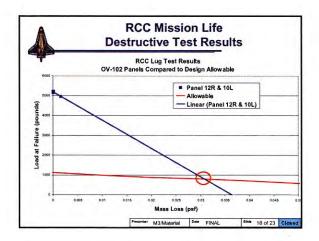


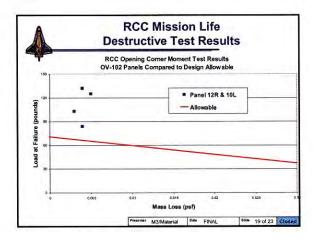














RCC Mission Life Category: Potential Contributor

· Findings:

- Insufficient data exists to compare predicted mass loss and strength to actual mass loss and strength on flown hardware due to repeated exposure
- However, results to date indicate need to accelerate additional destructive testing of flown hardware
- Only 2 tests were performed to determine oxidation associated with craze cracks used to develop tactile evaluation method for coating adherence reduction due to oxidation along interface
- Recent NASA GRC examination of OV-102 panel 12R has revealed coating and substrate anomalies that warrant further investigation

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RCC Mission Life Category: Potential Contributor

- Recommendations (Agreed to by Curry):
 - Develop a plan to conduct destructive testing of flown RCC components that addresses:
 - · Extensive NDE to select test specimen locations
 - Predicted mass loss rates and corresponding reduction in mechanical properties versus actual test results
 - Type A sealant loss on OML
 - Pinhole impact on coating adherence and mechanical property reductions
 - · Oxidation associated with craze cracks
 - · Substrate oxidation impact on mechanical properties
 - · Impact energy resistance due to launch/ascent debris
 - Conduct testing of flown hardware ASAP per above plan

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RCC Mission Life

Documentation:

- NASA GRC Briefing by A. Calomino, "Microstructural Characterization of RCC Materials", 16 May 2003
- NSTS 08171, Operations and Maintenance Requirements and Specifications Document, File II, Volume 3, "Limited Life/Time/Cycle Items", 1 May 2003
- Lockheed Martin Report 221RP10558, "RCC Pinhole/Sealant Loss Investigation", September 1996
- Lockheed Martin Report 221RP10551, "OV-102 Panel / Seal Set 10L Mechanical Properties Tests", August 1996
- Lockheed Martin Report 221RP10539, "RCC Pin-Hole / Sealant Loss Coating Adherence", May 1996

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RCC Mission Life

Documentation:

- Paper by A. Eckel et.al, "Oxidation Kinetics of a Continuous Carbon Phase in a Nonreactive Matrix", 4 April 1995
- NASA TM 106793, "Thermochemical Degradation Mechanisms for RCC Panels on the Space Shuttle, N. Jacobson, January 1995
- NASA TM 104792, "Analysis of the Shuttle Orbiter RCC Oxidation Protection System", D. Curry et.al., June 1994
- AIAA 94-2084, "Ablation Analysis of the Shuttle Orbiter Oxidation Protected RCC", June 1994
- DIR NO. 3-53200/RCC/4-0006, "June 1984 Convective Mass Loss Correlation", 28 June 1984

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Fleet Experience - Aging RCC



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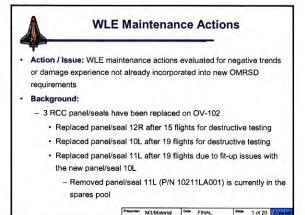
RCC Maintenance Actions 8-1 8-2 8-3 8-4

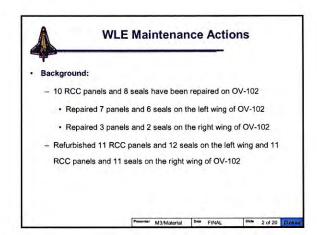
Pinholes in RCC Components

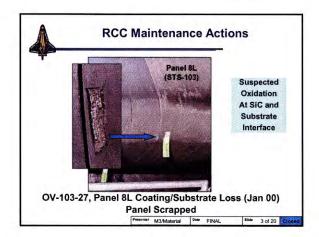
Deterioration of Type A Sealant

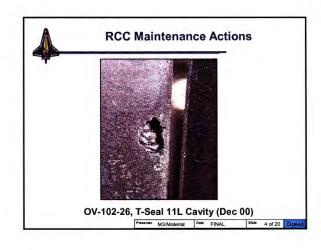
NDE of RCC Components

Matrix

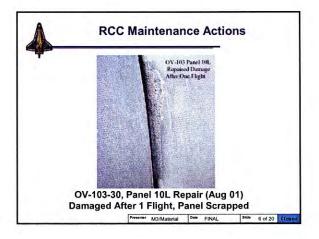


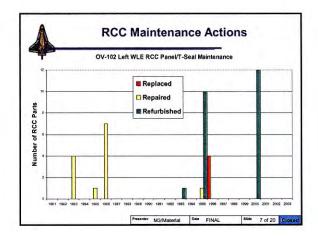


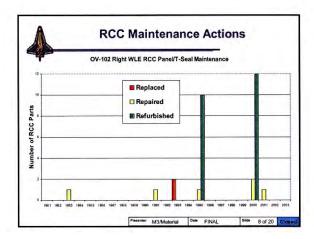


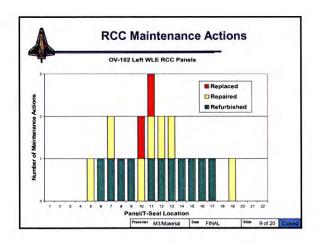


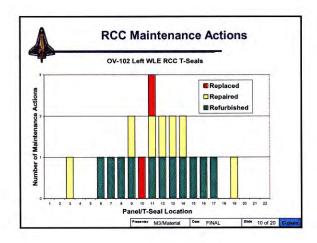


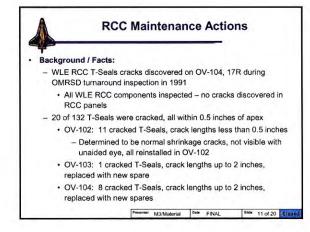


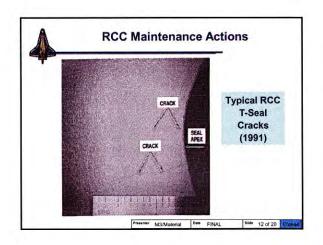












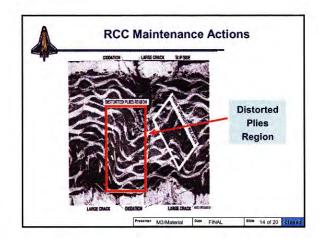


RCC Maintenance Actions

· Background / Facts:

- RCC T-Seal Cracking investigation documented in Rockwell Report LTR 4088-2401, November 1991
- Sectioned OV-104, 17R (worst cracking) and 18R (3rd worst case) for failure analysis
 - · No substrate cracks
 - · Laminates significantly distorted
 - · OV-104 panel 17R had oxidation damage
- Removed coating from several other T-seals no substrate cracks found
- Conclusions from failure analysis (metallurgical, fractography, etc.)
 - · Cracks only in SiC layer
 - Cracks due to variations in fabrication lay up process resulting in different laminate distortions

Presenter M3/Material Date FINAL Slide 13 of 20 Closes



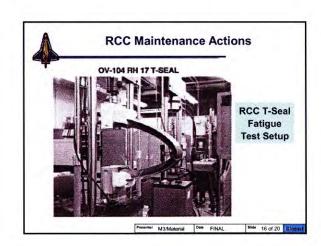


RCC Maintenance Actions

· Background / Facts:

- Determined full length SiC layer crack does not affect static strength
- Analyzed full-length substrate crack
 - Factor of safety > 1.4 for entry/landing
 - · Factor of safety = 1.38 for ascent
- Tested 2 T-seals for coating crack growth characteristics at a stress level of 80% of design limit in 1991
 - Tested OV-102 #9 left (between panels 9 and 10) for 400 cycles determined via analysis and inspection negligible fatigue damage occurred and re-installed T-seal in OV-102
 - Tested OV-104 RH #18 for 100 cycles no crack growth, part was scrapped for destructive testing

Presenter M3/Material Date FINAL Blide 15 of 20 Closes





WLE Maintenance Actions

Background / Facts:

- OV-102 wing leading edge spars have a history of degradation due to corrosion
 - Design corrosion protection system was a single coat of MB0125-055 primer (Koropon)
 - MB0130-119 Type II RTV adhesive applied as a galvanic barrier on forward most plane of corrugated spar
 Design change incorporated at J2 OMDP to apply 2 coats of
 - Design change incorporated at J2 OMDP to apply 2 coats of Koropon and cover with RTV topcoat as moisture and galvanic barrier

Inspection process updated

- Full inspection performed every 4 and ½ years (V30KG0.060 and V30LG0.060) which requires removal of all RCC panels and associated support fittings and insulators
- Sampling inspection performed every 3 years (V30KG0.065 and V30LG0.065) for 6 panels per side

Presenter M3/Material Date FINAL Slide 17 of 20 Clo



WLE Maintenance Actions

· Background / Facts:

- OV-102 inspections performed in conjunction with WLE refurbishment per MCR18457 during J2 resulted in significant corrosion findings
 - · 41 doublers required on the right side
 - · Multiple doublers required on the left side
- Exploratory holes were drilled for core inspection and no corrosion was detected
- Inspections during J3 did not detect evidence of corrosion on the WLE spars

Presenter M3/Material Date FINAL Slide 18 of 20 Closed





WLE Maintenance Actions

- · Findings (agreed to by Curry, Gordon and Grant):
 - More unplanned maintenance actions on OV-102 left versus right wing RCC parts (varies with other vehicles)
 - A fatigue tested T-seal was installed in OV-102
 - · Determined most likely not a contributor to the accident
 - However, the practice of utilizing fatigue tested components in a vehicle should be discontinued
- Recommendations (agreed to by Curry, Gordon and Grant):
 - Determine root cause for all exterior damage found and adjust maintenance requirements as needed

Presenter M3/Material Date FINAL Slide 19 of 20

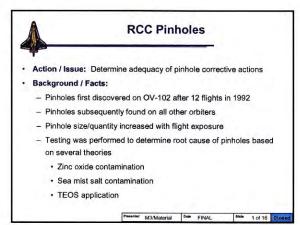


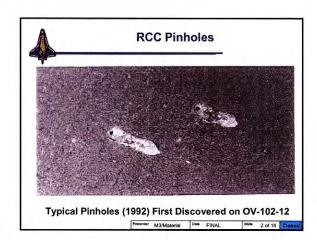
WLE Maintenance Actions

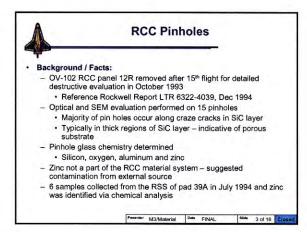
- · Documentation:
 - Briefing by M. Gordon, "Orbiter LESS/RCC Summary Major Events Since Last PRB", 29 March 2001
 - Boeing Report KLO-00-006, "Space Shuttle Orbiter Thermal Protection System Processing Assessment 2000", Appendix A and C, 17 October 2000
 - Vought Letter 3-47200/2L-146, "Failure/Problem, Analysis and Corrective Action Report (for Cracked T-Seals)", 3 March 1992
 - Rockwell Report LTR 4088-2401, "Shuttle Orbiter Leading Edge RCC T-Seal Cracking Investigation", November 1991

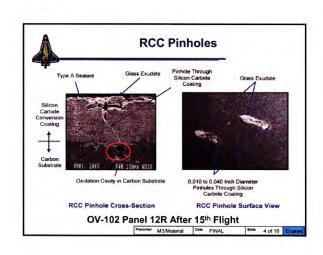
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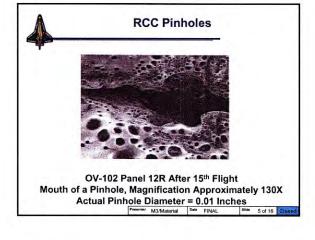
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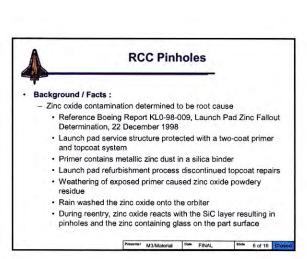












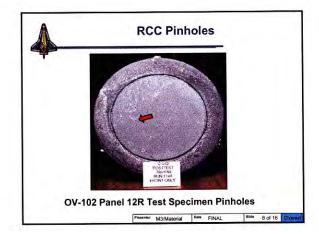


RCC Pinholes

· Background / Facts:

- NASA review of old plasma arc jet test specimens indicated formation of small anomalies similar to pinholes but not typical of flight induced pinholes
- Specimens with pinholes made from OV-102 panel 12R
 - · Tested for 3.5 hours
 - Temperature ranged from 2400F to 3000F
 - · Pressure ranged from 0.014 to 0.10 atmospheres
 - Testing did not significantly change pinhole dimensions nor substrate oxidation

Presenter M3/Material Date FINAL Slide 7 of 16 Closes





RCC Pinholes

Background / Facts:

- Developed Type A sealant refurbishment process at Lockheed-Martin to repair pinholes
 - Process described in maintenance requirements portion of the briefing
 - Added step to fill pinholes with Type A sealant
 - Refurbishment does not prevent pinholes from reforming or restore carbon substrate integrity
- Implemented refurbishment plan on all vehicles

Presenter M3/Material Date FINAL Slide 9 of 16 Close



RCC Pinholes

· Background / Facts :

- Inspection accept/reject criteria established
 - Documented in ML0601-0002, RSI Acceptance Criteria for Operation Vehicles, 19 September 2002
 - All pinhole-related glass formations are acceptable regardless of the localized surface roughness associated with the formation (paragraph 4.12.9.1)
 - Pinholes are acceptable during routine processing flows (paragraph 4.12.9.2)
 - Pinholes greater than 0.04 inches are unacceptable during OMM (paragraph 4.12.9.3)

enter M3/Material Date FINAL Slide 10 of 16 Clo



RCC Pinholes

Background / Facts :

- Launch pad sampling conducted in 1997 and 2003
- Zinc fallout rate (mg/ft^2/day) comparisons:
 - · Highest recorded value obtained in 2003 (8.69)
 - · Other 9 locations in 2003 less than 1997 results
- Zinc % content comparisons:
 - · 2003 results consistently around 9% with one exception
 - 1997 results ranged from 10% to 25%
- See next chart for results by locations

Presenter M3/Material Date FINAL Slide 11 of 16 Closes



RCC Pinholes

Plate	Fallout Rate (mg/ft^2/day)	2003/	Zinc % Content		2003/
Location	1997 Avg	2003	1997	1997 Avg	2003	1997
LH5/Plate 9	4.8	0.66	0.14	14.2	9.55	0.67
LH10/Plate 1	6.25	4.02	0.64	13.2	8.58	0.65
LH22/Plate 5	6.08	5.33	0.88	15.9	8.82	0.55
RH7/Plate 2	5.29	8.69	1.64	19	9.31	0.49
RH13/Plate 4	4.33	1.21	0.28	15.6	5.64	0.36
RH21/Plate 3	7.05	4.04	0.57	21.4	9.48	0.44
NC/Plate 6	1.97	0.56	0.28	10.4	8.91	0.86
AH/Plate 7	2.16	0.49	0.23	11.5	8.75	0.76
RSS/Plate 8	4,39	0.44	0.10	18.8	9.07	0.48
MI P/None	6.63	N/A	N/A	24.5	N/A	N/A

Highest values shown in red

Presenter M3/Material Date FINAL Slide 12 of 16 Close



RCC Pinholes

- · Findings (agreed to by Curry):
 - Refurbishment intervals and process established to repair pinholes,
 maintain sealant, and achieve maximum mission life
 - Accept/reject criteria allows for pinholes greater than 0.04 inches in service provided the underlying substrate is not exposed
 - 2003 launch pad zinc sampling indicates RSS is still a source for zinc contamination and potential pinhole formation

Presenter M3/Material Date FINAL Slide 13 of 16 Close



RCC Pinholes

- · Recommendations (agreed to by Curry):
 - Consider taking action to minimize the potential of zinc contamination by judicious maintenance of the topcoat and/or protection of the RCC material system from rain water
 - Determine the number and size of pinholes expected based on the current maintenance requirements and impact on structural integrity

Presenter M3/Material Date FINAL Slide 14 of 16 Close



RCC Pinholes

- · Documentation:
 - NASA report KSC-5600-6256, "Launch Pad Zinc Sampling at LC-39B", June 2003
 - NASA GRC Briefing by A. Calomino, "Microstructural Characterization of RCC Materials", 16 May 2003
 - ML0601-0002, "Reusable Surface Insulation Acceptance Criteria for Operation Vehicles", 19 September 2002
 - Boeing Specification ML0601-9026, "Thermal Protection System Material Review Maintenance Procedures"; TPS 365 "RCC Coating Repair", 25 July 2002
 - Boeing Report KL0-98-009, "Launch Pad Zinc Fallout Determination", 22 December 1998
 - NASA TM-1998-208659, "Space Shuttle Pinhole Formation Mechanism Studies", November 1998

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RCC Pinholes

- · Documentation:
 - Technical paper by Jacobsen et al., "Oxidative Attack of Carbon/Carbon Substrates Through Coating Pinholes", June 1998
 - Lockheed Martin Report 221RP10558, "RCC Pinhole/Sealant Loss Investigation", September 1996
 - Lockheed Martin Report 221RP10539, "RCC Pinhole/Sealant Loss Coating Adherence", August 1996
 - Rockwell briefing by M. Gordon, "RCC Pinhole & Sealant Loss Inspections at KSC", 11 September 1995
 - Rockwell Report LTR 6322-4039, "Examination of RCC Pinholes", December 1994
 - Rockwell briefing by G. Tiezzi, "Porosity of RCC Wing Edge Panels", 7 September 1993

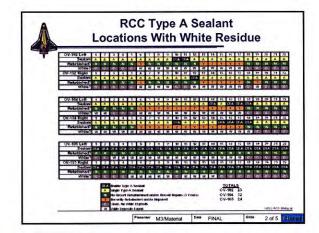
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RCC Type A Sealant

- · Action / Issue: Deterioration of Type A sealant
- Background / Facts:
 - Discovered white residue on WLE RCC panels on OV-102, OV-104 and OV-105 in November 2001
 - Lab results determined deposits to be sodium carbonate
 - Root cause determined to be the Type A sealant converting to sodium carbonate when exposed to rain water

Presenter M3/Material Date FINAL Blide 1 of 5





RCC Type A Sealant

- Background / Facts:
 - There are 3 possible outcomes for sodium carbonate deposits
 - · Deposits are washed off and removed
 - Would decrease sealant effectiveness
 - Deposits remain on surface, melt on re-entry, and combine with glass
 - Favorable outcome, restores the composition of Type A sealant
 - Deposits remain on surface, melt on re-entry, and flow to other parts
 - Potentially damaging and needs to be monitored





RCC Type A Sealant

- · Findings (Agreed to by Curry):
 - Root cause determined and found not to be detrimental to RCC
 - Deposits are potentially damaging to metallic hardware
- Recommendations (Agreed to by Curry):
 - Continue previous investigation of an improved sealant system
 - Continue monitoring for potential flow of deposits onto metallic hardware

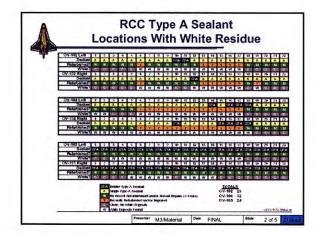
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Presenter M3/Material Data FINAL





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RCC Type A Sealant

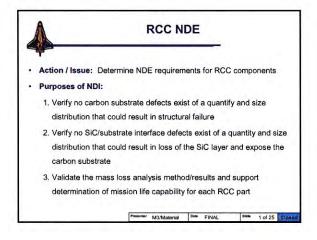
- · Findings (Agreed to by Curry):
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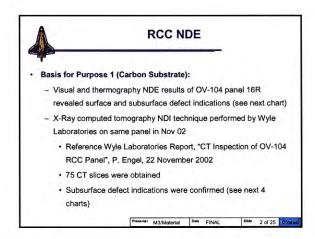
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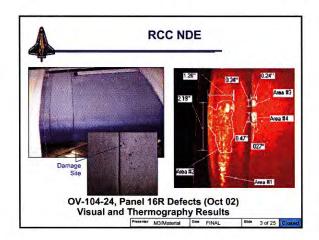


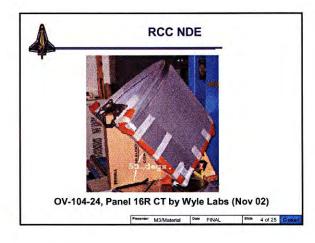
RCC Type A Sealant

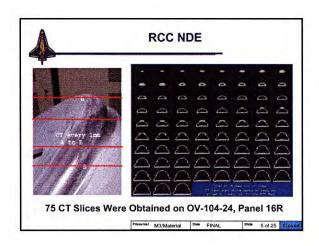
- · Documentation:
 - NASA Labs at KSC letter KSC-MSL-0127-2001, "White Deposits Removed From OV-102, OV-104 and OV-105", 15 March 2001
 - Briefing by N. Jacobson et al., "Chemistry of Sodium Carbonate Deposits on the Orbiter Wing Leading Edge and Nose Cap"
 - Briefing by D. Curry et al., "Orbiter Reinforced Carbon/Carbon Advanced Sealant Systems Screening Tests", January 2000

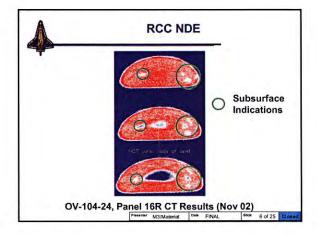


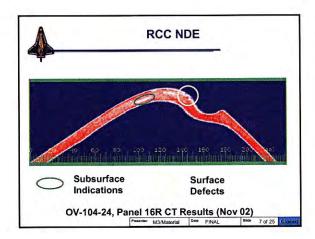


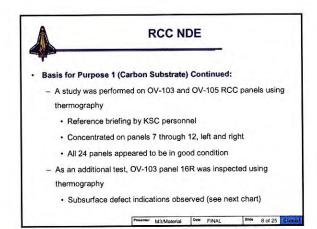


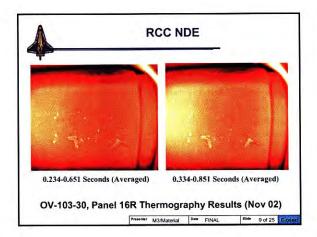


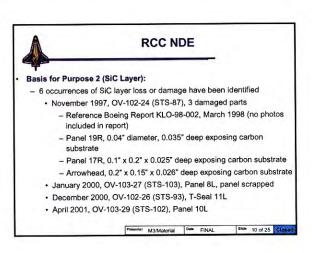


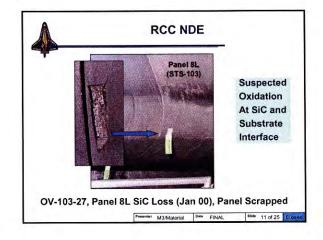


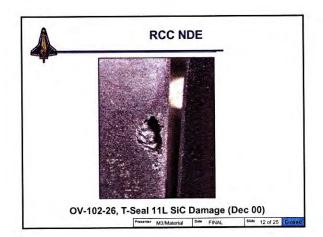


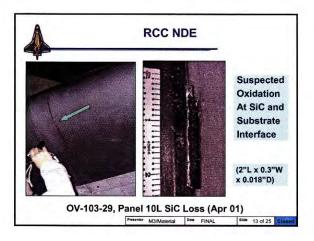


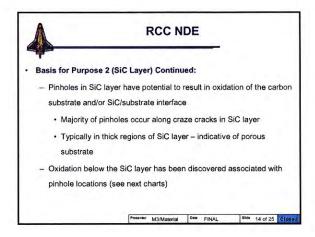


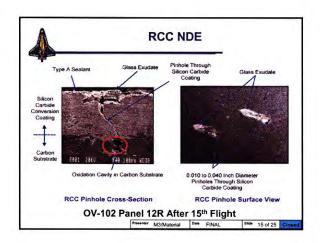


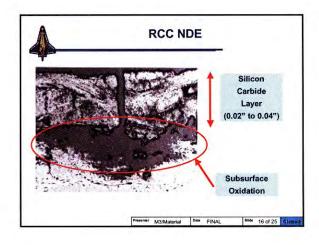


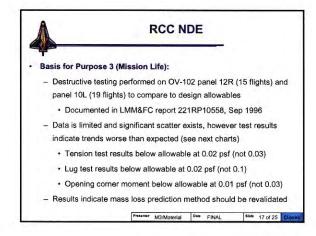


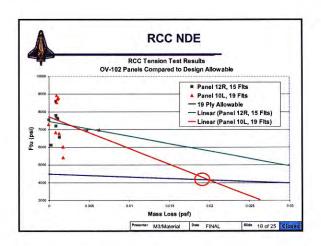


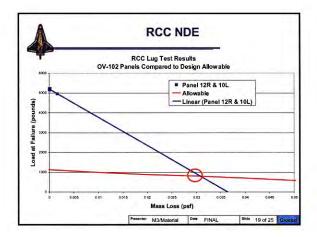


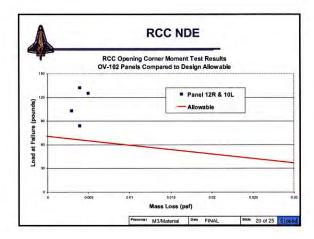














RCC NDE

- · Basis for Purpose 3 (Mission Life) Continued:
 - X-ray Computed Tomography (CT) NDI technique demonstrated to be viable for determining variable RCC mass loss due to oxidation
 - Reference Rockwell Report MPR 6146-2000, "Evaluation of Carbon-Carbon Materials and Structures Using Computerized Tomography Techniques", March 1994
 - Rockwell Report LTR 5928-2442, "Prediction of RCC Flexural Strength Using CT Techniques", September 1992
 - Reference Rockwell Report MPR 5806-2020, "Determination of Mass Loss coated RCC Carbon-Carbon Orbiter Structures", May 1992

Presenter M3/Material Date FINAL Slide 21 of 25 Closed



RCC NDE

- · Basis for Purpose 3 (Mission Life) Continued:
 - MCR19643, "Develop a NDE Method for RCC Components", 11
 March 2002 was presented to the ERB
 - Proposed a 3-year development program to develop a credible RCC NDE program
 - · Fabricate and characterize NDE standards
 - · Down-select NDE techniques
 - Fully characterize RCC flight hardware via destructive testing
 - Validate analysis predictions of mass loss and strength reduction using NDE results
 - Right approach!!! schedule can be accelerated

Presenter M3/Material Date FINAL Slide 22 of 25



RCC NDE

- · Findings (agreed to by Curry, Gordon and Grant):
 - Damage and defects discovered on RCC components warrants development of NDI techniques to verify structural integrity
- Recommendations (agreed to by Curry, Gordon and Grant):
 - NDE all flown WLE RCC parts ASAP to support investigation
 - · Determine defect quantity and size distribution
 - Use results to determine what parts should be included in the impact test program
 - Identify and implement NDE techniques for carbon substrate and SiC/substrate layer inspection as a <u>return to flight</u> criteria and for routine use
 - Develop and implement NDE techniques for carbon substrate mass loss to validate analysis methods and results (need date is TBD)

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RCC NDE

- Recommendations Continued (agreed to by Curry, Gordon and Grant):
 - NDE technique development and application should address the following
 - NDE standards
 - · Probability of detection
 - · Inspector certification requirements
 - Basis for accept/reject criteria
 - · Basis for inspection frequency
 - · How NDE results will be used in the mission life analysis
 - If production NDE techniques and processes are used, demonstrate the adequacy to include detection capability, accept/reject criteria, and implications to structural integrity via mechanical testing as was performed originally

Presenter M3/Material Date FINAL

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RCC NDE

Documentation:

- Documentation:

 Wyle Laboratories Report, "CT Inspection of OV-104 RCC Panel", P. Engel, 22 November 2002

 MCR19643, "Develop a NDE Method for RCC Components", 11 March 2002

 Boeing Report KLO-98-002, "Mission STS-87 OV-102 Flight 24 Thermal Protection System Post-Flight Assessment", March 1998

 LMM&FC report 221RP10558, "Final Report RCC Pin-Hole/Sealant Loss Investigation", September 1996

 Rockwell Report MPR 6146-2000, "Evaluation of Carbon-Carbon Materials and Structures Using Computerized Tomography Techniques", March 1994

 Rockwell Report LTS 5928-2442, "Prediction of RCC Flexural
- Techniques", March 1994
 Rockwell Report LTR 5928-2442, "Prediction of RCC Flexural Strength Using CT Techniques", September 1992
 Rockwell Report MPR 5806-2020, "Determination of Mass Loss coated RCC Carbon-Carbon Orbiter Structures", May 1992

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Date

Maintenance RCC



RCC Maintenance Requirements

9-1

RCC Maintenance Repair and Refurbishment Process

Left WLE Maintenance During OMM & Flows 9-2 9-3 9-4

LESS Hardware Use

CAIB/Group 1 Presenter

Matrix



RCC Maintenance Requirements

- · Action / Issue: Determine adequacy of RCC maintenance requirements
- Background / Facts:
 - RCC inspection requirements are documented in NSTS 08171,
 OMRSD File III, Volume 9 and Volume 30
 - · Inspection methods are primarily visual
 - Tactile pressure test of large craze cracks performed to identify excessive subsurface oxidation
 - Accept/reject criteria established for expected defect types and locations

Presenter M3/Material Date FINAL Slide 1 of 5 Closed



RCC Maintenance Requirements

Background / Facts:

- RCC tactile pressure requirements are documented in NSTS 08171,
 OMRSD File III, Volume 9, Number V09AJ0.075
 - Use compressive gloved-finger technique only at the inboard and outboard regions adjacent to each T-seal of each panel
 - Region limited to within 12 inches of panel apex
 - · Panels 6 through 17 are inspected as a minimum
 - Additional panels may require tactile inspection based on craze crack sizes

Presenter M3/Material Date FINAL Slide 2 of 5 Closed



RCC Maintenance Requirements

Background / Facts:

- Inspection accept/reject criteria are documented in ML0601-0002,
 RSI Acceptance Criteria for Operation Vehicles, 19 September 2002
 - Craze cracks with gap width less than 0.003 inches are acceptable
 - Flaking of Type A sealant is acceptable when depth is less than 0.015 inches
 - SiC chips, scratches, or abrasions are acceptable when depth is less than 0.015 inches and the substrate is not exposed
 - · Pinholes are covered in the aging portion of this briefing





RCC Maintenance Requirements

· Findings (agreed to by Curry, Gordon and Grant):

- Established maintenance requirements are thoroughly documented
- No NDE technique is routinely employed during maintenance of RCC
- Inspection requirements and accept/reject criteria appear to be difficult to implement consistently
- Protection of RCC during maintenance is inadequate against tool drops, impact from maintenance stands, etc.

Recommendations (agreed to by Curry, Gordon and Grant):

- Improve the protection of RCC components in the maintenance facilities
- Reevaluate adequacy of maintenance requirements considering inspection burden and reliability of visual method

Presenter M3/Material Date FINAL Slide 4 of 5 Gloss



RCC Maintenance Requirements

· Documentation:

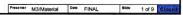
- NSTS 08171, "Space Shuttle Operations and Maintenance Requirements and Specification Document"; File III, Volume 9, "Thermal Protection System", 21 November 2002
- NSTS 08171, "Space Shuttle Operations and Maintenance Requirements and Specification Document"; File III, Volume 30, "Airframe Inspection", 1 May 2003
- ML0601-0002, "Reusable Surface Insulation Acceptance Criteria for Operational Vehicles", 19 September 2002
- Lockheed Martin Engineering Specification 508-RCC-43, "Process Specification for Split Bushing Removal and Installation", 29 March 2000

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RCC Repair & Refurbishment

- Action / Issue: Determine adequacy of RCC repair and refurbishment requirements
- · Repair Process:
 - Repairs are performed using Boeing Specification ML0601-9026, Procedure TPS-365, RCC Coating Repair
 - Repairs to RCC parts limited to minor damage to Silicon-Carbide coating
 - · Repairs are performed at KSC
 - · Not authorized for pinholes and substrate damage
 - RCC repair involves the following process steps:
 - · Part cleaning
 - Type A sealant application
 - · Sanding of repaired region to meet flushness requirements

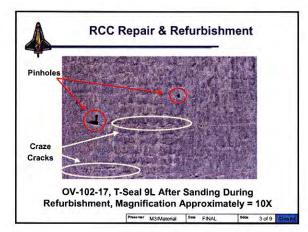


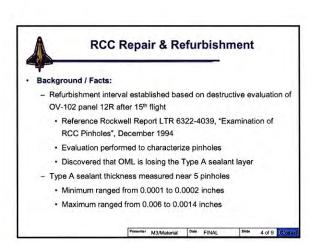


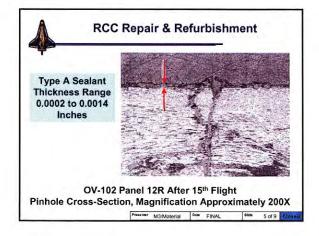
RCC Repair & Refurbishment

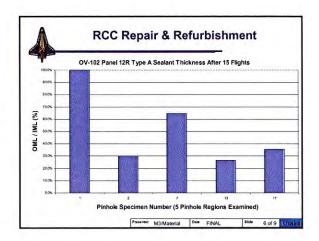
- · Refurbishment Process:
 - Refurbishments are performed using Lockheed-Martin Specification 508-RCC-318, Refurbishment of Flown RCC Parts, 16 February 2000
 - Refurbishments to RCC parts performed to achieve the desired part mission life by replenishing the Type A sealant
 - Refurbishments performed by only Lockheed-Martin using the following process:
 - · Type A sealant removed by sanding
 - · Vacuum heat clean to bake-out contaminants
 - Pinholes repaired using Type A sealant forcefully wiped into the holes
 - · TEOS impregnation and cure
 - · Type A sealant application and cure
 - · Reassembly of the metallic parts to the RCC panel

Presenter M3/Material Date FINAL Slide 2 of 9 GI













RCC Repair & Refurbishment

Background / Facts:

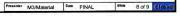
- Since significant substrate oxidation was not found with panel 12R, established refurbishment interval to be every other OMM
- Approach was supported by arc-jet testing in the mid-1990s
- Refurbishment intervals are documented in OMRSD File II, Volume 3
 - 18 missions for panel/T-seal assemblies 6 through 17
 - 36 missions for panel/T-seal assemblies 18 and 19
 - Implies no refurbishment is required for panel/T-seals 1 through 5 and 20 through 22





RCC Repair & Refurbishment

- Findings (agreed to by Curry):
 - Refurbishment of panel/T-seal assemblies 1 through 5 and 20 through 22 are not required
- Recommendations (agreed to by Curry, Gordon and Grant):
 - Conduct evaluation of RCC panels to determine Type A sealant thickness loss rate at various locations as part of the planned destructive testing of RCC panels
 - Use above result to confirm or revise current refurbishment intervals



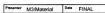


RCC Repair & Refurbishment

Documentation:

- Briefing by M. Gordon, "STS-107 Mishap Investigation Team Action Item OVE-195, RCC Specifics for CAIB Item B1-0036", 13 March 2003
- Boeing Specification ML0601-9026, "Thermal Protection System Material Review Maintenance Procedures"; TPS 365 "RCC Coating Repair", 25 July 2002
- Lockheed Martin Letter 3-47200/2L-129, "RCC Coating Repair History", 16 May 2002
- Vought Letter 3-47200/5L-276, "Refurbishment of OV-102", 1 November 1995
- Paper by S. Williams et al., "Ablation Analysis of the Shuttle Orbiter Oxidation Protected Reinforced Carbon-Carbon", September 1995
- Rockwell Report, "Field Repair of RCC Coating Advanced TPS Flight Demonstra

ation", August 1993	







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RCC Maintenance OMM in 2000

- Action / Issue: Determine potential for left WLE maintenance actions to be a contributing cause of the accident
- · Background / Facts:
 - OV-102 inducted into OMM after STS-93, 26th flight for OV-102
 - OMM conducted at Palmdale October 1999 through February 2001
 - All WLE RCC components were removed to accomplish required inspections
 - RCC panel/T-seals 6, and 13-17 were refurbished
 - RCC parts were inspected for pinholes, etc.
 - Pinholes in Panel 8 and 19 originally reported > 0.04 inches in diameter (TES-2-J3-0412, 0416)
 - Quality evaluated pinholes using optical comparator and determined them to be within acceptable limits

Presenter M3/Material Date FINAL Slide 1 of 13 City

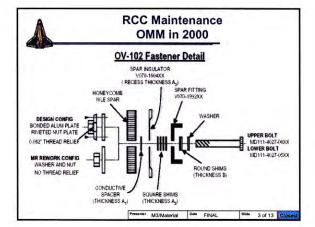


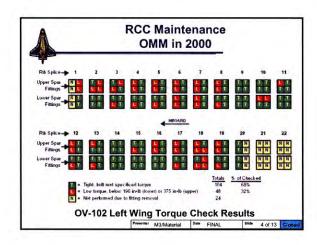
RCC Maintenance OMM in 2000

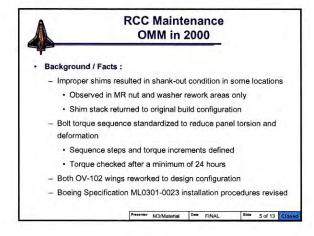
- · Background / Facts:
 - After re-installation of the RCC components, step and gap measurements were found to be unacceptable (TES-2-J3-0495)
 - Complete removal of Left WLE subsystem was performed and the following issues were discovered
 - · Spar fitting shims not per design (STR-2-J3-7033)
 - · Lower access panel nutplate issues (STR-2-J3-6689)
 - Debonded nutplates, low running torque and damaged nuts (TES-2-J3-0439)
 - Evaluated 152 of the 176 fitting fasteners (24 were not evaluated since some fittings were already removed)
 - 104 of 152 (68%) were per drawing requirements
 - · 48 of 152 (32%) had low torque values

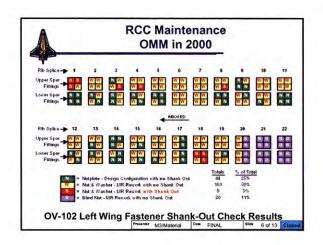
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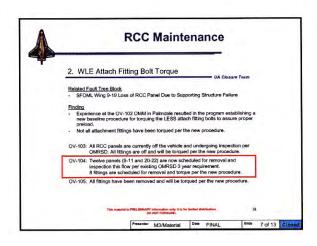
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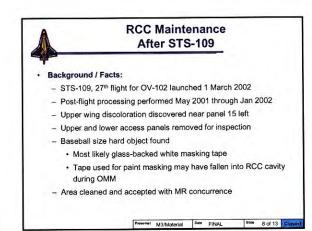




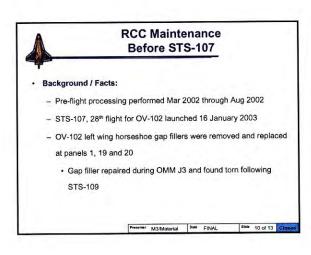


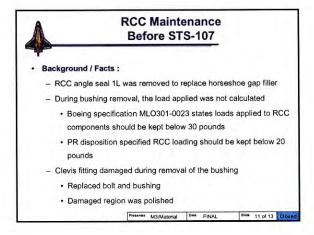


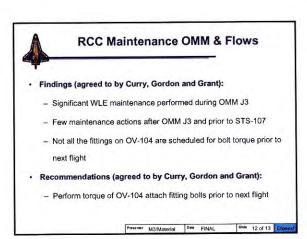
















RCC Maintenance OMM & Flows

· Documentation:

- Briefing by R. Herman, "J3-OMM/STS-109/STS-107 Left Wing Composite Review for Mechanisms, Thermal Protection, and Structures Systems", 2 April 2003
- Briefing by E. Statham, "Palmdale Processing Review Team Status Briefing", 25 February 2003
- Briefing by M. Gordon, "STS-107 Mishap Investigation Team Action Item OVE-150: Summary of LESS Work Performed Between J3 OMM and STS-107 Flow", 24 February 2003
- Briefing by M. Gordon, "OV-102 WLE RCC Panel Fitting Installation Issues", 13 November 2000

Presenter M3/Material Date FINAL Slids 13 of 13



RCC Maintenance

Maintenance Practices: LESS Hardware Use

- Action / Issue: Review/assess orbiter Leading Edge Structural Subsystem (LESS) maintenance practices regarding hardware use
- Background:
 - LESS consists of:
 - · 22 Reinforced Carbon-Carbon (RCC) panels on each wing
 - · 44 carrier panels: 22 upper, 22 lower on each wing
 - Numerous other components (spar insulators, clevis insulators, spanner beam insulators, attach fittings, brackets) and hardware (bolts, pins, sleeves, etc)
 - LESS subjected to thermal and aero stresses during reentry
 - · Proper inspection/maintenance of components essential to system performing as designed/intended



RCC Maintenance

Maintenance Practices: LESS Hardware Use

- Findings:
 - Work Authorization Documents (WADs) very specific on most tasks
 - One exception: carrier panel (C/P) hardware (A286 bolt) reuse
 - · 4 bolts per upper panel, 2 per lower panel
 - · Engineers initially stated bolts are reused
 - Technicians stated hardware is discarded/replaced
 - Inspected multiple storage containers holding removed C/Ps - No bolts found
 - · After further discussion, engineers restated bolts "can be reused" at technician's discretion, based on cleaning (using isopropyl alcohol) and visual inspection



RCC Maintenance

Maintenance Practices: LESS Hardware Use

- · Findings (cont'd):
 - · Unlike the predominance of WADs reviewed, the C/P WADs provide no clear guidance on hardware disposition
 - Both WADs (removal and installation of C/Ps) reviewed
 - No specific requirement to clean, inspect, or reuse (or replace)
 - · By contrast, WADs covering removal of RCC panels clearly state "...identify, bag and retain hardware for future use" with respect to four separate component removals
 - Verified through physical inspection of removed components
 - Inconsistent/lacking guidance allows varying interpretations and creates the potential for process variation(s)

M3/Maintenance Date FINAL



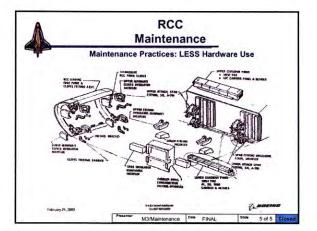
RCC Maintenance

Maintenance Practices: LESS Hardware Use

- Findings (cont'd):
 - Results of investigation by metallurgist
 - "There was no evidence of stress corrosion cracking at prelaunch conditions. There was no evidence of cumulative failures that started on previous missions."
- - Eliminate the potential for varying interpretations of carrier panel bolt reuse by making the WADs more specific

M3/Maintenance Date FINAL

4 of 5



Tile Design – Certification

Design for Impact Resistance

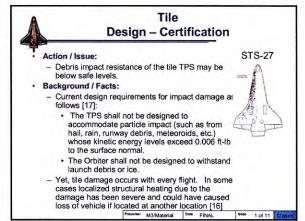
CAIB/Group 1 Presenter

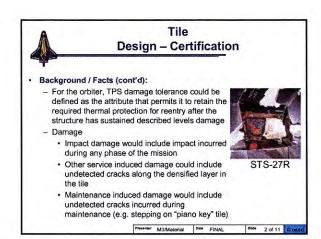
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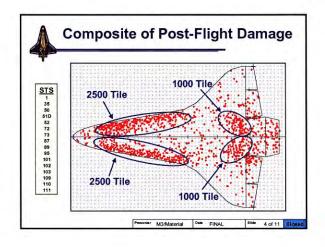
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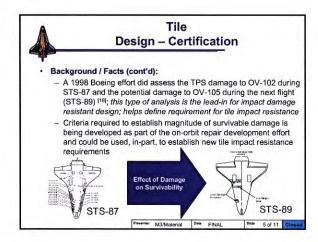
Matrix

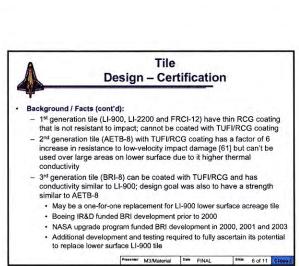














Tile Design – Certification

- · Background / Facts (cont'd):
 - Additional BRI development and testing required
 - · Assess dimensional stability for complex shaped tile
 - · Fully assess thermal characteristics (e.g. conductivity)
 - · Material allowables
 - · BRI at other densities
 - Evaluate impact resistance (various velocities and projectiles) based on damage tolerance requirements

LI-900



BRI-Hypervelocity Impact Testing





Tile Design – Certification

Findings:

- The loss of a single tile before entry interface on the lower surface of the orbiter forward of location X₀1357 could result in the loss of the orbiter. The loss of two tiles before entry interface on the lower surface of the orbiter forward of location X₀1357 would most likely result in the loss of the orbiter [67].
- Some tile possess more risk than others: some tile have a greater probability of being struck by debris, some locations are subject to greater heat load, and some locations have are adjacent to critical non-structural components [72]
- The orbiter has been subjected to debris strikes since its first flight.
 Yet the requirements to tolerate or resist debris impact are exceedingly weak for general impact resistance and nonexistent for debris impact during launch [17].

Presenter M3/Material Date FINAL Slide 8 of 11 Glose



Tile Design – Certification

- · Findings (cont'd):
 - Boeing has studied the consequence of impact damage resulting from debris impact under NASA sponsorship [74, 18]. The thermal and structural analysis performed as part of the study subsequent to the large debris impact damaged experienced during STS-87 [74, 18], demonstrated that plausible damage states could cause structural factors of safety to drop below 1.0 [46].
 - History has shown that the orbiters have suffered 10 tile loss events since Columbia first flew in April 1981. On average, that's one tile loss event every two years or 11 flights. One tile-loss event was directly attributable to debris impact from the SRB nose-cap.
 - A systematic approach to evaluate the effect of various tile damage scenarios on reentry survivability has not been performed.
 - As can be seen from the impact map, some areas of the orbiter are more likely to be damaged than others. Knowing the probability of where damage may occur is important, but the critical damage levels and consequences must also be ascertained.

Presenter M3/Material Date FINAL Slide 9 of 11 Classes

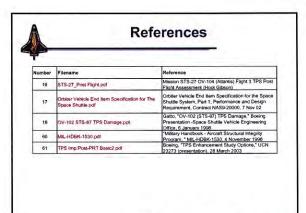


Tile Design – Certification

Recommendations:

- Compute/analyze the distribution of known damage sizes and locations
- Establish the critical damage size for each critical location
- Identify the consequences of sustaining critical damage in a critical location
- Compute the probability of sustaining critical damage in a critical location based upon a predictive model that accounts for impacts of debris emanating from various sources
- Develop a tile designed to withstand the critical damage computed for various locations and install it at those critical locations

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Slide 11 of 11 Cli

Fleet Experience - Aging Tile



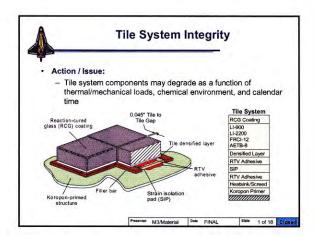
Tile System Integrity

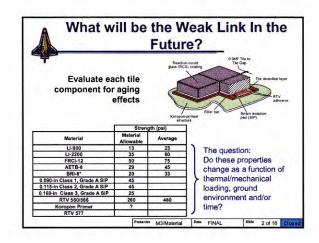
Lost Tiles

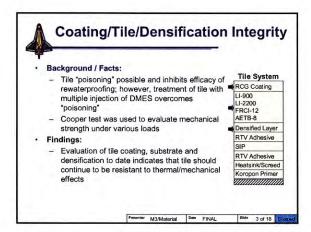
Lack of NDI/E

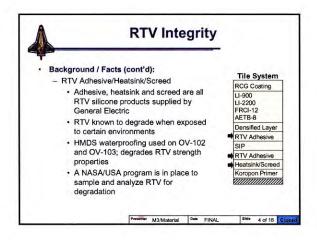
Potential for Corrosion 11-1 11-3 11-6 11-6

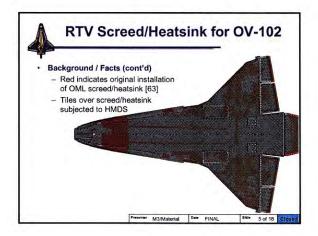
Tile Shrinkage

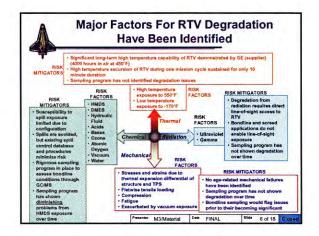


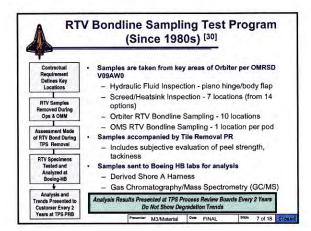


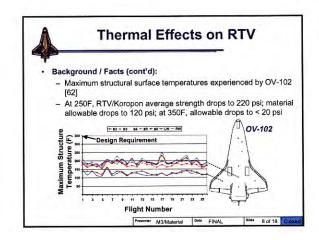


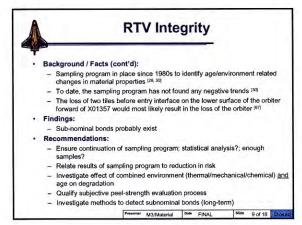


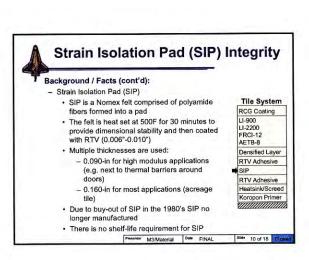


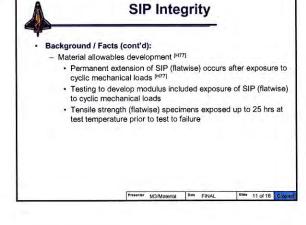


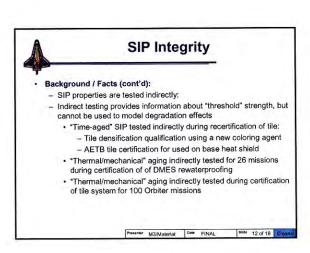


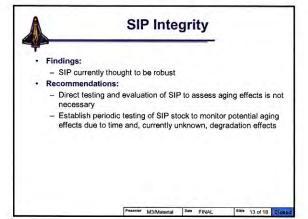


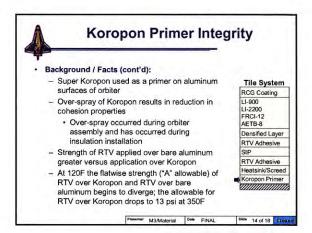


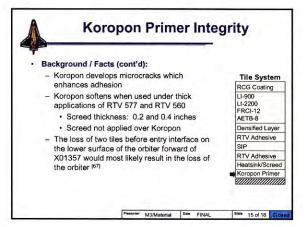


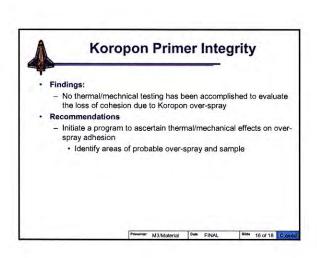


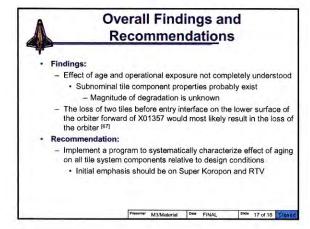


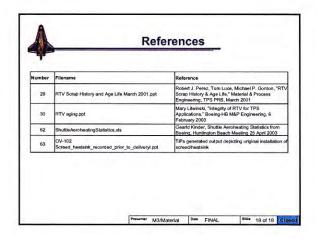


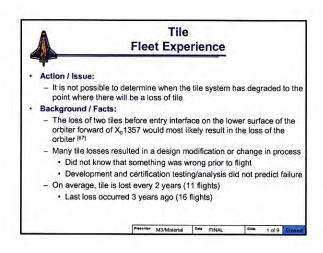


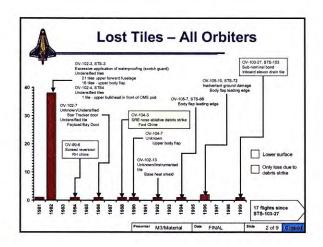






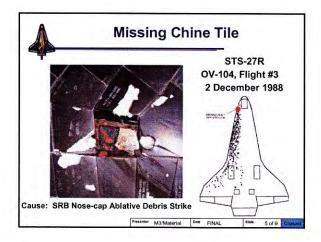


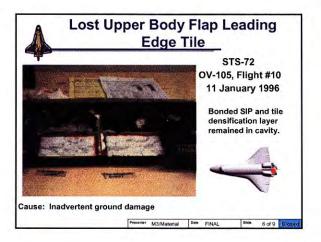


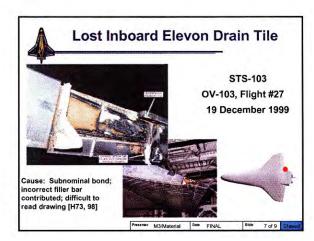


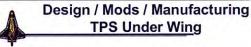










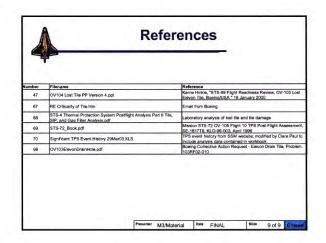


· Findings:

- Cannot predict tile failure
 - Failure due to design, maintenance process changes and inadvertent ground damage
 - Effect of aging difficult to predict and may be a risk contributor in the future

· Recommendations:

- The fact that a dominant or common cause does not exist underscores the need to address tile system integrity on several fronts: design and process change certification, training for maintenance personnel, clear process instructions, design of processes to reduce sensitivity and variance and NDI/E or "health monitoring" system to aid in determining when tiles are damaged.
- Continue RTV sampling program to help assure ability to to detect potential, and currently unknown, aging effects on tile system integrity [PRESENTER M3/Material] DIREF FINAL | BIREF 8 of 9 | Close | C





Tile Fleet Experience – Aging

- · Action / Issue:
 - Bond-line integrity and/or strength is unknown
- · Background / Facts:

Bond-line Integrity

- There are two techniques used to characterize bond-line integrity: a proof test (bond verification test) and the manual deflection test ("wiggle" test).
- Bond verification (BV), for regular tile, is performed by attaching a specialized tensile test unit over the tile and utilizing a vacuum chuck tool. The maximum applied load is generally determined by using the known bond surface area multiplied by the stress levels given in table specification. The load is held at the maximum value for at least one second. For a typical lower surface regular five-inch square SIP footprint, the test load required to achieve the required 10-psi would be 250-lbs.

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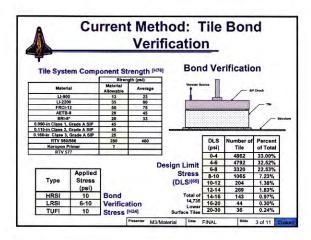
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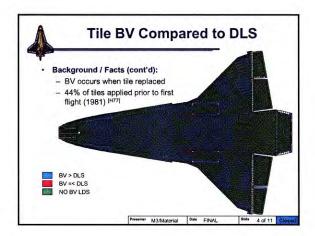


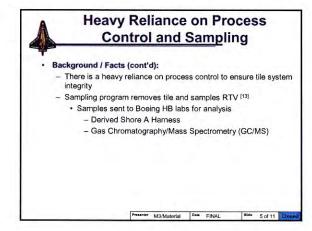
Maintenance Turnaround Work TPS Under Wing

- · Background / Facts (cont'd):
 - A partial bond could exist and the BV test would not detect it
 - There are specialized test load procedures for modified regular tile, irregular tile, structurally limited tile, tile bonded to filler bar, carrier panel tile, closeout tile and TUFI-coated and TUFI-RCG-coated tile
 - Structurally limited tiles will be tested using reduced loads due to the structural limitations of the underlying substrate.
 - The tile bond is characterized as acceptable if the required tension load is sustained for one second without the tile pull-off.
 - Another method used to evaluate the tile to substrate bond is through the manual deflection test, also known as the "wiggle" test. This test requires an experienced technician to "wiggle" the tile and sense when the tile to substrate bond is unacceptable.

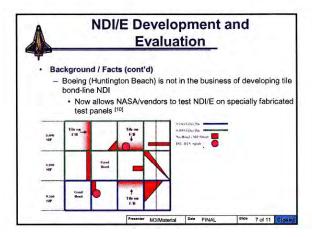
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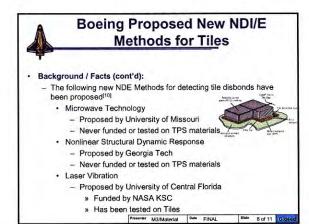






· indian	Matri		NDI/E Over th				valu	ated	
•	Method	Year	Company	Used for	Flaw Size	Strength	Weakness	Tested on TPS	
aligio lio	Film X-Ray	1980-2003	Lockheed & Boeing	Internal Voids	.025 inch x .025	established method Multi slices	Requires standards	Yes Production Unit Yes Production Unit	
	ст	1996	EGAG	Internal Voids/ Density	No voids or inclusions Density shall be 8 +-1.0 pcf		Time consuming		
On Orbiter	Acoustic Excitation	1986-1989	986-1989 EG&G		Target 10% disbond	Portable	No debonds were found	Yes	
	Laser Vibrometry	1991	Navcon Engineering Network/Ometron	Disbond	disbond	Portable	No debonds were found No debonds were found	Yes 1991 OV102 (43 Tiles) 1997 OV105 (470 Tiles) Yes OV105	
	Shearography	1991 & 1997	Laser Technology	Disbond					
	Reverse Geometry X-ray	1997	Digiray	Disbond	Target 10% disbond	Portable	No debonds were found		







General Results of NDE/I Methods^[10]

- · Background / Facts (cont'd):
 - Changes in material properties, Tile (Silica & Air), SIP (Nomex), RTV thickness, Gap fillers (Fabric) and Aluminum structure limit accuracy / repeatability of NDE to detect disbonds
 - None of the methods or combination of them could accurately detect disbonds
 - Suspect NDE disbond tiles were removed and evaluated as a good bond
 - NDE method would show promise when used on disbonded test panel but fail when tested on the Orbiter
 - New Tile disbond panel has been made and sent to NASA Marshall Space Flight Center for evaluation





Lack of Tile NDI/E

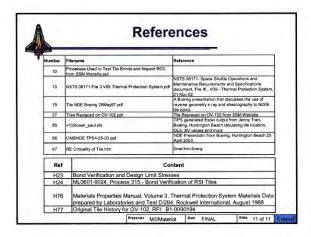
· Findings:

- There are no widely accepted NDI/E methods that are used to detect disbonds. General methods to detect a disbonds are in development, and the time when they will be available is unknown. A even more useful NDI/E method would be one that can measure the bond strength. This is an even more challenging problem and will not likely be resolved in the near future.
- The loss of two tiles before entry interface on the lower surface of the orbiter forward of X01357 would most likely result in the loss of the orbiter [67]
- NASA and Boeing seem to have a sense for the need to develop a method to better quantify the bond-line integrity and have tested various methods on test panels and the orbiters

· Recommendations:

 It is recommended that efforts to develop and evaluate NDI/E methods to assess bond integrity be given increased emphasis

Presenter M3/Material Date FINAL Slide 10 of 11 Close







Tile Fleet Experience - Aging

- Action / Issue: Current practice allows RTV adhesive over bare aluminum when bonding tile
- Background / Facts:
 - Process to remove and replace tile sometimes results in primer damage
- Findings:
 NASA has current waiver to use heavily chromated primer, a proven corrosion control component, but currently recommends the removal primer is the removal of the primer is the primer in the primer is the primer in the primer in the primer is the primer in the primer in the primer is the primer in the prim of all damaged primer, leaving bare aluminum, prior to the application
 - of a file; this process was certified using results of extensive testing

 Only one case of known corrosion according to NASA/USA personnel

 Corrosion found on dome heat shield; edge exposed to environment

 Active corrosion has never been detected on "acreage" tile
- Recommendations:
 - Initiate effort to determine long-term effect of practice



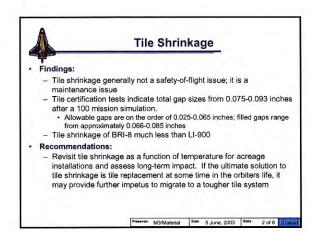


Tile Fleet Experience - Aging

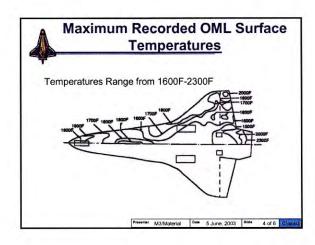
- Action / Issue: Current practice allows RTV adhesive over bare aluminum when bonding tile
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 NASA has current waiver to use heavily chromated primer, a proven corrosion control component, but currently recommends the removal of all damaged primer, leaving bare aluminum, prior to the application of a tile; this process was certified using results of extensive testing
 Only one case of known corrosion according to NASA/USA personnel
 Corrosion found on dome heat shield; edge exposed to environment
 Active corrosion has never been detected on "acreage" tile
- Recommendations:

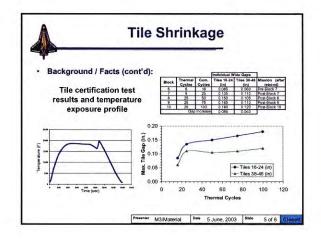
- Initiate effort to determine long-term effect of practice

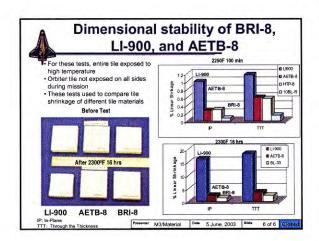










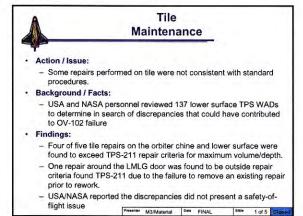


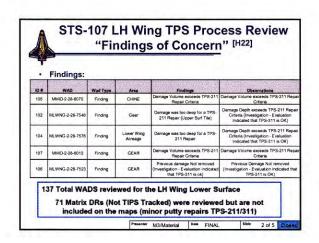
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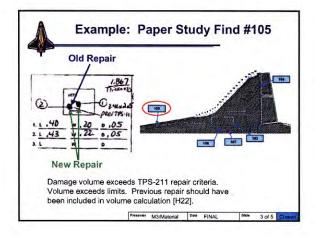
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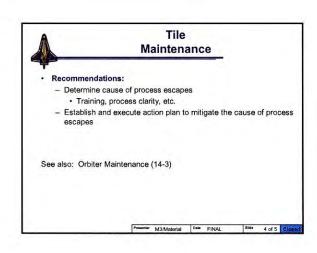
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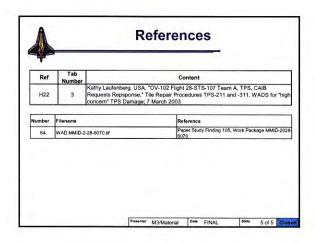
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Orbiter Design / Certification

Orbiter Design Concerns

28-1

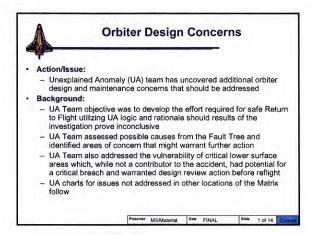
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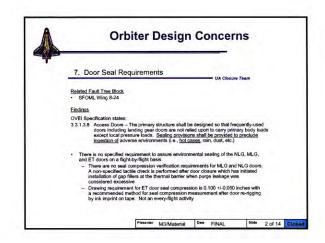
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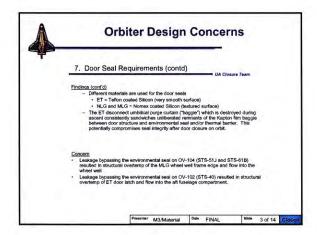
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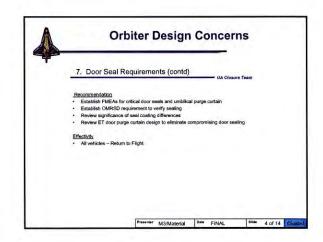
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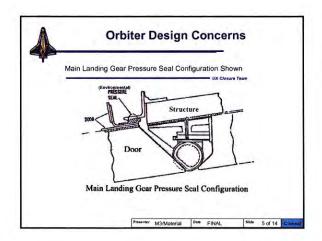
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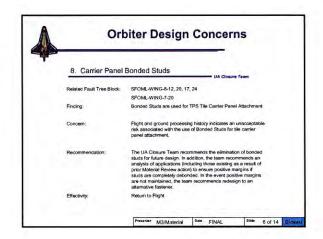


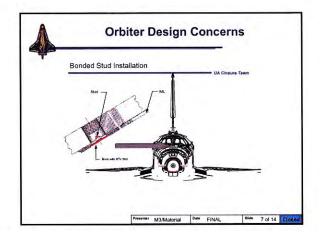


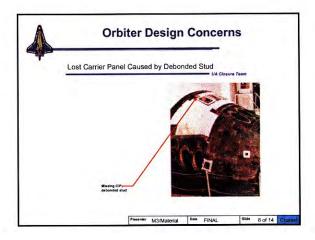


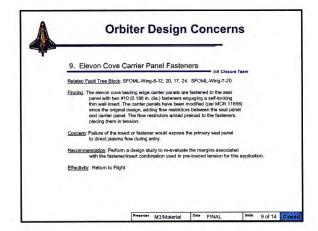


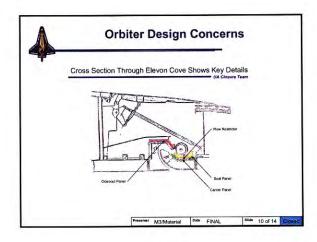


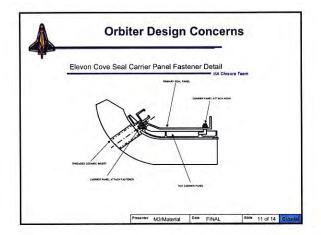


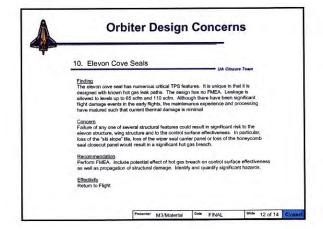




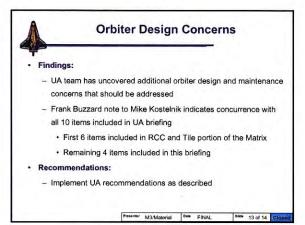


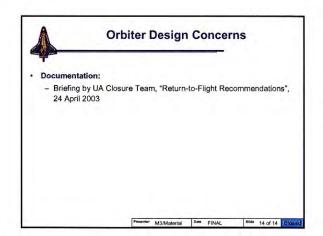












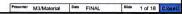
Fleet Experience - Aging Orbiter

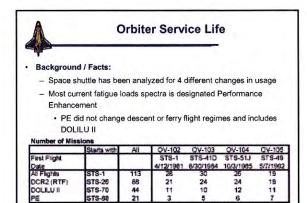
Environmentally Assisted Cracking of Carrier Panel Bolts Corrosion found on and near forward fuselage (X0 582) Challenges Associated with Wire Inspection OV-102 Exposure to the Elements Aging and Corrosion of OV-102 Service Life of the Shuttle Fleet Orbiter Service Life 13-3 13-2 13-5 13-4 13-6 13-1 13-7



Orbiter Service Life

- Action / Issue: Determine knowledge of OV-102 service life capability
- · Background / Facts:
 - Comparison of key parameters used to determine orbiter structure service life to the most current fatigue loads spectra (PE Cycle 6.0) is documented in RSS99D0510D, "Space Shuttle Life Tracking", March 2003
 - Includes all missions from 1981 through February 2003 spanning STS-1 through STS-107
 - OV-102, Columbia, 28 flights
 - · OV-103, Discovery, 30 flights
 - · OV-104, Atlantis, 26 flights
 - · OV-105, Endeavor, 19 flights



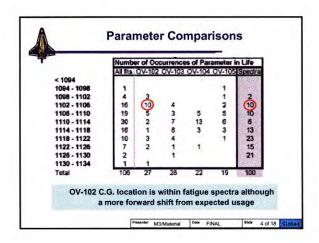


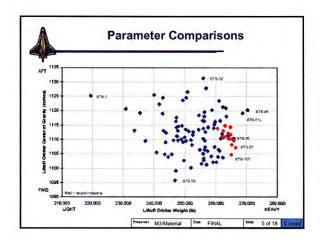
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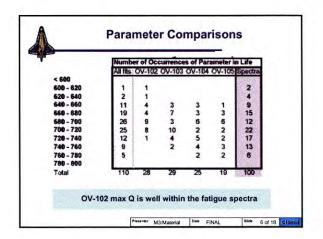
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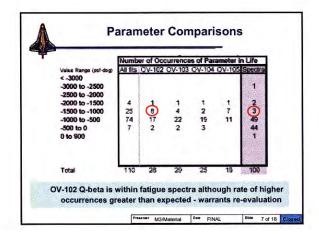
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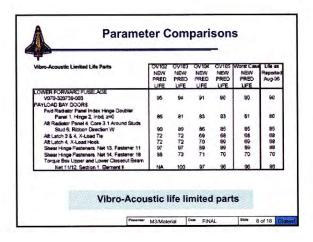
		er of Occ OV-102				
< 195,000	7 41 154	31 102	01-100	01-10-1	31-100	C)-CLUB
195,000 - 205,000						
205,000 - 215,000						
215,000 - 225,000	1	1				4
225,000 - 235,000	2	1		1		7
235,000 - 245,000	12	2	5	1	1	12
245,000 - 255,000	32	4	9	7	7	38
255,000 - 265,000	51	(17)	13	12	8	(21)
265,000 - 275,000	8	2	1	1	3	18
275,000 - 285,000						
285,000 - 295,000						
Total	106	27	28	22	19	100

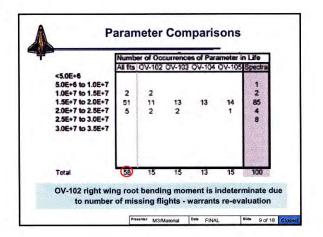


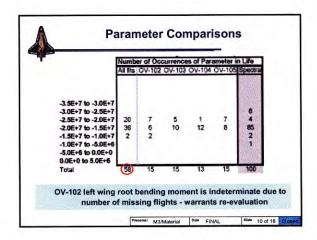


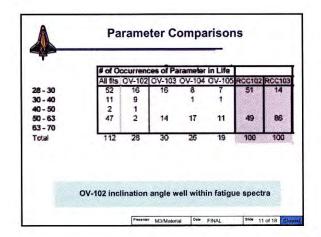


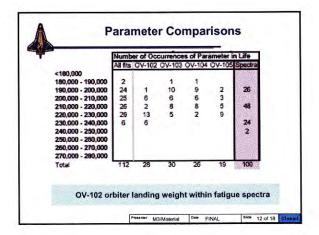


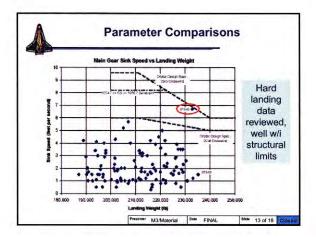


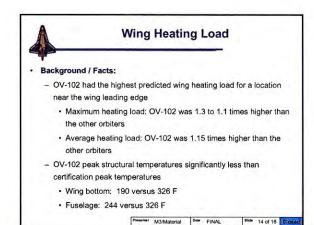














Spectra Comparisons PE Versus 5.4

- Background / Facts:
 - At the request of the CAIB (reference RFI B1-120), 9 wing and vertical stabilizer control points crack growth life predictions were determined using the certification spectra (5.4) and compared to the current spectra (PE)
 - PE spectra 1.4 to 1.6 times more severe for wing bending moment
 - · PE less severe for vertical stabilizer bending moment
 - Comprehensive analysis update performed for the airframe structure using the PE spectra (CAIB conducted spot check review)

Presenter M3/Material Date FINAL Blide 15 of 18 Closed



Orbiter Actual Usage

- · Findings:
 - Wing root bending moment results were not determined prior to STS-51
 - Parameters obtained and summarized in the Life Tracking report are not utilized to determine mission life capability (crack growth lives) for each orbiter based on actual usage
 - Fatigue testing of the wing structure has not been performed
 - Fatigue spectra appears to be adequate for near-term operations given the number of missions achieved (30 versus 100), however the spectra may need to be updated to safely achieve 100 missions

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Orbiter Actual Usage

Recommendations:

- If possible, fill in the missing wing root bending moment data and re-evaluate adequacy of fatigue spectra
- Carefully monitor the trends of the following parameters: liftoff weight, C.G. location, ascent Q-beta, ascent wing root bending moment
- Develop the capability to determine mission life capability (crack growth lives) for each orbiter based on actual usage

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Orbiter Actual Usage

Documentation:

- Responses to RFIs 120 and 195
- Briefing by T. Kott, "Orbiter Life Cycle Analysis Process Overview",
 3 April 2003
- Boeing Report RSS99D0510D, "Space Shuttle Life Tracking", March 2003
- Briefing by C. Modlin, "Orbiter Structural Life", 23 June 1992

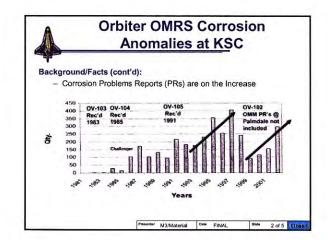
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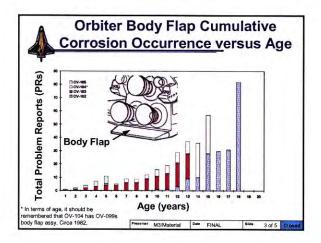


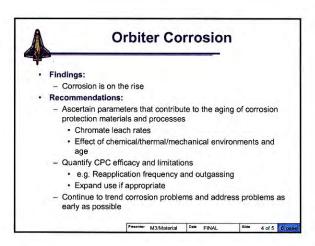
Aging Structural Issues

- · Action / Issue:
 - Aging and Corrosion
- Background / Facts:
 - Orbiter designed as maintenance-free for 10 years—all are now older than 10 years
 - Spar is aluminum honeycomb (known to be corrosion prone) in service for 24 years—concerns about galvanic couple between spar and IN718 or A-286 that could lead to degradation
 - Crevice corrosion known to occur on other shuttle locations with 2024-T81
 - 200 doublers reported on OV-102 in response to corrosion damage
 - Anecdotal evidence indicates that chromates leach out of primer after 6-12 years

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Orbiter Corrosion

- Recommendations (cont'd):
 - In order to better establish inspection requirements for corrosion based on environmental exposure, it's important to establish corrosion rates via test for environments, materials and structural configuration specific to the orbiter.
 - USAF and Navy aircraft structure very similar in construction to the orbiter. It may be beneficial to review their corrosion prevention and control practices.
 - Recent USAF and Navy R&D efforts aimed at providing practical modeling techniques for corrosion may also provide insight into the corrosion problem.
 - A USAF Air Mobility Command sponsored program developed an approach to ascertain the Economic Service Life for the KC-135.
 Their, and similar efforts by others, may be applicable to the obiter.

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Corrosion Near Aft End of Crew Module

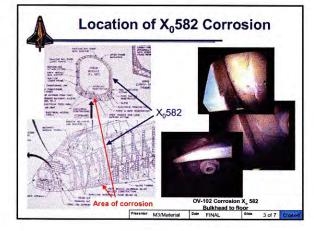
- Action / Issue:
 - Corrosion found on and near forward fuselage (X₀582) and was left unrepaired
- · Background / Facts:
 - X₀582 is a frame near the aft end of the crew module
 - Corrosion found and repaired on forward side of X0 582
 - Corrosion "monitored" but not repaired near X0 576 (slightly forward of X0 582)
 - While corrosion was not removed, CPC was applied to forward fuselage floor
 - · Use of CPC not straightforward; specialized application process required because outgassing may occur and interfere with Star Tracker

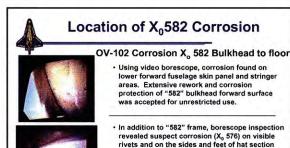
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Corrosion Near Aft End of Crew Module

- Background / Facts (cont'd):
 - OV-102 had different construction to subsequent orbiters making it more susceptible
 - · Goldized insulation blanket directly on aluminum stringers
 - · Uncoated steel fasteners
 - However, construction used for other orbiters not "corrosionproof"
 - · Titanium fasteners (react with aluminum)
 - · Aluminum not clad
 - · No faying surface sealant
 - · Susceptible materials





- Borescope View of Typical e: OV-102 V30/31 Inspection Repor
- revealed suspect corrosion (X_o 576) on visible rivets and on the sides and feet of hat section stringers.
- This PR was deferred due to the inability to fully access the area in question to effect a repair. The condition is to be visually assessed on a recurrent basis.

Presenter M3/Material Date FINAL



Corrosion Near Aft End of Crew Module

- · Findings:
 - Access to area between crew module and outer hull difficult to access for inspection and repair
 - Concern that unmitigated corrosion could progress and degrade structure below minimum safe level
 - OV-102 lower fuselage construction in area forward of X₀582 was unique and caused it to be more susceptible to corrosion
 - Corrosion cannot be eliminated as a potential degradation mechanism on the other orbiters
- Recommendations:
- To better understand potential impact, perform analysis of corrosion susceptibility, growth and damage consequences relative to factors influencing corrosion:
 - - Alloy, Temper, orientation, product form, anodized, clad/unclad

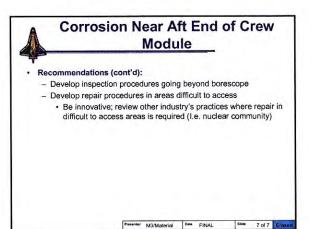


Corrosion Near Aft End of Crew Module

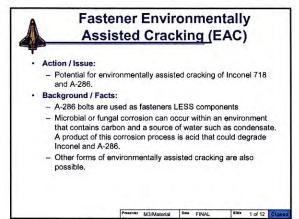
- Recommendations (cont'd):
 - Fasteners
 - Type, finish, AMS, wet/dry installed
 - Coating
 - Conversion coats, primer, CPC
 - · Mechanical load orientation
 - · Blanket insulation
 - Attachment material and method of attachment
 - Blanket material
 - Environment
 - Accidental fire suppression activation. OPF environment, rain exposure; pad exposure

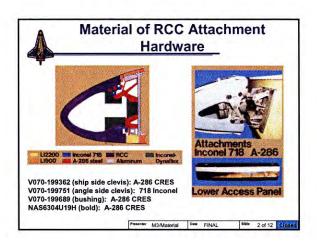
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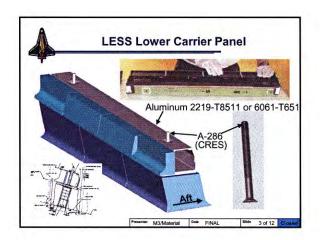


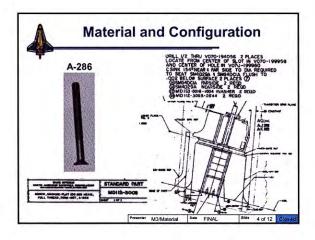


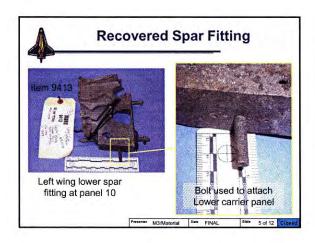


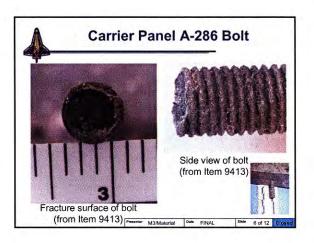


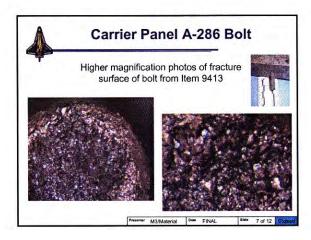


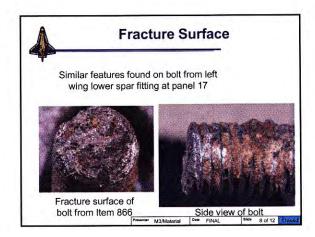


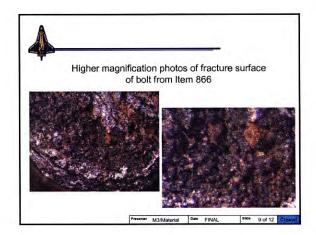


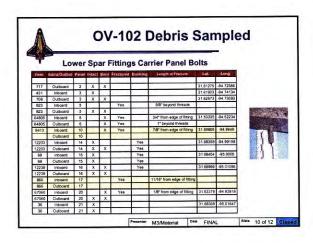














Fastener Environmentally Assisted Cracking (EAC)

Findings:

- Failure mode of recovered carrier panel bolts is consistent with hightemperature failure; failure is not due to EAC
- Current design and maintenance practices leave components at greater risk for corrosion

Recommendations:

- Obvious galvanic couples between aluminum and steel alloys should be avoided or clearly mitigated
- The use of TFE and MoS2 should be expressly forbidden in assembling components
- The use of primers and sealants such as RTV 560 and Korpon should be reviewed with respect to their possibly accelerating corrosion in real environments including in tight crevices.

Presenter M3/Material Date FINAL Stide 11 of 12 Closes



Fastener Environmentally Assisted Cracking (EAC)

Recommendations (cont'd)

- The negligible and compressive stresses presently occurring in A286 bolts provide protection against failure; assuring the continued presence of such low to negative residual stresses should be part of acceptance and qualification procedures.
- The detailed general and impurity chemistry of all paints, adhesives, and sealants should be reviewed periodically at the ppb to ppm concentrations, and such results should be reviewed from a corrosion point of view.
- The procedures and criteria for qualifying materials and coatings from a corrosion point of view should be reviewed for their relevance and adequacy.
- A substantially higher level of understanding and appreciation of damaging effects of all relevant ambient and applied environments on critical materials should be incorporated into the design and maintenance of the orbiters

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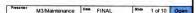


Maintenance Wiring Inspections

- Action / Issue: Kapton wiring, currently used in orbiters, poses inspection/maintenance challenges. Assess NASA actions to address these challenges.
- Background:
 - Each orbiter contains approximately 852,000 feet of wiring
 - · Amounts vary depending on modifications/instrumentation
 - · Most of the wiring is insulated with Kapton

· Findings:

Kapton (MIL-W-81381) refers to a type of insulation (technical name: aromatic polyimide) originally developed by DuPont in the 1960s





Maintenance Wiring Inspections

- Findings (cont'd):
 - When the shuttle was built, Kapton was state-of-the-art, exhibiting many positive attributes
 - 50% less space, 25% less weight, tough, durable to a wide temperature range, will not melt/drip/propagate flame
 - · Widely used in both military and civil aviation
 - Continues to be used today, though notable shortcomings have emerged over the years
 - Major concern is arc tracking
 - · A phenomenon in which overheated wiring carbonizes
 - · Overheating typically caused by broken insulation/arcing
 - · Carbonized Kapton acts as a conductor; result: "soft shorts"
 - "Soft shorts" (as opposed to "hard shorts") continue to conduct below the tripping threshhold of circuit protection devices, thereby propagating further carbonization/damage

M3/Maintenance Date FINAL

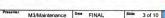


Maintenance Wiring Inspections

- Findings (cont'd):
 - Major causes of insulation failure (splitting/cracking/flaking)
 - Improper installation during manufacture (unknown at the time), such as routing (tight bends), clamping (too tightly), or positioning wires against burred screw heads/rivet tails/sharp edges; causes insulation wear/failure due to vibration and/or maintenance.

 Wire stress during inspection/maintenance: repositioning by technicians for access and/or unintentional actions (stepping)

 - Determined to be the single largest cause on orbiters · Exposure to elements such as solvents/corrosives/moisture
 - Parallel, extensive AF study (1986) concludes most problems due to design, installation, and maintenance
 - OV-102/STS-93 (Jul 99) incident raised awareness: loss of power to two of six Main Engine Controller computers 5 sec after liftoff
 - · Investigation identified root cause as damaged wire





Maintenance Wiring Inspections

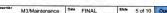
- Findings (cont'd):
 - NASA has taken numerous corrective actions since STS-93
 - Extensive inspections/corrective actions, starting with OV-102's J3 OMM (Sep 99); chit 1-month after roll-in complicated OMM
 - · Other orbiters grounded for inspection (partial); full inspections to be completed during scheduled OMMs
 - Results of OV-102/J3 OMM used to refine inspection/ documentation methodologies (more comprehensive/specific
 - · Improvements made in technician/inspector training and certification, maintenance procedures (e.g., calibrated crimpers)
 - Wiring inspection now required during any ground processing

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Maintenance Wiring Inspections

- Findings (cont'd):
 - OV-103 currently in OMM/undergoing remainder of wire inspection
 - Total discrepancies (stand down + OMM) nearing OV-102 proportions
 - Arc track testing using orbiter circuit protection/wiring displayed limited track lengths; worst case = 6.5 inches
 - Current mods include separating all critical wire paths from main bundles and individually protecting them
 - Numerous tests indicate Kapton is still the leading choice for orbiter environment despite development of hybrid insulators
 - Development of improved inspection equipment/techniques (to supplement visual) continues in the aviation community
 - Wholesale replacement, whether in military/commercial aviation, or the orbiter fleet, is costly
 - Hybrids used on new build B737/B757/F-15/F-22 (post-1995)



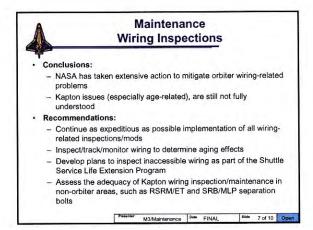


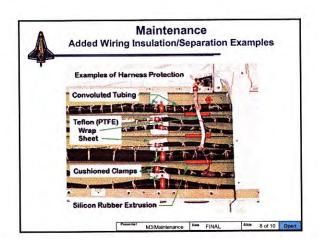
Maintenance Wiring Inspections

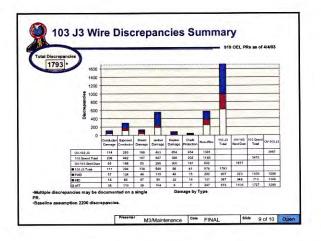
- Findings (cont'd):
 - Modifications either complete, in progress, or scheduled show ongoing efforts to mitigate wiring problems
 - MCR 19448: Orbiter Wire Protection Enhancements addressed routing of redendant Crit 1 wires; 127 cases ID'd
 - MCR 19527: Orbiter Wire Redundancy Separation corrects all 127
 - · MCR 19596: AC Bus Separation separates critical wires to C/B pnls
 - MCR 23167: Arc Track Protection continues efforts; Rev 1 for OV-102/Flt 29 (STS-107)
 - Approx 2,000 feet of orbiter wiring is inaccessible
 - Primarily below crew module
 - · No plans to inspect over the life of the orbiter
 - No technician traffic/hands-on maintenance due to inaccessibility
 - · NASA has confirmed, thru USA and Boeing, no Crit 1 wiring in
 - · Concern: installation-induced problems over 20+ yrs of service

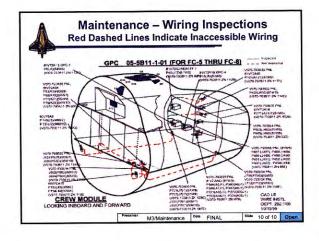
M3/Maintenance Date FINAL













Orbiter Environmental Exposure

- Action / Issue: Review/assess orbiter exposure to elements
- Background / Facts
 - OV-102 cumulative launch pad weather exposure 3.3 years
 - · Longest single exposure: STS-35/164 days (Apr-Dec 90)
 - Exposure to elements (rain, dew, salt air) has a negative impact
 - Corrosion to structure, oxidation/damage to RCC (suspected), wiring, etc.

Findings:

- Orbiter total exposure time (less -102) varies from 2.1 to 2.9 years
 - OV-102 leads fleet in total exposure time, but not in total launches
 - OV-102: 28 launches; OV-103: 30 launches
- Rollovers/rollouts/rollbacks due to launch scrubs, follow-on maintenance, & ops checks contribute to prolonged exposure

Presenter M3/Maintenance Date FINAL



Orbiter Environmental Exposure

- Findings (cont'd)
 - STS-35's 164-day exposure driven by scrubbed launch attempts

 - Rollout to pad (22 Apr) for initial launch attempt (30 May)
 Freon system repair 14 add'l days
 Launch scrubbed 30 May (MPS LH2 leak)
 Rollback 12 Jun (following troubleshooting/maintenance preps)

 - Rollout to pad (9 Aug) for second launch attempt (1 Sep)
 Stand down for payload telemetry repair 6 add'l days
 Launch scrubbed 5 Sep (Orbiter H2 leak, maintenance at pad)
 - Third launch attempt (18 Sep)

 - Launch scrubbed 18 Sep (MPS LH2 leak)
 Rollback 9 Oct (following troubleshooting, maintenance preps)
 - Rollout to pad (14 Oct) for fourth launch attempt
 Special LH2 tanking tests performed 2 add'l days

 - APU water valve problems; maintenance/servicing add'l 16 days
 - Launched 2 Dec



Orbiter Environmental Exposure

- - Besides pad exposure, most notable vulnerability is during mate/demate/ferry ops; three incidents noted
 - Sep 99: OV-102 caught in rain at KSC during mating
 - 128 lbs/16 gals removed after arrival at Palmdale
 - Feb 01: OV-102 caught in rain at Palmdale after mating
 - 747/shuttle could only be partially hangared (see picture)
 112 lbs/14 gals removed after arrival at KSC

 - Feb 01: OV-104 caught in rain during mating at Edwards AFB 1,600 lbs/200 gals removed after arrival at KSC
 - "Aft fuselage under bay 6 full of standing water"
 "Five inches deep along back of 1307 bulkhead"
 - Mate/demate ops highly vulnerable to inclement weather
 - · Lengthy operation; no shelter at any location
 - · No positive pressure inside shuttle, as at pad

Presenter M3/Maintenance Date FINAL

Slide 3 of 15



Orbiter Environmental Exposure

- Findings (cont'd):
 - Exposure is a major contributor to corrosion on all orbiters; trending upward 10% annually
 - 140+ PRs written due to corrosion damage in the body flap cove area alone (low point in vertical position)
 - 84 on OV-102 (51 in last flow)
 - 19 on OV-103 29 on OV-104
 - 6 on OV-105 · Frequency/quantity of PRs citing corrosion increasing
 - 91% of occurrences since '92
 - Impact on logistics (reparability/availability of spare parts)
 - Components (e.g., body flap actuators) being replaced due to corrosion
 - Repair taking longer: some piece parts beyond repair, must be manufactured, lead times as long as 1 year away
 - No serviceable spare actuators & 2 "holes"; first available Jun 03

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Orbiter Environmental Exposure

Findings (cont'd):

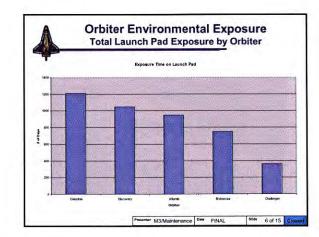
- Environmental (specifically weather) exposure constraints clearly outlined in RTOMI S0018.100, Adverse Environmental and Lightning Monitoring at LC39
 - Includes guidance on actions to be taken to minimize exposure to rain/hail/winds/freezing temps/tomadoes, etc.

Recommendations:

- Emphasize strict adherence to existing guidance
- Take every opportunity to avoid/minimize/reduce exposure
 - Review/analyze launches where exposure was significantly over or under the mean (e.g., >1 standard deviation) for lessons learned
- As some amount of exposure is unavoidable, an intensive
- corrosion program (inspection, treatment, prevention) is a must

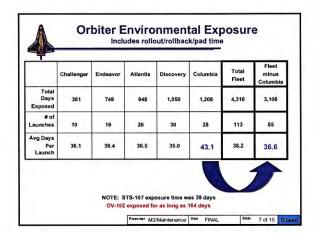
 See related "Action/Issue" slides on Corrosion and Service Life
 Extension Program (SLEP)

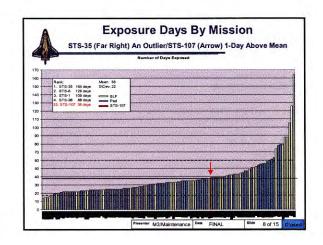
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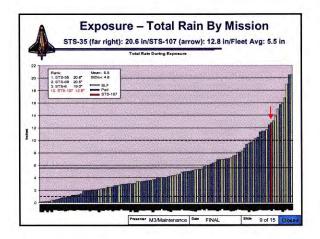


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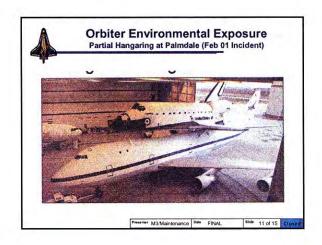


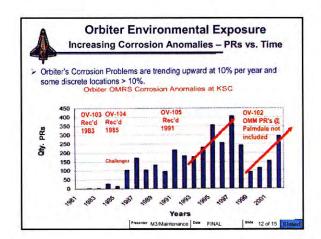


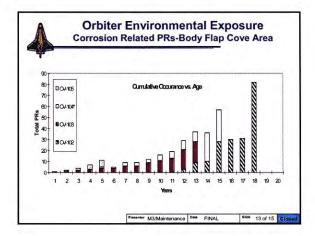


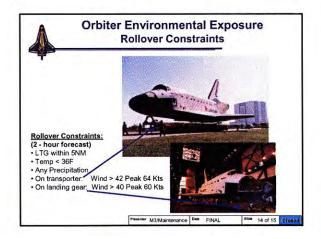


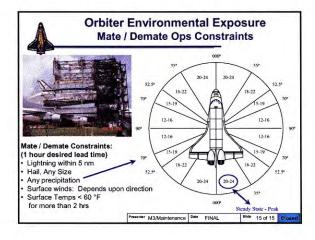














Maintenance Aging Vehicle/SLEP

- Action / Issue: Service Life Extension of Shuttle Fleet
- Background / Facts:
 - Shuttle fleet has been in service since 1980s
 - Originally programmed for replacement by early 21st century
 - Basic subsystem life requirement is 100 missions in 10 years
 - · Performance and Design Requirement (PDRD FE093)
- Findings:
 - SLEP objective very general: Integrated Space Trans. Plan says "middle of next decade", DAA ISS/SSP uses "2020 and beyond."
 - Original certification for 10 years, recertified in 1991 for 10 years
 - Limited structural data available; destructive testing of partial/ subscale structures at beginning, follow-on tests at subsystem level
 - SLEP initiated by HQ Code M Dec 2002, delegated to SSP Development Office is responsible for SLEP
 - First act...provide candidate projects list for SLEP independent panel review and final recommendation to Space Flight Leadership Council on May 7, 2003...over 100 collected

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Maintenance Aging Vehicle/SLEP

· Findings:

- Used Analytical Hierarchy Process (AHP) tool to compare projects on impact to life extension, safety, urgency and cost.
- 4 groups used to categorize the AHP priorities
- Must Do...imminent obsolescence or DMS concerns in 03; e.g. sustaining test equipment tasks for SSME and case hardware availability for RSRM.
- Current Commitments...e.g. CAU (glass cockpit), SSME Advanced Health Mgmt Sys (ph 1), Infrastructure (bldg, GSE), Industrial Engineering for Safety
- Foundational Activities...Aging vehicle studies, Mid-Life Certification, NDE upgrades, Project Feasibility Studies
 a.b.c. Sustainability, Improvement, New Capabilities...e.g. obsolescence iss vehicle health monitoring, Hydrazine Replacement, and crew survivability.
- Used AHP to prioritize over 50 projects for first budget submission
- Foundational Activities and Project Feasibility Studies may lead to increases in subsequent summit and budget cycles

Presenter M3/Maintenance Date FINAL

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Maintenance Aging Vehicle/SLEP

Findings:

- Funding request in May for initial studies to identify tasks in most crucial sustainment programs...Mid-Life Recertification (MLR), Fleet Leader, Corrosion Control and Risk Management.
 MLR will define tasks to be completed to recertify the STS for

 - continued used through foreseeable life span
 Results expected to identify necessary upgrades to structures and
 subsystems to assure safe operation as well as recommendations for
 additive maintenance and inspection programs
 - · MLR funding undefined
 - · Significant effort to prioritize previously identified candidate programs and add to budget request
- Higher headquarters supportive but concerned over financial impact of CAIB recommendations

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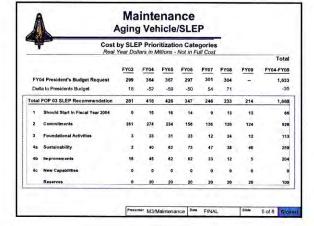


Maintenance Aging Vehicle/SLEP

Recommendations:

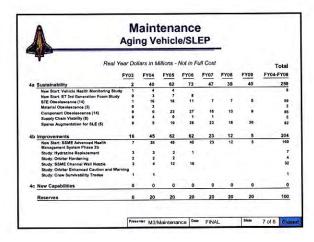
- Sustainment program needs a clearly enunciated goal in terms consistently applied across NASA to focus efforts
- Mid-Life Recertification is the foundation of SLEP. Accelerate funding to to ensure competitive consideration in budget request
- NASA is charting new ground and seems to be accepting the financial reality that sustaining systems is a long-term commitment
 - Will require programmatic support (organizationally and financially) throughout the remainder of the system's operational life.
- NASA should consider a sustainment-based reorganization and develop doctrine to guide them
 Restrictively define the SLEP mission. Current construct establishes this program as the central repository for nearly any shuttle related project.
 This will leave SLEP vulnerable to budget cuts and dilution of NASA's ability to resolve sustainment issues.

Presenter M3/Maintenance Date FINAL



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	99			OLL		-			
Real Ye		T	Total						
	FY03	Y04	FY05	FY06	FY07	FY08	FY09	FY04-F	
Total POP 03 SLEP Recommendation	281	416	426	347	246	233	214	1	.668
1 Should Start In Fiscal Year 2004	0	15	16	14	9	13	13		66
RSRM - Case Hardware Availability Orbiter - Certify PRSD Tank Supplier & Procure Spares	0	5	5	5	5	5	5		25 31
SSME - Sustaining Test Equipment Tasks	0	6	3	1	0	0	0		10
2 Commitments	261	274	234	156	136	126	124		926
Vehicle Cockpit Avionics Upgrade (CAU)	89	91	77	14	0	0	0		182
Vehicle Main Landing Gear Tire & Wheel SSME Advanced Health Management System (AHMS Phase 1)	, 3	4	3	2	1	0	0		10
Industrial Engineering for Safety	8	15	15	15	15	15	15		75
RSRM Obsolescence	12	18	19	20	20	21	21		98
Infrastructure	91 50	92 51	43	78	79	10	80		406
Others	50	51	43	27	21	10	8		152
3 Foundational Activities	3	23	31	23	12	24	12		113
Aging Vehicle Studies Mid-Life Certification Assessment & Issue Mitigate Fired Leader Program Compsion Control STE Gurvey Evaluation Non-Destructive Evaluation Upgrades	2 on	10	- 14						24
Ground Test Program	0	4	10	20		21	9		64
Performance Trade Studies / Lift, Power	1	2	2						4
Improved Tools / Metrics Probabilistic Risk Assessment Sustainability Health Metrics	1	7	5	3	3	3	3		21
Analytical Hierarchy Tool System	Presenter		faintena	Date	FINA		Slide	6 of 8	Clos







Maintenance Aging Vehicle/SLEP

- Aerospace Safety Advisory Panel-2002, excerpt
- Aerospace Safety Advisory Panel-2002, excerpt

 The Panel is confident that the service life of the Space Shuttle can be extended without compromising safety if adequate rigor is applied and resources are committed. The service life of a Space Shuttle orbiter as originally designed was 10 years or 100 missions. With the appropriate recertifications and inspections, the Space Shuttle's flight and ground systems have operated successfully for over 20 years...These flaws, resulting from aging or environmental factors, escaped detection by standard preflight tests and were found late in the launch process...Similarly, the orbiter liquid hydrogen (LHZ) line flow-liner cracks escaped detection for an unknown number of missions because the work instructions did not include inspection for this problem.

 Recommendation 02-1a: Through proactive review, revalidate and revise the
- Recommendation 02-1a: Through proactive review, revalidate and revise the criteria for critical ground and flight systems recertification.

 Recommendation 02-1b: Based on the findings and technical information garnered from the recertification process, validate and update the maintenance, test, and inspection requirements."

Presenter M3/Maintenance Date FINAL Slide 8 of 8 Cla

ACCIDENT INVESTIGATION BOARD

Maintenance Orbiter



Assessment of OV-102/STS-90 Hard Landing

Hypergolic Fuel Spill

WAD Accuracy

OV-102 Unique Wiring Configuration 14-1 14-3 14-4 14-5

OMDP - OMM

Date CAIB/Group 1

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Slide

FINAL

Presenter

Matrix





OV-102 Hard Landing

- Action / Issue: Review NASA assessment of OV-102/STS-90 hard landing (May 98)
 Background / Facts:
- - Background / Facts:

 Main gear impact was highest sink rate in flight history

 Estimated max of 6.7 fps through camera data

 Crosswind: 4 11 kts range

 Worst case (11) used in assessment

 Landing weight: 233,000 lbs

 Combined sink rate/x-wind/landing weight exceeded design criteria

 Design criteria of 5.97 fps versus estimated 6.7 fps

Presenter M3/Maintenance Date FINAL 1 of 2



OV-102 Hard Landing

- Findings:

 - Design criteria not equally critical at all landing weights
 Possible to exceed design criteria and still remain within structural capability
 - Calculated MLG loads/reviewed & approved by Loads Panel/Load
 - factors used in structural analysis

 Reconstructed loads less than half of design load

 Energy comparison explains why capability can be higher than design
 - MADS flight strain data confirmed accelerations/analytical
 - conclusion Reviewed/approved by Orbiter Structures Team 14 Jul 98
- **Group Recommendations:**
 - None. Eliminate as a causal factor.

Presenter M3/Maintenance Date FINAL



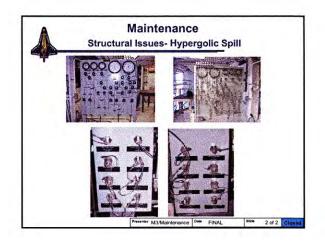


Maintenance Structural Issues- Hypergolic Spill

- Action / Issue: Hypergolic Fuel Spill (McDonald-Gehman letter)
 Background / Facts
 SIAT learned of hypergolic fuel spill 20 Aug 99 at KSC
- - Occurred during OV-102 prep for shipment to Palmdale
- Issue briefed to Shuttle Operations Advisory Group 1 Nov 99

- Issue briefed to Shuttle Operations Advisory Group 1 Nov 99
 Findings
 2.25 oz. dripped from GSE onto left wing inboard elevon trailing edge
 Spill cleaned; 2 tiles removed for inspection; no damage found
 USA employees at KSC received training; GSE improvements proposed to minimize risk of future spill
 Quick disconnects now separated at vehicle/GSE interface only
 Permanent panels now installed in each OPF, eliminates multiple QDs and flex lines on interface and test panel for each job
- **Group Recommendations**
 - None; spill was small/cleaned/assessed no effect on TPS or wiring









Maintenance Paper Work Review

- Action / Issue: NASA's review of STS 107/109 paperwork showed that current WAD accuracy may not be adequate to assure CoFR.
- Background: CAIB requested NASA explain the methodology and summarize their findings from the paper work audit with emphasis on how they will use them wrt trends/corrective actions/applicability
- Findings:
 - Review of subsystem WADs is ongoing. Early results reveal many "Findings" and "observations" in -107/-109 records
 - "Finding" = "discrepancies that impact the technical execution of the work" per KSC/Palmdale Processing Review Teams Guidelines and Criteria, Rev G.
 - Ex: incorrect guidance provided by the author/engineer and failure to document corrective action or initiate PR/MR

Presenter M3/Maintenance Date FINAL



Maintenance Paper Work Review

- Findings:
 - New WADs will be reviewed by one to three people (depending on the system) who will sign it or stamp before being issued
 - Monthly sampling of WADs called Technical Accuracy Measurement

 - Mortunity sampling of WADs called Technical Accuracy Measurement
 Completed WAD steps may be reviewed by USA & NASA QA
 Closed WADs undergo several review layers by supervisors, USA and NASA QA, engineers before passed to Quality Data Center
 - No apparent documentation of findings outside PRACA if relevant
- Recommendations:
 - SSP program management should consider review of STS 114/115 records prior to flight
 - NASA should institute a system to review and evaluate all CRIT 1 and 2 systems paperwork and sample the rest.

 Build a documentation quality control process to sample and document errors to use in trend analysis and process feedback

Presenter M3/Maintenance Date FINAL





Fire (Pyro /Wiring / etc.) **OV-102 Unique Wiring Configuration**

- Action / Issue: Determine reason for OV-102's unique wiring configuration (left wing) and its role in data loss leading up to LOS Background / Facts:
- - OV-102 wiring outboard of MLG wheel well routed in 4 large bundles; other orbiters have 7 small bundles

- other orbiters have 7 small bundles
 Findings:

 As the first operational orbiter, OV-102 had additional
 instrumentation; nearly 90% of wires routed through this area
 associated with OEX data gathering and/or disconnected systems

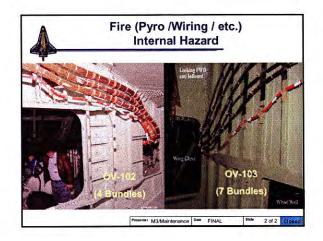
 Bundle securing method changed from clamps to tape straps in
 later orbiters; tape less able to secure large bundles additional
 smaller diameter bundles (0.5 in or less) required

- Group Recommendations:

 Not causal, but inclusion in OEX data analysis/sequence of events
- leading up to LOS will enhance investigation

 Role in data loss sequence TBD; NASA wire heating tests ongoing







Orbiter Major Modification (OMM)

- Action / Issue: Review/assess past OMM performance, movement of OMMs from Palmdale (PD) to KSC, and OV-102's most recent OMM; identify significant issues/concerns.
- Background / Facts
 - NSTS 07700, Volume III, requires each orbiter to undergo an OMM every 8 flights or 3 years
 - · Orbiters are removed from service for varying amounts of time. depending on work to be performed
 - Length of OMM driven more by mods than inspections
 - Work includes baseline rqmts (time/cycle changes), routine inspections (structural), special inspections (wiring), mods, deferred work, and correcting "stumble ons" (est'd at ≥40% of total work)
 - OMMs typically involve more intrusive inspections/maintenance/mods than during flows (down-/up-mission processing)
 - OMMs are a subset of OMDPs (Orbiter Maintenan which also include down-/up-mission processing (DMP/UMP)



Orbiter Major Modification (OMM)

- Background / Facts (cont'd)
 - 10 OMMs to date
 - 8 at PD (OEM), including OV-102 "AA" (demod from test/development to operational configuration)
 - 2 at KSC: OV-103/J1 (2-8/92) and OV-103/J3 (in progress)
 - Durations (as measured from landing to launch) have ranged from 5.7 months (OV-102/J1) to 19.5 months (OV-104/J1)
 - Wide variation in durations result from variations in OMM content
 - Historical challenges meeting 8 flight/3 year interval
 - . OV-102: 9 flights/4 years between J2 and J3
 - · OV-103: 9 flights/4.5 years between J2 and J3 (in progress)
 - OV-105: currently 8 flights/>5 years; next OMM: 11 flights/6+ years
 - . OV-104: 12 flights/6 years based on manifest & Oct 05 OMM

Presenter M1/Maintenance Date FINAL



Orbiter Major Modification (OMM)

Background / Facts:

- Studies/analysis since 99 on how intervals might be extended to 12 flights/6.0 years
 - · Major challenge: Calendar rqmts versus flight rqmts; e.g., clock continues to run during post-Columbia grounding
 - · General rule in industry: Time-based inspections become more frequent as vehicles age
 - · No decision to date
- By numbers alone, more mods performed in DMP/UMP than OMM
 - · 2,177 (36%) of 5,985 total mods (fleet) done in OMM
 - Remainder, or 3,808 (64%), accomplished during flow (DMP/UMP)
 - Reflects philosophy of getting mods done when possible (schedule permitting) vice deferring to OMM
 - Scheduling less complex mods during flows leaves OMMs with increased

flexibility for more complex mods & unexpected problems M1/Maintenance Date FINAL

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Orbiter Major Modification (OMM)

Findings:

- OMM location weighed since early 90s: PD or KSC?
 - NASA IG (95): Cost savings at KSC, but due to complexity of scheduled work and launch schedule, leave next 2 at PD
 - NASA IG (98): PD costlier, but "risk...greatly reduced"; "risk [at KSC] outweighs potential cost savings"; "...reevaluate location when significant changes occur.
 - SSP conducted reviews, starting in May 01, to address most efficient use of resources (personnel, infrastructure)
 - JSC Sys Mgt Office concluded significant savings between worst case at
 - Feb 02: NASA approved OV-103 OMM (Sep 02) at KSC
 - Short term factors cited: FY03 budget shortfalls, FY 02 impact
 - Long term: Life cycle cost reduction
 - Slightly decreased launch rate from '01 (7) to '02 (6) a 2ndary factor

Presenter M1/Maintenance Date FINAL



Orbiter Major Modification (OMM)

Findings (cont'd):

- Facilities: 3 bays at KSC, 2 at PD; KSC max'd after OMM move
 - Challenged to "juggle" 4 orbiters between 3 bays; increased workload/ disruption from movements; OV-103 moved 6 times in 9 months (prior to OMM start in 9/02)
 - · PD OMMs historically a buffer; OV-102's loss alleviated situation
- Logistics: Capabilities growth at NASA Shuttle Logistics Depot (NSLD) has reduced the need for West Coast duplication; even prior to OMM move, support increasingly from NSLD
 - OV-102/J3: 2,663 orders/76,894 pieces shipped from KSC; 50% hardware, 20% LRUs, 10% other (e.g., paints/chemicals)
 - OV-104/J2 (prior to OV-102): 1,538 orders/47,487 pieces
 - · PD industrial shops have generally atrophied (TPS, avionics), with a few exceptions (17" disconnect, cold plates); others (machine shop) continue supporting other work & are called on for KSC backup capacity

M1/Maintenance Date FINAL



Orbiter Major Modification (OMM)

Findings (cont'd):

- Workforce/labor expenditures appear more efficient at KSC, but too early for any definitive conclusions
 - · Last 4 PD OMMs: 324 to 448 (blue/white collar) equivalent personnel (EP); 383 average
 - Additional KSC augmentation: 30-40 techs/inspectors/engineers
 - Current KSC OMM (first 7 months): 235 EP projected, averaging 301
 - No other recent OMMs for comparison (last OMM 10 yrs prior)
 - Potential reasons for KSC efficiency compared w/PD
 - Larger workforce allows flexibility in shifting resources to match peaks/valleys
 - Steadier overall workload (not just OMMs) keeps worker proficiency at a higher level; workers not laid off/moved to other jobs as at PD

· One concern voiced by several managers: ability of fluid workforce (especially engineers) to focus

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Orbiter Major Modification (OMM)

Findings (cont'd):

- Workforce experience levels more stable at KSC due to fewer workload fluctuations
 - · 176 additional workers hired at KSC for OMM relocation; assimilated throughout entire workforce (1,900) to minimize training load/impact of inexperience
 - By contrast, 85% of PD workforce (342) during OV-102/J3 had prior OMM or orbiter manufacturing experience
 - Some experienced personnel strategically placed in other Boeing jobs to preserve expertise, then recalled for OMMs
 - Others laid off after OMMs, rehired prior to next OMM
 - As OV-102/J3 requirements/workload increased, the workforce grew to 500, experienced personnel were quickly "tapped out", and experience dropped to 58%; time spent training new/inexperienced workers increased, including on-the-job training

Presenter M1/Maintenance Date FINAL



Orbiter Major Modification (OMM)

Findings (cont'd):

- Support equipment capability comparable; slight advantage at PD WRT large component removal/reinstallation due to OEM
 - Ground Support Equipment readily moved between sites

- Last PD OMM: OV-102 J3

- Roll-in: 26 Sep 99: roll-out: 24 Feb 01
- · Initial duration: 293 days; actual: 517 days (76% growth)
- . Despite delay, roll-out achieved with 98% of work completed
- · Major mods included MEDS (glass cockpit), GPS, wireless video
- · Large growth in requirements/"stumble ons" (see chart)
- HEDS IA KS-0003 (3/28/01) perspective
 - "Poor performance on NASA, USA, and Boeing" (schedule/cost)
 - · "Work quality very good to excellent" (product)
- Offers MANY important lessons learned applicable to the fleet

Presenter M1/Maintenance Date FINAL



Orbiter Major Modification (OMM)

Findings (cont'd):

- HEDS Independent Assessment (IA) of OV-102 OMM
 - Contractor estimated 331-day flow; SSP directed 293; contractor initially assessed schedule as "red", though management subsequently agreed based on anticipated efficiencies & revised schedule risk assessment
 - PD adequately staffed (initially) for the OV-102/J3 OMM, but unforeseen problems/add'l work quickly exceeded capabilities
 - OMM requirements increased by 103% over initial planning (MSRR), and by 82% after roll-in; high by comparison with other OMMs (see chart)
 - · Wire inspection added 1-month after roll-in, 8-week extension based on expectation of 500-700 anomalies; actual - 4,600+ anomalies; SSP allowed a second 8-week extension; inspection chit revised 6 times
 - Other technical surprises (e.g., cold plate corrosion) and procedural problems (e.g., payload bay door rigging) exceeded scheduled time by more than double and slipped power-on testing



Orbiter Major Modification (OMM)

Findings (cont'd):

- Additional HEDS IA determinations
 - · OMM management suffered due to an inexperienced flow manager Message to SSP was regularly optimistic re: key milestones
 - Flow manager used a new, unproven scheduling tool that proved inadequate; returned to previous tool after 12-months
 - . The rapidly rising number of anomalies made integration of workload scheduling increasingly difficult
 - Integrated scheduling meetings were not held frequently enough to keep abreast of changes (weekly vice daily); daily mtgs 12-months into OMM
 - The large volume of PRs generated by nonconformances inundated the system and contributed to management difficulties
 - · OMM problems were exacerbated by the Program Office turning the process over to USA without a structured insight function in place

Presenter M1/Maintenance Date FINAL



Orbiter Major Modification (OMM)

Findings (cont'd):

- Despite the large number of complications during OV-102/J3 OMM, Columbia was delivered with 98% of all scheduled work completed
- "Traveled work" to KSC equaled 9,071 hours (0.66% of total)
 - · OV-102 J2: 7.886 hours (0.89%)
 - · OV-103 J2: 2,252 hours (0.38%)
 - · Fully coordinated...no surprises
- OV-102 J3 "lessons learned" being applied to OV-103 J3 at KSC
- · Efforts at better communication; scheduling meetings 3X/wk; Ground Ops reviews 2X/wk; program management reviews monthly
- · Healthy "give and take" observed at PMRs
- · Capabilities assessments for resource constrained areas (OPF tile technicians and tile backshop) presented at PMRs

Presenter M1/Maintenance Date FINAL

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Orbiter Major Modification (OMM)

Findings (cont'd):

- OV-103 J3 OMM still a challenge
 - · Requirements growth continues: 20 mods originally scheduled due to budget limitations and conservative approach (first KSC OMM); however, mods alone have increased to 84 (320%) by mid-April (67% thru OMM)
 - 24 additional mods being held to not overload capability
 - Despite growth, overall OMM flow well managed (compared to OV-102)
- AF Depot Maintenance Team benchmarking visit to KSC in Jun Invited by NASA Code M to assess OMDP/OMM processes
 - Benchmark areas: documentation, policy/procedure adherence, logistics
 - (NSLD) support, "ship side" engineering support, safety, communication Areas requiring review/increased attention: · Requirements definition plans (e.g., MVP, OMRSD, QPRD) lack a
 - closed loop feedback to process to routinely/systematically adjust Plans and scheduling can benefit from increased stability

Presenter M1/Maintenance Date FINAL



Orbiter Major Modification (OMM)

Findings (cont'd):

- AF Depot Maintenance Team/OMM areas requiring review (cont'd)
- Orbiter sustainment roadmap must be tied into OMM requirements
- Gov't/contractor relationships require review to ensure the right OMM "behavior" is being incentivized

Conclusions:

- While there are specific baseline elements, no two OMMs are alike; variations occur as orbiters age (wiring inspection, cold plate corrosion), as mission rqmts change (reconfiguration for MIR) and, in some cases, due to lack of funding; improving schedule and funding stability can help reduce process variation and aid in better planning/scheduling and less turmoil
- Increasing OMM intervals as orbiters age is counter to industry norms; for high performance systems, it raises even greater questions





Orbiter Major Modification (OMM)

Conclusions (cont'd):

- Relocation of OMMs to KSC provides many advantages over PD (e.g., a more stable, more fully/steadily employed workforce), but also creates new
 - · KSC advantages can still be overwhelmed if not carefully managed
 - Several NASA/USA/Boeing managers expressed concern over a fluid workforce's (especially engineers) ability to focus
- The wire inspection chit and its timing (1-month after OV-102 roll-in) played a major role in OMM schedule slippage

 • A "must do", representative of technical surprises that will continue
- OV-102 J3 OMM "lessons learned" have fleet implications because:
 - · As orbiters age, workload will likely increase
 - · The likelihood of technical surprises will also increase
 - A significant return-to-flight workload is highly probable
 - All of the above will generate new challenges, similar to those encountered during OV-102's OMM, for both managers/workforce

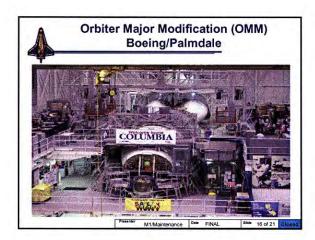


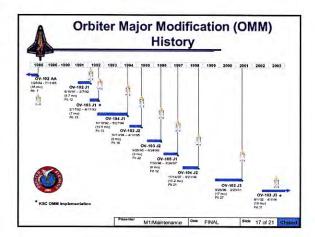
Orbiter Major Modification (OMM)

Recommendations:

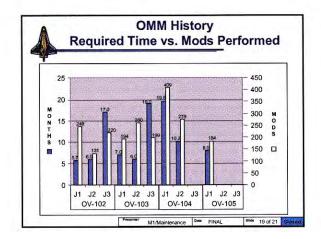
- The Program Office MUST work to achieve greater stability in OMMscheduled work, particularly the number of mods (biggest driver of schedule/workload variation); a continually changing schedule (rqmts growth) creates unnecessary turmoil/stress and increases the potential for quality escapes
- Managers (NASA/USA) MUST understand workforce/facilities capabilities, schedule to those capabilities, and take necessary actions to avoid exceeding them (ref. Capabilities Assessment briefing)
- The SSP Office MUST determine how it will effectively meet the challenges of inspecting/maintaining an aging orbiter fleet prior to increasing the OMM interval
- NASA/USAF benchmarking efforts should be continued using the same personnel as much as possible for continuity

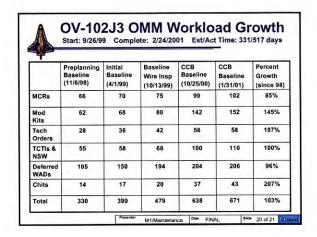
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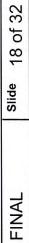


Orbiter Modifications OMM vs. Flow						
ORBITER	MODS IN OMM	MODS IN FLOW	TOTAL MODS			
OV-102	608	1,058	1,666			
OV-103	675	936	1,611			
OV-104	691	725	1,416			
OV-105	203	1,089	1,292			
TOTAL	2,177	3,808	5,985			





OMM Requirements Growth Comparison					
ORBITER	INITIAL PLANNING	CCB BASELINE	PERCENT		
OV-103 J2 9/95 – 6/96	383	532	39%		
OV-105 J1 7/96 – 3/97	278	405	46%		
OV-104 J2 11/97 – 9/98	461	844	83%		
OV-102 J3 9/99 – 2/01	330	671	103%		
OV-102 J3 w/o WIRE INSP	330	591	79%		



Date

CAIB/Group 1

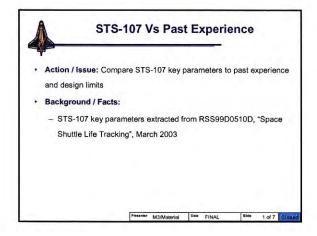
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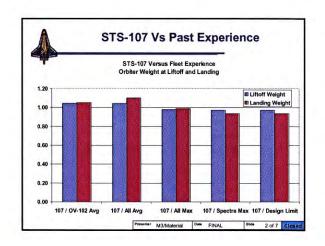


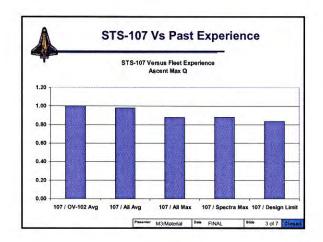
STS-107 Key Loads Parameters Versus Design and Experience STS-107 Ascent Loads (DOLILU) STS-107 OEX Ascent Data 15-2 15-1 15-3

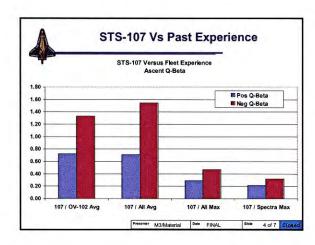
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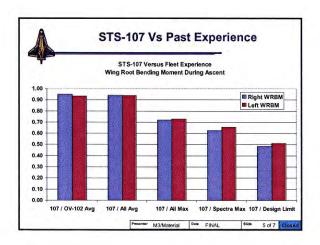


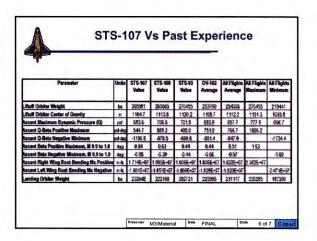














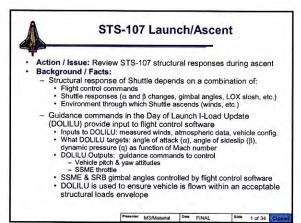


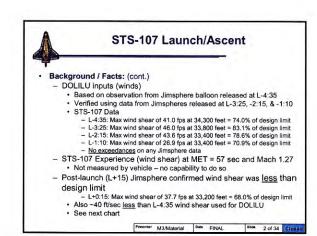
STS-107 Vs Past Experience

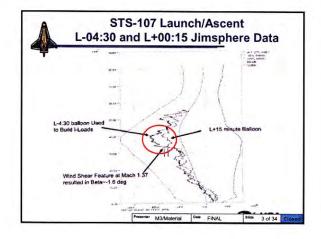
- · Findings:
 - All STS-107 key parameters compared have responses less than the maximum experienced in the fleet and the design limit values
 - No issue discovered to date
- · Recommendations:
 - Incorporate information into Ascent Integrated Scenario

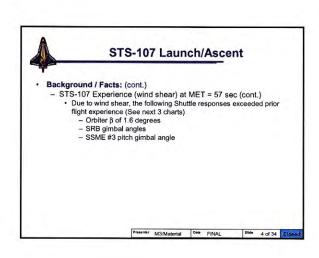
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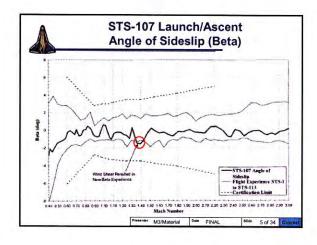
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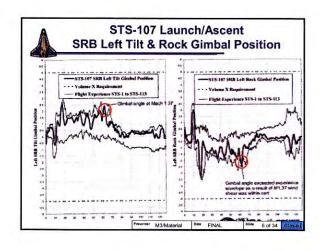


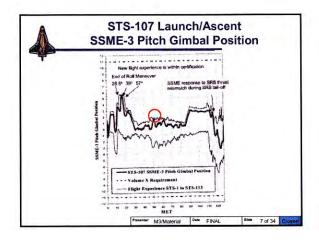


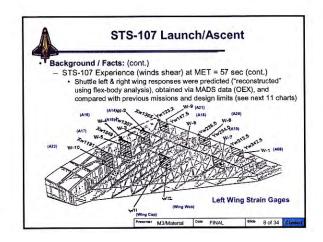


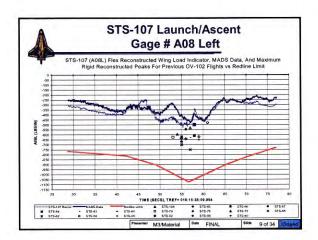


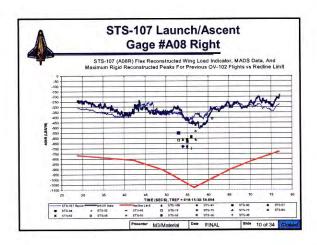


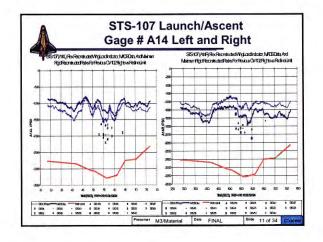


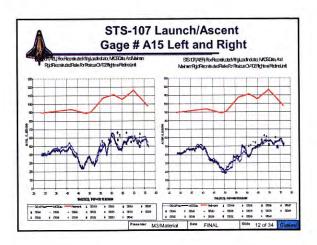


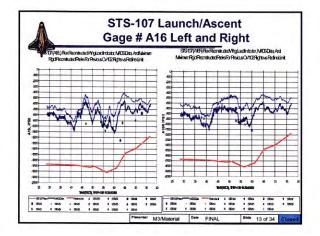


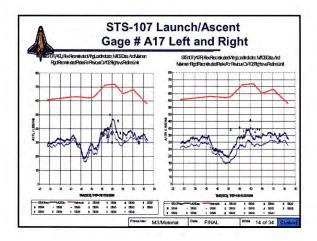


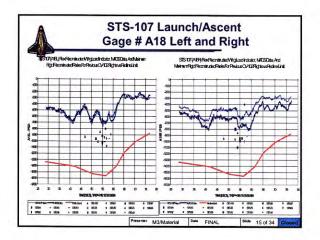


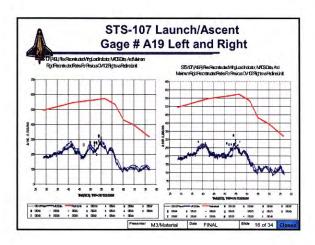


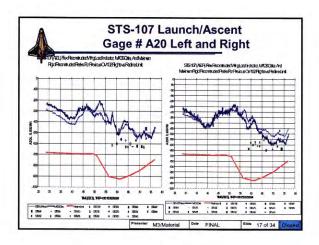


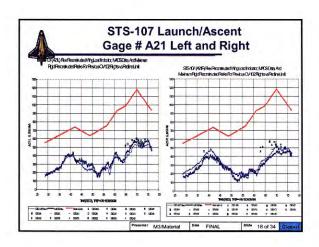


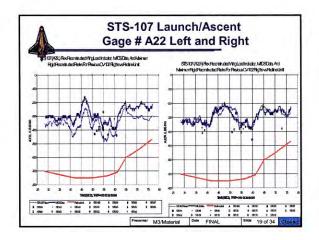


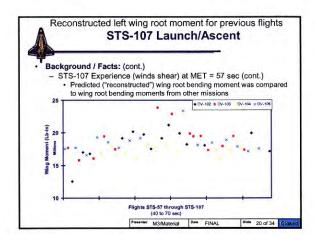


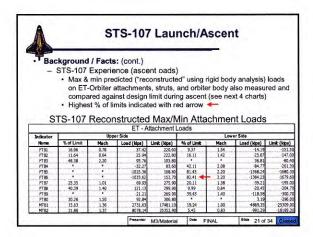


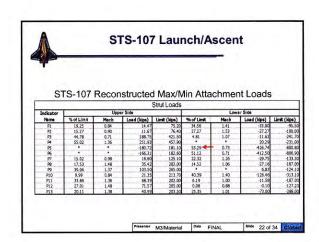


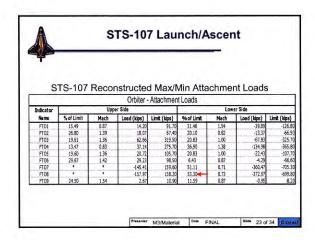




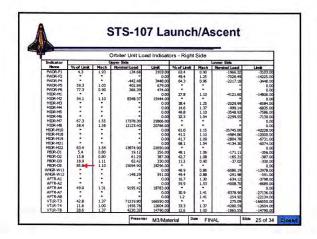


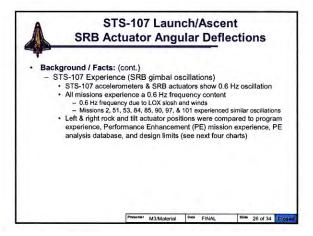


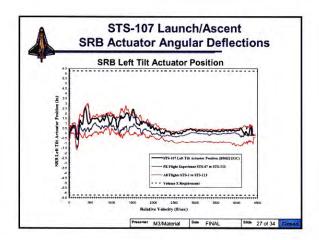


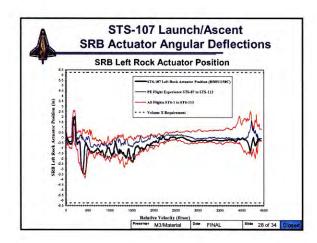


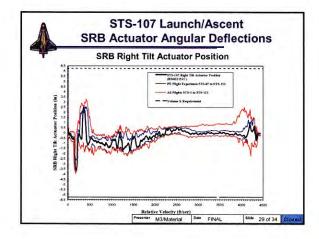
		_		/ Lau				
and a			Orbiter Unit Lo	oad Indica	tors - Left	Side		
Indicator	ator Upper Side			Lower Side				
Name	% of Limit	Mach	Nominal Load	Limit	% of Limit	Mach	Nominal Load	Limit
PWOL-F1	1.5	1.95	46.94	3103.00	62.5	0.86	-1938.01	-3103.0
PWDL-F2	*			0.00	39.1	1.30	-5562.40	-14225.0
PWDL-F4	A**		-488.32	3448.00	65.6	0.92	-2260.92	-3448.0
PWOL-F5	59.6	1.00	404.41	679.00				0.0
PWDL-F6	73.6	0.86	348.74	474.00				0.1
MIDL-M1	3 * C			0.00	32.2	1.10	4761.89	-14806.0
MIDL-M2	50.4	1.10	7783.51	15444.00				0.0
MIDL-M3				0.00	40.9	1.36	-2695.55	-6584.1
MIDL-M4				0.00	27.1	1.38	-1951.70	-6835.0
MIDL-M5		. *		0.00	46.6	1.10	-3535.50	-7586.
MIDL-M6		*		0.00	34.0	1.55	-2423.70	-7130.0
MIDL-M7	69.4	1.55	17905.80	25806.00			*	0.0
MIDL-M8	70.0	1.25	14527.50	20766.00			*	0.0
MIDL-M10	*	*	1	0.00	56.2	1.14	-23742.60	-42228.
MIDL-M18				0.00	39.5	1.09	-4738.97	-12000.0
MIDL-M19				0.00	40.5	1.08	-2729.22	-6731.0
MIDL-M21	*	*		0.00	71.6	1.55	-4347.18	-6074.
MIDL-M22	64.6	1.55	14255.10	22050.00				0.0
PBOL-D1			-16.42	356.00	44.9	1.05	-159.89	-356.0
PBOL-D2	8.7	0.80	33.73	387.00	33.8	1.05	-130.83	-387.6
PBOL-03	33.0	1.06	108.94	330.00	24.0	0.80	-79.07	-330.
PBDL-D5	85.8	1.10	15694.90	18296.00				0.0
WNGL-W11	* *			0,00	49.9	1.25	-6473.27	-12978.0
WNGL-W12			-146.32	591.00	54.3	1.25	-320.67	-591.0
AFTL-A1				0.00	25.2	1.37	-958.00	-3798.0
AFTL-A2			*	0,00	60.4	1.54	-4037.63	-6689.
AFTL-A4	61.0	1.25	11455.50	18783.00			200.00	0.
AFTL-A7		:	1	0.00	29.3	1.51	-7960.54	-27136.
AFTL-AB			Same	0.00	1	1	179.42	-22134.
VTIL-T3	22.7	1.37	37806.90	166550.00			374.08	-166550. -12604.
VTLL-T4	33.3 12.6	1.37	4199.12	12604.00	11.6	1.00	-1457.09	-12604/

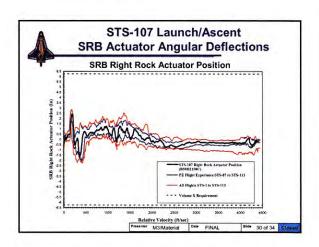
















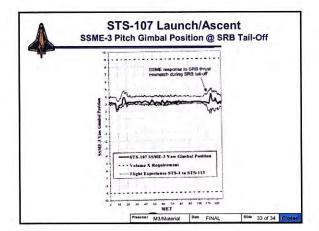
STS-107 Launch/Ascent

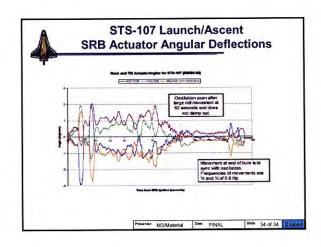
Findings:

- Out-of-experience events were within certification limits
- Flight Control System operated as designed During the wind shear event at MET = 57 sec, wind shears, sideslip (β) angle, SRB gimbal angles, SSME #3 gimbal angle, and observed & predicted left & right wing loads were all below design limits
- All wing loads were ≤ 50% of design limits
 Maximum attachment and orbiter body loads during entire ascent were below design limits
- Wing instrumentation indicates more cycles on left vs. right wing
 Left & right SRB rock and tilt actuator positions were within design limits
- · Recommendations: None

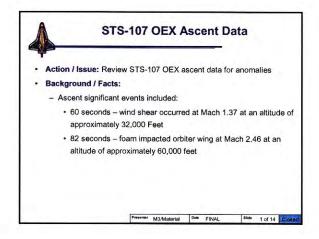
Presenter M3/Material Date FINAL Slide 31 of 34 C

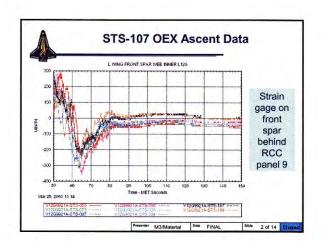


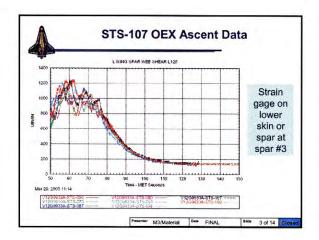


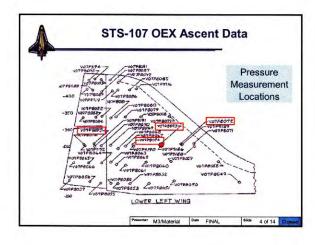


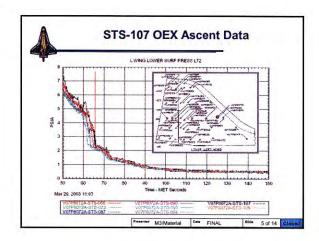
COLUMBIA ACCIDENT INVESTIGATION BOARD

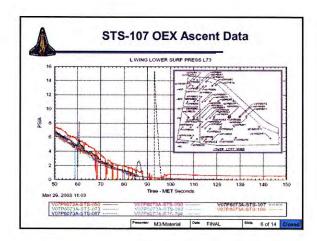


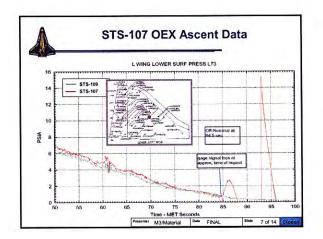


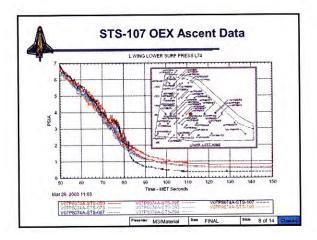


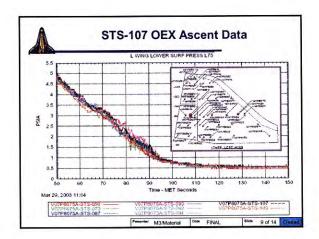


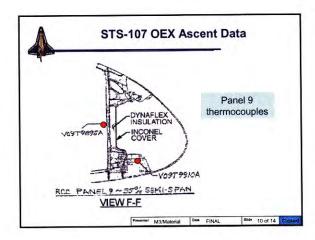


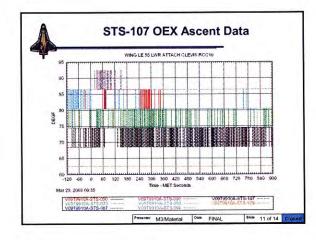


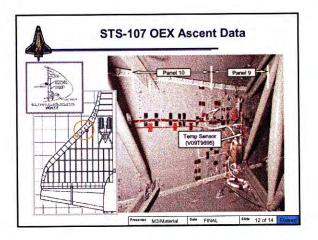


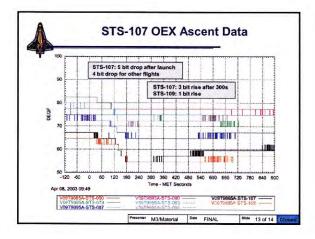


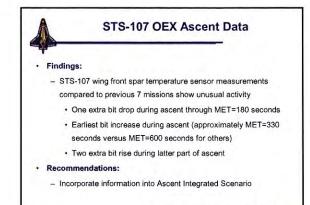












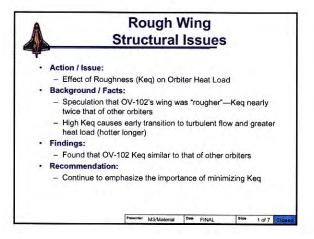
Presenter M3/Material Date FINAL Slide 14 of 14 Characteristics

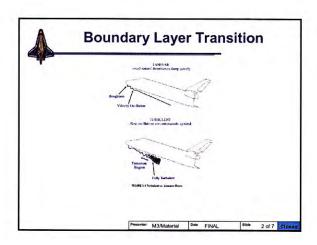
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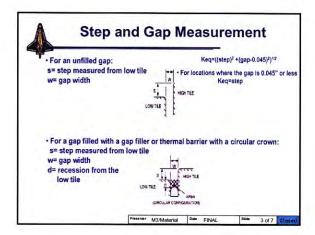
ughness (Keg)	Kapton Wiring	Premature Firing of Pyrotechnic Devices
Effect of Roughness (Keq) on Orbiter Heat Load		chnic Devices

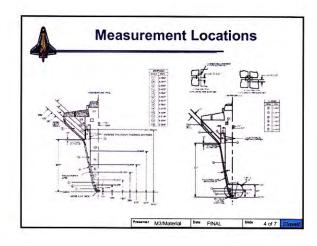
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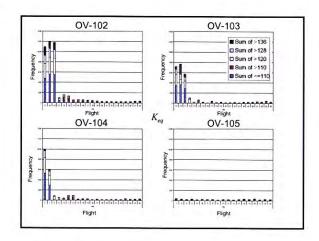


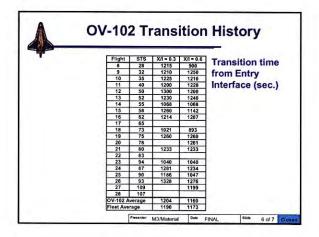


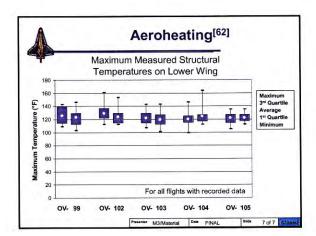














Fire (Pyro /Wiring / etc.) Kapton Wiring as Causal

- Action / Issue: Assess Kapton wiring as a fire/explosion risk to OV-
- Background / Facts:
 - Kapton insulation proven to degrade under certain conditions Insulation degradation leads to risk of shorting between wires "Arc tracking" along length of wire

 - Arcing can damage adjacent wires
- Findings:

 In-depth inspection of OV-102 during J3 OMM (Sep 99 Mar 01)
- In-depth inspection of OV-102 during 35 ownin (Sep 95 war o') identified/corrected numerous nonconformances (nearly 5,000)

 Prompted by damaged insulation/shorted wire/loss of power to two of six main engine controller computers during STS-93 (Jul 99)
 OV-102 inspection results formed a good baseline for subsequent studies/development of preventive measures

 Most common cause: work-induced, either during inspection/maintenance.
 - inspection/maintenance
 - Other causes: improper installation (routing/securing) during manufacture; moisture intrusion, chemical spillage



Fire (Pyro /Wiring / etc.) Internal Hazard

- Findings (con't.):

 Despite numerous ongoing studies of alternate insulators, Kapton still viewed as a leading candidate

 Various reasons: Kapton does not burn, but carbonizes at approx 650 degrees C; also lightweight, durable

 Telemetry from OV-102's last minutes prior to breakup does not point to Kapton wifton as causal

 - Formulation (1941) The state immulas brid to be darked to some particle state (1941) The state (1941) T
- ett wing diefmal infutision, NOT with Kapton-associated failure Actual/extensive NASA testing immediately following Columbia tragedy verified failure signature analyses

 Kapton wiring subjected to oven, blowtorch, and arc jet heating Testing/analysis for years prior to STS-107 showed Kapton wiring w/low voltages & low currents associated with orbiter instrumentation (such as in the left wing) have a very low probability of arc tracking

Presenter M3/Maintenance Dese FINAL



Fire (Pyro /Wiring / etc.) Internal Hazard

Conclusions:

Based on extensive wiring inspections/maintenance/modifications to OV-102 prior to STS-107, analysis of sensor/wiring failure signatures, physical verification of those signatures, and prior Kapton wiring studies, Kapton's role as causal to Columbia's loss is highly unlikely

Recommendations:

- Inspection of remainder of fleet planned/being executed
 Partial inspection completed on all orbiters during initial grounding
 Complete inspection to occur during respective OMMs
 OV-103 currently in progress with expected completion in Apr 04
 OV-105 to be completed in 04 (input date accelerated to summer
- · OV-104 must be fully inspected as soon as possible

Presenter M3/Maintenance Date FINAL Slide 3 of 4







Fire (Pyro /Wiring / etc.) Internal Hazard

- Action / Issue: Determine conditions necessary for auto-ignition of pyrotechnic devices and their role in STS-107's loss Background / Facts:

 137 NASA Standard Initiators (NSI) used throughout shuttle
 102 units fired during nominal mission
 35 units for emergency applications (including landing gear extension)
 Findings:

- Findings:

 Qualification requirement: No auto-ignition with thermal soaking of 425 deg F for 1 hr.

 Individual component chemicals auto-ignite at 700-750 degrees F Actual cartridge testing (1 Feb):

 Assets removed from NASA stock; manufactured Feb 84

 Auto-ignited at 598 deg F

 Group Recommendations:

 While not likely to be causal, pyro cartridge auto-ignition due to wheel well heating must be included/accounted for in any failure scenario involving thermal intrusion into the LMLG well

Presenter M3/Maintenance Date FINAL

Design - Certification Other

Date CAIB/Group 1 Presenter

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Slide

FINAL

SRB ET Attach Ring Structure Factor of Safety

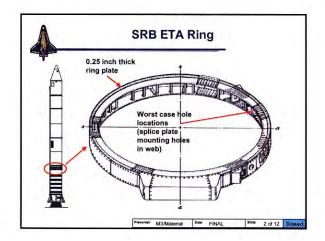
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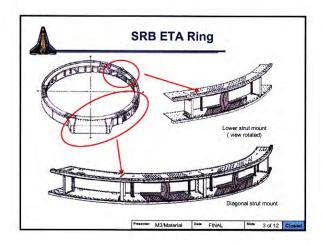


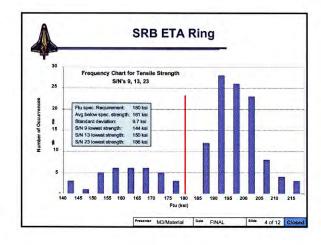
SRB ETA Ring

- Action / Issue: SRB ET attach (ETA) ring has reduced properties
- Background / Facts:
 - Recent material testing discovered strength values less than the design requirement
 - · Minimum requirement is 180 ksi
 - Lowest value from 2 S/Ns is 144 and 150 ksi
 - Issue presented during ET tanking meeting on 16 Jan 03
- SSP CR S091496 approved on 16 Jan 03
 - · Waived the factor of safety requirement of 1.4, accepted 1.25
 - No full technical review prior to launch of STS-107
- ETA design life is 40 missions (inspection interval is 13 missions), STS-107 ETA rings:
 - · Left: S/N 19, 9 flights prior to launch
 - · Right: S/N 6, 12 flights prior to launch









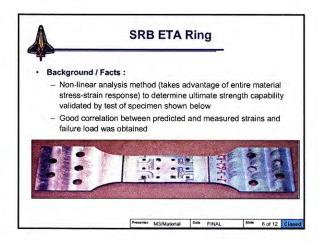


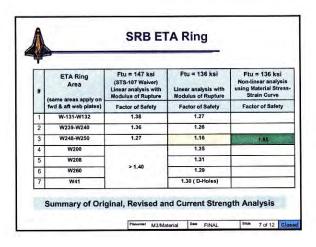
SRB ETA Ring

Background / Facts :

- STS-107 strength analysis performed using 147 ksi
- Factor of safety reduced to 1.25 (ET tanking meeting value)
- MSFC recommended using 136 ksi based on metallurgical assessment in March 2003
 - Factor of safety reduced to 1.16
- Below design minimum thickness measured on 7 ETA rings in March 2003
- Strength analysis being revised accounting for hardness test results correlated to strength and actual part thickness
 - Both the current analysis method (linear material properties) and non-linear analysis methods are being utilized

Presenter M3/Material Date FINAL Blide 5 of 12 Closed





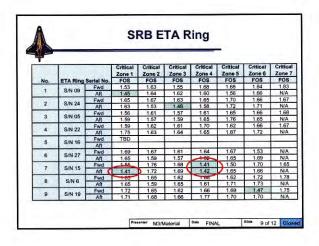


SRB ETA Ring

Background / Facts

- Total quantify of SRB ETA rings is 17
- 9 rings were readily available for hardness and thickness measurements (the others require some level of disassembly) and have been completed
- S/Ns: 5, 6, 9, 15, 16, 19, 22, 24, and 27
- Strength analysis performed using linear analysis (more conservative) and actual hardness and thickness results
 - S/N 16 has a region with a factor of safety less than 1.4 and a region with low hardness results
 - The other 8 S/Ns have a minimum factor of safety > 1.4
 - · S/N 15 has a couple of regions with marginal hardness results
- All rings have factor of safety > 1.4 using non-linear analysis
- 9 rings have completed NDE in the critical regions
- All rings will undergo a complete re-baselining NDE, S/Ns 9 and 24 are in-work to support first return to flight

Presenter M3/Material	Dase FINAL	Slide 8 of 12	Closed





SRB ETA Ring

Background / Facts:

- NASA's short-term plan:
 - · Complete NDE on 9 uninstalled rings
 - · Uninstall the remaining 8 rings and perform hardness and thickness measurements and NDE
- NASA's long-term plan:
 - · Replace ring web plates with new material or material that meets specification and proper thickness
 - · Implementation plans have not been approved by the program

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SRB ETA Ring Category: Other Significant Finding

Findings:

- Short-term plan to include hardness and thickness measurements and NDE of the 8 remaining rings is adequate
- 7 of the 9 rings measured to date appear to be adequate for limited
- Long-term plan is the best approach, funding and implementation schedule has not been authorized by the program

Recommendations:

- Don't use S/N 16 and 15 in their present condition
- Accelerate implementation of long-term plan





SRB ETA Ring

Documentation:

- PCRB briefing, "SRB External Tank Attach Ring Status", June 5, 2003
- MSFC/ED33 document, "Strength and Safe-Life Parameters for 4130 ET Attach Ring", 28 May 2003
- Briefing by D. Martin, "SRB External Tank Attach Ring"; Action CAIB-NAIT-00154, B1-00153, 14 April 2003
- Briefing by P. Gutierrez, "SRB External Tank Attach Ring Program Requirements Control Board", 26 March 2003
- SRB ETA Ring Factor of Safety Change Request, 28 Jan 03
- Briefing by R. Elliott, "STS-107 (BI116) ET Tanking Meeting Program - Solid Rocket Booster", 16 January 2003

Presenter	M3/Material	Date	FINAL	Slide	12 of 12	Close
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FINAL

Date

CAIB/Group 1

Presenter

Maintaining Critical Technical Knowledge 18-2 18-1

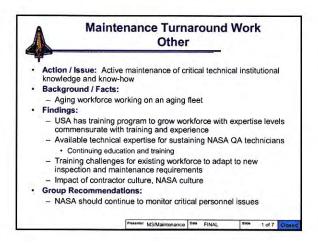
S&MA Quality Assurance Organization

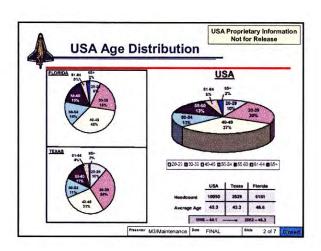
USA/NASA FOD Prevention Programs 18-3

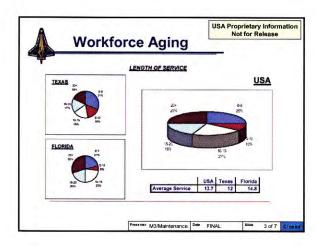
Capabilities Analysis

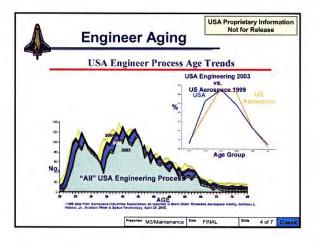
Matrix

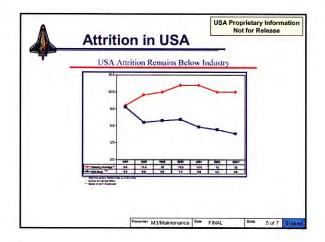


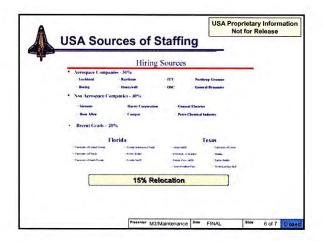
















Maintenance Safety & Mission Assurance

- Action / Issue: NASA/USA's Safety & Mission Assurance has had significant changes in workforce & inspection methodology
- Background / Facts:
 - Sufficiency of Government Mandated Inspection Points (GMIPs) was questionable by numerous testimonies
 - KSC GMIPs reduced from 44,000 in 89' to 22,500 in 96' to 8,500 now
- Observations and interview information:
 - Need thorough review of quality program requirements (doing non-value added looks but not some critical items - e.g., hydraulic pump installation, mating of SRBs)
 - Penny wise and pound foolish? (batteries, lights, inspection mirror tools)
 - Yielding to contractor (FOD definition, schedule, nonexistent unscheduled surveillance)
 - Unsupportive quality program management at KSC (instances of having to go to NASA HQ for resolution); dysfunctional organization of "camps"

Presenter M3/Maintenance Date FINAL



Maintenance Safety & Mission Assurance

- Observations and interview information
 - Abundance of "fly as is" dispositions
 - Government inspector hiring eval needed (DCMA and NASA PDs)
 Disgruntled employees at MAF

 - Safety and security consistently rated strong
- Potentially too few government inspectors

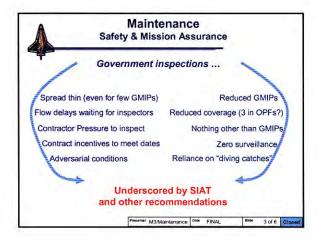
Findings:

- Quality assurance done by S&MA, SQ&MA and some engineering
- QA's role in process improvement through interpretative trend analysis of PRACA and the Integrated Quality Support database is inconsistent and not integrated between the players
- NASA inspectors inconsistently use the Hex or reject stamp for jobs closed out by SQ&MA (testimony given to CAIB staff)
 - Consequently, NASA S&MA has no means of tracking/trending for use as evaluation tool for personnel training and assessment

Presenter M3/Maintenance Date FINAL

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Maintenance Safety & Mission Assurance

Findings:

- NASA involvement beyond GMIPs is very limited. Sampling of routine or non-critical tasks not formally done
- GMIPs review process is ad hoc with no regular methodology for review of historic data to adjust QA emphasis
- S&MA manning levels dropped due to retirements and moves to engineering posts without replacement

- KSC with additional quality inspectors (several suggested by previous interviewees), and the head and deputy of the quality program
- MAF -- with additional quality inspectors (several suggested by previous

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Maintenance Safety & Mission Assurance

Reviews

- Contract regarding items such as FOD, engaging NASA inspectors during the flow
- Facility upkeep and needs
- Quality Planning Requirements Document
- Quality inspector PDs
- Past reports observations & recommendations (e.g., SIAT, Rogers, ASAP, GAO)

Recommendations:

- Independently-led bottom-up review of QPRD at KSC and MAF with intent to validate adequacy of oversight in terms of # of GMIPs, scope of authority outside the enumerated GMIPs and manpower
- Add tasks to GMIPs that evaluate hardware and housekeeping
- Build a regular review process to evaluate assurance program to provide trend analysis data, for training and inspection targeting

Presenter M3/Maintenance Date FINAL



Maintenance Safety & Mission Assurance

Recommendations:

- Broaden S&MA inspections to include statistically-driven sampling of all maintenance-related processes
 - Should go beyond GMIPs specific events to validate USA Quality inspection results <u>and</u> verify work quality before close out
 - Include a process to sample/validate documentation of maintenance for completion of the tasks and adequacy of the audit trail
- Validate S&MA workforce is adequately sized and manned to accomplish it's mission to enforce quality and safety
- Implement the NNBE "model for compliance verification"
- Return to past closed loop discrepancy system
- Return to true FOD definition, enforce "clean as you go" program
- Ensure no closeout work can be done by a single person alone (e.g., foam spraying)
- Allow employees to accomplish the duties in their PDs (!)
- NASA Code Q examination of safety specialist manning and responsibilities at KSC (in relation to USA safety)

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Maintenance **FOD Policy**

- Action / Issue: USA / NASA Foreign Object Damage (FOD) Prevention Programs Require Evaluation
- Background / Facts:
 - USA program consists of daily debris walk-downs by management, workers "clean as you go," and statistically-based process sampling
 - 23 separate checks of launch pad complex from pre- to post-launch accomplished in varying levels of detail by various organizations USA FOD prevention metrics differentiate "FOD" and "process debris"

 - "FOD" -- After job is stamped
 "Processing Debris" -- Before job signoff or end of shift - No other NASA contractor uses this category
- Findings:
 - FOD prevention is highly emphasized in USA/NASA daily operations
 - Assessment of responsibility is delineated: S&MA (NASA) responsible for FOD and SQ&MA (USA) primarily responsible for Process Debris

Presenter M3/Maintenance Date FINAL



Maintenance **FOD Policy**

- NASA inspects and assesses FOD failures only after USA has closed a WAD
- "FOD" is an industry standard term basis for prevention programs and immediately recognized as critical part of prevention
- Commonly expressed opinion: FOD was redefined to accommodate SFOC award fee determination
- FOD and Process Debris are "feeder" metrics that are rolled up into the TMR's scoring for inclusion in the SFOC award calculation.
 - First half FY 03 performance assessment: the "good" FOD rate canceled out the moderate Process Debris rate
 - · Unique effect of splitting FOD into two metrics
 - Second half FY 02: 2nd straight poor performance in both categories, award fee impact minimal, received highest score ever in roll up
- FOD found on launch pad is a direct award fee impact

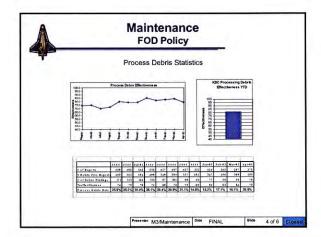
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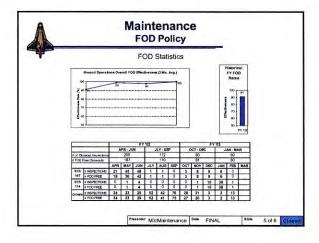


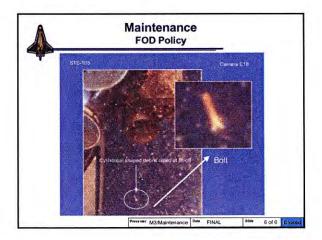
Maintenance **FOD Policy**

- Recommendations:
 - Greater NASA involvement in FOD program beyond GMIPs or occasional process sampling may improve program emphasis
 - NASA's role regarding the FOD program should be evaluated for expansion of inspector involvement, and expansion of inspections
 - Add random "Process Surveillance" of all processes, including FOD prevention
 - Eliminate alternative definitions of FOD
 - · Could be interpreted as diminishing significance
 - · Eliminate lines that separate NASA and USA quality assurance by authority over FOD prevention
 - Realign Award fee algorithm to increase FOD impact

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Maintenance Capabilities Analysis

Action / Issue:

- Do NASA/USA ground operations managers routinely assess their capability to support the launch schedule?
 - Do they have the tools to identify when they are approaching (or exceeding) the "ragged edge"?
 - At what point does a launch schedule become unsupportable from a ground processing viewpoint?

Background / Facts:

- Six launches originally planned for FY02/03; 4 more in FY04/1&2Q
- · Compare with 8 in FY 91/7 in FY 92
- SSP combined workforce (NASA/USA) at KSC totals 4,400 today
 - Compare with 8,900 in FY 91/8,400 in FY 92
- A professional, high-tech workforce (both white- and blue-collar) is typically not easily expanded to respond to fluctuating requirements

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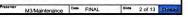


Maintenance Capabilities Analysis

Findings:

- Workload variations driven by numerous factors
 - · Vehicle age, modifications, mission requirements, etc.
- One example: OV-103, currently 8 months into J3 OMM
 - · 28 percent growth over original tile replacement projections
 - · 11.5 percent tile growth over original projected man hours
 - · Potential additional tile growth ranges from 7 to 24 percent - From original 82,522 to 111,892 man hours
- Second example: TPSF ("tile backshop")
 - · Currently supporting OV-103 OMM, OV-104 flow
 - · Test tile production (CAIB support) increasing rqmt by 473%

- Mar - May 03: 128 originally projected, 606 now required





Maintenance Capabilities Analysis

Findings (cont'd):

- Both Orbiter Operations (OPF) and Integrated Logistics (TPSF) are assessing capabilities against requirements
 - · Briefed at 1 May OV-103 OMDP Program Management Review
 - · Presented various options to potential increases in requirements
 - Work employees longer, augment work force with additional manpower, slip delivery schedule
 - For TPSF, additional options included:
 - · Reactivating Palmdale tile shop to produce test tiles
 - · Augmenting KSC with Palmdale technicians
 - · Both capability assessment efforts in a fledgling state
 - Represent efforts to communicate workforce constraints and mitigation options to higher management levels

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M3/Maintenance Date FINAL



Maintenance Capabilities Analysis

Findings (cont'd):

- Ground Operations managers also "plowing new ground" with capability assessments using "equivalent flow" (EF) model

 Based on OPF standard flow of 315,000 man hours

 - Total (OPF/ET/Booster/Integration) of 525,000 man hours
 - OMM baseline being developed using OV-103 700,000 man hours estimated
 - Adjustments made based on OMM/flow content
 - EF capabilities being applied against launch schedule (manifest) to determine shortfalls
 - Original FY 03/04 manifest exceeded EF capability by as much as 64%
 - Managers envision being able to level "peaks" and fill in "vallevs"
 - Managers using EF capabilities to develop mitigation plans
 - Key question: How flexible can/will the launch schedule be?





Maintenance Capabilities Analysis

Findings (cont'd):

- What if the launch schedule is inflexible?
 - Work longer hours, increase workforce size, or adjust milestones internal to the processing flow
- Longer hours bring well-recognized concerns
- · Potential for increased mistakes, injuries, higher costs
- The workforce has been "leaned out" by 50 percent since 91
- While more efficient than ever, surge capability is primarily thru overtime Increasing the size of a professional, high-tech work force is not quick
- Tile technician (OPF): approx 1 year necessary to work independently, longer until fully qualified
- Tile technician (back shop): approx 3-months necessary to work independently, 3-5 years until fully qualified

 Management must have the ability to routinely/accurately forecast
- capabilities, compare against requirements, and have sufficient lead time to take mitigating actions



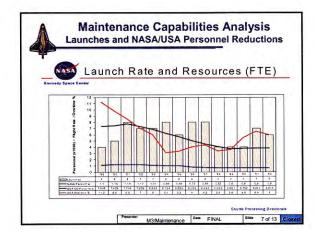


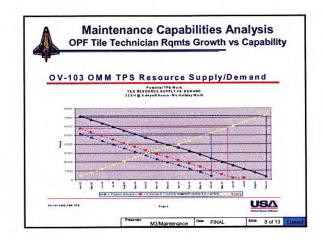
Maintenance Capabilities Analysis

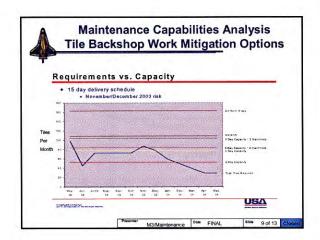
Recommendations:

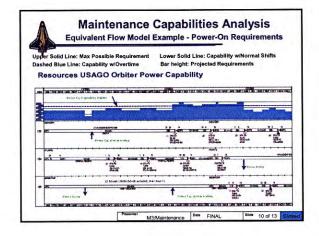
- Ground Operations managers have been developing a complement of tools in recent years to do capability assessment modeling
 - · They should expedite efforts to refine these models (e.g., the equivalent flow model) and use the results to take prope action(s) when requirements exceed capabilities
- Managers need to develop sufficient confidence in capability assessments to use them in manifest and resource planning

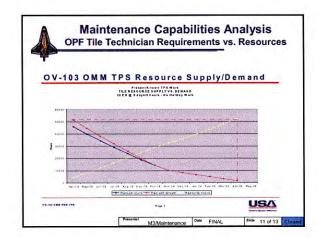
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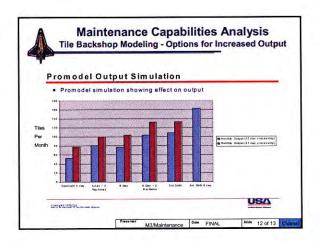


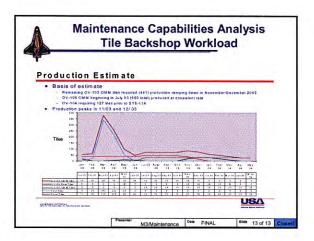












FINAL

Date

CAIB/Group 1

Presenter

Programming for Aging Infrastructure **Loose Carrier Panel Fasteners** 19-1 19-2



Carrier Panels

- Action / Issue: Determine adequacy of maintenance requirements for carrier panel fasteners
- Background / Facts:
 - Upper and lower access/carrier panels closeout the WLE between the RCC panels and the wing front spar
 - OV-102 has 794 total carrier panels including the OMS pods
 - WLE lower carrier panel utilizes a gap filler referred to as a horsecoller.
 - OV-102 left wing lower access panels had 27 horsecollars replaced, 9 HRSI tiles replaced, 9 fills in the gap filler material, 12 HRSI tile repairs and 7 MRs
 - OV-102 left wing upper access panels had 7 HRSI tiles replaced, 7 HRSI tile repairs and 7 MRs

Presenter M3/Material Date FINAL Slide 1 of 11 Gloss

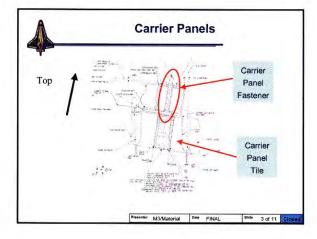


Carrier Panels

· Background / Facts:

- Post-flight inspection after STS-87 (OV-102-24, 1997) revealed a large step in the number 4R lower access panel
 - Reference Boeing Report KLO-98-002, "Mission STS-87 OV-102 Flight 24 Thermal Protection System Post-Flight Assessment", March 1998
 - A 0.4" gap under the head of the bolt was discovered during panel removal
 - · No signs of overheating were noted
 - The remaining fasteners were inspected and low torque values were found but none were unseated (report doesn't provide quantity)
 - · "Bolts were retorqued and the problem was resolved"

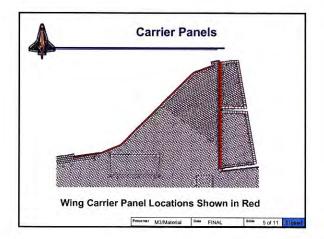
Presenter M3/Material Date FINAL Slide 2 of 11 Close

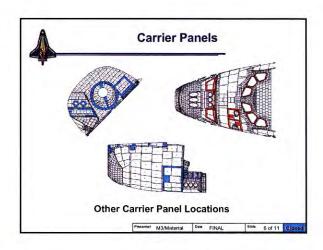


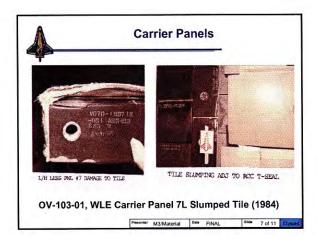


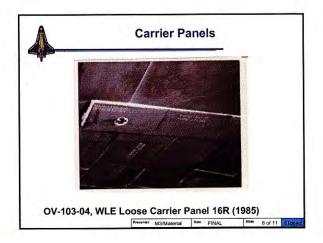
- During OV-103-25, STS-95, 1998 a carrier panel on the OMS pod Y-web door peeled back and structure under the panel was damaged during entry
- Torque check of all the fasteners on OV-103's and OV-105's OMS pod Y-web doors were performed
 - OV-103 had 4 loose washers found spinning under the fastener heads, and 13 out of 44 fasteners with low torque
 - · OV-105 had 7 fasteners found with low torque
- Concluded "no concern for loose TPS carrier panel fasteners"
- Recommended monitoring plan for fastener torque
 - 2 lower LESS carrier panels (1 LH and 1 RH)
 - 2 star tracker carrier panels
 - · 2 OMS pod stringer carrier panels

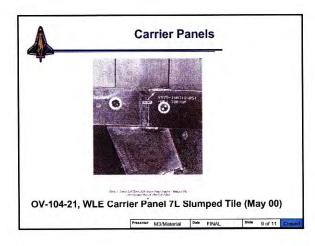
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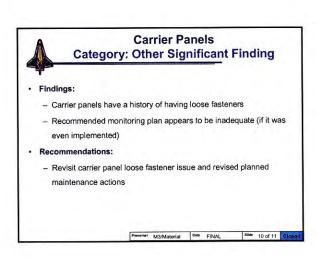


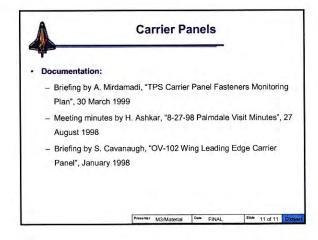














Aging Infrastructure Facilities/Equipment

- Action / Issue: Assess aging infrastructure, to include planning/ programming of sustainment/replacement actions
- Background / Facts:
 - Much of NASA infrastructure (facilities/equipment), was built in the Apollo era ('60s); design life was 10 years
 - Rehabilitated/modified numerous times to remain "launch ready"
 - KSC further challenged by accelerated corrosion due to proximity to ocean; acidic SRM exhaust compounds pad-vicinity problems
 - Primary focus on infrastructure deemed critical to immediate mission; many other systems have received only basic attention (at best) and are well past their projected service life
 - Major budget cuts from 1994 led to NASA strategy to absorb most reductions from infrastructure
 - Facility maintenance strategy WRT SSP abruptly changed from "life support until imminent retirement" (1990s) to "sustain until 2020"

Presenter M3/Maintenance Date FINAL



Aging Infrastructure Facilities/Equipment

- **Findings**
 - Example 1: Launch Pads
 - · Extensive structural corrosion due to SRM propellant/proximity to ocean
 - · Older designs trap corrosive elements despite post-launch washdo
 - Delaminating walls in RSS Payload Changeout Room (temp fixed)
 - · Concrete deterioration problems at pad base & blast deflector area
 - · Railroad boxcars (83 between LC 39A & B) serve as offices/work centers
 - Severely deteriorated, some with evidence of leaking ceilings
 - · Efforts to reverse this deterioration evident in some areas
 - Pad wiring upgrades in Pad Terminal Control Room reflect continuous attention to sustainment; critical to launches
 - Later structural additions reflect designs less prone to trap corrosives
 - Boxcar replacement facilities funded, move-in this year (FY 03)

Presenter M3/Maintenance Date FINAL

Slide 2 of 22



Aging Infrastructure Facilities/Equipment

- Findings:
 - Example 1: Launch Pads Zinc Fallout Issue
 - · Reinforced carbon-carbon (RCC) pinholes initially ID'd in 1992
 - Subsequently found on all orbiters
 - Affects service life of RCC panels
 - Rain sampling (1994) linked pinholes to zinc oxide contamination; exposed inorganic zinc primer on launch pad washing onto RCC
 - · Despite improved corrosion control management and execution since initial discovery, recent rain sampling (July 2003) confirmed problem still exists, though zinc levels were lower in all but one
 - · Illustrates the direct impact infrastructure maintenance can have, not just on immediate shuttle operations, but also on service life

Presenter M3/Maintenance Date FINAL



Aging Infrastructure Facilities/Equipment

- Findings (cont'd):
 - Example 2: Crawler/Transporter
 - Designed/built for the Apollo program (circa 1965); only two in world
 - · Currently have an average of 1,700 miles each
 - · Critical for launches & during hurricane season (to "safe haven" shuttle)
 - · Challenges: age, obsolescence, vanishing vendors, small fleet size, uniqueness, highly corrosive environment/outdoor storage, etc.
 - Despite these challenges, C/Ts are recognized for their critical role and are well supported (e.g., control room upgrades/laser docking)
 - One notable exception: outdoor storage accelerates corrosion and leads to continual weather disruptions (work stoppage for lightning)
 - Managers track resources expended (cost of mods/parts/labor) over time vice per unit of output (e.g., miles driven or operating hours)
 - In certain cases, analysis/trending of support costs based on unit of output can more clearly define cost/benefit tradeoffs

Presenter M3/Maintenance Date FINAL



Aging Infrastructure Facilities/Equipment

- Findings (cont'd):
 - USA in its 3rd yr using a web-based corrosion info/tracking system "CorrPro/Basecoat"); adopted from offshore oil industry

 "Light years" ahead of former paper system...file cabinets w/folders & paper reports...time consuming to prepare, review, & update

 Using CorrPro, engineers annually assess infrastructure, using digital photo documentation, work prioritized based on corrosion severity

 - CorrPro also enables forecasting time/labor/mat'ls for corrective actions
 - Valuable tool in prioritizing rqmts w/add¹¹ "drill downs" (e.g., for launch pads, rqmts categorized by level and further by component); helpful in sizing budget and scheduling work in increments if necessary
 - Ground Systems Working Team (GSWT) assesses/prioritizes infrastructure requirements
 - Considers risks associated with likelihood of failure and consequences
 - Factors in cost savings/avoidance
 - Uses Ground Systems Survivability Assessment (GSSA) database

Presenter M3/Maintenance Date FINAL



Aging Infrastructure Facilities/Equipment

- Findings (cont'd):
 - "The hardest part of our job is getting the funding, the resources, and the operations schedule window to line up"...senior NASA/USA mgrs
 - Effective scheduling of preventive/corrective maintenance of ground support systems essential to maximizing windows of opportunity
 - USA's Ground Systems Support (GSS) established a master planne position in late CY 02
 - Similar position established for horizontal operations in early CY03
 - These two new planners routinely interface w/a vertical operations master planner to better align/deconflict activities
 - · Overtime hours and work time deviations/violations have bee decreasing with this new focus

Another expectation: more infrastructure support will be accomplished based on lining up "windows" more efficiently



Aging Infrastructure Facilities/Equipment

- Findings (cont'd):
 - MSFC/Michoud Assembly Facility (GOCO-govt owned contractor operated)
 - Some facilities date to 1940s; add-ons for Apollo (60s) and SSP (70s)
 - Advantages (over KSC): smaller operation, more single-mission focused fewer "balls to juggle", much less corrosive environment
 - Kudo: 15-yr Strategic Plan prioritizes rqmts in "big picture" context
 - Developed in 97; ongoing updates; disciplined, systematic approach
 - Also have a comprehensive 15-yr Equipment Strategic Plan

 - CoF funding increased by 371% (97 vs 03), \$7.9M to \$37.2M
 - Repair of 43-acre roof on Main Mfg Bldg in 2nd/final yr of funding
 - 1940s-vintage 480V electrical system upgraded 4 1-yr segments
 - Despite being challenged by old infrastructure, MAF's approach has typically secured needed funding

Presenter M3/Maintenance Date FINAL



Aging Infrastructure Facilities/Equipment

- Findings (cont'd):
 - Stennis Space Center (SSC)
 - Built as part of Apollo ramp-up (mid-60s)
 - · Primary mission: liquid fueled rocket engine testing Every shuttle engine tested after mod/overhaul
 - Three test stands "national assets" A1, A2, B1/2
 - Only A1 capable of testing gimbaling
 - A1 to be mothballed in FY 03 (infrastructure reduction)
 - Remaining test stands deemed adequate
 - Known romts do not include gimbal testing
 - Palmdale facilities (aka Plant 42) leased from AF
 - · Facilities/equipment generally in good condition due to environment
 - Degradation (primarily equipment) due primarily to decreased activity/use

Presenter M3/Maintenance Date FINAL



Aging Infrastructure Facilities/Equipment

- Findings (cont'd):
 - The NASA "big picture"
 - >2,600 bldgs, >2,600 other major structures, avg age nearing 40 yrs
 - \$21.9B Current Replacement Value (CRV); avg NASA CRV 40% > DoD
 - Reflects unique nature/small # of facilities (e.g., VAB, launch pads)
 - NASA-wide infrastructure assessment conducted in FY 02
 - Backlog of Maintenance and Repair (BMAR) not consistent/ auditable, subject to "spin", difficult to roll up
 - New uniform "yardstick" via Deferred Maintenance (DM)
 - · >\$2B DM NASA-wide
 - 100%>BMAR estimate, which did not consider all facilities
 - 10% of NASA CRV; industry rule of thumb: 2-4% annual funding
 - NASA playing catch up based on years of underfunding
 - Uniqueness/small #s of facilities also drive a "must fix" approach
 - Code JX working to apply DM database to planning/programming

Presenter M3/Maintenance Date FINAL

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Aging Infrastructure Facilities/Equipment

- Findings (cont'd):
 - The "big picture" continued
 - · A second uniform "yardstick": Facility Condition Index (FCI)
 - 5-pt scale: 5 is excellent, 1 is bad
 - Average ratings based on FY 02 NASA-wide assessment:
 - Code M: 3.5 JSC: 3.6 MSFC: 3.9 SSC: 3.1 - NASA: 3.6
 - KSC: 3.3 - KSC rating reflects large number of assets (>60%) dedicated to SSP
 - SSC rating skewed by high \$ value/condition of test stands relative to overall center value; stands are 37% of SSC CRV w/FCI of 2.2; w/o stands, SSC is 3.6
 - Assessments "peel back" to individual areas: structure/roof/exterior/
 - interior/electric/HVAC/plumbing/equipment
 - NASA goal: improve average to 4.2 by FY 09; requires \$312M/yr

Presenter M3/Maintenance Date FINAL





Aging Infrastructure Facilities/Equipment

- Findings (cont'd):
 - NASA "big picture" continued
 - Code JX has adopted DoD's Facility Sustainment Model (FSM)
 Refining model for NASA use

 - FSM requires \$333M annual facility maintenance funding to arrest deterioration
 FY02: \$224M (67% of actual)
 FY 95: \$273M (82% of planned)

 - Facility Revitalization Rate (FRR) measures how often a facility will be replaced/revitalized based on investment funding
 OSD FRR target is 67 yrs; industry standard is 55 yrs; current NASA FRR > 100 yrs (down from 200+ yrs)
 Estimated cost for NASA to reach 67 yrs: \$302Myr
 Improvement also possible by reducing infrastructure
 GAO (1996): NASA problems identifying, assessing, implementing
 - infrastructure cost reduction opportunities
 - NASA addressing this via DM/FCI assessments & tools such as FSM/FRR

Presenter M3/Maintenance Date FINAL



Aging Infrastructure Facilities/Equipment

- Findings (cont'd):
 - NASA road ahead
 - · Identify/dispose of excess infrastructure
 - Make better use of under-utilized facilities through consolidations

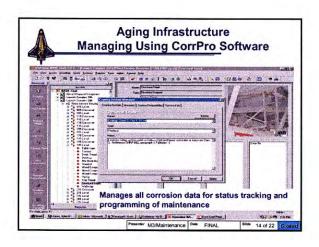
 - Sustain remaining infrastructure by:
 Reducing backlog of maintenance and repair
 - Bringing revitalization rate down from 100+ yrs
 Advocating for "repair by replacement" where smart
- Successfully advocating/securing funding to support all of above Conclusions / Recommendations:
 - Strategic level assessment/planning by Code JX on the right track
 - Provides a structured approach to assess and prioritize requirements

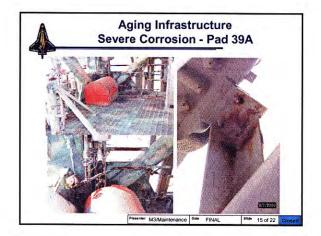
 - Based on recognition that past assessments have not presented an accurate picture nor a NASA-wide requirements prioritization 15-yr Strategic Plans at MAF are worthy of benchmarking across NASA Allow a long range view (beyond 5-yr POP) for proper prioritization of both facilities and equipment

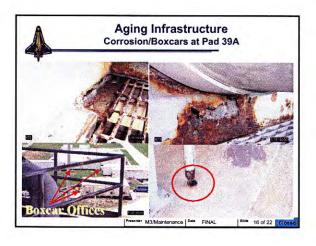
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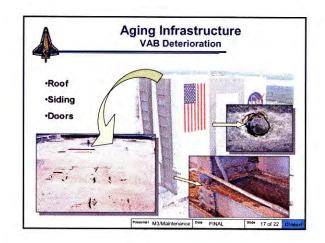
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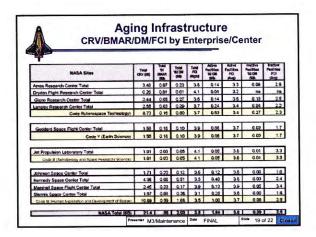


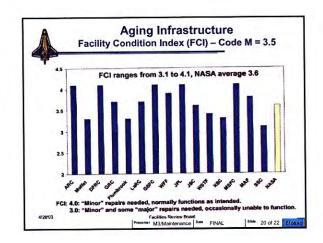


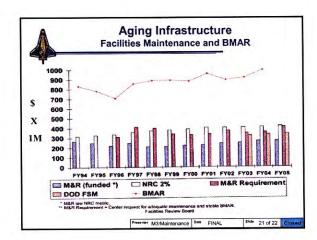


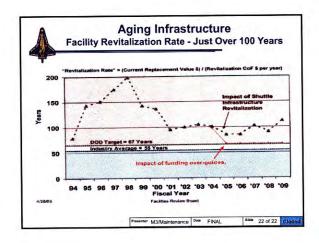












Other Maintenance

Engineering Orders

20-1

Date CAIB/Group 1

23 of 32

Slide

FINAL

Presenter

Matrix



Maintenance **Engineering Orders**

- Action/Issue: Backlog of unincorporated Engineering Orders (UEO) is significant and may impact the quality and timeliness of maintenance
- Background:
 - Last 5 ASAP reports document a large and growing number of UEOs (over 1600 with > 10 changes ea; now 1400 with removed from schedule)
 - NNBE referenced using Navy's zero level as a baseline

· Facts:

- Observed examples of UEOs in shop and OPF
 - Observed the impact and difficulties of navigating EO with multiple unincorporated changes and potential for human error
 - NASA built a noteworthy plan to incorporate the most important changes to drawings for orbiter on basis of highest use and complexity (2002-2004)
- Recommendations:
 - Draft a plan to finish incorporating the >10 UEOs

Presenter M3/Maintenance Date FINAL



Maintenance **Engineering Orders**

Aerospace Safety Advisory Panel, 2002... report excerpt:

Aerospace Safety Advisory Panel, 2002...report excerpt:

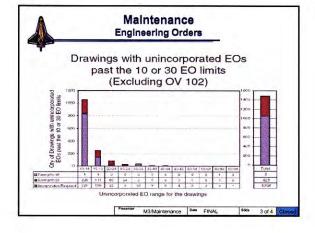
"Previously, the Panel has been concerned with the large number of orbiter drawings that are out of date. Many EO changes have not been incorporated into the drawings. Although they are noted on the drawings, engineers must refer to additional paperwork to understand the state of the hardware systems. Over 1,600 drawings have more than 10 unincorporated EOs. The orbiter program will update and incorporate all EOs on 59 of the most frequently used drawings by the end of 2003. Also during the year, an effort to address the 589 drawings referenced most frequently after those 59 will begin. The remaining drawings will be updated as opportunity permits. Orbiter program management has committed to maintaining the upgraded drawings at no more than 10 unincorporated EOs. The orbiter program is now reviewing the possibility of identifying the safety-critical drawings that should always be kept current.

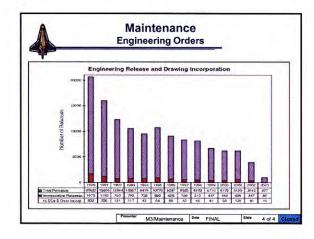
Recommendation 02-8:

Recommendation 02-8:

Identify drawings that are critical to flight safety, update them to include all EOs, and keep them current."

Presenter M3/Maintenance Date FINAL





FINAL

Date

CAIB/Group 1

Presenter

Launch – Ascent Other



Day of Launch Assets, Hardware Security, and Scenarios 21-1

SRB Bolt Catchers

Separation Bolt Certification 21-2 21-3 21-4 21-5

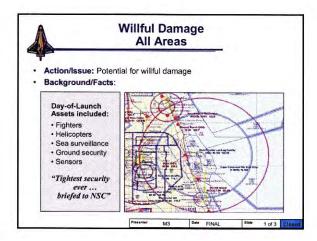
RSRM Flex Boot Tear

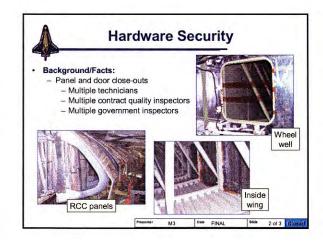
STS-107 Impact Analysis

STS-107 Ascent Debris (Radar & Imaging) 21-6

Hold-Down Cable Anomaly

21-7







Presenter M3

Date FINAL



Maintenance **Bolt Catcher**

- Action / Issue: Did a malfunction of the SRB forward Bolt Catcher contribute to the accident chain of events?
- Background / Facts:
 - Function: Catch fired separation bolts attaching SRBs to ET
 - · Upper catcher attached to ET, lower attached to SRB, different design
 - · Good example of SIAT (99) documented concern with "fly what you test, test what you fly"
 - SUMMA and Harris manufacture, subKtr, USA serial #
 - · Pulled from supply to install on ET, coated with (SLA) ablative which requires # removal-- MAF assigns new serial #
 - · Serial # discrepancy between USA and MAF serial #s on STS -- 107

Presenter M3/Maintenance Date FINAL



Maintenance **Bolt Catcher**

- Background/Facts:
 - Bolt Catcher never qualified as flown...79/80 tests
 - · Attachment to ET qualified with through-bolts (vice inserts)
 - SLA 561 not applied on test articles
 - · Reduced resistance aluminum honeycomb not tested
 - System changes certified by "analysis and similarity"
 - In-flight photograph of STS 107 Bolt Catcher black and unusable
 - Radar images at 126 seconds point originally considered normal
- Findings:
 - Tests run 27 May 8 July of representative articles to evaluate/determine as-flown environment and safety margin

 - Test profiles designed to verify engineering profile of system performance as certified including as-flown configuration

 18 tests completed ...4 bolts fired into instrumented catcher, seven stress tests of catcher to failure





Maintenance **Bolt Catcher**

- Dynamic test #2 measured 46KIPs in Summa serial #50 dome
- Stress test #3 of catcher failed at weld at 44KIPs...engineering analysis expected bolt failure at 68,000lb
 - · Same failure point as 1979 certification test
 - · Implies 0.956 safety margin
 - · Additional tests requested
- X-Ray film of #50 showed poor quality film and strong evidence of substandard welding...would not have been certified today
- STS-107. Summa catcher #1 installed on left SRB/ET
 - · X-Ray film failed in quality as well as substandard weld



Maintenance **Bolt Catcher**

Findings

- STS-107 launch radar data comparison with bolt catcher radar cross section (RCS) complete
 - Event #33 at 128 second similar in size to bolt catcher RCS
 - Lack of photographic evidence means event #33 cannot be ruled out as a possible bolt catcher or fragment.

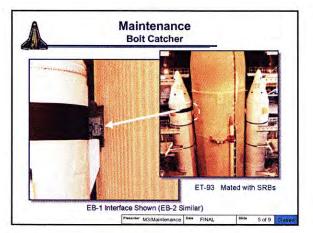
Group Recommendations

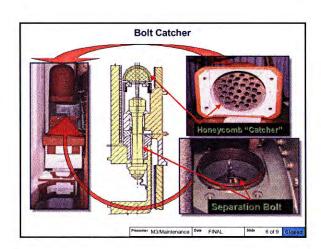
- Certification by "analysis and similarity" flawed...how many other bolt catchers on SSP?
- Remove all Bolt Catchers from service
- Redesign system to assure 1.4 safety margin at a minimum

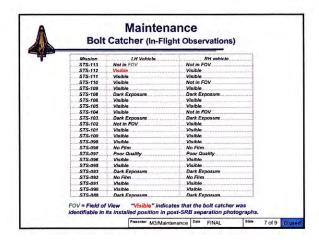
Presenter M3/Maintenance Date FINAL

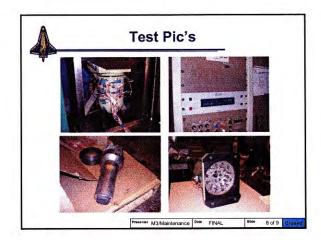
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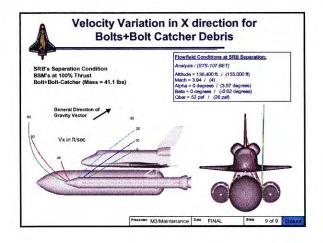














Maintenance **Separation Bolt Certification**

- Action / Issue: Separation bolts manufactured by Pacific-Scientific were not adequately NDI'd before flight on STS 107
- Background / Facts:
 - USA replaced Hi-Shear as the prime contractor for separation bolts in May 2000. Certification of new bolts may have been done without adequate NDI (magnetic particle) of the internal bore
- Findings:
 - P-S used Pacific Magnetic and Penetrant for NDI verification
 PS/PMP used same NDI specifications as Hi-Shear

 - First lot (Lot AAN) used on STS 107 and installed on STS 114 All NDI results were approved and certified by PS, USA, and DCMA

 - 2nd lot (AAP) magnetic particle inspection eval'ed by DCMA NDI expert
 Determined process inadequate WRT analysis of Magnetic Part. Insp.
 - . ASTM E 1444-01, par. 5.7.3 stipulates use of a borescope

Presenter M3/Maintenance Date FINAL

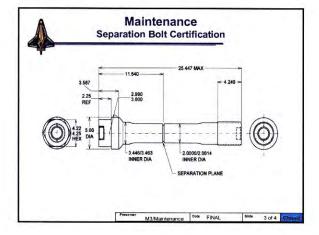


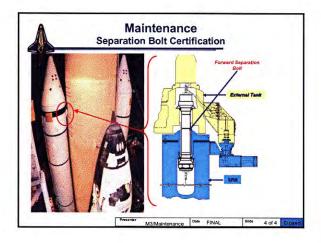
Maintenance Separation Bolt Certification

- Findings (con't):
 - USA had verbally authorized PMP to deviate from the purchase order specification since borescope was not available
 USA and DCMA NDI experts disagree over test sufficiency

 - USA built a Defect Standard Bolt with known flaws to evaluate
 - "Initial assessment of PMP's inspection procedure by USA NDE confirms procedure meets engineering requirement imposed but could be improved"...USA briefing to CAIB
 - USA impounded existing supply of 1st lot: dedicated to test only
 - This situation is not a contributor to the STS-107 mishap
- Recommendations:
 - Use more stringent inspection criteria IAW ASTM E 1444, par.
 5.7.3, Restricted Area Examination with borescope or new method that can adequately identify flaws in the ID

M3/Maintenance Date FINAL









Ascent Debris Strike Other

- Action / Issue: 57-inch tear in the flex boot on the right RSRM adjacent to the inner boot ring—first time observation
- Background / Facts:

 - Flex boot is key to allowing reuse of the RSRM
 Separation did not result in violation of flex boot thermal protection—not sure of the cause—might have been water impact
- Findings:
 - None at this time
- · Group Recommendations:
 - Issue closed per RSRM Fault Tree closeout on 9 Apr 03

Presenter M3/Material Date FINAL



Ascent Impact Analysis (includes Crater)

- Action / Issue:
 - The impact damage analysis process did not accurately predict the damage sustained by OV-102 during the ascent of STS-107
- Background / Facts (Impact Analysis Process):

 - Crater is a tool <u>used in</u> impact analysis "Impact Analysis" includes Crater, thermal, & stress analyses
 - For STS-107, the impact analysis was performed using the image analysis team's assessment of debris size and location

 - Crater program predicted severe damage to several tiles
 Thermal and stress analyses predicted localized heating but safe return of orbiter
 - Boeing's Debris Assessment Team recently experienced a transition from Huntington Beach to Houston

Presenter M3/Material Date FINAL Slide 1 of 17



Ascent Impact Analysis (includes Crater)

- Background / Facts (Crater):

 Crater is a semi-empirical/semi-theoretical set of equations that Crater is a semi-empirical/semi-theoretical set of equations that results in a tile damage prediction for LI-900 titles
 Crater is only model used by NASA to predict impact damage to titles
 Crater is conservative and predicts worst case damage
 Crater originally designed for "in family" (small < 3 in³) hits
 Crater is appropriately named, accounts for only for cratering (no other damage mechanisms considered)
 Never intended to be used for large projectiles (STS-107 analysis)
 Extrapolation to higher energy debris never validated through testing
 Crater predicted severe damage to several titles for STS-107
 Crater's capabilities are limited by test data used to verify the model

 - Most probable cause of Columbia accident has been identified as
 - impact damage to RCC panels
 - · Revised photo analysis
 - · Analysis of onboard instrumentation
 - Forensics

Presenter M3/Material Date FINAL Slide 2 of 17



Ascent Impact Analysis (includes Crater)

- Findings (Impact Analysis Process):
 - Basic types of analyses performed at Boeing-Huntington Beach (pre-transition) and Boeing-Houston (for STS-107) appear to have been
 - Boeing-HB and Boeing Houston differ in their assessment of the effectiveness of the training program
 - One key engineering analyst, as reported by HB had only several hours of training on Crater but not by the HB personnel

 - Boeing-Houston team believes training quality & quantity sufficient

 Boeing Houston team states OJT occurred in Houston, independent
 of HB training to understand:

 - » Supporting documentation
 - » Crater equation development
 » V* threshold development
 - Sensitivity studies reported to have been conducted prior to STS-107 final analysis release

Presenter M3/Material Date FINAL Slide 3 of 17



Ascent Impact Analysis

(includes Crater)

- Findings (Impact Analysis Process):
 - Impact analysis uses an iterative, multidisciplinary (transport, impact, Crater, thermal, stress) team-based process
 - · STS-107 analysis appears to have been done in the same manner however, without enough feedback between analysis components
 - Thermal analysis may have had minor errors due to communications issues with the Crater analysis hand-off

Slide 4 of 17 Presenter M3/Material Date FINAL



Ascent Impact Analysis (includes Crater)

- Findings (Impact Analysis Process):
 - Photo analysis during the mission identified the most probable location of foam impact on wing acreage tile, not RCC

 Also indicated no debris over top of wing – impact below WLE apex
 - The Orbiter RCC design requirements did not include debris
 - impact tolerance
 - pact tolerance
 Some impact testing was performed, but was limited to small projectiles that
 resulted in localized "cratering" or penetration

 Mostly ice tests, no foam tests
 No impacts of the size and mass that occurred on STS-107 were previously
 predicted, analyzed, or tested.
 - The tools and models available to the analysis team during the
 - flight did not account for the bending failure mode that is currently believed to be the failure cause on STS-107. Data from preliminary detailed analyses and initial fiberglass impact test support this failure mode

Presenter M3/Material Date FINAL



Ascent Impact Analysis (includes Crater)

- Findings (Crater):
 - Crater's use on STS-107 was far outside it's verified limits of applicability
 - Crater limitations:
 - · Only for LI-900 tiles
 - Does not account for special geometry present on some tiles
 - · Valid for ascent impact velocities only
 - Hypervelocity impacts not part of this methodology
 - · Valid for a limited set of impactor materials
 - Impactor shapes limited to cylinder, rectangular block, or sphere For rectangular block impactors, predicts damage for only
 - · Does not include effects of crossing tile boundaries in large impacts
 - Need to define more stringent limits to Crater's useage when tile depth reaches a defined % of total tile thickness

Presenter M3/Material Date FINAL



Ascent Impact Analysis (includes Crater)

- Findings (Crater):
 - Crater works well within its established limits
 - In the experimental space in which Crater was developed (foam projectiles up to 3 in³), it provides a reasonable solution
 - Extrapolating beyond the limits of Crater may be performed with:
 - · Interpretation based on experience
 - . An understanding that the accuracy of predictions will be reduced
 - Crater does not capture "non-cratering" effects on tile or substructural response
 - Crater is not a "turn-key" code
 - Effective use of Crater assumes users have knowledge of model's development and experience in interpreting results
 - Crater has been underutilized in developing acceptable debris/ice criteria for "In Family" hits

Presenter M3/Material Date FINAL Slide 7 of 17



Ascent Impact Analysis (includes Crater)

- Findings (Crater):
 - For STS-107, the Crater model predicted severe damage to
 - Crater results were interpreted using potentially un-conservative assumptions based upon inherent conservatism of model
 - · Extent of tile damage assumed to stop at tile's densified layer

Presenter M3/Material Date FINAL side 8 of 17



Ascent Impact Analysis (includes Crater)

- Recommendations (Impact Analysis Process):
 - Boeing should not view the process for knowledge capture as "complete," despite the completion of the transition period
 - · They should build on previous efforts to develop a systematic and comprehensive training process to ensure ongoing proficiency in
 - Boeing/NASA should conduct an in-depth training curriculum for Boeing-Houston to assure proper understanding and interpretation of impact damage analysis models and procedures
 - Free & open communication between Boeing-Houston and Boeing-HB should be encouraged and financially supported until it is agreed that a full and proper transition is complete

Presenter M3/Material Date FINAL Stide 9 of 17



Ascent Impact Analysis (includes Crater)

- Recommendations (Impact Analysis Process):
 - Boeing, under NASA supervision, should review training matrices for transitioned personnel to verify individuals meet established requirements
 - Upon completing the review, action plans should be developed to remediate those not meeting set job criteria.
 - Boeing should risk manage the remediation process, not only on a group/technology area level, but also on an individual employee
 - » Particular attention should be given to new hires with low shuttle experience and areas with several inexperienced personnel.
 - Boeing should employ HB incumbents to remediate new/transitioned personnel failing to meet established job criteria
 - » Affected employee's time should be dedicated to the programmed remediation

Presenter M3/Material Date FINAL



Ascent Impact Analysis (includes Crater)

- Recommendations (Impact Analysis Process):
 - Boeing should facilitate team building within their Houston-based Debris Assessment Team to achieve a greater degree of cohesion and more effective (i.e., "closed-loop") communication flows.
 - This could be accomplished through close monitoring by SSMs, holding regular staff meetings, group training sessions, and routine feedback sessions.
 - · The desired outcomes of such efforts would be improved overall decision-making practices and calculation usage methodology. Upon completing the review, action plans should be developed to remediate those not meeting set job criteria.
 - When a decision is to be made by upper management, the engineering solutions given to management should include a quantifiable uncertainty analysis and risk analysis.

Presenter M3/Material Date FINAL Slide 11 of 17

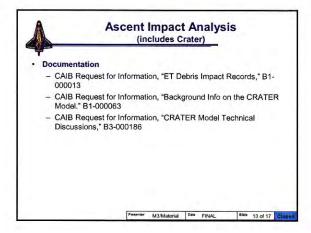


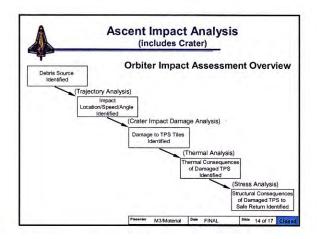
Ascent Impact Analysis (includes Crater)

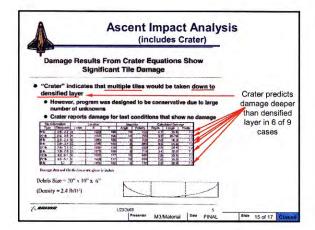
- Recommendations (Crater):
 - NASA/USA/Boeing should continue to develop a more robust, physics-based model to analyze impact damage to tile and RCC
 - · Development should take advantage of expertise from all
 - Boeing should work to develop a user's manual for thermal and stress analysis associated with impacts
 - Boeing should continue to encourage communication between Houston and Huntington Beach technical communities in the future

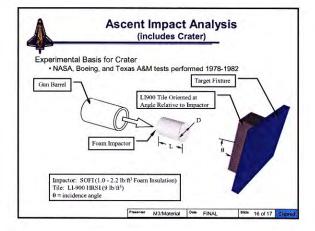
M3/Material Date FINAL

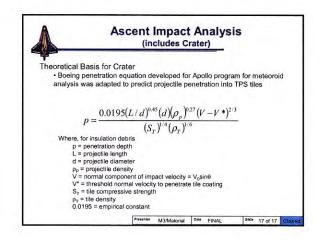
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Ascent Debris

- Action / Issue: Review radar and optics results for evidence of debris during ascent
- · Background / Facts:
 - STS-107 was tracked during ascent by Eastern Range land-based
 C-band radar and metric optics
 - Data was examined to identify any previously undetected debris
 - No radars detected debris prior to SRB separation
 - Only the Cocoa Beach Distant Object Attitude Measurement System (CB DOAMS) optical telescope observed debris around 81 seconds
 - 81.66 sec: single object between Orbiter nose cone and ET 1st detected, appeared white
 - 81.82 sec: struck under Orbiter's left wing, disintegrates into a cloud of orange-colored debris

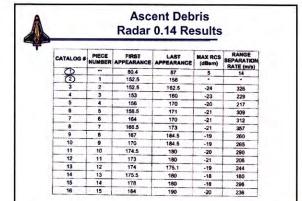
Presenter M3/Material Date FINAL Slide 1 of 7



Ascent Debris

- · Background / Facts:
 - Debris detected by radar following SRB separation from T+150 to T+230 seconds
 - · One radar (radar 0.14) detected 21 items
 - · Another radar (radar 28.14) detected 6 items
 - Radar Cross-Section (RCS) ranged from –26 to –15 dBsm
 - Radar return signal was not of sufficient strength to determine approximate shape, size or rigidity of the debris
 - Radar analysis results are consistent with the debris analyses from previous STS missions

Presenter M3/Material Date FINAL Slide 2 of 7 Classid





Ascent Debris Radar 0.14 Results (Continued)

CATALOG #	PIECE NUMBER	FIRST APPEARANCE	LAST APPEARANCE	MAX RCS (dBsm)	RANGE SEPARATION RATE (m/s)
17	16	187	192.5	-20	649
18	17	204.5	210	•	
19	18	204.5	214	-26	326
20	19	204.5	212	-24	166
21	20	206	212	-24	225
22	21	211.5	228	-22	219

The RCS and range separation rate of these pieces cannot be determined due the low level of signal returns. RCS is estimated to be within 0 to 3 dB of the Minimum Detectable RCS.

ents have been determined to be due to plume effects.

Presenter M3/Material Date FINAL Slide 4 of 7 Closes



Ascent Debris Radar 28.14 Results

CATALOG #	PIECE NUMBER	FIRST APPEARANCE	LAST APPEARANCE	MAX RCS (dBsm)	RANGE SEPARATION RATE (m/s)
23	2	152	158.5		•
24	4	154.5	162	-17	400
25	8 or 9	167	176.5	-20	221
26	14	179	187.5	-15	884
27	16	201	207	•	
28	17 or 18	205	208.5	•	

* The RCS and range separation rate of these pieces cannot be determined due to the low level of signal returns. RCS is estimated to be within 0 to 3 dB of the Minimum Detectable RCS.

Presenter M3/Material Date FINAL Slide 5 of 7

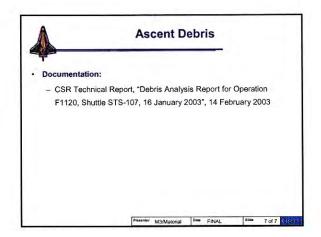


Ascent Debris

- · Findings:
 - Radar detected debris after T=150 seconds
 - · Debris could not be identified
 - · Radar returns similar to past STS missions
 - CB DOAMS observed debris between orbiter and ET at 81.66 seconds
- · Recommendations:
 - Issue should be closed

Presenter M3/Material Date FINAL Slide 6 of 7 Class







Maintenance **Hold Down Cable Anomaly**

- Action / Issue: Could orbiter MECs/cabling failure to the hold down post (HDP) pyrotechnics and ET vent arm system (ETVAS) be catastrophic?
- Background / Facts:
 - PIA #3007 stated that STS 112 had a failure in the system that controls firing of the initiators in each SRB restraint nut
 - Redundancy in each Master Events Controller (MEC)
 - MEC#1 feeds A system, MEC#2 feeds B system
 - Each nut has two initiators, one on A system, one on B
 - Signal sent by MECs to nut to fire and ETVAS to retract
 - Either MEC will operate system in event of failure in the other
 - During STS-112 the Ground Launch Sequencer (GLS) issued "Cut Off" at T+ 3 Seconds
 - Post launch review indicated that system A HDP and ETVAS
 Pyrotechnic Initiator Controllers (PICs) did not discharge

M3/Maintenance Date FINAL



Maintenance **Hold Down Cable Anomaly**

Findings:

- Pyro systems A and B are independent and redundant
- The HDP and ETVAS systems receive Fire commands at T-0 Fire 1 and Fire 2 commands are sent as a nearly simultaneous event
- Each redundant pyro device is initiated by a dedicated PIC

 16 separate PICs for "A" and "B" HDP devices and four separate PICs for "A" and "B" ETVAS devices

 The PIC design requires 3 separate commands to detonate its NASA Standard Initiator (NSI)

- ARM—Activates the PIC's power supply and charges capacitor bank
 Fire1—Activates a switching transistor controlling the PIC output return and enables the Fire2

- Fire2—Activates a switching transistor controlling the PIC output ETVAS pyro Fire commands are branched from the HDP Fire commands
- HDP "A" PIC and ETVAS "A" PIC failed to discharge

M3/Maintenance Date FINAL



Maintenance **Hold Down Cable Anomaly**

Findings:

- Extensive analysis and study was initiated immediately
- Approx. 25 different potential fault chains were considered as source of A system failure
- Definite cause never determined, considered intermittent
- Most probable cause: the fire 1 command wasn't transmitted properly from MEC 1 to PIC Rack 6743 in the MLP
- Focus of command path anomaly is on T-0 electrical interface
 - Not cleared during investigation since normal function (T-0 separation) destroyed evidence
- Inspection has detected wear and contamination at interface

M3/Maintenance Date FINAL



Maintenance **Hold Down Cable Anomaly**

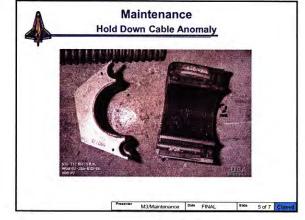
Findings:

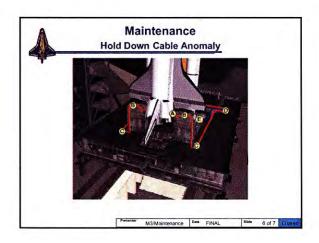
- STS-112 investigation recommendations implemented:
 - All T-0 Ground Cables have been replaced after every flight
 - · T-0 interface to PIC rack cable in redesign, ETIC July 03
 - Old T-0 Ground cable and this Kapton
 - · All Orbiter T-0 Connector Savers have been replaced - Pyro connectors prescreened with pin retention test
 - · Connector saver mate will be verified using Videoscope

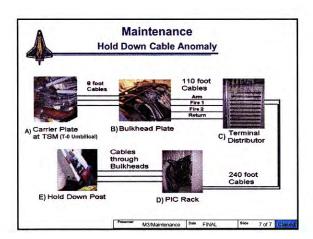
Recommendations:

- Inquiry released for failure potential on this CRIT IR system
- Specifically, what is chance of a concurrent failure of a MEC/cable and one or more initiators? What would result? Can NASA redesign system to add cable from each system to every initiator so a signal system failure would not disable half of the initiators?

M3/Maintenance Date FINAL





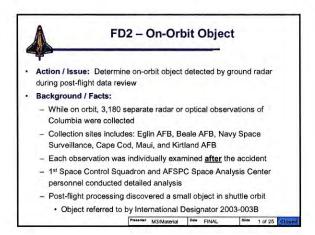


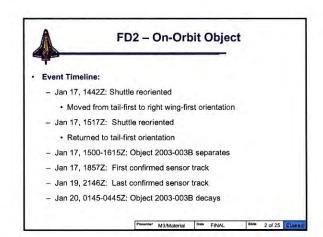
22-1 FD2 On-Orbit Object

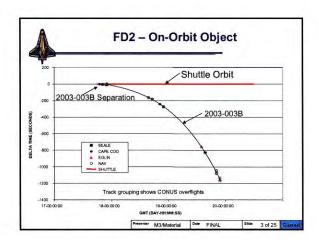
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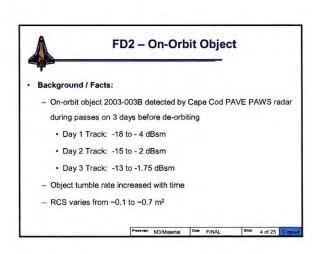
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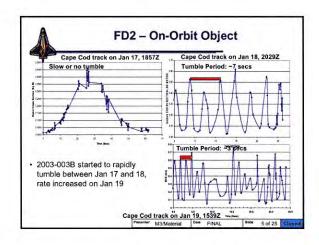
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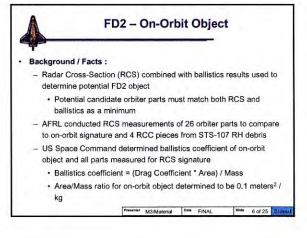


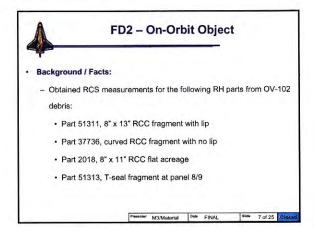


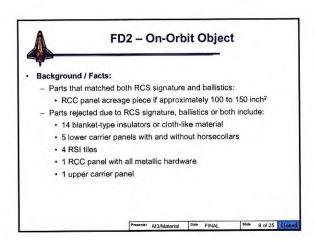


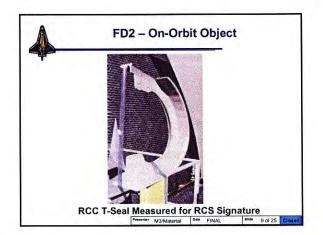


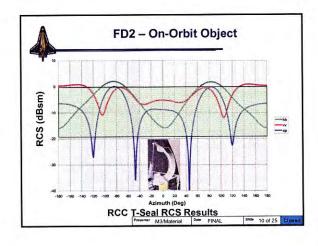


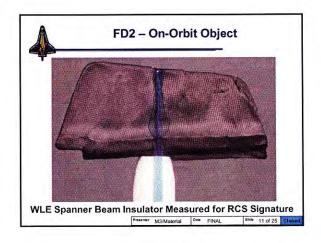


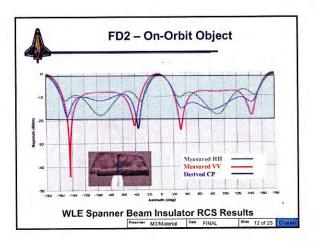


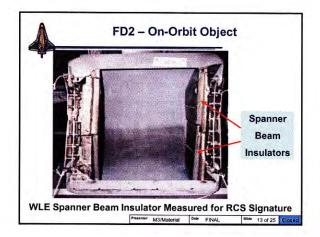


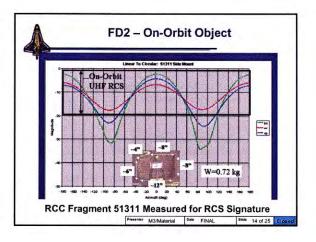


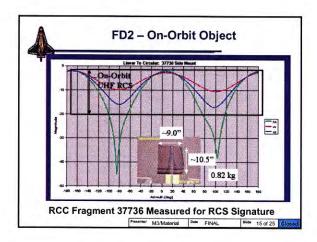


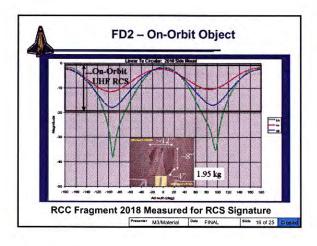


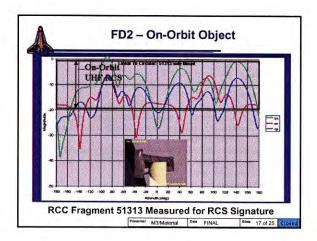


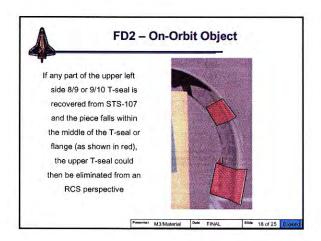


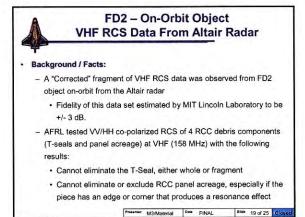


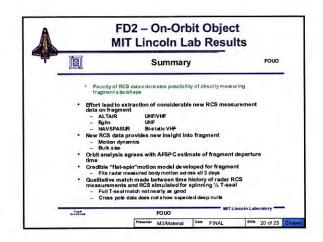


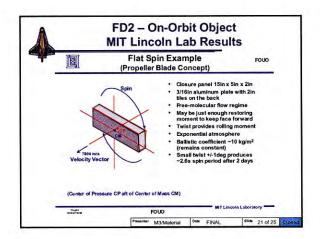


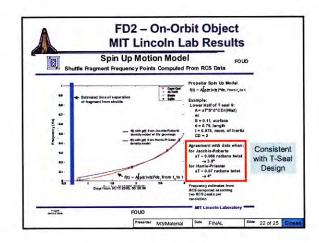


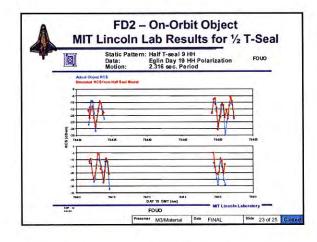


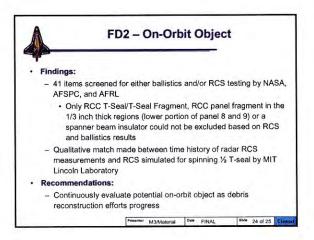




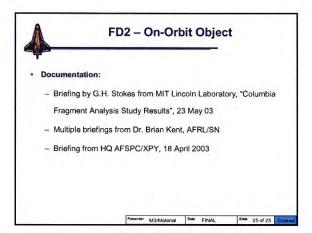












FINAL

Date

CAIB/Group 1

Presenter

SSP Centralization/Decentralization Contract Management Culture CoFR Process Integrity 23-5 23-1





Production-Organization Centralization/Decentralization in SSP

- Action / Issue: Organizational Characteristics, Policies, & Practices
- Background / Facts:
 - Centralized and formal communications, decision-making, and risk management to cope with "tight coupling" linked to the numerous events associated with "normal operations" to provide for immediate responses (e.g., FRR, COFR, etc.).
 - Decentralized and more informal communications, decision-making, and risk management to provide for deliberate analysis to handle unplanned "interactive complexity" of failures by those closest to subsystems (e.g., MMT, MER, etc.).
 - Scheduling demands, workload, staffing shortages/inexperience, performance incentives, etc. increase the opportunity for tighter coupling and additional interactive complexity for both normal and emergency operations.

Presenter M3/Human Factors Date FINAL

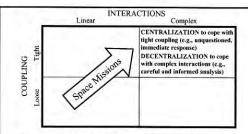


Production-Organization Centralization/Decentralization in SSP

- Findings: Demands associated with centralized and decentralized processes are incompatible, while the former presses for inputs to address scheduled events, the latter presses for time to thoroughly make assessments. Centralization leads to more prescribed meetings. documentation, etc., whereas decentralization tends to be more informal and have varied patterns of interactions, level of documentation, etc.
- Recommendations: SSP should be viewed as a flight test environment, therefore the post-launch management should be more formal and systematic, similar to that for the Pre-Launch COFR

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Stide 2 of 4



"For the interactively complex and tightly coupled system the demands are inconsistent. Because of the complexity, they are best decentralized; because of tight coupling, they are best centralized. While some mix might be possible, and is sometimes tried, this appears to be difficult for systems that are reasonably complex and tightly coupled, and impossible for those that are highly complex and tightly coupled. We saw the space missions move from a highly centralized mode in the first missions to a more decentralized one in the moon shots, and the somewhat less complex and tightly coupled space shuttle may allow for more decentralization. But I predict that the tensions between the two modes will remain, and consume a good deal of organizational energy." "For the interactively complex and tightly coupled system the demands are inconsistent

(Source: Perrow Normal Accidents

Centralization/Decentralization in SSP: Pre- vs. Post- Launch Comparison

- Pre-Launch:
 - Centralized Decision Making w/Defined CoC Roles/Actions
 - Formalized Mission Planning, Problem Resolution, & SOF Determination
 - Theme:
- "Prove There Is Not A SOF Problem"
- NASA Space Centers Visibly Interacting
- Interactive Complexity Due To Geographic Dislocation & Component Integration Process
- Tight Coupling Due to Mission Schedule & Stovepipe Communication of the CRIT 1 Hazards & Lack of Redundant Systems Schedule & Stovepipe Operations:
- Post-Launch:
 - Centralized Decision Making w/Delegated Responsibilities
 - Less Formal Mission Monitoring, Anomaly Review, & SOF Determination

Theme:

"Prove There Is A SOF Problem"

- JSC Primary w/Minimal Outside Center Input
- Greater Interactive Complexity Due To Orbiter Technologies & Space Environment
- Increased Tight Coupling Due to Real-time OPS & Little On-Orbit Flexibility; # CRIT 1 Hazards & Lack of Redundant Systems



Organization-Production: SSP Contracting Culture

- Action / Issue: Evolution of NASA SSP culture from engineering to one dominated by contract management
- Background / Facts: Transition to SFOC & Primary Contractors has altered the balance of SSP engineering efforts from NASA to contractors
- Findings:
 - SSP engineering personnel shortages have led to reduced oversight of contractor activities, and increased use of "insight" within them.
 - Planned SLEP extension and an aging shuttle require added attention
 - to analyze operational stress effects, identify new hazards, etc. Potential exits for reduced engineering awareness to identify problem areas as well as engineering capability to effectively address them.
 - NASA SSP engineering and scientific oversight is necessary to ensure aging aircraft issues are monitored, studied, and acted on.

M3/Human Factors Date FINAL



Automation-Contracting Analogy

- Reasons for Implementation of Automation in Aircraft
 - Reduce Pilot Workload to Cope w/Advanced
 - Technology
 Shift Pilot Primary Focus to
 Mission vs. A/C Operation
 Decrease Potential for Pilot
- Declares Published of Finds
 Errors
 Actual Outcomes
 Shift from Psychomotor to
 Primarily Cognitive Workload
 Causes Similar Errors;
 Generated New Types
- Reasons for Instituting SFOC & Other Contracts Reduce NASA SSP
 - Neduce NASA SSP Workload to Cope w/Budget Constraints Shift SSP Primary Focus to Operations vs. R & D effort Increase Efficiency; Maintain Safety
- Increase Efficiency; Maintain Safety
 Actual Outcomes
 Shift from Engineer Oversight to Contract Manager Insight
 Some Efficiencies; May have Impacted Safety

Factors Date FINAL



Automation-Contracting Analogy

- - Increased Systems Monitoring
 - Automation
 - Complacency - Loss/Erosion of
 - Situational Awareness - Selective Signal Display Filtering
 - Eroded Pilot Skills
- Effects of Automation
 Effects of Contracting
 - Increased Contract Monitoring
 - Contract Complacency
 - Loss/Erosion of
 - **Program Awareness**
 - Selective Signal Display Filtering
 - Eroded Engineer Skills

M3/Human Factors Date FINAL 3 of 4



Organization-Production: SSP Contracting Culture

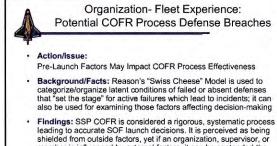
Recommendations:

- NASA must develop a capacity to provide oversight, not only for S&MA, but also oversight on the engineering level for each critical technology area.
- NASA must acquire and develop an engineering staff and provide for requisite training to support both oversight roles

M3/Human Factors Date FINAL

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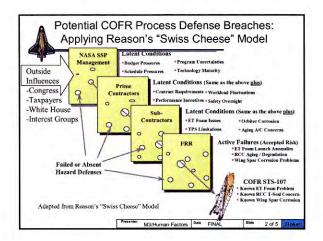


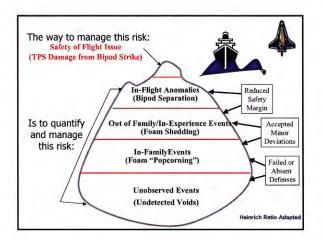


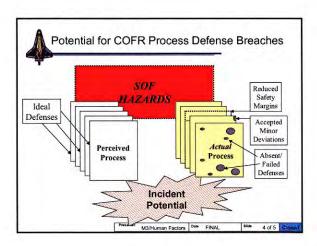
member is influenced by external factors, it can be contended the process can miss signals of absent/failed defenses, accept perceived minor deviations, or permit margin of safety reductions.

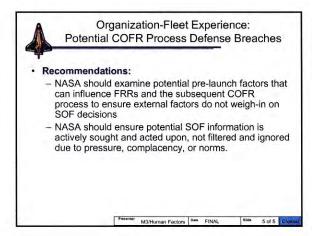
M3/Human Factors Dete FINAL

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Presenter

Fleet Experience - Aging Organization



High Reliability Organizations 23-2

Risk Acceptance in the SSP 23-3

Role of Space Shuttle Systems Integration Office 23-9



Organization-Fleet Experience: SSP as a High Reliability Organization

- Action / Issue: The SSP needs to more closely align itself as
- Background / Facts: Organizations that have less than their fair share" of failures (e.g., nuclear submarines, petrochemical plants, etc. despite:
 - managing complex & demanding technologies
 meeting peak requirements & time pressures

 - routinely handling significant risks & hazards
 - executing dynamic/intensely interactive tasks are termed High Reliability Organizations (HROs). They exhibit "mindfulness", an ability to identify an maintain awareness of potentially hazardous situations and to act quickly to contain or mitigate them

Presenter M3/Human Factors Date FINAL



Organization-Fleet Experience: SSP as a High Reliability Organization

- Background / Facts (con't):

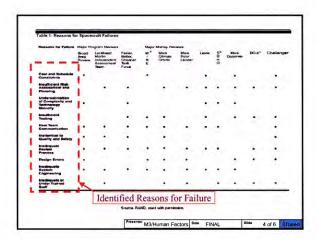
 ✓ Preoccupation with failures- treating any performance lapses as a symptom of a system based problem
- ✓ <u>Reluctance to simplify interpretations</u>- deliberately taking steps to create more complete/nuanced pictures
- Sensitivity to operations- attending to front-line conditions for well-developed situational awareness
- Commitment to resilience- develop capabilities to detect, contain, and recover from inevitable errors
- Deference to expertise- encouragement of a fluid decision-making system using appropriate personnel



Organization-Fleet Experience: SSP as a High Reliability Organization

- Findings: Pre-launch events as well as historical factors indicate the SSP is not fully aligned as an HRO. Some examples that the SSP does not fully exhibit the characteristics of a HRO, include : Preoccupation with Success: - ET foam shedding accepted as in-family event
- Tendency to Simplify Interpretations:
- Shuttle is operational and its technology is mature
- Insensitivity to Operations:
 - Effect of consolidation moves on experience and skill level
- Non-Commitment to Resilience:
 - Predisposition for post-landing vs. on-orbit damage assessment
- Lack of Deference to Expertise:
 - Limited post-launch JSC interactions w/centers (OPS vs. R&D)

Presenter M3/Human Factors	Date	FINAL	Slide	3 of 6	Close



Reason for Failure	STS-107		
(Taken from Rand report)	Pre-Launch Issues		
Cost & Schedule Constraints	OMM Overrun, #Mission Slips, & ISS Schedul-		
Insufficient Risk Assessment	Previous Foam, Tile, & RCC Events		
& Planning	& Potential Interaction		
Underestimation of Complexity &	TPS- Tile/RCC & Foam		
(Overestimation of) Technology Maturity	(e.g., MFG, Install, Aging, & Repairs)		
Insufficient Testing	TPS- Tile/RCC & Foam		
(e.g., Testing, Analysis, NDE, etc.)	(e.g., MFG, Install, Aging, & Repairs)		
Poor Team Communication	Stove-Piping of Component Operations & Horizontal Integration in Technology Areas		
Inattention to Quality & Safety	SFOC Transition: NASA Insight vs. Oversight		
Inadequate Review Process	TPS- Tile/RCC & Foam (e.g., MFG, Install, Aging, & Repairs)		
Design Errors	TPS-Tile/ RCC & Foam		
(e.g. Inadequate Specs, Criteria, etc.)	(e.g., Anomalies, Specifications, BiPOD, etc.)		
Inadequate System Engineering	Component Integration Concerns (e.g., ET Foam Mating Damage)		
Inadequate or	ENG: Staffing Levels, Size, & Experience*		
Under Trained Staff	OMM: QA Insp., Aging Workers, & Workload*		



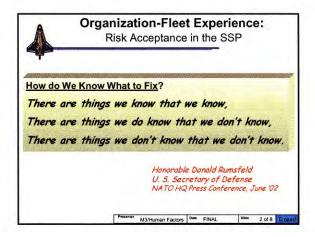
Organization-Fleet Experience: SSP as a High Reliability Organization

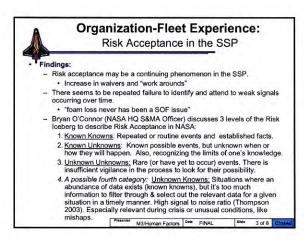
Recommendations:

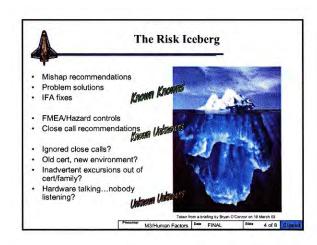
- Re-examine treatment/resolution of past, present & future anomalies
- Provide for greater hands-on presence & involvement of NASA personnel in all aspects of the SSP
- Reform pre-/ post- launch reviews, add a pre-landing review, & retool on-orbit mission monitoring/support
- Provide for improved post-launch & on-orbit vehicle assessment as well as on-orbit repair & escape
- Establish a matrix of Subject Matter Experts to be enlisted for respective technology areas impacted by anomalies

Presenter M3/Human Factors Date FINAL





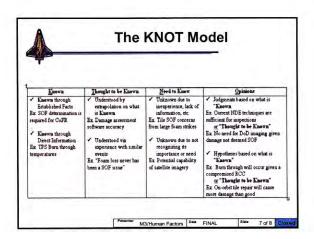


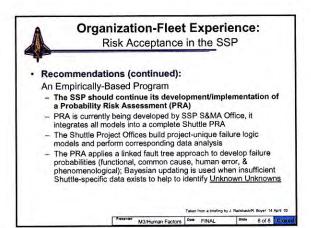
















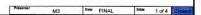
Space Shuttle Systems Integration Office

Action / Issue:

Space Shuttle Systems Integration Office (MS) stovepiped and not organized to enhance horizontal integration of the various STS elements and projects.

Background / Facts:

- Space Shuttle Systems Integration Office (MS) supposedly conducts integration responsibilities across all STS elements and projects
- Tasks involving the Orbiter are worked by MV
- MS, MV equal on organizational charts; both at JSC
 Integration relationship between MS and the MSFC projects (ET, SSME, SRB, RSRM) better defined
- Rank for the respective managers in MS is GS-15 and MV is an





Space Shuttle Systems Integration Office

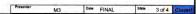
- MV does not send representative to Integration Control Board (ICB) run by MS
- MS representation not required participant at MV Vehicle Engineering Control Board
- Not every bipod shedding resulted in IFA.
- Sometimes the Orbiter office had responsibility, sometime the ET office at MSFC
- No contingency plan for using fault trees.
 - MV started an Orbiter fault tree
 - MSFC started a fault tree for each of its projects (ET, SSME, SRB, RSRM) independent of JSC



Space Shuttle Systems Integration Office

Findings (to date):

- MS does not integrate the STS.
 - office works closely with MSFC projects, MS does not integrate the Orbiter under MV
 - MS is an interaction office stovepiped to the Shuttle projects at MSFC and works with the Orbiter office.
 - If MS office properly used, could have focused away from day-to-day brush fires and worked proactively to prevent problems
 - MS has limited integration responsibility with the SFOC (SRB is under the SFOC) contract and contracts for the ET, RSRM and SSME.
 - If all contractor elements of the STS were integrated from MS, tracking the bipod shedding might have been centrally monitored and worked.





Space Shuttle Systems Integration Office

Recommendations (to date):

- SSP needs to reorganize the Space Shuttle Integration Office to make it organization for all the elements of the STS, not just the ones at MSFC and separate from the Orbiter.
- Any integration needs to include the STS contracts: SFOC (KSC and SRB), LM (ET), Thiokol (RSRM) and Boeing/Rocketdyne (SSME)
- Integration will be particularly important in all the Return to Flight
- Setting up a more efficient integration office will allow the SSP to focus on the strategic planning and program development for the STS and not just on operations.

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Date

Maintenance Organization

Human Factors and Maintenance Operations 24-2

Human Factors in NDE, QA, and Inspection

24-3

24-4

Human Factors in FOD Prevention

CAIB/Group 1 Presenter





Organization-Maintenance: Human Factors in Maintenance Error Prevention

- Action / Issue:
- Human Factors is Critical to Error Prevention in Maintenance Operations
 Background / Facts:
- - Background / Facts:

 MX errors typically associated w/ the "Dirty Dozen"
 Lack of communication, learnwork, awareness, knowledge, resources, & assertiveness
 Abundance of pressure, norms, stress, distraction, fatigue, & comptacency
 Common Management factors in MX errors tied to information dissemination, organizational policyforcodures, & supervision.

 Common human factors in MX errors tied to communication, individual skills, technical knowledge, job/task, & A/C design.

 Findings:

Findings:
Given projected workforce tumover, potential for QA vs QC practices to miss potential errors, recognized deficiency in oversight, and increased maintenance requirements associated with an aging aircraft

Recommendations:

Need to provide for a human factors analysis of maintenance practices and provide targeted intervention, including maintenance resource management training

Presenter M3/Human Factors Date FINAL





Organization- Maintenance: **Human Factors in Inspection**

- Action / Issue:
 Human Factors is Critical in NDE, QA, & Inspection Activities
- Primary human factors associated with inspection process effectiveness are training, OJT, co-worker information, understanding of fault modes, & expectations of faults
- expectations of faults

 Job factors include documentation, standards, SPECs, lighting, and visual/physical access
 Findings:

 Numerous inspection activities related to ET foam installation, TPS integrity/repair, & aging orbiter are critical to safety of flight

 Numerous inspection activities related to orbiter and component construction, overhaul, and repair are critical to safety of flight

 Recommendations:





Organization-Maintenance: Human Factors in FOD Prevention

- Action / Issue:

 Human Factors Is an Essential Component in FOD Prevention

 Background / Facts:

 Human factors in FOD prevention includes preventative practices, training, & personnel awareness.
- Management factors in prevention include specialized assignments, awards programs, housekeeping guidelines, tool control, material handling, & reporting, Findings:
- FOD concerns should not be compromised by renaming to facilitate contract award and operations; potential for FOD to create a Safety of Flight issue is great
- Recommendations:

 Provide for a human factors analysis of FOD practices, handling, and disposition to to provide for optimized Human Systems Integration

 Need to observe the impact of workforce norms, complacency, etc. on the FOD prevention and provide proper oversight

Presenter M3/Human Factors Date FINAL Stide 1 of 1 Closetal

ACCIDENT INVESTIGATION BOARD

Organization Orbit



Langley and JSC E-Mail Exchange 23-4 23-7 23-8

Engineer Simulation Training

Boeing Transition of Orbiter Support from CA to TX

Date CAIB/Group 1

Presenter

FINAL

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Decentralization & Resilience in Handling Anomalies: LaRC-JSC Exchanges on MLG Concerns

Action / Issue:

- Decentralization is critical in detecting anomalies and providing for resilience
- Background / Facts:
- Jan 27th JSC & LaRC engineers had phone/e-mail exchanges on the foam debris assessment (included charts indicating that the left MLG area could be
- JSC engineer stated there was concern the MLG door was "vulnerable", perhaps leading to a two flat tire landing (or compromising MLG). Discussed simulating landings to evaluate outcomes, but no formal request was pending; Explored doing "after hours" piggy-backing on astronaut training underway at NASA ARC.
- LaRC engineer expressed concerns to JSC counterpart to be prepared in case a problem arose on landing; contacted management on JAN 28th an about
- Reviewed previous related data runs; JAN 30th provided scenarios tied to potential MLG problem (most had severe outcomes). Simulation results for a two flat tire landing provided on JAN 31st showed it was survivable/controllable
- Based on established working relationships, the negative scenario observations (with caveats) were passed to select JSC personnel for consideration, whereas favorable simulation results were given to a wider JSC audience for review.

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Decentralization & Resilience in Handling Anomalies: LaRC-JSC Exchanges on MLG Concerns

Findings:

- Formal dissemination of foam debris assessment did not make it directly (or in a timely manner) to all potentially affected parties, especially those who may have the expertise for the proper diagnosis of associated problems and /or the development of mitigation/containment procedures.
- Ineffective dissemination leads to informal channeling that can not be relied upon to get information expeditiously to affected system/technology experts and provide them an adequate chances to make inputs for decision-making.
- E-mail/Powerpoint are tools for asynchronous communication (often to a select audience), however they can not be relied upon to ensure understanding, influence decision-making, or elicit action (especially from non-targeted recipients/respondents).
- Note. The actions these working level engineers took to overcome limited horizontal integration between OPS and R&D (& NASA Centers) so as to network, marshal resources, and prepare for a potential contingency is an example of the resilient spirit that led to the successful return of Apollo 13.

M3/Human Factors Date FINAL



Decentralization & Resilience in Handling Anomalies:

LaRC-JSC Exchanges on MLG Concerns

Recommendations:

- Guidelines regarding communication of safety issues/concerns should be established to ensure early/full dissemination of information to recognized government and contractor system and technology experts who work OPS, R&D, etc. at all NASA
- All channels of communication (e-mail, phone, etc.) should be open and encouraged to discuss/disseminate safety concerns, but assurance must be made that information is raised to appropriate management and safety oversight personnel.
- Disseminate information prior to decision-making sessions (if possible) for preliminary review and potential comment to increase early feedback, participation from attendees, as well as comments from interested parties unable to attend.

M3/Human Factors Date FINAL Slide 3 of 5



Decentralization & Resilience in Handling Anomalies:

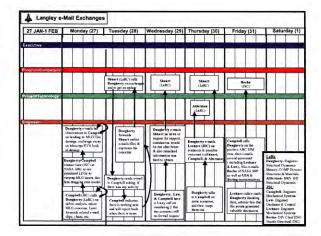
LaRC-JSC Exchanges on MLG Concerns

References:

- E-mail exchanges on foam damage and LaRC and JSC interactions regarding the initial damage assessment. Complete set of email beginning on Jan. 23.
- . Http://www.nasa.gov/bdf/2207main COL_email_030/226.pdf)
 E-mail exchange on Jan. 28-31, 2003, on assessment of potential for a breach
 in the landing gear door or wheel well during re-entry into Earth's atmosphere
 (http://www.nasa.gov/bdf/2205main_COL_debris_email.pdf)
- E-mail exchange within LaRC regarding main gear breach concerns on Jan. 31.
- (http://www.nasa.gov/pdf/2208main COL email larc.pdf)
- Daugherty, R. & Shuart, M. (10 MAR 03) NASA Langley Press Conference (http://www.spaceref.com/news/viewsr.html?pid=8270)
- NASA HQ Records Management Bulletin 97.01

- NASA HQ Records Management buildin 97.01 (http://www.han.asa.gov/office/codea/codea/recon/201.html)
 NASA Information Systems Directorate e-mail Guidelines (http://isd.isc.nasa.gov/GA/computer/email/EmailQosDorits.html)
 Palme, J. (23 MAY 99) Support for Decisions by E-mail. TERENA Conference (http://www.dsv.su.se/~ipalme/setf/JPMADS.html)

M3/Human Factors Date FINAL Sade 4 of 5







Organization-Orbit: **Engineer Simulation Training**

- Action / Issue:
 - Lack of Ongoing Formal Event Simulation Training for Shuttle Engineers involved in the MMT/MER
- Background/Facts:
 - Comparisons with SSP and DoD safety performance should consider differences in training levels
 - DoD trains at all levels, across nearly all operations, with all affected personnel: An established and accepted organizational norm.
- Findings:
 - In SSP, only the Astronaut crew and Flight Control team receive on-going formal training; the MMT conducts a simulation exercise once/18 months
 - The MER and other principle engineering support teams receive no on-going formal training beyond initial orientation

Presenter M3/Human Factors Date FINAL



Organization-Orbit: **Engineer Simulation Training**

Recommendations:

- A formal training program should be developed to meet 2 major goals:
 - 1. Strengthen basic & advanced skills and processes during routine and unusual conditions
 - Strengthen team integration & communication processes within & among technical & management elements, specifically the MER & MMT
- Training should include practice problems, simulations, realistic scenario play, performance evaluation, & feedback (strengths, weaknesses, & lessons learned).
- Seasoned engineers (i.e., mentors) should be incorporated into training exercises to continue the knowledge transfer effort (Note. Particularly important to develop trouble shooting skills and situations requiring subjective judgment calls.).

Presenter M3/Human Factors Date FINAL



Organization-Orbit: Boeing Transition of Orbiter Support from CA to TX

- Action / Issue:
 - Boeing transition (12/01-03/03) of Shuttle operations (OPS) support function from Huntington Beach, CA (HB) to Houston,TX (HOU) precipitated a large turnover in personnel with significant program experience and technical expertise. To minimize effects from a potential loss of experience/expertise, Boeing planned a risk managed knowledge transition process, with an emphasis on key positions.

 - Process was not uniformly implemented, potentially impacting support capabilities.

Background:

- In Ditternore's March 6th testimony to the CAIB, he indicated the transition was a contractor-based initiative to get "engineering closer to the customer" and achieve ", efficiencies that would lower the overall cost".
- Pre-transition Boeing had ~1,300 jobs: ~1,000 (76%) in HB & ~150 (12%) in HOU; Post-transition Boeing had ~500 jobs in HB (38%) & ~580 jobs (45%) in HOU. Only 97 HB Boeing incumbents transferred to HOU, requiring over 30 jobs to be filled (This included both critical SSM and various engineering positions).

Presenter M3/Human Factors Date FINAL



Organization-Orbit:

Boeing Transition of Orbiter Support from CA to TX

Boeing Proprietary Information Not for Release

· Background (con't):

- By March 31, 2003 there were 531 total jobs that transferred from Huntington Beach to Houston and Florida
- Of the 531 jobs that transferred, 140 people relocated from Huntington Beach. The remaining 391 positions were filled by replacements

Job Distribution by Category (March 31, 2003)

	Engineer	Management	Others	Totals
Total Jobs Transferred (est)	424	55	52	531
Relocations (est)	89	33	18	140
Replacements (est)	335	22	34	391

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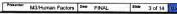
Organization-Orbit:

Boeing Transition of Orbiter Support from CA to TX

Overall, their plan appeared to be both systematic and comprehensive, encompassing:

- Knowledge capture process (KCP), to catalog incumbent KSAs through questionnaires, video interviews, and
- Critical skill checklists, based on inputs from each incumbent performing a task *
 comprising a given "job"
- HB competency managers and HOU Integrated Team Managers review of KCPs w/ corresponding checklists,
- Risk management of the task transition process, to effectively identify, assess, and address hazards; "Red-flagging" areas for additional oversight based risk
- two shuttle missions (STS 112 & 113), providing "real time" OJT
- Set 3-month period for individual job transition, to include face-to-face training
- Certification process for key positions (e.g.,Sub-System Manager) & Integrated Team Manager sign-off for others
- Established guidelines for identifying and selecting critical personnel and engineering replacement candidates

Pairing a job candidate with respective incumbents for formal task training and mentoring whenever possible





Organization-Orbit:

Boeing Transition of Orbiter Support from CA to TX

Background (continued):

- Boeing transition review (11/02) accomplishments listed hired 95% of replaceme completed 85% of programmed training (70% completed all of the training), and replaced 98% of critical skills
- Boeing HB site director indicated that a further endorsement of the transition's success was USA's consideration to use this KCP model in their organization.
- Boeing performance and safety award fee scores were higher than pre-transition. Findings:

Witness Impressions of the Overall Transition Process

- Despite the official reports' positive tone and the site director's comments, witnesses questioned the actual success of the transition process (including knowledge capture, individual training, and exit evaluation).

 Witnesses characterized the process as compressed (and consequently rushed); lacking standardization, clear job-based criteria, and post transition group/ individual
- risk re-assessment.
- Further, former analysts (aero, stress, thermo, & structures) had additional concerns that the transition could impact the on-orbit reported damage assessment process/findings.

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Organization-Orbit:

Boeing Transition of Orbiter Support from CA to TX

Findings (continued):

Knowledge Capture Process (KCP)

- Witnesses' General Observations:

 The KCP was seen as "too little, too late."

 Parts of the KCP were not as useful as others; whereas some felt the entire KCP was not useful
- The KCP was not as specific on analyses functions as it was in hardware areas; but lead analysts reported they did effectively document troubleshooting, problem-solving, lessons learned, etc.
- elearned, excessed to management in both formal and informal settings, including alt-hands, staff, and hallway meetings. HOW the work of t

Questionnaires:

The job questionnaire documented inputs, processes, and products of a position.

Some witnesses indicated it was adequate, but it could not capture decades of experience. It was perceived as too brief and inadequate, as it gathered only top-level, generic information about positions.





Organization-Orbit:

Boeing Transition of Orbiter Support from CA to TX

Findings (continued):

Knowledge Capture Process (KCP)

Video Interviews:

- The video-taped interviews were intended as a "how-to" demonstration of
 procedures lending themselves to hands-on or hardware processes.
 Many incumbents were not asked to participate in videotape interview.
 Most felt they were useful for technical, hands-on tasks, but not useful for
 other activities, like procedures and analysis.
- . One analyst thought this was the only useful KCP component.

Toolboxes:

- DIDDIVES:
 Incumbents were asked to make a complete listing of all files, references, locations of guiding documents, policies, analytical tools, software, etc. that would be relevant for a particular position.
 While this compilation was not required of some lower-level engineers, most agreed that this was the most useful part of the KCP.
- HOU engineers acknowledged there is continuing work being done on the

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Organization-Orbit:

Boeing Transition of Orbiter Support from CA to TX

Findings (continued):

Knowledge Capture Process (KCP)

- Management Review:
 - Review of the KCP products after the incumbent compiled them was sporadic at best.
 - They generally indicated that their manager received it and in some cases reviewed it, and asked for clarification. In other cases they merely took it, with no revision or refinement.
 - The witnesses collectively stated there was no training on how to do the KCP, no standardization of the product produced, and it was not systematically/uniformly implemented.
 - The process was more difficult for senior personnel and for management types, e.g., to produce an effective video interview as stated above.
 - Overall, the KCP did not consistently follow the transition plan in many cases, especially for non-critical positions.

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Organization-Orbit:

Boeing Transition of Orbiter Support from CA to TX

Findings (continued):

Selection, Training, & Certification

- HOU mgmt. oversaw most new personnel hiring. Except for a few senior positions and transfers from HB, the HB supervisors were not involved in the selection
- process. KCP end products were collected from the incumbents and then provided to the Integrated Team Managers (ITMs) who oversaw the transition training for new hires and transfers. ITMs were either senior SSP people who transferred or experienced SSP people recruited from NASA or USA. There were some instances where the ITM themselves were new hires.
- training utilized the HB incumbent when they were available. The incumbent conducted 2-3 weeks of training with the trainee at HB, while the ITMs oversaw the remainder of the training process at HOU.
- Training plans or checklists were to be covered over a 3-month period (approx.) for each job; all jobs were to be transitioned over an 18-month period. When incumbents and management were satisfied with trainer's performance, the incumbent was given a 60-day notice. Incumbent remained available to the trainee during this time period.
- New SSMs required a controlled, multi-step training and certification process. Certifications requirements and processes were approved by USA/NASA. Each SSM was evaluated by Boeing/Customer Boards foe final certification.

Presenter M3/Human Factors Date FINAL



Organization-Orbit:

Boeing Transition of Orbiter Support from CA to TX

Findings (continued):

Selection, Training, & Certification

- The transition's beginning phases appeared rushed. Thus some positions and any process perturbations (e.g., a candidate or incumbent leaving) compromised process integrity.
- process integrity.

 Toward the transition's end, some witnesses stated there was pressure to finish training to complete the transition. Though incumbents were available for training candidates, they were not given 3 dedicated months to train: either the incumbent attended to other duties or the candidate was not no site.

 During the 3-month training period, the incumbent charged a special transition job order number, while the candidate charged to SSP.
- There was some pressure not to exceed the allotted transition time, despite the trainee's proficiency status and/or checklist completion.
 HOU management stated the training budget was under-run by \$2M in contrast to HB incumbent experience, the replacement HOU based employees reported the training to be sufficient in quantity and quality.
- Most candidates were deemed proficient for normal tasks and conditions. However, incumbents indicated that training was conducted with an understanding that in unusual cases (out of family, etc.), the incumbent and trainine would work together.

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Organization-Orbit:

Boeing Transition of Orbiter Support from CA to TX

Findings (continued):

Selection, Training, & Certification

- Exit criteria for the training process was unclear to incumbents, other than completing the checklist/training plan. In some instances, the list was not completed or the candidate was not proficient to the task(s) by the time the transition ended. Some witnesses expressed significant frustration and concern about this
- Most SSM training and certification processes were coordinated by managers. They indicated the process was rigorous and included USA/NASA participation. Most SSMs held significant seniority with the SSP. Although some portions of the certification process was not highly structured, most witnesses said this process went very well. Records indicated that the training and certification process for SSMs was well documented.
- The incumbent and candidate worked together for STS 112 & STS 113, two missions flown during the transition process. STS-107 was the first mission flown after transition completion, with HOU holding primary responsibility.
- After the transition was complete, incumbents provided further assistance only as sted by the new employee

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Organization-Orbit:

Boeing Transition of Orbiter Support from CA to TX

Findings (continued):

- Risk Management and Over-Site

 Risk mitigation plans for each task/task group were incorporated into official Task Transition Plans. This process included assessment of probability, severity, and risk mitigation for each risk item. Tasks were identified and tasked on team schedules; monitoring of the knowledge capture, transition training, and certification/completion processes were employed. However, Witnesses observed the process as non-systematic in overall implementation.

 - systematic in overall implementation, Baseline risk assessments were not adjusted on an individual basis to consider experience level, "out of family" selection, etc.

 A 02/02 NASA SSP S&MA risk mgmt. report indicated "yellow" (5- "high" likelihood & 2-med-low" consequences) through FY 02 for supportability and safety due to the Boeing relocation, A 10/02 NASA SSP S&MA risk mgmt. report indicated "yellow" (4-high-med likelihood & 2-med-low consequences) for supportability and safety through FY 03 (est. Resolution 01/03) due to the Boeing relocation.
 Listed as a "Top Issue", the impacts listed were "Low percentage of incumbent personnel willing to relocate" and "Could impact COFR process integrity." It also indicated various concerns: loss of existing skills and experience, challenges to replace personnel, incumbent retention to support contracted tasks and train replacements, and quality of NASA/USA available for out-of-family support.

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Organization-Orbit:

Boeing Transition of Orbiter Support from CA to TX

Findings (continued):

Risk Management and Over-Site

- is maintegenent and Vert-cities \$TS-107 & \$TS-114 were listed as yellow due to some Orbiter replacement personnel generating flight products with approved work around plan and some \$ystem Integration personnel having no certified back-up. The action plan to mitigate risk was listed as "Transition plan has been developed and partnered with NASA" and NASA and USA in oversight mode until transition completed:
- Once the transition process was complete, no re-assessment of individual risk was
- Boeing contracted Independent Risk Assessments (IRA) for the transition
 - The goal was to complete staff training by the end of 12/02. "Victory Criteria" included: completing 90% of the hiring, 90% of the training, 90% of the critical skill replacement, 90% of the redeployment, and 100% SSMs trained and certified.
 - Their analysis indicated a 95% chance that criteria would **not** be met by the end DEC 02, a 50% chance by 02/02, and a chance it may extend until 03/03 (and until 05/04 without careful management).
 - Given the situation, they recommended a "supercharged" interview and pre-screening process; acceleration of making offers, hire decisions, reporting dates, and training start-up; carefully control/manage training time and work on scheduling (especially fi incumbent is leaving).

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Organization-Orbit:

Boeing Transition of Orbiter Support from CA to TX

- Findings (continued):

 Analysis from a High Reliability Organization (HRO) Perspective

 Process Auditing- Boeing should have ensured knowledge capture from incumbents was working, transition training with replacements was adequate, and training axit criteria was appropriate to ensure workers were proficient in the tasks they were to perform.

 Quality Assurance, ensuring that the trained candidate was proficient for both normal and emergency operations, appropriate/adequate tools were issued in toolboxes, and tool use instructions were complete and covered any limitations.

 Risk Management- assessing risk on an job level for each transfer to HOU; assessing risk pretraining to talor training for railvidual replacements, reassess risk after training to determine if risk was within acceptable ranges and maintain awareness of specific hazards, and establish needs for targeted intervention.

 Reward System- providing incentives for brining replacements to a level of demonstrated proficiency for all pols (not just SSMs), and not just simply meeting the deadline to fill all jobs and get them signed off as qualified. Ensuring there are no perceived pressures/ punishments for holding off on sign off due to deficiencies.

 Command & Control- making adjustments for situations where the incumbent/candidates were not in constant contact during the transition training process, when the training was not fully completed or the incumbent was not available for the training, establishing and supporting mentioning relationships, e. and not providing for lifetimes of networked experts to support

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Organization-Orbit:

Boeing Transition of Orbiter Support from CA to TX

Recommendations

- Boeing should place additional emphasis on continued skill building and knowledge acquisition from seasoned incumbents to new and transitioned personnel (beyond any remediation).
- Boeing should devise a systematic method for incumbents and new hires/transitions to Boeing should devise a systematic method for incumbents and new hirestransitions to have regular communication exchanges on both formal and informal bases (e.g., VTCs, web-based bulletin/chat boards, etc.)

 Boeing should utilize the HB Mission Support Room for the next shuttle mission, with incumbent personnel "shadowing" to provide oversight.

 Regular and ongoing training opportunities should be developed for new employees and provided by the incumbents.

- Boeing's plan for additional transitions to HOU should be reviewed to provide for standardized knowledge capture, risk management, systematic training, and evaluation of proficiency. Further, the process for selecting new hires and in-house transfers should be scrutinized for requisite critical skills, quality, and experience.
- USA should underwrite costs for the complete Boeing Shuttle OPS Support transition skills evaluation, knowledge capture, risk management, remediation training, incumbent mentoring, exit-criteria, and follow-on risk assessment.

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Design - Certification Contract

Contracting & Financial Considerations

25-1



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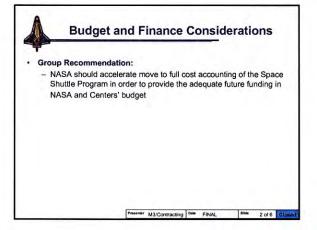
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Budget and Finance Considerations

- Action / Issue: Budget and Finance Considerations Influence Shuttle Program Performance
- Background / Facts:
 - Cost pressure may adversely influence mission success at USA and sub-contractors as ISS cost overruns take greater share of NASA budget
 - Reduction at NASA funded level would be distributed to program based on NASA priorities. Cost growth in other priority programs could negatively affect funding on the SFOC and other SSP contracts.
- Findings:
 - Committee reports, new media, etc. indicate extensive cost growth on ISS



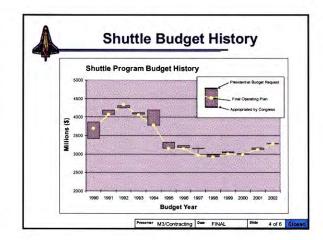




SSP Budget

- · Human Space Flight is approx 40% of NASA budget
- · Space Shuttle is half of human space flight Budget
- No recent large congressional cuts
- FY2001 necessary to redirect advanced areas to address cost and program management needs of the ISS

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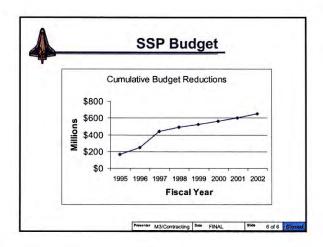




Shuttle Budget History

- 2002 reduced \$50mil
- · 2001 reduced \$40mil for Mars initiative
- · 2000 earmark of \$40mil transfer to ISS
- 1999 reduced \$31mil
- · 1998 transferred \$50mil to ISS
- 1997 transferred \$190mil to ISS
- · 1996 reduced \$53mil; transferred \$30mil to ISS
- 1995 general reduction \$168 to Human Space Flight

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26-1	Non-SFOC Contracts
26-2	Foam Application Process not Specified as Contractual Requirement
26-3	ET Not Subject to Catastrophic Loss Penalty Clause
26-4	Pressure to Decrease Costs on SRB



Contracting Issues Non-SFOC Contracts

- Action / Issue: Non-SFOC Contracts "evolve" to shift emphasis away from cost savings
- Background / Facts:
 - MSFC has contract cognizance over Space Shuttle element contracts that are not part of the SFOC
- Findings:
 - MSFC evaluates whether contractor headcount had been reduced to minimum safe level and whether continued personnel reductions would have a negative rather than a positive effect
 - ATK Thiokol Propulsion has been Reusable Solid Rocket Booster (RSRM) supplier since 1974
 - Contracts from Buy 1 to Buy 4 included cost savings share line, allowing Thiokol to share in any savings below target cost
 - Current buy, while including a 1% incentive fee at target cost, contains no incentive for underrun



Contracting Issues Non-SFOC Contracts

- · Group Recommendation:
 - NASA JSC should examine removing cost savings incentives from SFOC

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Fee Structures of Non-SFOC

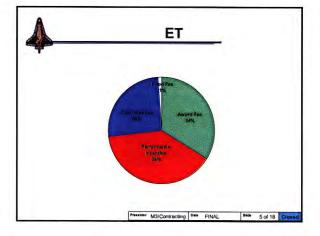
- Issue: SFOC was planned to include other "element" contracts as
- Only SRB added (1998)
- Elements not included in SFOC
 - External Tank (ET)
 - Space Shuttle Main Engine (SSME)
 - Reusable Solid Rocket Motor (RSRM)

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Non-SFOC: External Tank

- · Michoud Assembly Facility (GOCO) operated by Lockheed Martin
- Estimated Cost (ET Production): \$2.06 B
- Estimated Fees: \$134.4 M (Incentive, Employee Motivation, Award)





ET Production Award Fee

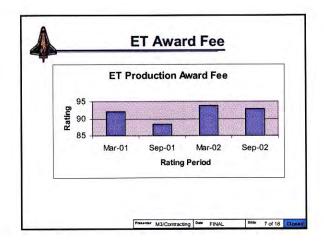
- Quality Performance
- 70%

30%

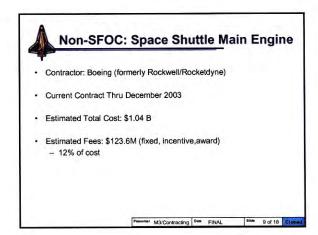
- Subcriteria: Quality of hardware; problem reporting/resolution; hardware performance; safety performance
- Management Performance
 - Subcriteria: Project management; flight support; contract management

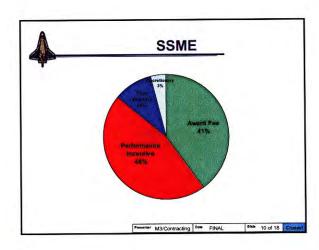
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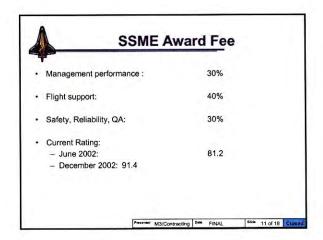
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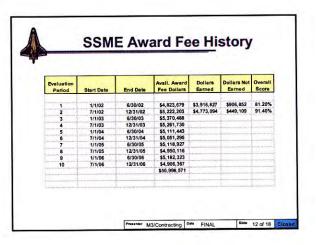


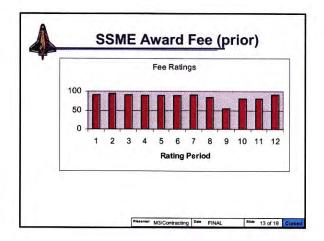
	ET		
Production Award Fee Pools	- Lange		
Period	Amount Available	Earned Amount	Earned Percent
October 1, 2000 - March 31, 2001	\$1,499,664	\$1,370,693	91.40%
April 1, 2001 - September 30, 2001	\$2,493,361	\$2,202,136	88.32%
October 1, 2001 - March 31, 2002	\$3,273,186	\$3,070,903	93.82%
April 1, 2002 - September 30, 2002	\$2,498,684	\$2,296,290	91.90%
Total	\$9,764,895	\$8,940,022	91.55%
October 1, 2001 - March 31, 2002 April 1, 2002 - September 30, 2002 Total	\$658,718 \$761,736 \$2,251,229	\$645,544 \$717,555 \$2,159,382	98.00% 94.20% 95.92%
B02063 – "Implementation of Friction Stir V Period	Amount Available	Earned Amount	Earned Percen
May 1, 2000 - March 31, 2001	\$ 343,218-	\$314,044	91.50%
April 1, 2001 - September 30, 2001	\$297,000	\$268,785	90.50%
October 1, 2001 - March 31, 2002	\$128,000	\$114,278	89.25%
	200 000	\$83,840	99.00%
April 1, 2002 - September 30, 2002 Total	\$84,687 \$852,905	\$780.947	91.56%

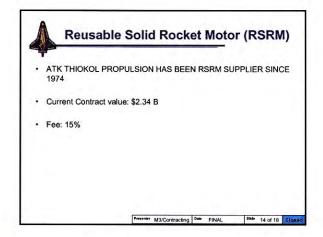


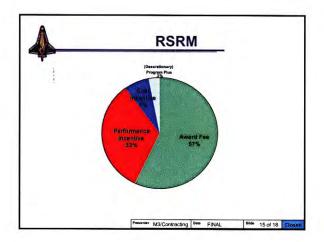


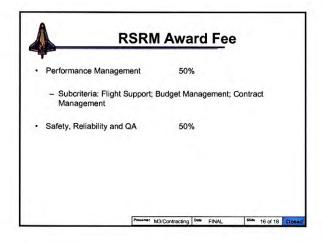


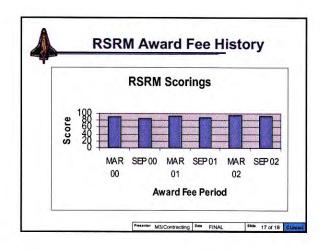


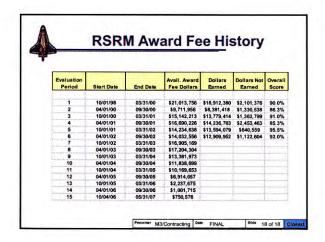












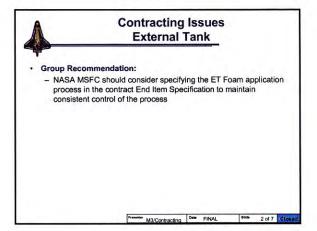


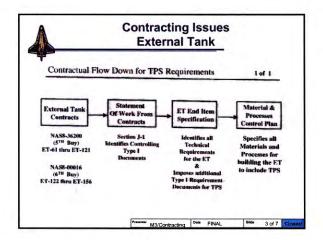


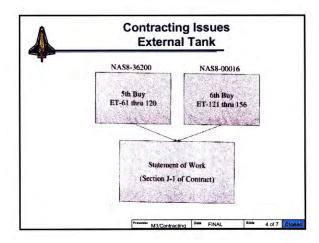
Contracting Issues External Tank

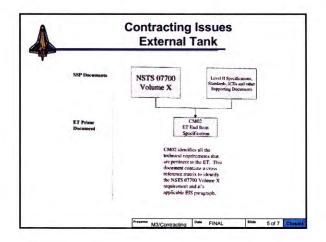
- Action / Issue: Foam Application Process not specified as contractual requirement
- Background / Facts:
 - External Tank Contract NAS8-00016 does not specify the application process to be used by Lockheed Martin Michoud Assembly Facility for the External Tank
- Findings:
 - ET Statement of Work (SOW) as included in the contract imposes the ET end Item Specification, CM02 and materials Process Control Plan as Type 1 documents.
 - Items below SE 16 level include engineering drawings, product processes and manufacturing plan (MPP)
 - NASA and DCMA are to review any changes the contractor that affect form, fit or function

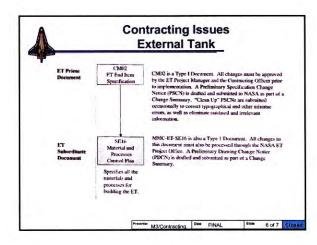
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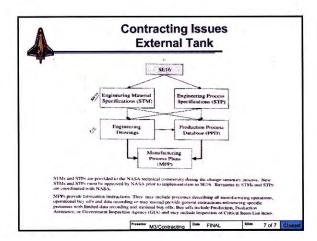














Contracting Issues External Tank

- Action / Issue: External Tank used on STS-107 not subject to Catastrophic Loss Penalty Clause
- Background / Facts:
 - External Tank 93 was delivered in 2000 under MSFC contract. Tank was held by the Government until needed
- Findings:
 - Current buy for Tanks ET-122 through ET-156 contains a catastrophic loss penalty clause
 - Category 1 Failure, death of crew or loss of orbiter: \$10M
 - Category 2 Failure, mission failure: \$5M
 - Contract NAS 8-00016 was awarded September, 1999 for production of 35 tanks

Presenter M3/Contracting Date FINAL



Contracting Issues External Tank

- · Findings (con't):
 - In negotiation, Lockheed Martin wanted fee raised considerably before accepting a catastrophic loss penalty
 - MSFC decided benefit of including the clause did not support the cost of the additional
- Group Recommendation:
 - Should NASA determine ET contractor culpability, complete contract review should be accomplished to identify whether other provisions exist in prior contracts to assign penalties or fee forfeitures



RSRM Loss Provisions

- · Fee reduction for loss of crew, vehicle or mission
- Category I failure
- Incident directly attributable to an RSRM
- Results in loss of life or vehicle
- Forfeiture of \$10M plus all fee earned or available during award fee period in which loss occurs
- Category II failure
 - Incident directly attributable to an RSRM
 - Results in loss of mission
 - Forfeiture of \$5M plus all fee earned or available during award fee period in which loss occurs

Presenter M3/Contracting Date FINAL



SSME Loss Provisions

- · Fee reduction for loss of crew, vehicle or mission
 - Category I failure
 - Incident directly attributable to an SSME
 - Results in loss of life or vehicle
 - Forfeiture of \$10M plus all fee earned or available during award fee period in which loss occurs

 Category II failure

 - Incident directly attributable to an SSME
 - Results in loss of mission Forfeiture of \$5M

 - Category I and II failures to be determined by a failure investigation board per NMI 8621.1
 - If failure determined to be both category I and II, only category I penalties shall be applied

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SRB Under SFOC

Action / Issue:Increased pressure to decrease costs on the Solid Rocket Booster (SRB) portion of SFOC may have detrimental effects on SRB technical issues

· Background / Facts:

SRB was not originally part of the SFOC, but was added in 1998. It is currently the sole Space Shuttle hardware element included in the SFOC. The External Tank, Space Shuttle Main Engine, and Reusable Solid Rocket Motor are each covered by separate contracts with their own incentive plans.

· Findings:

- SRB is weighted at 10% of SFOC Award Fee rating.
- USBI achieved significant cost savings under the predecessor SRB contract, declaring an underrun of \$46 Million though 1999.

Presenter M3/Contracting Date FINAL



SRB Under SFOC

 Savings are implemented by the reduction in manpower, but without specific identification about which (unnecessary) tasks were eliminated or efficiencies achieved.

· Group Recommendation:

- JSC should examine whether some elements should be excluded from contract cost savings incentives

Presenter M3/Contracting Date FINAL

2 of 2

ACCIDENT INVESTIGATION BOARD

Maintenance Contract



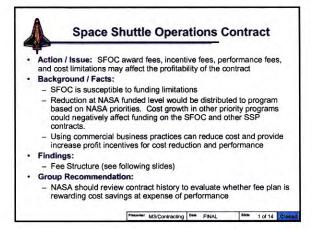
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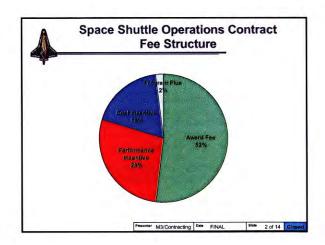
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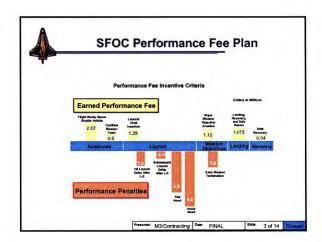
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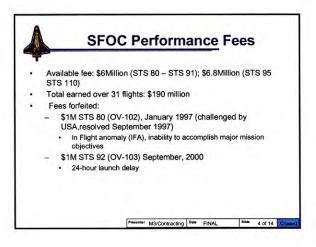


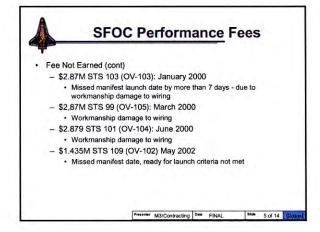
SFOC Fees and Cost Limitations TMR Weights **USA Benefits** 27-1 27-2 27-3

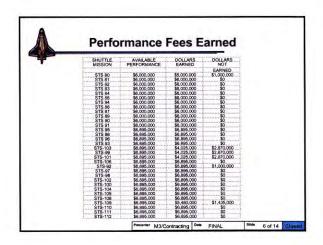


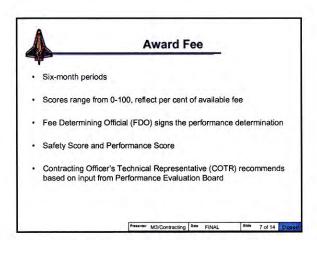


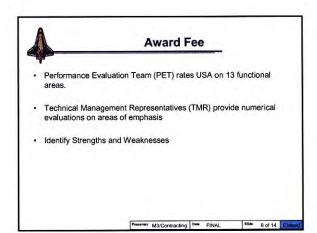


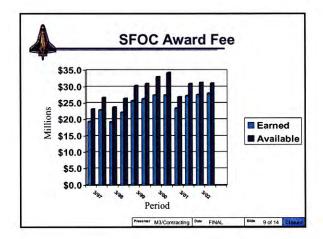


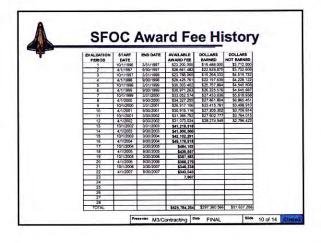


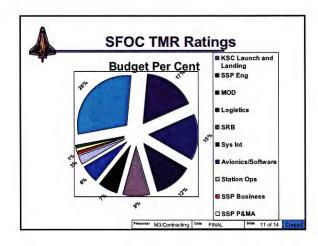


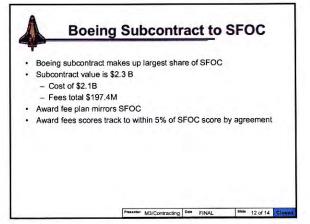




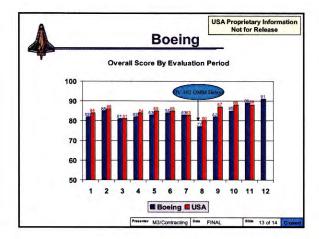


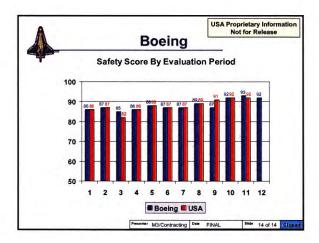
















Contracting Issues SFOC

- Action / Issue: Technical Management Representatives score weightings may hide substandard performance on contract requirements
- Background / Facts:
 - Each Technical Management Representative (TMR) assigns USA a performance grade in each of 6 areas. TMR Scores are weighted based on an individual share of the budget
 - Weighted scores are totaled to provide recommended score
- · Findings:
 - 13 TMRs rate contractor performance every 6 months
 - Weighted scores become the recommendation to the PEB
 - Weights of TMRs on small share elements "disappear" when summary number produced



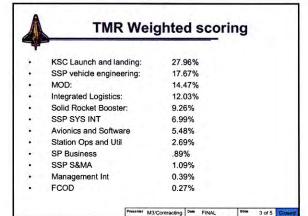


SFOC TMR Weighted Ratings

- · Group Recommendation:
 - NASA should review low ratings regardless of budget weights; consider assigning award fee pools to each TMR to reward performance in each area rather than aggregate.

Presenter M3/Contracting

slide 2 of 5





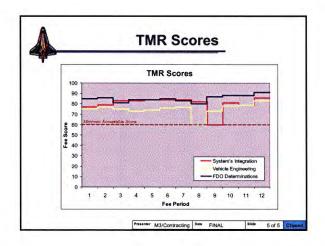
SFOC TMR Weighted Ratings

- KSC Launch and Landing weighted at 30%
- Vehicle Engineering weighted at 17%
- System Integration weighted at 6.5%
- · Safety and Mission Assurance weighted at 1.1%
- Reinforces commitment to meeting manifest

Presenter M3/Contracting Date FINAL

FINAL

4 of 5 Cto







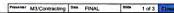
USA Employee Benefits

· Action / Issue:

Potential "Substandard" United Space Alliance (USA) Benefits package May Impact Workforce Retention, Quality, and Morale

· Background / Facts:

- USA's employee benefit package is viewed by some as as being below aerospace industry average.
- Defense Contract Audit Agency (DCAA) conducted audits of several areas of compensation including:
 - · Compensation System Internal Controls
 - Fringe Benefits
 - · Health Care Cost





USA Benefits

- Compared to Chamber of Commerce Study of companies with over 5,000 employees, USA is excessively generous
- Industry-wide healthcare company contribution 83%; employee contribution 17%
- Watson Wyatt survey of comparable companies: company contribution 86%; employee contribution 14%
- USA pays 92% of employee healthcare costs
- Also, excessive Paid Time Off (PTO) not charged as leave
- At least one more paid Holiday than average
- DCAA suggested that USA could save \$12 million annually by REDUCING benefits to comparable average



USA Benefits

- Federal Acquisition Regulations (FAR) directs that compensation be considered sum of ALL pay and benefits, rather than Pay OR Benefits separately
- · Group Recommendation:
 - Perception of poor benefits may be in comparison with heritage aircraft industries (Lockheed; Boeing) where large hourly labor force historically drives generous benefits packages. There is no support to the suspected issue and it should be disposed of.

Presenter M3/Contracting Date FINAL

Stide 3 of 3



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Volume V Appendix G.5

Vehicle Data Mapping (VDM) Team Final report, Jun 13, 2003

This Appendix contains NSTS-37383 <u>Vehicle Data Mapping Team Final Report in Support of the *Columbia* Accident Investigation, 13 June 2003.</u>



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Vehicle Data Mapping (VDM) Team Final Report

in support of the Columbia Accident Investigation

June 13, 2003

Prepared by:

John D. Albright NASA-JSC-EP4 VDM Team Data Manager

Approved and Submitted by:

Gene Grush NASA-JSC-EP VDM Team Lead











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Executive Summary

The Vehicle Data Mapping (VDM) Team was created to support the Orbiter Vehicle Engineering Working Group (OVEWG) investigation of the OV-102/Columbia accident that occurred during the STS-107 mission on February 1, 2003. The VDM team charter included the creation of unique and innovative data display products that aid in understanding the hardware configuration, sensor response data, and complex sequence of events during Columbia's entry.

In meeting this charter, approximately 125 personnel from NASA, Boeing, USA, and multiple support contractors from around the country produced seven major products and six supporting products in accordance with the VDM team product flowchart contained in Appendix A. Four special activities related to these products and encompassed by the VDM team charter were also pursued. All of these products and activities are discussed in detail in this report, along with related findings generated by the VDM team during this effort.

Due to the large volume of data produced by the VDM team, this report is best reviewed from the <u>VDM team share drive</u> or a compact disk (CD) containing all related product files, thus enabling embedded hyperlinks to work properly and maximizing data availability and organization. Accordingly, the planned method of distribution for this report is a CD. Note that a <u>readme file</u> is included to explain the general content and provide key usage instructions for the final report.



1.0 INTRODUCTION

The Vehicle Data Mapping (VDM) Team, headquartered at Johnson Space Center (JSC) and lead by NASA-JSC-EP/Gene Grush, was created to support the Orbiter Vehicle Engineering Working Group (OVEWG) investigation of the OV-102/Columbia accident that occurred during the STS-107 mission on February 1, 2003. The VDM team charter was as follows:

- To perform data collection, organization, and analysis for select vehicle parameters during entry.
- To research sensor installation details, wire routings, and power and signal conditioning configurations for associated instrumentation.
- To perform testing as required to anchor analytical models and define failure modes/signatures for associated instrumentation.
- To create unique and innovative data display products that aid in understanding the hardware configuration, sensor response data, and complex sequence of events during entry.

In general, the VDM team did not provide detailed interpretation of the flight data. Instead, the existing Problem Review Team (PRT) for each Orbiter subsystem performed this task with oversight from the Data Review and Timeline Reconstruction Team, who then used the results as an input to the master entry timeline. One exception, discussed later in this report, involved analyzing the timing and failure signatures of certain Orbiter sensors to identify trends and patterns in the data.

In meeting the VDM team charter, seven major products and six supporting data generation/gathering products were produced in accordance with the VDM team product flowchart contained in Appendix A. Four special activities related to these products and encompassed by the VDM team charter were also pursued. All of these products and activities are discussed in this report. To maximize efficiency and accountability, the VDM team structure and action tracking system were product oriented, including the assignment of a lead engineer for each product. To organize and control VDM team products and inputs, a VDM team headquarters (building 15, room 131) was established for meetings/telecons and display/storage of hardcopy data. A VDM team share drive was also established on a JSC server for display/storage of electronic files.

Over a 4-month period, approximately 125 personnel from NASA, Boeing, and United Space Alliance (USA) at JSC, Kennedy Space Center (KSC), Marshall Space Flight Center (MSFC), and Huntington Beach (HB), plus technical support personnel from Analytical Graphics, Inc., GHG Inc., IMC Incite, Lockheed Martin, Muniz Engineering, Inc. (MEI), Information Dynamics, Inc. (IDI), and SAIC, Inc., responded to action items and produced the products described in this report. A comprehensive list of VDM team members, action items (98 total), and action item response files is contained in <a href="https://doi.org/10.1001/ncit.com/nci

supplemental information was also provided directly to the *Columbia* Accident Investigation Board (CAIB) in several instances upon request.

2.0 PURPOSE AND SCOPE

This report is intended to provide final documentation of the VDM team products and findings. Due to the large volume of data produced by the VDM team, this report is best reviewed from the <u>VDM team share drive</u> or a compact disk (CD) containing all related product files, thus enabling embedded hyperlinks to work properly and maximizing data availability and organization. Accordingly, the planned method of distribution for this report is a CD.

3.0 PRODUCTS AND SPECIAL ACTIVITIES

In accordance with the VDM team product flowchart contained in Appendix A, seven major products, six supporting data generation/gathering products, and four special activities were created and pursued to help document, visualize, and comprehend the data associated with *Columbia's* entry on STS-107. The major source of flight data used for this effort included telemetry data from the Operational Instrumentation (OI) sensors and Orbiter Experiment (OEX) recorder data from the Modular Auxiliary Data System (MADS) sensors. This data was obtained in hardcopy and/or electronic form directly from the Mission Evaluation Room (MER) via formal data requests. Also, as mentioned previously, a key input to many VDM team products and activities was the master entry timeline from the Data Review and Timeline Reconstruction Team, which was used for identification and annotation of key events.

Unless otherwise specified for individual products or activities, ending times for OI sensor data include loss of signal (LOS) at Greenwich Mean Time (GMT) 2003/032:13:59:32.136 (data set referred to as "107 data") and post-LOS at GMT 2003/032:14:00:31.102 (data set referred to as "107-edit data"). Similarly, the ending time for MADS sensor data is GMT 2003/032:14:00:14.290 (data set referred to as "OEX data"), with entry interface (EI) occurring at GMT 2003/032:13:44:09.000 (frequently used as a point of reference).

VDM team efforts initially focused on OI sensor data from the vehicle. The first OI indications of off-nominal performance involved a hydraulic line temperature on the inboard sidewall (Yo-105) of the left wheel well (V58T1703A, LMG Brake Line Temp D) at GMT 2003/032:13:52:17. Subsequently, other OI sensors began showing off-nominal trends. Of these, particular attention was given to the following 14 OI sensors (seven left wing, seven left wheel well) that went off-scale low (OSL) or unexpectedly changed state (starting at GMT 2003/032:13:52:56) prior to LOS:

Failure Order	MSID	Description	Sensor Location	Panel/ Connector	Mode
1	V09T1006A	LH Inbd Elev Lwr Skin Temp	Wing	Glove/P105	OSL
2	V58T0157A	Hyd 1 LH Inbd Elvn Actr Rtn Ln T	Wing	Glove/P105	OSL
3	V58T0394A	Hyd Sys 3 LOE Rtn Ln T	Wing	Glove/P105	OSL

4	V58T0257A	Hyd 2 LH Inbd Elvn Actr Rtn Ln T	Wing	Glove/P105	OSL
5	V58T0193A	Hyd Sys 1 LOE Rtn Ln T	Wing	Glove/P105	OSL
6	V09T1002A	LH Lwr Wing Skin Temp	Wing	Glove/P105	OSL
7	V09T1024A	LH Upr Wing Skin Temp	Wing	Glove/P105	OSL
8	V51P0570A	MLG LH Outbd Tire Press 1	W-well	W-well/P87	OSL
9	V51P0571A	MLG LH Inbd Tire Press 1	W-well	W-well/P87	OSL
10	V51T0574A	MLG LH Outbd Wheel Temp	W-well	W-well/P89	OSL
11	V51P0572A	MLG LH Outbd Tire Press 2	W-well	W-well/P89	OSL
12	V51T0575A	MLG LH Inbd Wheel Temp	W-well	W-well/P87	OSL
13	V51P0573A	MLG LH Inbd Tire Press 2	W-well	W-well/P89	OSL
14	V51X0125E	LH MLG Downlock Prox	W-well	W-well/P59	State

After the OEX recorder was recovered, attention was shifted to the MADS sensor data that provided 600+ additional pressure, temperature, and strain measurements of interest to the investigation, the first of which (V12G9921A, Left Wing Front Spar Strain) began showing signs of off-nominal performance at GMT 2003/032:13:48:39, approximately 3:38 sec before the first off-nominal OI sensor reading was detected.

The following sections in this report describe each VDM team product and special activity in detail. A complete list of these items is as follows:

- VDM-P01: 3D Full Animation Event Sequence Playback
- VDM-P02: Physical Mockup
- VDM-P03: 3D Graphical Events Sequence
- VDM-P04: 2D Static Storyboard
- VDM-P05: 2D Graphical Events Sequence
- VDM-P06: 3D CAD Modeling
- VDM-P07: Wire Routing / Sensor Placement Reconstruction
- VDM-P08: Events Timeline
- VDM-P09: Instrumentation Listing and Sensor Location
- VDM-P10: Sensor Signal Characterization for Failure Scenario
- VDM-P11: Structure / Installation Drawings
- VDM-P12: Wire Routing Details
- VDM-P13: Closeout Photos
- VDM Team ASA4 Anomaly Assessment
- VDM Team Testing
- VDM Team Leading Edge Wire Run Assessment
- Miscellaneous Tasks

3.1 VDM-P01: 3D Full Animation Event Sequence Playback

Product VDM-P01 is a digital video disk (DVD)-based movie/animation displaying telemetry data from select OI pressure and temperature sensors in the left wing, wheel well, and fuselage areas during entry. As of this writing, rev 2 is the latest version of the DVD, which conforms to rev 15 of the master entry timeline and rev 5 of product VDM-P05 (2D Graphical Events Sequence). As such, all animation sequences run from GMT 2003/032:13:51:00.000 to GMT 2003/032:14:00:31.000. In addition, a total of 39 OI



sensors are depicted in the CAD model used to create this product. A complete list of these sensors is contained in Appendix C. Note that this product does not attempt to visualize specific failure scenario sequences (e.g. hot gas plumes, structural deflections, debris shedding, etc.) due to the complex and speculative nature of these details, although similar computer graphics techniques could be employed for this purpose if desired.

The following key inputs were used to generate this product:

- Product VDM-P04: 2D Static Storyboard (including OI sensor data from the MER)
- Product VDM-P05: 2D Graphical Events Sequence
- Product VDM-P06: 3D Orbiter CAD models
- Product: VDM-P07: Wire Routing/Sensor Placement Reconstruction
- Product VDM-P12: Wire Routing Details
- Master entry timeline

The product contains the following main computer graphics sequences:

- A "flythrough" of the left wing and wheel well areas allowing user familiarization with the vehicle physical configuration and geometry. Wing structure, wire runs and sensors, and wheel-well contents are all depicted in detail. Due to their small size, the sensors called out in the master entry timeline are represented as "balloons." Minor license was taken in the X-Y-Z positioning of the sensor balloons to ensure that they would be visible with the camera angles selected. Callouts and highlighting are employed to identify relevant features.
- A wing plan-form sequence showing the left side of the vehicle, including the fuselage sidewall. When selected, this sequence progresses in real time from a point prior to the onset of anomalous sensor indications during the STS-107 entry. A digital clock supplemented by an analog timeline display indicates current time. Sensor temperature and pressure indications are represented by color changes of the balloons: green representing nominal indications, yellow-orange-red representing increasingly above-nominal indications, and light-medium-dark blue representing below-nominal indications. White and black are used to indicate off scale high (OSH) and OSL, respectively, while gray indicates a sync/data loss. A side view of the Orbiter in an inset window illustrates vehicle attitude and Reaction Control System (RCS) thruster and aerosurface activity (aerosurface positions are exaggerated for visibility), and a simplified ground track plot indicates geographic location. Captions are superimposed to call out significant events from the entry timeline.
- A wheel well close-up sequence providing an enlarged view of the left wheel well, including the landing gear structure, hydraulic lines, and wire runs. The same balloon color change conventions used in the wing plan form sequence are employed here.



 A trajectory/ground track sequence with four sub-windows: one for timeline and caption data, an Orbiter side view comparable to the plan form view, a "gun camera" (camera trailing behind the Orbiter) view to further enhance visualization of Orbiter attitude, and an augmented ground track in aeronautical map format.

A menu on the DVD allows the user to select between these various animation sequences. Standard DVD angle functions allow the user to switch between the wing plan form, wheel well, and trajectory sequences in real time.

The first three sequences described above were created in the Integrated Graphic Operations and Analysis Laboratory (IGOAL) at JSC using an in-house developed application called Enigma, with 3D solid models of the Orbiter created in Pro/Engineer under product VDM-P06 (3D CAD Modeling). The fourth sequence was also created at JSC (with significant technical support from Analytical Graphics, Inc.) using Satellite Tool Kit (STK) software. Special graphics features and unique data intervals related to the use of STK are as follows:

- Animations of the Orbiter's attitude and trajectory over the Earth surface, including RCS and aerosurface activity.
- Separate "gun camera" and "right wingtip" (camera looking towards the Orbiter right side) views.
- Ground track views ranging from simplified maps showing only the Pacific coastline and U.S. state borders to fully detailed aeronautical maps.
- Special captions denoting significant events from the master entry timeline.

Note that all STK features/views are terminated at LOS+5 sec (GMT 2003/032:13:59:37.396), with interpolation used to represent sensor data during the brief communication dropout periods included in the master entry timeline.

The Enigma and STK output files were originated in AVI format. The individual caption, aeronautical map ground track, and STK gun camera and wingtip windows were integrated into one "quad view" window using Discrete Logic Combustion software. Subsequent compression and reformatting to MPEG2 format was performed to support DVD authoring using Spruce Maestro software (with significant technical support from IMC Incite for nonlinear editing).

One of two known issues with the current rev 2 version of the VDM-P01 DVD is that captions were inadvertently omitted from the wing plan form sequence. These captions are present on all other sequences. The other issue is that the color-coding for the Environmental Control and Life Support System (ECLSS) nozzle temperature sensors on the forward fuselage was erroneously scaled. Rev 3 of the DVD is in now in work to correct these two issues, begin earlier in the entry profile (GMT 2003/032:13:48:00.000), and conform to rev 16 of the master entry timeline. However, it still will not contain any MADS sensor data.

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An organized list of all electronic files on the <u>VDM team share drive</u> related to product VDM-P01 and applicable to this report is contained in <u>Appendix C</u>. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report. In the case of product VDM-P01, the product itself is a DVD and all files contained therein are duplicated on the <u>VDM team share drive</u>. As of this writing, the large number of intermediate source files used in creating the DVD are managed individually and do not reside in either location.

3.2 VDM-P02: Physical Mockup

Product VDM-P02 is 1/10 scale physical mockup of the Orbiter left wing that includes major structural components such as wing ribs and spars, wing leading edge (WLE) spars, partial fuselage bulkheads, wheel well and landing gear elements, and wire harnesses associated with select OI sensors. A total of 28 OI sensors are depicted in the mockup, including 8 pressures and 9 temperatures associated with the tires and hydraulic system lines/components in the wheel well; 2 skin temperatures in the wing; 1 bondline temperature on the mid-fuselage sidewall; and 8 hydraulic line/component temperatures in the elevon coves. A complete list of these sensors is contained in Appendix C.

Despite structural elements being present, the mockup does not attempt to present a highly accurate and detailed structural model of the wing. It also does not include wing skin, Thermal Protection System (TPS) components, aerosurface or landing gear actuators, fluid lines, or any MADS sensors and associated wire runs. Instead, the mockup was built early in the investigation when detailed drawings were first becoming available and OI sensor data was initially being analyzed. Therefore, the mockup represents a quick-response solution to providing a reasonably detailed physical model that could be used as an aid to the visualization of major components and key wire harnesses, along with the physical relationships between them.

Several key inputs were used to generate this product:

- Product VDM-P06: 3D CAD Modeling
- Product VDM-P12: Wire Routing Details
- Product VDM-P13: Closeout Photos

The mockup was constructed as follows:

 Prints of the major structural spars and cross sections at the ribs were plotted at 1/10 scale. These prints were applied to 3/16" foam-core single-sided adhesive board. This was cut to finished size using the prints as a guide for their outer shape. Slots were cut at each intersection to allow the ribs and spars to slip together. As updated versions of a spar or rib cross section became available,



the part was re-plotted and affixed to a new board. Then the new part would replace the older part. A functional landing gear assembly was also fabricated using plastic and foam to provide realistic structure for the attachment of select OI sensors.

- Wire runs for OI sensors shown were modeled with a variety of materials, including multicolored micro-gauge wires formed into bundles and 20 gauge insulated wires with color coding that matched the color scheme in use at the time of model construction. The OI sensors depicted on the mock-up include the mockup are referenced in <u>Appendix C</u>.
- For ease of transport, the wing model was built in two sections: from the 1365 spar at the elevon cove to the 1009 spar in the wing glove just forward of the wheel well, and from the 1009 spar to the 807 bulkhead at the wing chine interface.

The resulting mockup was used routinely during meetings, discussions, briefings, and throughout the VDM team investigation process to better visualize physical relationships and potential fluid flow paths through the left wing. The mockup was also provided to the CAIB upon request for temporary use while more detailed and accurate versions were being built to CAIB specifications. These improved mockups used similar construction techniques but slightly different materials, including clear polycarbonate backing for the wing rib sections to improve appearance, fidelity, and handling tolerance. They also included numerous TPS elements and many more sensors, had better internal vent path representations, and went further forward on the vehicle.

An organized list of all electronic files on the <u>VDM team share drive</u> related to product VDM-P02 and applicable to this report is contained in <u>Appendix C</u>. Collectively, these files constitute the product itself or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report.

3.3 VDM-P03: 3D Graphical Events Sequence

Product VDM-P03 no longer exists in the VDM team product flowchart. Its intent is captured by products VDM-P04 (2D Static Storyboard) and VDM-P05 (2D Graphical Events Sequence).

3.4 VDM-P04: 2D Static Storyboard

Product VDM-P04 refers to plots of relevant sensor data coupled with maps of vehicle hardware that emphasize the communication of overall vehicle status information during the last hour of the STS-107 mission. Above all, this product attempts to present the flight data in an unbiased and non-timeline format that is unrelated to any given failure scenario. The finished product consists of the following sub-elements:

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- A five-sheet E-size (34 in x 44 in) poster displaying relevant sensors and associated data plots to illustrate performance trends. The first two sheets (S1, S2), created early in the investigation, contain OI pressure and temperature sensor locations, data plots, and a comparison between left and right sides of the vehicle on STS-107 through LOS. The last three sheets (S3, S4, S5), created later in the investigation after the OEX recorder was recovered, contain MADS pressure, temperature, and strain sensor locations, data plots, wire routings, and a comparison between STS-107 and three other *Columbia* missions (STS-073, -090, -109) through EI+1000 sec. All five sheets use a common color-coding scheme to represent sensor status (nominal, off-nominal, off-line). They also contain one or more applicable vehicle drawings/schematics to aid in visualizing sensor locations and wire runs as known at the time of product release.
- A 40-page booklet (a.k.a. quantitative report) containing similar OI and MADS sensor information to the poster but with more detail including closeout photos, sensor information spreadsheets, 3D CAD model pictures, cable burnthrough timing plots, and data plot grouping based on future analysis efforts.
- Presentation charts containing similar OI sensor information to the poster and booklet but in a concise presentation format. Two sets of charts exist, the first involving various OI sensors through LOS and the second involving the same OI sensors through the post-LOS time period.

Several key inputs were used to generate this product:

- Raw OI and MADS sensor data from the MER
- Product VDM-P06: 3D Orbiter CAD Modeling
- Product VDM-P07: Wire Routing/Sensor Placement Reconstruction
- Product VDM-P09: Instrumentation Listing and Sensor Location
- Product VDM-P12: Wire Routing Details
- Product VDM-P13: Closeout photos
- Master entry timeline

The raw OI and MADS sensor data used to create the P04 product was acquired in electronic form (CSV format) directly from the MER as soon as it became available. The data was then manipulated and plotted (i.e. reduced) by the P04 product team while concurrently identifying/verifying all active sensors on the vehicle. This process was repeated multiple times until confidence in the data sets reached a high level and the product reached its final state of maturity. To ensure accuracy, results were spotchecked by independent reviewers from other VDM product teams through comparison to hardcopy plots created in the MER. In addition to being used directly in the P04 product, the raw and reduced sensor data was also distributed to the following recipients/teams to save time, ensure consistency, and minimize data processing overhead in the MER:



- Product VDM-P01: 3D Full Animation Event Sequence Playback
- Product VDM-P05: 2D Graphical Events Sequence
- Data Review and Timeline Reconstruction Team
- Failure Scenario Team
- Columbia Accident Investigation Board (CAIB)

As of this writing, rev 6 is the latest version of the poster and booklet, and rev 5 is the latest version of the presentation charts, all of which correspond to rev 15 of the master entry timeline.

An organized list of all electronic files on the <u>VDM team share drive</u> related to product VDM-P04 and applicable to this report is contained in <u>Appendix C</u>. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report.

3.5 VDM-P05: 2D Graphical Events Sequence

Product VDM-P05 is a set of presentation charts depicting the overall sequence of events during *Columbia's* entry in a graphical step-by-step manner. The heart of the product is a top-level drawing of the Orbiter, with sensors of interest shown highlighted in their approximate X-Y-Z location and color-coded according to their readings relative to nominal values. Sensor color-coding is as follows, with nominal values defined by the individual subsystem PRT's (with oversight from the Data Review and Timeline Reconstruction Team):

- Green = good sensor with nominal readings
- Yellow = sensor off-nominal high (for temperature, $0^{\circ}F<\Delta T<15^{\circ}F$)
- Orange = temperature sensor is off-nominal high, 15°F<ΔT <30°F
- Shaded Red = temperature sensor is off-nominal high, 30°F<∆T <100°F
- Solid Red = temperature sensor is off-nominal high, ΔT >100°F
- Light Blue = temperature sensor is off-nominal low, ΔT <0°F
- Shaded Blue = sensor has experienced wire damage, readings no longer represent reality
- Solid Blue = sensor has experienced wire damage, readings have gone off scale and no longer represent reality

To provide a more complete view of the Orbiter, the product is separated into two distinct parts. Each part can stand-alone or be combined for greater insight. Part 1 shows the vehicle from above ("plan view" looking at the X-Y plane), including all sensors and wire runs as viewed from that perspective for each event depicted. It also includes a ground track map to show the exact location of the Orbiter above the earth, corresponding altitude and Mach number information, and an indication of how many sensors went offline in each of the three main wire bundles routed through the left wing (i.e. those running down the outboard and forward walls of the wheel well, sometimes

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referred to as bundles A, B, and C). Part 2 shows the vehicle from the port side (side view looking at the X-Z plane), including all sensors and some wire runs for each event depicted in part 1. It also includes an embedded plot of the highlighted sensor's output during a longer portion of the entry profile to give a broader view of trending at that sensor's location. Finally, a three dimensional perspective is shown from behind the vehicle to illustrate vehicle attitude.

Several key inputs were used to generate this product:

- Product VDM-P04: 2D Static Storyboard
- Product VDM-P09: Instrumentation List and Sensor Location
- Product VDM-P10: Sensor Signal Characterization (including the MADS sensor signature database)
- Product VDM-P13: Wire Routing Details
- Master entry timeline

This product went through many revisions, being continually updated as new information became available. Initial versions contained only a few sensors, all of which were OI measurements in the left wing and wheel well showing anomalous behavior during entry. As time passed and more information was obtained, additional sensors and other details were added, eventually expanding the scope of the product to include MADS and OI sensors, key wire runs, aerodynamic events, communication events, and debris events. As of this writing, rev 7 is the latest and intended final version of this product. It utilizes information from master entry timeline rev 17, MADS sensor signature database rev 4, and wire routing details through May 20, 2003.

In its final form, this product provides valuable insight into the sequence of events during entry by allowing a quick flip-through of the charts to visualize: (1) initial heating on the left wing leading edge, (2) heating/burnthrough of the sensor cables routed on the back side of the WLE spar, (3) heating/burnthrough of the sensor cables routed on the outboard and forward walls of the wheel well, (4) temperatures increasing inside the wheel well, and (5) heating/burnthrough of sensor cables routed inside the wheel well.

An organized list of all electronic files on the <u>VDM team share drive</u> related to product VDM-P05 and applicable to this report is contained in <u>Appendix C</u>. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report.

3.6 VDM-P06: 3D CAD Modeling

Product VDM-P06 is a complete solid model representation of *Columbia's* left wing, including wing structure, wheel well structure, main landing gear, hydraulic lines, select OI sensors and associated wire runs, and leading edge reinforced carbon-carbon (RCC) panels. Some areas and features of the mid fuselage are also included. Note that this



model represents the "as-designed" vehicle and does not attempt to recreate the "as-built" configuration, with the exception of certain OI sensor locations that were modified according to inputs from key KSC personnel with first-hand knowledge of the vehicle hardware configuration.

Several key inputs were used to generate this product:

- Product VDM-P07: Wire Routing/Sensor Placement Reconstruction
- Product VDM-P12: Wire Routing Details
- Engineering drawings from the Shuttle Drawing System (SDS)
- Hardcopy engineering drawings

NASA-JSC personnel coordinated the modeling effort. Additional inputs were provided from a variety of different NASA and Boeing organizations as follows:

Contributing Organization	Models Created/Provided
NASA-JSC Structural Engineering	RCC Panels
Division (ES), with assistance from	Spar Fittings
Lockheed Martin support contractors	Wing Spars
	Wing Ribs
	Main Landing Gear
NASA-KSC Shuttle Engineering Group	Wing Wiring
	Main Landing Gear
Boeing-Huntington Beach Structures	Mid Fuselage Structure
Group	Main Landing Gear Door
	Wing Glove Ribs
	Elevon Ribs and Actuators
Boeing-KSC Structures Group	Wheel Well Hydraulics
	Wing Tile
	Carrier Panels
Boeing-KSC Design Visualization Group	Main Landing Gear Uplock Mechanism
NASA-JSC Energy Systems Division	Mid Fuselage Tanks and Fluid Lines
(EP)	
NASA-MSFC	RCC Panel Fittings

The master model exists in Pro/Engineer format and resides in an Intralink database at JSC (Root Folder\Space Shuttle\Accident Investigation\Top Level\V070-000002_012_gen_assy.asm). Mirror sites exist at KSC, MSFC, and Boeing-HB. The overall assembly currently contains over 2000 individual components, models of which have different levels of fidelity. Early on, "envelope" models approximating basic component geometry were built. In some cases these models were sufficient. However, in most cases additional details were later added at the request of the model end-users. Models are named using their part numbers, and the assembly is structured to match the Orbiter drawing tree.

As part of the overall CAD modeling effort, detailed models were created for much of the fluid systems hardware located in the mid fuselage region of the Orbiter. This effort

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was undertaken to develop a better representation of the vehicle in areas of potential interest, particularly those that may have been affected by off-nominal port fuselage sidewall temperatures. Models were developed for the Power Reactant Storage and Distribution (PRSD) tanks and select feedlines, in addition to the Main Propulsion System (MPS) gaseous helium (GHe) tanks and the ECLSS gaseous nitrogen (GN2) tanks located on the port side of the vehicle in mid-fuselage bays 7 though 11. These models were originally intended for integration into the overall vehicle assembly model. However, as it turns out, these components and areas were not of sufficient interest to warrant inclusion of these models.

Another aspect of the CAD modeling effort involved displaying the X-Y-Z locations of numerous OI and MADS sensors on the vehicle. Initial interest focused on OI sensors in the left wing, wheel well, and mid-fuselage areas. A total of 37 OI sensors were modeled as part of this activity, including the 14 sensors (seven left wing, seven left wheel well) that went OSL or unexpectedly changed state during entry prior to LOS. Later, additional OI temperature sensors from "area 40" on the vehicle were modeled after being identified as relatively sensitive external measurements that might provide additional insight into the local thermal environment. A total of 58 OI temperature sensors were modeled as part of this activity. Finally, after the recovery of the OEX recorder, a large number of MADS sensors were modeled based on relevance to the investigation. A total of 615 sensors were modeled as part of this activity, including pressure, temperature, and strain measurements throughout the vehicle. However, seven more sensors of interest were not modeled due to lack of location information.

For both OI and MADS sensors, X-Y-Z locations were obtained from a variety of sources, some of which were incomplete or in conflict with others. Best attempts were made to determine accurate locations when conflicts were present, and multiple checks were made to maximize accuracy of the final product. Although this was a CAD modeling task, the results of the effort relate directly to product VDM-P09 (Instrumentation Listing and Sensor Location) discussed in section 3.9. Accordingly, all files summarizing the sensors modeled and the associated X-Y-Z locations are kept with other VDM-P09 documents.

An organized list of all electronic files on the <u>VDM team share drive</u> related to product VDM-P06 and applicable to this report is contained in <u>Appendix C</u>. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report. In the case of product VDM-P06, all electronic files are in Pro/Engineer format and are maintained in a separate JSC Intralink database.

3.7 VDM-P07: Wire Routing / Sensor Placement Reconstruction

Product VDM-P07 consists of three sets of charts intended to organize and consolidate the large volume of design, installation, functionality, and performance information



related to the *Columbia* investigation that resides on the <u>VDM team share drive</u>. These files emphasize graphical display methods (3D CAD models, wire routing drawings, closeout photographs, etc.) to aid in visualizing hardware installation. Initially, key information was posted on the walls of the VDM team headquarters and incrementally provided to the OVEWG. Subsequently, this information was organized into a set of more detailed "hardware description" charts for distribution to the OVEWG and CAIB.

Several key inputs were used to generate this product:

- Product VDM-P06: 3D CAD Modeling
 - Pro-E integrated CAD model of OV-102 (pulled from JSC Intralink 3/11/03 8:00am)
- Product VDM-P12: Wire Routing Details
 - Boeing-HB plan view wire routing stick drawings (wing1_Rev4.ppt)
 - Boeing-HB wire routing blacklines (wing2part1_rev0.ppt, wing2part2_rev0.ppt, WIRE RUN SKETCH.ppt)
 - o P105 Pinout Rev0 Galvez.ppt
 - Boeing-HB wheel well isometric (wheel well isometric-Rev4.ppt)
 - Boeing-HB wire routing blacklines (V070-796051 LMLG Dark Line Rev4 Pt 1 of 3.ppt)
 - Boeing-HB Wheel Well Plan View (Wing-wheelwell-Rev4.ppt)
- Product VDM-P13: Closeout Photos
 - o OV-102 photographs from the Palmdale Orbiter Major Modification (OMM)
 - o OV-102 KSC close-out photographs from SIMS
- Left wing and wheel well vent and leak path information provided by Boeing-Houston (Maingearwellvent_info3.xls)

An organized list of all electronic files on the <u>VDM team share drive</u> related to product VDM-P05 and applicable to this report is contained in <u>Appendix C</u>. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report. In the case of product VDM-P07, no further revisions of the hardware description charts are planned even though several key inputs, particularly those related to product VDM-P12 (Wire Routing Details), have already been appended or revised.

3.8 VDM-P08: Events Timeline

Due to the importance of the master entry timeline as an input to many of the VDM team products, this product consisted of assigning a VDM team member to be a liaison to the Data Review and Reconstruction Timeline Team. Although no electronic files were created, this product ensured a thorough understanding of the timeline team's products and conveyed VDM team needs, questions, and comments directly to the timeline team.

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3.9 VDM-P09: Instrumentation Listing and Sensor Location

Product VDM-P09 consists of instrumentation system schematics and master measurement lists (MMLs) for all OI and MADS sensors on *Columbia* during STS-107. This information was used as a basic and critical input to many VDM team products, particularly those that involved data plotting, sensor signature characterization and trending analysis, and commonality assessment between measurements. Attributes of primary interest for each measurement included MSID, description, sensor type and X-Y-Z location, power supply and signal conditioner assignments, engineering units and range, sample frequency and most/least significant bit, etc. Since all of this information cannot be found in a single source for OI or MADS sensors, numerous files are used to capture the intent of this product.

Several key inputs were used to generate this product, some of which became part of the product itself due to complexity associated with file and database consolidation:

- For OI sensors:
 - Orbiter Instrumentation Program and Components List (ICPL), Orbiter 102, Flight 28, STS-107, dated 10/29/01
 - Volume one (Equipment List)
 - Volume two (Signal Conditioner and Telemetry Loading List)
 - Volume three (PCM MUX and downlink formats)
 - Electronic database version of the IPCL maintained at Boeing-HB
 - JSC 18366: Operational Instrumentation, Space Shuttle Orbiter, Temperature Measurement Locations, revised January 1992
 - Electronic MML Notebook on Boeing-KSC, NASA Systems website (http://p51.ksc.nasa.gov/aps/mml/)
- For MADS sensors:
 - JSC 23560 Modified for STS-107 (OV-102) Investigation: Modular Auxiliary Data System (MADS) / Orbiter Experiments (OEX) Measurement Locations, dated 4/16/03
- For all sensors:
 - Shuttle drawing system (SDS)

Inconsistencies exist between the items listed above, particularly with respect to sensor X-Y-Z location. Despite this conflict, an attempt was made to document the exact X-Y-Z locations used for sensor placement in product VDM-P06 (3D CAD Modeling) and correlate these placements to their respective sources. As of this writing, a supplemental action external to the VDM team exists to resolve any conflicts and consolidate all attributes mentioned above into a single source.

An organized list of all electronic files on the <u>VDM team share drive</u> related to product VDM-P09 and applicable to this report is contained in <u>Appendix C</u>. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs,



observations, and results/conclusions in much greater detail than this report. In the case of product VDM-P09, some of the files are just electronic versions of the documents mentioned above.

3.10 VDM-P10: Sensor Signal Characterization For Failure Scenario

Product VDM-P10 consists of a failure mode assessment for various OI and MADs sensors and associated signal conditioners on the vehicle. As such, the intent of this product was met through a combination of analysis and testing.

Analysis, described in this section, involved predicting sensor/signal conditioner outputs for a variety of fail-open and fail-short conditions based on a detailed knowledge of instrumentation system hardware configuration and functionality, along with past experience. In this case, efforts focused on a subset of the 14 OI sensors (seven left wing, seven left wheel well) that went OSL or unexpectedly changed state prior to LOS. This subset included five hydraulic system line/component temperatures in the wing and two tire pressures in the wheel well. For the temperatures, OSL readings were only predicted to be possible under certain fail-short conditions. For the tire pressures, OSL readings were predicted to be possible under both fail-short and fail-open conditions.

Testing, described in section 3.15, involved non-destructive open/short tests with actual sensors and flight-like signal conditioners to confirm analytical predictions. It also involved wire burnthrough tests with flight-representative cables, bundles, and harnesses in a variety of environments and configurations to recreate sensor output signatures observed during entry. As also mentioned in section 3.15, testing showed that breakdown in the Kapton insulation on the sensor wires at temperatures beginning at 750 °F produces a gradual decrease in resistance between adjacent conductors in a cable and adjacent cables in a bundle, eventually creating a hard-short condition that results in the predicted and observed OSL outputs.

An important extension of this product involved analyzing and interpreting/characterizing MADs sensor signatures to explain erratic behavior and address concerns about data validity. The primary objective was to establish a single point in time beyond which (or a range of time during which) the data for each relevant MADS sensor can be considered unreliable (a.k.a. "unphysical"). This was accomplished by first segregating the data according to measurement and sensor type. Examples include resistance temperature devices (RTDs) vs. thermocouples for temperature, Statham vs. Kulite transducers for pressure, and full-bridge gauges for strain. Then, failure modes and commonalities between the sensors were examined to explain the data observed. The result of this activity was a spreadsheet (referred to as the MADS sensor signature database) and set of charts to describe and categorize sensor signatures, define sensor commonalities, and identify the point (or range) in time where sensor data is considered invalid.

A further development of this effort involved using the MADS sensor signature database, instrumentation and sensor location data from product VDM-P09, and wire



routing information from product VDM-P12 to correlate MADS sensor failure timing with wire run locations, particularly along the WLE spar. This activity is described in detail in section 3.16.

An organized list of all electronic files on the <u>VDM team share drive</u> related to product VDM-P10 and applicable to this report is contained in <u>Appendix C</u>. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report. Note that all files related to testing are contained in <u>section 3.15</u> and all files related to the WLE wire run assessment are contained in <u>section 3.16</u>.

3.11 VDM-P11: Structure / Installation Drawings

Product VDM-P11 no longer exists in the VDM team product flowchart. Its intent is effectively captured by products VDM-P06 (3D CAD Modeling) and VDM-P07 (Wire Routing / Sensor Placement Reconstruction (Drawings/Photos)).

3.12 VDM-P12: Wire Routing Details

Product VDM-P12 consists of simplified two-dimensional "stick" drawings and detailed three-dimensional "blackline" drawings to document sensor installation, wire routing, and connector pin-out details for all failed and non-failed OI and MADS sensors in the left wing and wheel well. Blackline drawings were created from engineering drawings and engineering orders (EOs) residing in the SDS. Closeout photos taken during *Columbia's* third and most recent OMM (J2) at Boeing-Palmdale were also used to confirm sensor placements and wire routing details.

The task of gathering all the necessary information was broken down into areas and functions. Initial assessment involved the following items:

- Failed and non-failed OI sensors and wiring in the wing
- Failed and non-failed OI sensors and wiring in the wheel well
- Failed and non-failed end-effector power and control wires in the wing
- Failed and non-failed end-effector power and control wires in the wheel well

Significant findings of this initial effort included a determination that all seven OI measurements failing OSL in the wing were contained in a common wire bundle routed along the outboard and forward walls of the wheel well (one of three major bundles, sometimes referred to as A, B, and C). It was also determined that wires for these same sensors were routed through a common connector (P105) in the midbody interface connector panel located in the wing glove area (on the Yo-105 bulkhead between the Xo980 and Xo1009 spars). Other OI sensors not lost but located nearby did not share common wire routings with the failed OSL sensors. Additional indications were that six of the seven affected measurements in the wheel well shared common wire runs to the



wheel well interface connector panel. The seventh measurement shared portions of the same wire run but went to a different connector on the panel.

After the OEX recorder was recovered, the product scope was expanded to include stick drawings for all remaining sensors in the wing plus select blackline drawings of sensor installations and wire routings near the left WLE spar. This last task was necessary to support the Failure Scenario Team. The investigation of MADS sensors was by far the biggest effort of the wire routing team. Upon completion, it consisted of eleven batch files of strain gauge measurements (147 measurements total), seven batch files of wing pressure measurements (80 total), two batch files of wing and Orbital Maneuvering System (OMS) pod temperature measurements (23 total), and one acoustic sensor.

The total effort was divided among numerous engineering groups at KSC, JSC and Boeing-HB. Wire routing information was also used by KSC Orbiter Electrical (OEL) personnel for incorporation into their Pro/Engineer model that depicted key OI sensor wire runs, which was eventually incorporated into product VDM-P06 (3D CAD Modeling).

One interesting observation was that some of the blackline drawings conflict with the closeout photos taken during *Columbia's* last OMM. This is most likely due to flexibility in the way the wiring is installed in the vehicle, which pertains to the accessibility of the intended wire routing and the amount of wire the supporting fixtures (cable clamps, aluminum tape, etc.) can handle.

An organized list of all electronic files on the <u>VDM team share drive</u> related to product VDM-P12 and applicable to this report is contained in <u>Appendix C</u>. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report.

3.13 VDM-P13: Closeout Photos

Product VDM-P13 consists of an organized collection of photos, some available electronically and some not, to help define or confirm structural configurations, sensor locations and installation details, and wire runs applicable to other VDM team products. Where possible, OV-102 closeout photos taken just prior to the STS-107 mission or just after the last OMM (J2) were used as the preferred source of information for this purpose. However, OV-102 original build photos and other vehicle photos were also used as needed, with an acknowledged sense of uncertainty regarding the applicability to OV-102.

The overall photo collection created under product VDM-P13 includes some photos that are available in electronic form and some that are not. Sources of electronic photos include:

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- The USA-KSC Still Image Management System (SIMS) website (http://kscgrndtsk1/SIMS/sims.htm)
- The NASA-KSC Investigation Links website (http://www-launchops.ksc.nasa.gov/etd/Investigation/Links.shtml)

Local copies of particularly relevant photos from these websites also reside on the <u>VDM</u> team share drive. Other photos are available electronically on CD or are available in hardcopy form only. An inventory of all photo items generated and tracked by the VDM team as part of product VDM-P13 is contained in <u>Appendix C</u>. As of this writing, all relevant photos have been retrieved and distributed so no additional work is planned on this product.

3.14 VDM Team ASA4 Anomaly Assessment

The aerosurface servoamplifier assembly #4 (ASA4) anomaly was discovered during review of the OI sensor pre-LOS data, which showed that the channel 4 position feedback signal on the speedbrake began to rise unexpectedly in the last three data samples before LOS, indicating speedbrake opening. However, the commanded and expected position of the speedbrake during entry is closed, as observed prior to this time. Post-LOS data showed the following additional anomalous events:

- Speedbrake position indication was bleeding off towards null.
- Right and left inboard and outboard elevon channel 4 isolation valves went to bypass
- A force fight occurred between channels 1-3 and channel 4 on the left outboard elevon for approximately 2 seconds
- Remote power converters (RPCs) that provide main power (bus A & C) and isolation valve power (bus B) to ASA4 both tripped

Upon discovering these events/conditions, a small group of VDM team members with expertise in flight control hardware, hydraulics, and electrical power distribution and control (EPDC) system hardware performed a root cause assessment for this anomaly. The first task was to gain a thorough understanding of the power/control circuits and functionality of the channel 4 flight control actuators. This was accomplished by mapping the wire routing for these signals and investigating the inner workings of the ASA4 box and associated actuator sensors/transducers. During this process, the following significant details were discovered:

- ASA4 receives DC power from three separate RPCs. Primary power is supplied by main buses A and C "OR'd" together through a diode logic circuit. Isolation valve power is supplied to ASA4 by main bus B.
- Excitation power (26 VAC) to the actuator position feedback and delta pressure transducers is derived internal to ASA4 from the main bus A and C feeds.



- Loss of DC power to ASA4 will cause the fail flags to be raised on all channel 4
 actuators, thus causing the isolation valves to bypass (i.e. release channel 4
 hydraulic pressure within the actuator power valve).
- Loss of excitation power to the actuator position feedback and delta pressure transducers will cause a transition in output to the null value
- Loss of DC power to the isolation valves will prevent valve bypass.
- Excitation wiring to the actuator position feedback and primary delta pressure transducers is separate from equivalent wiring to the secondary delta pressure transducer

After several detailed review meetings and discussions, the team concluded that the most likely events explaining the ASA4 anomaly were as follows:

- Two shorts occurred at approximately the same time due to burning wires between ASA4 and the left outboard elevon actuator
 - The first short involved the AC excitation power wires to the actuator position feedback sensor
 - The second short involved the DC power wires to the isolation valve
- The current-limiting feature of the RPCs feeding the shorts reduced the bus voltage to ASA4 with a corresponding degradation in ASA4 performance and eventual RPC trip
- The shorts combined with degraded performance of ASA4 and tripped RPCs resulted in a loss of AC power to the actuator position sensor and DC power to the isolation valve
 - Position feedback output transitions to null state starting a force fight
 - o Isolation valve fails to bypass and end the force fight before RPC trip

In the end, these events were considered credible and consistent with the behavior of Kapton-insulated wires when exposed to a high heating environment. However, these events occurred very late in the entry timeline, had no negative effects on flight control performance at the time, and were a symptom of a larger problem involving hot plasma flow into the left wing.

An organized list of all electronic files on the <u>VDM team share drive</u> related to the ASA4 anomaly assessment and applicable to this report is contained in <u>Appendix C</u>. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report.

3.15 VDM Team Testing

The VDM team conducted nine separate test programs in support of the *Columbia* investigation. All nine test programs are summarized in this report, with additional test set-up details and test data available in separate reports and briefings contained on the

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<u>VDM team share drive</u> and referenced in <u>Appendix C</u>. Important observations and/or conclusions resulting from each test program are also summarized below.

1. Main Landing Gear Uplock Release Cartridge Auto Ignition Test – ESTA

This test was conducted at the Energy Systems Test Area (ESTA) at JSC. A class III main landing gear uplock release cartridge was placed in a thermal chamber and subjected to increasing temperature at 25 to 30 °F per minute until propellant ignition occurred. Results showed autoignition at 598 °F, far above any temperatures observed in the wheel well during entry.

2. Main Landing Gear (MLG) Proximity Sensor Failure Test – NSLD

This test was conducted at the NASA Shuttle Logistics Depot (NSLD) at KSC. Proximity sensors in each wheel well detect uplock vs. downlock position of the main landing gear. Entry data from these sensors, included in the OI telemetry stream, showed an unexpected change of state from uplock to not-uplock on the left main gear uplock proximity sensor prior to LOS. To examine the failure modes of this sensor and its "proximity box" signal conditioner, a series of tests was run to characterize the output for simulated failures of the sensor cabling. Test conditions included various combinations of hard open circuits, hard short circuits, and soft short circuits for various combinations of conductors in the sensor cabling. Results showed which conditions provide a gear uplock vs. not uplock output. Furthermore, it was determined that a soft short within a particular resistance range could cause a change in indicated output for a "target far" sensor like the one in question, but not for "target near" sensors like those that did not change state in flight. For this reason, it is presumed that the change of state in the left MLG downlock sensor is a false indication resulting from local heating/burning of the sensor wires.

3. Sensor / Signal Conditioner Failure Test – SAIL

This test was conducted in the Shuttle Avionics Integration Laboratory (SAIL) at JSC. Entry data for numerous OI pressure and temperature sensors from before LOS showed unexpected output changes from nominal to OSL, some decaying quickly and others much more slowly. To examine the failure modes of these sensors (or equivalent electric circuits) and the associated signal conditioners, a series of tests was run to characterize the output for simulated failures of the sensor cabling. Test conditions included hard open circuits, hard short circuits, and soft short circuits for various combinations of conductors in the sensor cabling. Results showed those cable failures / combinations of failures that produce a normal, off scale high (OSH), or OSL output. More importantly, it was determined that multiple hard short and hard open combinations could produce an OSL output but always with a step-function signature. A smooth decay as seen in flight could only be produced under variable resistance conditions similar



to those generated in the wire burnthrough tests (to be described in the following sections).

4. Initial Cable Burnthrough Characterization Test (oxygen-acetylene torch) – ESTA

This test was conducted at ESTA at JSC. Early in the STS-107 investigation, evidence from OI sensors indicated a left wing overtemperature condition. Accordingly, a quick test was performed to determine the behavior of Kaptoninsulated cables when subjected to localized heating from a small oxygenacetylene torch. Although this heat source was recognized to be very different than the flight plasma environment, the objective of the test was simply to provide generic data on the behavior of Kapton-insulated cables when rapidly heated. Individual twisted shielded cables and small harnesses consisting of multiple twisted shielded cables were all heated with the torch. Temperature and resistance between conductors within a single cable were measured and recorded. Results from single cable testing showed that a short gradually develops between conductors when heated, with some finite time required for the short to propagate. Based on available literature for Kapton insulation, this behavior is caused by breakdown of the insulation at high temperature as it transitions to being a conductor. Results from the harness testing showed that there can be a significant time delay in the onset of a short circuit for different cables depending on the location within a harness. These factors are presumed to explain the variability in signal decay profile (i.e. time from nominal to OSL) and times at which signal decay began for each sensor.

5. Hot Oven Cable Overtemperature Test (GN2 Environment) - ESTA

This test was conducted at ESTA at JSC. To supplement the initial cable burnthrough test, a hot oven test was performed to characterize the behavior of a longer section of a Kapton-insulated twisted shielded cable when uniformly heated. Single cables were individually subjected to heating in a 12 in long tube oven. Temperature and resistance between the conductors in the cable were recorded. A nitrogen purge was implemented to minimize potential reaction between oxygen and the cable materials at elevated temperature. Heating of the test cables was performed at various rates by adjusting oven settings. Results showed that the short circuit between conductors in a cable initiates at 750 to 950 °F. Results also showed that the propagation time for the short (from essentially infinite resistance to some very low value) was a strong function of heating rate; higher heating rates produced a shorter propagation time. Although this result was qualitative in nature, since heating rates were not actually measured, the observed behavior did relate to the Columbia flight data where sensor failures showed varying times to decay from a nominal reading to OSL. The conductor-to-conductor resistance data from this test was subsequently applied to the sensor calibration curves and results of the SAIL testing to show the predicted vehicle signal conditioner output if the sensor cables were subjected to an overtemperature condition like that simulated in the oven. The

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resulting plots of these simulated flight measurements showed a very similar profile to the flight data.

6. Hot Oven Cable Overtemperature Test (Vacuum Environment) – WSTF

This test was conducted at the White Sands Test Facility (WSTF). Since the offnominal sensor signatures were observed with the vehicle at such a high altitude, portions of the hot oven GN2 test were repeated at vacuum conditions to evaluate any effects of ambient pressure. Again, single Kapton-insulated twisted shielded cables were individually subjected to heating in a long vacuum oven with temperature and resistance between conductors measured and recorded. As expected, results showed the same resistance decay profile as seen during the hot oven tests in GN2, thus supporting previous conclusions.

7. Cable Burnthrough Thermal Model Calibration Test (small propane torch) – ESTA

This test was conducted at ESTA at JSC. Early on in the investigation, the analysis team developed detailed thermal models of Orbiter cables, harnesses (multiple cables), and bundles (multiple harnesses) being impinged upon by hot gas flow. Cable and harness burnthrough testing was subsequently performed to provide engineering data to correlate/calibrate these thermal models. Various Kapton-insulated twisted shielded cables and 40-cable harnesses were heated with a small propane torch from various distances and incident angles to vary the local heat rates. Instrumented metal specimens, consisting of steel rods and tubes to simulate the size and shape of the flight cables and harnesses, were also heated with the torch and used as a calorimeter. Temperature and resistance between conductors within the cables and harnesses were recorded, as were numerous temperatures within the calorimeters. Results were used to support initial development and correlation of the thermal models. However, the small torch size was insufficient to allow testing of a large bundle similar in size to those carrying the sensor signal and excitation wires in the wing and wheel well areas. Therefore, complete thermal model calibration was not yet possible.

8. ESTA Cable and Bundle Burnthrough Test (large propane torch)

To enable additional burnthrough testing on a large wire bundle representative of those being modeled/analyzed on the vehicle, a larger propane torch was used. Test bundles of 1.75 in diameter, consisting of 290 Kapton-insulated twisted shielded cables, were also built from flight spare inventory to simulate the wire bundles routed along the forward and outboard walls of the wheel well. Within each test bundle, temperature and resistance between conductors were measured and recorded on 33 individual cables. These bundles, along with instrumented metal calorimeters built to simulate the size and shape of large bundles, were then individually heated with the torch. Results were used to complete development and correlation of the thermal models.



9. Arc Jet Cable Bundle Failure Test

This test was conducted in the Atmospheric and Reentry Materials Structural Evaluation Facility (ARMSEF) at JSC. During STS-107, many OI and MADS sensors showed anomalies in their output signals, likely related to localized cable heating. In this test, cable bundles simulating those carrying numerous OI and MADS sensor wires on the Orbiter were subjected to hot plasma impingement representative of the entry environment through various sized holes in an aluminum plate. The test bundles were approximately 1.75 in diameter and consisted of 290 separate 24 AWG, Kapton-insulated, twisted, shielded cables secured with flight-like aluminum cable clamps. Within each bundle, 33 separate cables were monitored for changes in conductor-to-conductor resistance as a function of temperature and time.

The general purpose of the test was to gain an understanding of the convective heating environment and associated thermal failure mechanism for the cable bundles routed inside the left wing. The specific objective was to obtain the failure mechanism characteristics, failure initiation time, failure rate, and burnthrough time for a cable bundle subjected to a representative plasma environment. Test results showed that arc jet plume heating could produce the same cable failure mechanism seen in previous torch tests (but much more quickly and dramatically) and the same sensor output signatures seen in flight. They also showed a very rapid erosion of the hole in the aluminum plate with a corresponding increase in cable failure rate. Finally, test-derived heating rate and cable failure rate data can be used to validate thermal models of the vehicle to support failure scenario development for the *Columbia* investigation.

3.16 VDM Team Leading Edge Wire Run Assessment

As an extension of product VDM-P10 (Sensor Signal Characterization for Failure Scenario), a detailed assessment was performed to examine the correlation between MADS sensor failure timing and sensor wire routing. The MADS sensor signature database from product VDM-P10 and wire routing information from product VDM-P12 were both used as inputs to this assessment.

Results of the assessment indicate that all 18 MADS sensors with wires contained in one of the five separate harnesses routed along the left WLE spar (sometimes referred to as A, B, C, D, and E) were lost. Furthermore, 17 out of 18 of these events occurred during a 10 sec time interval (EI+487 sec to EI+497 sec) preceding the loss of any other MADS sensors with different wire routings. The only exception involved four unrelated MADS sensors sharing a common power supply with the failed WLE-routed sensors. These four sensors are presumed to have been lost due to electrical commonality, not wire heating/burning away from the left WLE spar. Finally, wire routing geometry and sensor failure order (top to bottom, outboard to inboard) suggest specific boundaries for left WLE spar burnthrough behind RCC panel 8.



Based on engineering drawings and closeout photos, some uncertainty still exists regarding which sensor wires are contained in which of the five main WLE harnesses. The most notable example involves the WLE spar temperature sensor behind RCC panel 9, which was the last of the 18 WLE-routed sensors to fail and did so even after other MADS sensors in the three main wheel well wire bundles began to fail. Despite this uncertainty, confirmed information about the wire routing still provides strong evidence that a breach in the WLE spar occurred at RCC panel 8, allowing hot plasma to enter the wing.

The product resulting from this assessment is a set of presentation charts containing a tabular summary of all WLE-routed MADS sensors, a 3D CAD picture showing sensor locations and cable routings, closeout photos confirming these routings to the extent possible, and relevant plots of sensor data. This information is kept on the VDM team share drive and is also referenced in Appendix C.

3.17 VDM Team Miscellaneous Tasks

Several miscellaneous tasks were performed by select VDM team members based on expertise in Orbiter propulsion and power subsystems, including the Auxiliary Power Unit (APU); Electrical Power Distribution and Control (EPDC) System; Fuel Cells (FC); Hydraulics/Water Spray Boiler (Hyd/WSB); Main Propulsion System (MPS); Orbital Maneuvering System (OMS); Power Reactant Supply and Distribution (PRSD) System; Pyrotechnic Devices (Pyro); and Reaction Control System (RCS). In particular, hardware inventories and hazard assessments applicable to STS-107 were created to aid the debris recovery teams with hardware identification and handling safety. In addition, pre-flight data records that are not controlled (i.e. organized and stored) in any other configuration management system were identified and impounded, including Pyro acceptance data packages (ADPs) and Space Shuttle Engineering Integration (SSEI) flight readiness statements (FRSs).

An organized list of all electronic files on the <u>VDM team share drive</u> related to the miscellaneous tasks and applicable to this report is contained in <u>Appendix C</u>. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report.

4.0 CONCLUSIONS AND SIGNIFICANT FINDINGS

The VDM team charter included the creation of unique and innovative data display products that aid in understanding the hardware configuration, sensor response data, and complex sequence of events during *Columbia's* entry. Accordingly, the team focused on producing the products defined by the VDM team product flowchart in Appendix A and responding to all related action items listed in Appendix B. All VDM team products have been described in this report. Action items were not discussed but



relate directly to the VDM team products as indicated by the action tracking number and associated closeout files in Appendix B. Since the VDM team was not formally tasked with detailed interpretation of the flight data, significant findings are limited to those areas in which testing or analysis took place to create a product, pursue a special activity, or respond to an action. The resulting list of conclusions and findings is shown below. Most of these items have previously been discussed in this report.

- The VDM team produced seven major products and six supporting data generation/gathering products. Four special activities related to these products and encompassed by the VDM team charter were also pursued. Finally, the VDM team worked 98 formal action items. The content, revision status, and findings of each VDM team product and special activity were previously discussed in this report. As of this writing, only two action items remain open. The first involves plasma impingement testing of flight-representative cable bundles under VDM Team Testing (section 3.15). The second involves production of the latest and expected final revision of product VDM-P01 (3D Full Animation Event Sequence Playback, section 3.1).
- The first OI indications of off-nominal system performance involved a hydraulic line temperature on the inboard sidewall (Yo-105) of the left wheel well (V58T1703A, LMG Brake Line Temp D) at GMT 2003/032:13:52:17. Subsequently, other OI sensors began showing off-nominal trends. Of these, a total of 14 OI measurements went OSL or unexpectedly changed state (starting at GMT 2003/032:13:52:56) prior to LOS, as listed in section 3.0. Seven of these sensors were located in the left wing and seven were located in the left wheel well. All seven in the left wing shared a common wire bundle routed along the outboard and forward walls of the left wheel well. They also shared a common connector panel and connector in the wing glove area (midbody interface connector panel located on the Yo-105 bulkhead between the Xo980 and Xo1009 spars, connector P105). Six of the seven in the wheel well shared a common wire run along the aft wall (Xo1191 spar), ceiling, and forward wall (Xo1040 spar) of the wheel well, with the seventh signal sharing portions of this same run. All seven of these signals shared a common connector panel in the wheel well (wheel well interface connector panel located on the Y-105 bulkhead) but they did not all share a common wire bundle or connector.
- Recovery of the OEX recorder provided 600+ additional MADS pressure, temperature, and strain measurements of interest to the investigation, the first of which (V12G9921A, Left Wing Front Spar Strain) began showing signs of offnominal performance at GMT 2003/032:13:48:39, approximately 3:38 sec before the first off-nominal OI sensor reading was detected.
- Based on analysis and testing performed by the VDM team, nearly all notable OI
 and MADS sensor signatures observed during entry (OI sensors lost OSL or
 unexpectedly changing state before LOS, MADS sensors showing erratic
 behavior then failing OSL or OSH, OI sensors indicating the ASA4 anomaly, etc.)



are consistent with plasma-induced heating/burnthrough and progressive shorting of the associated Kapton-insulated cables, rather than actual events occurring at the location of each sensor. Propagation of the short, as manifested in failure start time and signal decay time, is dependent on cable location within a harness/bundle and local heat flux, with arc-jet plasma impingement tests showing the greatest similarity to flight data.

- Product VDM-P05 (2D Graphical Events Sequence) provides an excellent overall view of the sequence of events that occurred during entry. The format and content of this product allow a quick flip-through of the charts to visualize: (1) initial heating on the left wing leading edge, (2) heating/burnthrough of the sensor cables routed on the back side of the WLE spar, (3) heating/burnthrough of the sensor cables routed on the outboard and forward walls of the wheel well, (4) temperatures increasing inside the wheel well, and (5) heating/burnthrough of sensor cables routed inside the wheel well. When combined with product VDM-P04 (2D Static Storyboard), a comprehensive view of all events and sensor data observed during entry is obtained.
- A comprehensive 3D solid model representation of the Orbiter's left wing was created in Pro/Engineer under product VDM-P06 (3D CAD Modeling). The top-level assembly file contains over 2000 individual components, including wing structure, wheel well structure, main landing gear, hydraulic lines, OI sensors and associated wire runs, and leading edge RCC panels. Additional modeling was performed to show fluid systems hardware located in the mid fuselage area adjacent to the left wheel well, in addition to 37 OI sensors in the left wing, wheel well, and mid-fuselage areas; 58 OI temperature sensors in area 40; and 615 MADS pressure, temperature, and strain sensors throughout the vehicle.
- An extension of product VDM-P10 (Sensor Signature Characterization for Failure Scenario, section 3.10) involved analyzing and interpreting/characterizing MADs sensor signatures to explain erratic behavior and address concerns about data validity. The result of this activity was a comprehensive sensor signature database representing MADS sensor failure signatures and timing. Related work on the leading edge wire run assessment (section 3.16) indicated that all 18 MADS sensors with wires contained in one of the five separate harnesses routed along the left WLE spar were lost. Furthermore, 17 out of 18 of these events occurred during a 10 sec time interval (EI+487 sec to EI+497 sec) preceding the loss of any other MADS sensors with different wire routings. The only exception involved four unrelated MADS sensors sharing a common power supply with the failed WLE-routed sensors. These four sensors are presumed to have been lost due to electrical commonality, not wire heating/burning away from the left WLE spar. Finally, wire routing geometry and sensor failure order (top to bottom, outboard to inboard) suggest specific boundaries for left WLE spar burnthrough behind RCC panel 8.



APPENDIX A: VDM Team Product Flow Chart



APPENDIX B: VDM Team Roster and Action List

NOTE:

Closeout files referenced in the VDM team action list are available in the final report folder on the VDM team share drive and on the final report CD. However, unlike the product document list in Appendix C, embedded hyperlinks to the action closeout files are not present. Instead, base filenames and file extensions are given without regard to revision or date. This was done to minimize action list upkeep as response files were continually being revised. For those files that are common to both lists, hyperlinks to the revision available at the time of this writing can be accessed from the product document list in Appendix C. For those that are not common (with the exception of 100+ MB raw data files associated with product VDM-P04), the base filenames and file extensions can be used to locate a particular document of interest in the final report folder on the VDM team share drive or on the final report CD (or better yet, the related product folder on the VDM team share drive where the latest revisions of all VDM files are kept).



APPENDIX C: VDM Product Files for the Final Report

Product/Activity	Files Applicable to VDM Final Report?
VDM-P01: 3D Full Animation Event	<u>YES</u>
Sequence Playback	
VDM-P02: Physical Mockup	<u>YES</u>
VDM-P03: 3D Graphical Events Sequence	NO
VDM-P04: 2D Static Storyboard	<u>YES</u>
VDM-P05: 2D Graphical Events Sequence	<u>YES</u>
VDM-P06: 3D CAD Modeling	<u>YES</u>
VDM-P07: Wire Routing / Sensor Placement	<u>YES</u>
Reconstruction (Drawings/Photos)	
VDM-P08: Events Timeline	NO
VDM-P09: Instrumentation Listing and	<u>YES</u>
Sensor Location	
VDM-P10: Sensor Signal Characterization	<u>YES</u>
For Failure Scenario	
VDM-P11: Structure / Installation Drawings	NO
VDM-P12: Wire Routing Details	<u>YES</u>
VDM-P13: Closeout Photos	<u>YES</u>
VDM Team ASA4 Anomaly Assessment	<u>YES</u>
VDM Team Testing	<u>YES</u>
VDM Team Leading Edge Wire Run	<u>YES</u>
Assessment	



APPENDIX D: Acronyms and Abbreviations

Acronym/Symbol	Definition
Δ	Delta
2D	2-Dimensional
3D	3-Dimensional
AC	Alternating Current
Actr	Actuator
ADP	Acceptance Data Pack
APU	Auxiliary Power Unit
	Atmospheric and Reentry Materials Structural
ARMSEF	Evaluation Facility at JSC
ASA	Aerosurface Servo Amplifier
AVI	Audio Video Interleave
AWG	American Wire Gauge
CAD	Computer
CAIB	Columbia Accident Investigation Board
CD	Compact Disk
CSV	Comma Separated Variable
DC	Direct Current
DVD	Digital Video Disk
ECLSS	Environmental Control and Life Support System
El	Entry Interface
Elev	Elevon
EO	Engineering Order
EP	Energy Systems Division at JSC
EPDC	Electrical Power Distribution and Control
ES	Structures and Mechanics Division at JSC
ESTA	Energy Systems Test Area at JSC
FC	Fuel Cell
FDM	Frequency Division Multiplexer
FRS	Flight Readiness Statement
GHe	Gaseous Helium
GMT	Greenwich Mean Time
GN2	Gaseous Nitrogen
НВ	Huntington Beach, CA
Hyd/WSB	Hydraulics / Water Spray Boiler
IDI	Information Dynamics, Inc.
IGOAL	Integrated Graphic Operations and Analysis
IGUAL	Laboratory at JSC
Inbd	Inboard
IPCL	Instrumentation Program and Components List
JPEG	Joint Photographic Experts Group
JSC	Johnson Space Center
KSC	Kennedy Space Center



LH	Left Hand
LMLG	Left Main Landing Gear
LMG	Left Main Gear
Ln	Line
LOE	Left Outboard Elevon
LOS	Loss of Signal
Lwr	Lower
MADS	Modular Auxiliary Data System
MEI	Muniz Engineering, Inc.
MER	Mission Evaluation Room
MLG	Main Landing Gear
MML	Master Measurement List
MPEG	Moving Pictures Experts Group
MPS	
MSFC	Main Propulsion System
MUX	Marshall Space Flight Center
NASA	Multiplexer National Aeronautics and Space Administration
NSLD	
	NASA Shuttle Logistics Depot at KSC
OEL	Orbiter Electrical
OEX	Orbiter Experiments
Ol	Orbiter Instrumentation
OMM	Orbiter Major Modification
OMS	Orbital Maneuvering System
OSH	Off-Scale High
OSL	Off-Scale Low
Outbd	Outboard
OVEWG	Orbiter Vehicle Engineering Working Group
PCM	Pulse Code Modulation
Press	Pressure
Prox	Proximity
PRSD	Power Reactant Storage and Distribution
PRT	Problem Review Team
Pyro	Pyrotechnic
RCC	Reinforced Carbon-Carbon
RCS	Reaction Control System
RPC	Remote Power Controller
RTD	Resistance Temperature Detector
Rtn	Return
SAIL	Shuttle Avionics Integration Laboratory
SDS	Shuttle Drawing System
SIMS	Still Image Management System
SSEI	Space Shuttle Engineering Integration
STK	Satellite Took Kit
T	Temperature
TPS	Thermal Protection System



Upr	Upper
USA	United Space Alliance
VAC	Volts AC
VDC	Volts DC
VDM	Vehicle Data Mapping
WLE	Wing Leading Edge
WSTF	White Sands Test Facility



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Volume V Appendix G.6

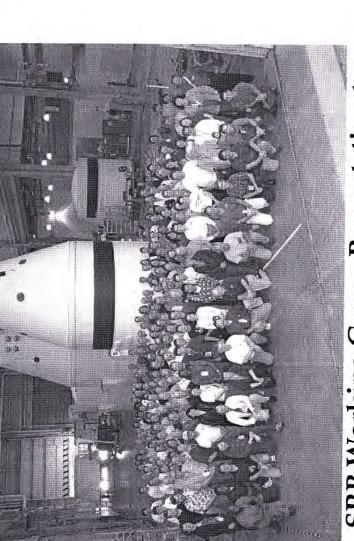
SRB Working Group Presentation to CAIB

This Appendix contains the SRB Working Group Presentation to Columbia Accident Investigation Board, 28 May 2003.



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Solid Rocket Booster Working Group Agenda



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• List of Members, Advisors, Observers, and Others

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Special Circumstances

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Fault Tree Closure Summary

Summary

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Executive Summary

SRB Working Group

Objective

• To Determine if the Solid Rocket Boosters (SRBs) were a contributor to the loss of the STS-107 crew and vehicle.

Approach

- Develop credible Fault Tree failure scenarios for events that could have contributed to the loss of STS-107. Follow structured and methodical approach for closure of all fault tree blocks.
- Perform in-depth hardware and documentation assessment using all available analysis, test, recovered hardware inspection, pedigree documentation, processes, and discrepancy data.

Fault Tree Summary

• 509 blocks (including Top Level block) rolled up into 88 closure blocks

	Total Blocks	Total Blocks Closure Blocks Multi-Element	Multi-Element	Open Blocks
Load & Environments	70	18	1	0
Active Subsystems	14	2	3	0
Debris	424	89	35	4
Total 508	508	88	39	4

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Executive Summary

SRB Working Group

Fault Tree Closure Definitions

- · Closed Fault Tree Blocks in which the event or failure scenario has been deemed Not Credible by the SRBWG.
- "Not Credible" is defined as "Extremely remote possibility that Failure Scenario caused the loss of STS-107. Either strong controls in place or hardware evidence shows event did not occur."
- Open Fault Tree Blocks where SRBWG cannot obtain majority consensus on Failure Scenario being "Not Credible."
- Fault Tree Block B.1.3.2.4.2 (Debris Ejection from Motor (FWD BSM)) Closed (Minority Report)
- Fault Tree Blocks B.1.3.4.4.3.1, B.1.3.4.4.3.2, B.1.3.4.4.3.3, B.1.3.4.4.3.4 (Bolt Catcher) -Open (Pending Test Results)
- Fault Tree Block number B.1.3.6.1.1 (Loss of Aft Separation Area ET Side TPS Causes Transport Analysis from Level II is pending but is related to return-to-flight rather Debris) is closed based on engineering judgment by the SRBWG. Final Debris than fault tree closure..

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COLUMBIA ACCIDENT INVESTIGATION BOARD

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FT Acronym List

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ACO	Assembly Check Out	FT	Fault Tree
AFT	Rear of the spacecraft	FWD	Forward
AMS	Aerospace Material Specification	GNC	Guidance, Navigation and Control
AP	Ammonium Perchlorate	09	Ground Operations
APRT	Ascent Performance and Reconstruction Team	HDI	High Density Indication
APU	Auxilliary Power Unit	HDP	Holddown Post
ATVC	Ascent Thrust Vector Control	ICD	Interface Control Document
BET	Best Estimate Trajectory	IPR	In Process Review
BI	Booster Identifier	JSC	Johnson Space Center
BSM	Booster Separation Motor	KSC	Kennedy Space Center
BTA	Booster Trowelable Ablative	L&E	Loads and Environment
CDF	Confined Detonating Fuse	TCC	Launch Commit Criteria
CDFA	Confined Detonating Fuse Assembly	LH	Left Hand
CDFI	Confined Detonating Fuse Initiator	TOV	Loss of Vehicle
CDFM	Confined Detonating Fuse Manifold	LSBR	Liquid Strand Burn Rate
CIL	Critical Items List	LSC	Linear Shaped Charge
CSD	Chemical Systems Division now known as P&W Space Propulsion	MAF	Michoud Assembly Facility
CWSI	Critical Weld Stress Indicator	MCC-1	Marshall Convergence Coating - I
DAS	Data Acquisition System	MET	Mission Elapsed Time
DCMA	Defense Contract Management Agency	MLP	Mobile Launch Platform
E&I	Electrical and Instrumentation	MLP	Mobile Launcher Platform
ECP	Engineering Change Proposal	MPP	Manufacturing Process Plan
ECR	Engineering Change Request	MSFC	Marshall Space Flight Center
ED	Engineering Directorate	NDE	Nondestructive Evaluation
EMI	Electromagnetic Interference	NIS	Nonconformance Information System
SSD	Electrostatic Discharge	NSD	NASA Standard Detonator
ET	External Tank	ISN	NASA Standard Initiator
ETA	External Tank Aft	NSI-PC	NASA Standard Initiator - Pressure Cartridge
FEM	Finite Element Mode	OMI	Operations and Maintenance Instructions
FEM	Finite Element Model	OMRSD	Operations and Maintenance Requirement Specification Document
FEP	Fluorinated Ethylene Propylene	P&W	Pratt and Whitney
FIV	Fuel Isolation Valve	PDL	Polymer Development Labs
FMEA/CIL	Failure Mode and Effects Analyses/Critical Items List	PIC	Pyrotechnic Initiator Controllers
FOD	Foreign Object Debris	PR	Problem Report
SO	Factor of Safety	PRCBD	Program Requirements Change Board Directive
·SM	Fuel Supply Module	PSC	
			Dogo

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COLUMBIA ACCIDENT INVESTIGATION BOARD



Executive Summary

SRB Working Group

Acronym List

Reaction Control System

Right Hand ROD

Routing Operation Document

Redesigned Solid Rocket Motor RSRM RSS

Range Safety Systems

Room Temperature Vulcanizing

RTV S&A SIRB

Safe and Arm

Systems Integration Requirement Board

Shelf Life Extension Test Super Light Ablator SLET SLA

Solid Rocket Booster Tracking Subsystem Solid Rocket Booster SRB

SRBTS

Solid Rocker Booster Working Group SRBWG

Space Shuttle Main Engine Solid Rocket Motor SSME SRM

Space Shuttle Program Thrust Load Indicator SSP ITI

Thermal Protection System Fail Service Mast LSM IPS

Jnited Space Alliance Thrust Vector Control IVC

United Space Booster, Incorporated Vehicle Assembly Building USBI VAB

Work Authorization Documents WADS

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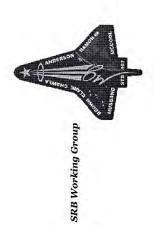
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Note: The symbol 📗 indicates a link to back up information.

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SRB Working Group

Solid Rocket Booster Working Group **Team Members**

SRB Working Group (NASA Team)

Darrell Davis

loe B. Davis

Pyrotechnics

Thermal

Structures

Jeff Dilg Don Ford

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SRBWG Deputy Chair and Assistant Project

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Mechanics and Thermal Department

BSM

Randall Tucker George Story

Renee Wilson

S&MA

SRBWG Secretary

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ACCIDENT INVESTIGATION BOARD



SRB Working Group

Review and Assessment

Chantel Jacob Peggy Frazier Mike Norris

Systems Fault Tree Review Team

Richard Sheppard John Townsend Dan Mullane foe Brunty

DCMA Key Players

Robert Kauffman Terence Young Norm Powers Mike Smutek Dave Kedell Ron Koehn Tom Root Robert Kaufmann Carlos de Mattos Myles Campbell foe Giedlinski Jim Anderson Primo Correa Craig Bennett

NASA S&MA MSFC and KSC

Robert Osterblum Rick Sizemore Art Morales Shane Canerday Foster Anthony Neal Hooten

NASA MSFC SRB Resident Office at KSC

Homero Hidalgo Robin Ferebee Sandy Norris Tom Engler

Other Key Players

SRBWG Senior Advisory Group

Erich Engler(retired), Former Chief, Structural Development Branch, Vince Caruso(retired), Former Manager, Systems Management and Bob Henry (retired), Former Senior Technical Assistant to the Chief Keith Coates (retired), Former Chief Engineer, Solid Rocket Motor Bill Horton(retired), Former Chief Engineer, Solid Rocket Booster Integration Office, Space Shuttle Main Engine Engineer, Solid Rocket Booster Program Science and Engineering Directorate Program Program

Senior Independent Review

Moody Davis(retired), Former Manager, Testing and Operations Office, Chief Engineer's Office, Solid Rocket Motor Program

Jim Thomas(retired), Former Manager, Technical Operations Office, Solid Rocket Motor Program

Fault Tree Independent Review

Robert Schwinghamer(retired), former Assistant Center Director -Technical, MSFC Page 9

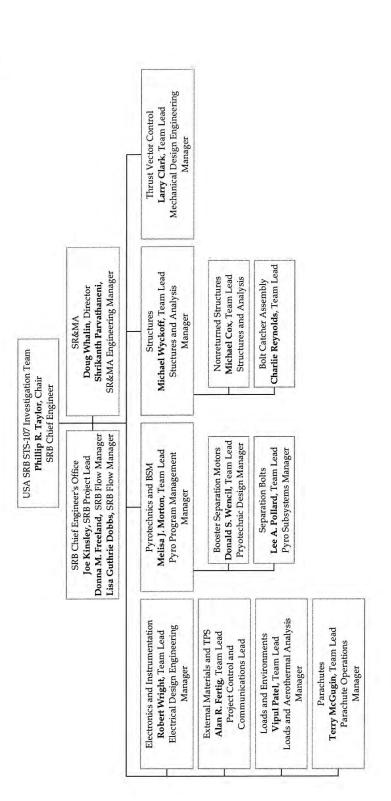
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NASA

Solid Rocket Booster Working Group Team Members

SRB Working Group

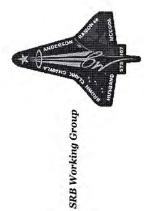
USA Investigation Team Leads/Key Players



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Special Circumstances

Investigation Process

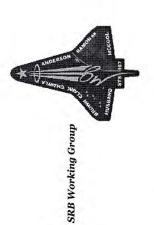
Fault Tree Closure Summary

Summary

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CAB093-0012

Special Circumstances



Hardware Status As of February 1, 2003:

- Open Assessment of STS-107 SRB/RSRM Hardware Completed on 1/20/03
- The SRB/RSRM Disassembly Schedule Was Nearly Complete
- Refurbishment Was in Work
- USA Post Flight Assessment Team Performed Initial Thorough Assessment of Hardware
- Hardware as it was in the Disassembly and Refurbishment SRBWG Reviewed Post Flight Data and Photography plus

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Solid Rocket Booster Working Group Agenda

SRB Working Group

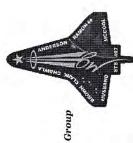
- Executive Summary
- List of Members, Advisors, Observers, and Others
- Method of Investigation
- Special Circumstances
- Investigation Process
- Fault Tree Closure Summary
- Summary

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Investigation Process

SRB Working Group



SRB Hardware classified into two categories

Retrieved Hardware

Post-Flight Assessment

SRBWG Philosophy:

"All Hardware is

- SRBWG Re-Assessment
- Video and Photography
- 10MNL-0035 Requirements Document Flight Loads Analysis/Flight Data

Proven Innocent."

Guilty until

John Key

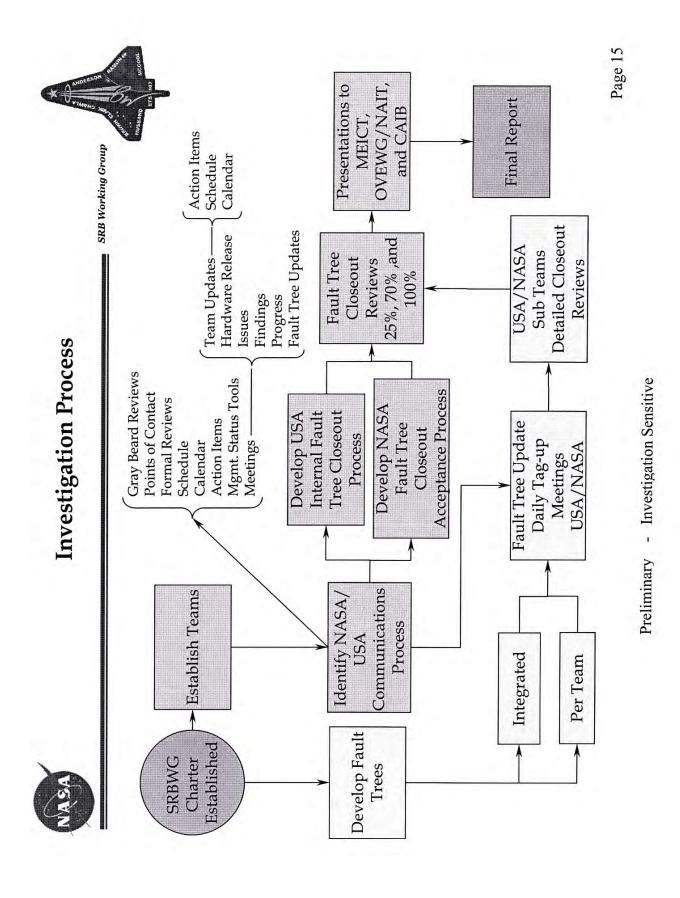
Non-Retrieved Hardware

- Video and Photography
- Comparison to Retrieved Hardware with Equal Processing
 - Flight Data (DAS, Telemetry)
- Occumentation Assessment Including:
- As-designed vs. As-Built
- Engineering Changes Affecting STS107
- Problem Reports/Squawks/Non-Conformances
 - SRB Build-up and Consumables
- Ground Operations Build-up Documents
 - NASA ALERTS
- Hazard Analysis and CIL Correlation
- SRB Waiver List Review

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Investigation Process



Operational Experience and Design Limits

- Knowledge of both existing data base and design limits (overall and second-by-second) needed to understand hardware performance
- Each Shuttle flight adds to our knowledge and experience base
- planned activities to understand the "what", "how" and "why" of event. Deviations/Exceedances from the experience base result in executing

Fault Tree Development

Fault Tree developed and checked against Hazards Analysis and Critical Items List (CIL)

Independent Reviews

- Senior Advisory Group
- 2 Reviews for Fault Tree Development
- 3 Reviews for Closure Development
 - 2 Final Presentation Reviews
- MSFC Systems Team 1 Fault Tree Development Review

SRBWG Fault Tree mapped to MEIC/Systems and CAIB Fault Tree

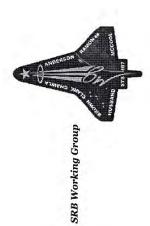
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Investigation Process



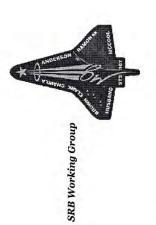
Fault Tree Closure Process

Closure Rationale Developed jointly by USA/SRBWG/DCMA

- USA Teams provided initial write-up
- Including input from SRBWG members and DCMA
 - USA SRB Chief Engineer Office Review
- SRBWG Chairman/MSFC S&MA performed individual one-on-one reviews with USA team lead and SRBWG discipline/hardware lead for each closure sheet
- Entire SRBWG and SRB Project Personnel performed final closeout review on each closure sheet. DCMA present at each closure discussions.



Solid Rocket Booster Working Group Agenda



- Executive Summary
- List of Members, Advisors, Observers, and Others
- Method of Investigation
- Special Circumstances
- Investigation Process
- Fault Tree Closure Summary
- Summary

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Solid Rocket Booster Working Group Fault Tree Multi-Element Blocks



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B.1.0						
		B.1.3	6.			
B.1.3.2	B.1.3.3	B.1.3.4	B.1.3.5	B.1.3.6	B.1.3.7	
B.1.3.2.4.3.F		B.1.3.4.B		B.1.3.6.1	B.1.3.7.A	
		B.1.3.4.2.D		B.1.3.6.2	B.1.3.7.1.D	
		B.1.3.4.2.G		B.1.3.6.2.3.1.E	B.1.3.7.1.E	
		B.1.3.4.4		B.1.3.6.4	B.1.3.7.1.G	
		B.1.3.4.4.1.1	1	B.1.3.6.4.1	B.1.3.7.2	
		B.1.3.4.4.2.1.1.E	1.1.E		B.1.3.7.4	
		B.1.3.4.4.2.1.2.1.E	1.2.1.E		B.1.3.7.6	
		B.1.3.4.4.2.1.2.2.E	1.2.2.E			
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B.1.3.1

B.1.1.2

B.1.1.1

B.1.1

B.1.3.1.3.E

B.1.3.4.4.2.1.3.E

B.1.2.2

B.1.2.1.A B.1.2.1

B.1.2.1.E B.1.2.1.F

B.1.2

B.1.3.4.4.2.2.1.E B.1.3.4.4.3.2.C B.1.3.4.4.2.3.E B.1.3.4.4.3.1.C

B.1.3.4.4.3.2.2.D B.1.3.4.4.3.3.E

B.1.3.4.4.3.4.E

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Solid Rocket Booster Working Group SRBWG-to-MEICT Mapping



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Working Group	0790
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G649	1.3.6.1 1.3.6.1.1 1.3.7.1
_	B. B.

C649	B.1.3.6.1	B.1.3.6.1.1	B.1.3.7.1
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B.1.3.4.4.2 B.1.3.2.4.3

B.1.3.1

B.1.3.6.4.1.B

B.1.3.4.4.1.A B.1.3.4.4.1.B

G525

B.1.3.6.4.1.2 B.1.3.6.4.1.1

B.1.3.7.A

B.1.3.7.B

B.1.3.7.1

B.1.3.4.4.2

B.1.3.2.4.A B.1.3.2.4.1 B.1.3.2.4.2 B.1.3.2.4.3 B.1.3.2.4.4

B.1.3.2.2 B.1.3.2.1

B.1.3.5.A B.1.3.5.B B.1.3.5.C

B.1.3.6.5

B.1.3.4.4.1.1.B B.1.3.4.4.1.1.A

B.1.3.2.A B.1.3.2.B

B.1.3.1.1

B.1.3.4.4.1.1.1 B.1.3.4.4.1.1.2

G526

B.1.3.6.2

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L	

G527

B.1.3.7.1.1.A B.1.3.7.1.1.B

B.1.3.7.2.B B.1.3.7.2.M B.1.3.7.2.S

B.1.3.7.2

B.1.1.1.1	B.1.1.2.3.1.2.2
B.1.1.1.2.A-G	B.1.2.1, B.1.2.2
B.1.1.2.A	B.1.3.4.4.1.1.1
B.1.1.2.B	B.1.3.4.4.1.1.2
B.1.1.2.1	B.1.3.4.4.1.1.A
B.1.1.2.1.D	B.1.3.4.4.1.1.B
B.1.1.2.2	B.1.3.6.4.1.1
B.1.1.2.3	B.1.3.6.4.1.2
B.1.1.2.3.1.1.1	B.1.3.6.4.1.A
B.1.1.2.3.1.1.2	B.1.3.6.4.1.B
B.1.1.2.3.1.2.1	

B.1.3.6.4.1.	B.1.3.6.4.1.]	B.1.3.6.4.A	B.1.3.6.4.B	.1 B.1.3.7.A	.2 B.1.3.7.4.1	.A B.1.3.7.4.2	1.B B.1.3.7.B	A B.1.3.7.2	B.1	B.1.3.7.2.M	B.1.3.7.2.S	B.1.3.7.6.A	
B.1.3.5.1	iω	B.1.3.4.B	B.1.3.4.2	B.1.3.4.4.1.1	B.1.3.4.4.1.1	B.1.3.4.4.1.1	3.4.4.1.	B.1.3.4.4.1.A	B.1.3.4.4.1.B	B.1.3.4.4.2	B.1.3.6.A	B.1.3.6.2	B.1.3.6.4.1.1

B.1.3.7.6.A B.1.3.7.6.B

B.1.3.6.3.G

B.1.3.6.4.1.A

B.1.3.4.3

B.1.3.6.4.B B.1.3.6.4.A

B.1.3.4.2.N

B.1.3.4.2.M B.1.3.4.2.C

B.1.3.7.5

B.1.3.7.4.1 B.1.3.7.4.2

B.1.3.6.1.1

B.1.3.6.1

B.1.3.4.B

B.1.3.4.1

B.1.3.4.A

B.1.3.6.2 B.1.3.6.3

B.1.3.4.1.1

B.1.3.4.2

B.1.3.7.3

B.1.3.6.A B.1.3.6.B

B.1.3.3

B.1.3.5.2 B.1.3.5.1

B.1.3.2.5

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Solid Rocket Booster Working Group Fault Tree Multi-Element (1 of 5)

SRB Working Group

111	The Comment of the Co	
F1 Cause ID#	Fault Tree (FT) Block Name	Level 2
B.1.1	Anomalous Loads and Environments on SRB Adversely Affect Mission, Vehicle & Crew	G499/G814
B.1.1.1®	Extreme Environments Adversely Affect SRB or SRB/ET Interface	
B.1.1.1.	Extreme Natural Environments Adversely Affect SRB or SRB/ET Interface	
B.1.1.2.A	Adverse Effects From Conducted or Radiated Electro Magnetic Interface (EMI)	
B.1.1.1.2.B	Adverse Aerothermal Effects During Ascent	
B.1.1.1.2.C	Adverse Vibro-Acoustic Effects While on Pad or During Ascent	
B.1.1.1.2.D	Adverse Vehicle Dynamics Effects While on Pad or During Ascent	
B.1.1.1.2.E	Adverse Aerodynamic Effects During Ascent	
B.1.1.2.F	Improper Venting During Ascent	
B.1.1.1.2.G	Pryo Shock While on Pad or During Ascent	
B.1.1.2®	Anomalous Loads Adversely Affect SRB or SRB/ET Interfaces	
B.1.1.2.1	Anomalous Loads During Prelaunch Operations	
B.1.1.2.1.D	Adverse Loads Induced by SSME Thrust Build Up	
B.1.1.2.A	Anomalous Induced Loads Caused by Holddown Stud Hangup	
B.1.1.2.2	Anomalous Loads During Ascent	
B.1.1.2.B	Anomalous Loads During Liftoff	
B.1.1.2.3	Anomalous Loads During Booster Separation	
B.1.1.2.3.1.1.1	Premature Ignition (Aft BSM)	
B.1.1.2.3.1.1.2	Low/Inadequate Thrust Output for any Two BSMs (Aft BSM)	
B.1.1.2.3.1.2.1	Premature Ignition (Forward BSM)	
B.1.1.2.3.1.2.2	Low/Inadequate Thrust Output for any Two BSMs (Forward BSM)	

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SRB Working Group Solid Rocket Booster Working Group Fault Tree Multi-Element (2 of 5)

FT Carree ID#	Family Trace (ET) Rivers	
" Transati	radii rice (1.1) Dioen indiile	Fevel 7
B.1.2.1	Anomalous Electrical & Instrumentation Subsystem Performance	
B.1.2.1.A	Anomalous SRB/ET Separation Performance	G499/G814
B.1.2.1.E	Anomalous SRB Guidance, Navigation & Control Performance (Rate-Gyro)	G499/G814
B.I.2.1.F	Anomalous SRB Electrical Power/Data Cable Performance	G499/G814
B.1.2.2	Anomalous Thrust Vector Control (TVC) Subsystem Performance	G499/G814
B.1.3.1	Nose Cap Assembly Damage/Malfunction Causes Debris	
B.1.3.1.3.E	Overload [Nose Cap Fastener]	G524/G526
B.1.3.2. ®	Frustum Assembly Damage/Malfunction Causes Debris	
B.1.3.2.4.3.E	Aerodynamic Loading Causes Debris	G524/G526

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G524/G526

Solid Rocket Booster Working Group Fault Tree Multi-Element (3 of 5)

B.134.8 [Conserd Skirt Assembly Damage/Malfunction Causes Debris Stirt] B.134.8 [Loss of Elec. Breakaway Cables & Connector Components (Sep. Plane) Causes Debris Stirt] B.134.2 [Loss of Floward Skirt/RSRM Interface Hardware Causes Debris Loss of Forward Skirt/RSRM Interface Hardware Causes Debris Loss of Fwor ET Attach Components Causes Debris Loss of Fwd. ET Attach Components Causes Debris B.134.4.1.8 [Loss of Fwd. ET Attach Components Causes Debris B.134.4.1.8 [Loss of Fwd. ET Attach Components Causes Debris Debris Due to Premature Separation B.134.4.1.1 [Consider of Fracture Plane Causes Debris B.134.4.1.1. [Consider of Fracture Fracture (ET side)] [Consider of Fracture Fracture Fracture (ET side)] [Consider of Fracture Fracture Fracture Fracture (ET side)] [Consider Fracture	FT Cause ID#	Fault Tree (FT) Block Name	Level 2
A A A A A A A A A A A A A A A A A A A		vard Skirt Assembly Damage/Malfunction Causes Debris	
A B B B A.1.1.A A.1.1.B I.4.1.1.1 I.4.1.1.1 I.1.E I.2.1.E I.3.E I.3.E I.1.C I.		Loss of Elec. Breakaway Cables & Connector Components (Sep. Plane) Causes Debris [Fwd Skirt]	G524/G526
A B B 1 1 1 4.1.1.A 4.1.1.B 1.1.1.E 1.1.1.E 1.2.2.E 1.2.C 2.C 2.C 2.C 3.E		of Thrust Post Attach Components Causes Debris	G524/G527
A B B B B B 11 1.1.1.A 1.4.1.1.1 1.4.1.1.2 1.1.1.E 1.2.2.E 1.1.3.E 2.1.1.E 3.3.E 3.3.E 3.3.E 3.3.E 3.3.E 3.3.E 3.3.E		of Forward Skirt/RSRM Interface Hardware Causes Debris	G524/G527
1.1.A 1.1.B 1.1.B 1.1.E 1.E 2.2.E 2.2.E 2.2.E C C C C C		of SRB Fwd Crossover Components Causes Debris	G524/G527
De D		of Fwd. ET Attach Components Causes Debris	G524/G527
11.1.4 Fa 1.1.1.8 Re 1.1.1.1 M. 1.1.1.1 M. 1.1.1 M. 1.1.1.1 M. 1.1.1.1 M. 1.1.1.1 M. 1.1.1.1 M. 1.1.1.1 M. 1.1.1 M. 1.1.1.1 M. 1.1.1.1 M. 1.1.1.1 M. 1.1.1.1 M. 1.1.1.1 M. 1.1.1 M. 1.1		ris Due to No Separation	
11.1.8 Re 11.1.1.1.1.8 Re 11.1.1.1.1.1.8 Re 11.1.1.2 M. 11.1.1.1.2 M. 11.1.1.2 M. 11.1.1.2 Ov C C C C C C C C C C C C C C C C C C		ris Due to Premature Separation	
A: A: B:		ris Due to Improper Separation	G499/G814
H		ure Outside of Fracture Plane Causes Debris	
	_	ontact Causes Debris	
		erial Defects Causes Debris	
	B.1.3.4.4.1.1.2 Man	infacturing Defect Causes Debris	
		rload [RSS Crossover Fastener]	G524/G526
		rload [RSS Crossover Disconnect Housing]	G524/G526
	Ó	rload [RSS Crossover Subparts]	G524/G526
		rload [RSS Crossover Gimbal Cover]	G524/G526
	Ó	rload [RSS Crossover Fastener (ET side)]	G524/G526
D E E O		rload [RSS Crossover Gimbal Cover Fastener]	G524/G526
D Ex O		rload [Bolt Catcher Attach Fastener]	G524/G526
D Ex		ssive Aerodynamic Loading	G524/G526
Ó		ssive Force From Separation Bolts	G524/G526
	Ŏ	rload [Bolt Catcher ET Thrust Fitting or Inserts]	G524/G526

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Excessive Separation Bolt Loading Causes Debris

B.1.3.4.4.3.4.E

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ASA

Solid Rocket Booster Working Group Fault Tree Multi-Element (4 of 5)

FT Cause ID#	Fault Tree (FT) Block Name	Level 2
B1.3.5 ®	Tunnel Cover/Floor Plate Assembly Damage/Malfunction Causes Debris	G524/G527
B.1.3.5.1	Loss od Thermal Protection System (TPS) Causes Debris [Tunnel Cover/Floor Plate Assembly]	
B.1.3.5.A	Structural Damage to Tunnel Cover Assembly Caiuses Debris	
B.1.3.5.B	Loss of Electrical Cables and Connector Components causes Debris [Tunnel Cover/Floor [Plate Assy]	
B.1.3.5.2	Loss of Tunnel over/Floor Plate Components Causes Debris (SRB/RSRM)	
B.1.3.5.C	Improper Operation of Pyrotechnic Components Causes Debris [Tunnel Cover//Floor Plate Assembly]	
B.1.3.6 ®	ETA Ring/Aft Attach Strut Assembly Damage/Malfunction Causes Debris	
B.1.3.6.A	Loss of Elec. Breakaway Cables & Connector Components (Sep. Plane) [ETAR/Aft Attach Strut Assy]	G524/G527
B.1.3.6.1	Loss of Thermal Protection System (TPS) Causes Debris [ETAR/Aft Attach Strut Assy]	G524/G649
8.1.3.6.2	Aft Strut Component Failure (ET Strut Half)	G524/G527
B.1.3.6.2.3.1.E	Overload [Aft Strut ET Fastener]	G524/G526
B.1.3.6.4	Aft Separation Bolt Components Causes Debris	G524/G527
B.1.3.6.4.A	No Separation Causes Debris	
B.1.3.6.4.B	ETA Ring Structural Failure	
B.1.3.6.4.1	Improper Separation Causes Debris	G499/G814
B.1.3.6.4.1.A	Failure Outside of Fracture Plane Causes Debris	
B.1.3.6.4.1.B	Recontact Causes Debris (Strut Half)	
B.1.3.6.4.1.1	Material Defects Causes Debris	
B.1.3.6.4.1.2	Manufacturing Defect Causes Debris	

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COLUMBIA ACCIDENT INVESTIGATION BOARD

Solid Rocket Booster Working Group Fault Tree Multi-Element (5 of 5)

SRB Working Group

	Loss of Holddown Hardware Causes Debris (includes Stud Washer, Nut & Breaklink Nut)	B.1.3.7.6.C
	Loss of GN2 Purge Line Assembly Causes Debris	B.1.3.7.6.B
	Loss of Aft Skirt Shoe Hardware Causes Debris (includes Shims and Ground Straps)	B.1.3.7.6.A
G524/G527	Loss of MLP Holddown Components Causes Debris	B.1.3.7.6
	Improper Operation of Booster Separation Motor Ignition Components	B.1.3.7.4.2
	Improper Operation of SRB/MLP Holddown Release	B.1.3.7.4.1
G524/G527	Improper Operation of Pyrotechnic Components Causes Debris [Aft Skirt]	B.1.3.7.4
G524/G527	Loss of Aft Skirt Components Causes Debris	B.1.3.7.2
G524/G649	Loss of RTV133/RTV108 From Aft Skirt Assembly Causes Debris	B.1.3.7.1.G
G524/G649	Loss of BTA without Hypalon From Aft Skirt Assembly Causes Debris	B.1.3.7.1.E
G524/G649	Loss of RT455 without Hypalon From Aft Skirt Assembly Causes Debris	B.1.3.7.1.D
G524/G527	Aft Skirt Assembly Structural Failure Causes Debris	B,1,3,7,B
G524/G527	Loss of Electrical Breakaway Cables & Connector Components (Separation Plane) [Aft Skirt]	B.1.3.7.A
	Aft Skirt Assembly Damage/Malfunction Causes Debris	B.1.3.7 ®
Level 2	Fault Tree (FT) Block Name	FT Cause ID#

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COLUMBIA ACCIDENT INVESTIGATION BOARD

Fault Tree Block Presentation Sequence

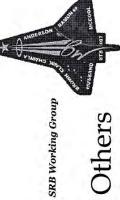
SRB Working Group

File #	Block ID.	Order of Presentation	Number of Closure Sheets	Title or related areas
File #1	B.1.1	9	18	Anomalous Loads and Environments on SRB Adversely Affect Mission, Vehicle and Crew
File #2	B.1.2	7	2	Anomalous Performance of Active Subsystems
File #3	B.1.3.1	5	2	Nose Cap Assembly Damage/Malfunction Causes Debris
File #4	B.1.3.2 B.1.3.3	2	111	Frustum Assembly Damage/Malfunction Causes Debris, Parachutes
File #5	B.1.3.4	1	20	Forward Skirt Assembly Damage/Malfunction Causes Debris
File #6	B.1.3.5 B.1.3.6	4	19	Tunnel Cover/Floor Plate, ET Attach Ring and Aft Attach Strut Cause Debris
File #7	B.1.3.7	3	16	Aft Skirt Assembly Damage/Malfunction Cause Debris
File #8				Executive Summary/Presentation
		L	Total 88	

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Solid Rocket Booster Working Group Agenda



• List of Members, Advisors, Observers, and Others

- Method of Investigation
- Working Group Organization
- Special Circumstances
- Investigation Process
- Fault Tree Closure Summary
- Summary

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Summary



- Individually or as a Sub-Block to a Higher Level Closure Sheet. All Multi-Element Fault Tree Blocks Have Been Addressed
- All SRB Systems Performed Nominally within Specifications and with No Unexplainable Experience-Base Deviations.
- Solid Rocket Boosters are Known STS Debris Generators:
 - All Debris Generating Events Have Been Identified
 - Debris at Liftoff
- Debris during Flight
 - Debris at Separation
- Debris after Separation
- Four Bolt Catcher Fault Tree Blocks Remain Open until after Testing is Complete (Estimated Completion 6/9/03).
- Investigation Results Thus Far Indicate SRBs did not Cause Loss of

SRB Launch through Recovery Environments

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Volume V Appendix G.7

Starfire Team Final Report, Jun 3, 2003

This Appendix contains NSTS-37379 <u>Starfire Team Final Report in Support of the Columbia Accident Investigation, 3 June 2003</u>.



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NSTS-37379



Starfire Team Final Report

in support of the Columbia Accident Investigation

June 3, 2003

Submitted by:

/s/ Douglas White	
Douglas White, USA	
Team Leader	

/s/ Kandy Jarvis
Kandy Jarvis, LMSO
Team Member

Dewey Houck, Boeing Karen Watts, USA Julian Christou, CFAO Robert Fugate, SOR Maj. Robert Johnson, USAF Rick Cleis, SOR Roger Petty, SOR Rich Rast, SOR













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Executive Summary

The Starfire Team was created in support of the STS-107 Orbiter Vehicle Engineering (OVE) investigation effort. The team's charter was to review imagery, both still photography and video taken at the Starfire Optical Range (SOR) at Kirtland Air Force Base in New Mexico, in order to determine the state of the orbiter at that time in its re-entry.

As part of this investigation about 18,800 video frames and 3 digital stills were reviewed and a small portion of these were processed and analyzed. All were categorized as to potential return of information regarding the condition of the orbiter. A total of ten anomalous optical signatures (AOS) were identified and images associated with these signatures were processed to some degree. An AOS here is considered to be a visual appearance of the orbiter containing a characteristic that appears irregular; i.e., lack of symmetry, pulsation, scintillation. Difficulties arose due to motion blur related to the relative motion of the orbiter and camera, failure to track due to relative angular velocity, lack of comparative nominal condition images, saturation of images, and lack of resolution. In some cases these difficulties were prohibitive in determining a conclusion regarding the condition of the orbiter.

Of the ten AOS, two were concluded to be nominal (with the understanding an off-nominal condition contribution was indeterminate for one image), two were not classifiable as nominal or off nominal, and six were considered off nominal. See Table 1 for a summary. Of the six AOS identified as off nominal, the Wing Leading Edge (WLE) "bulge(s)" is the single AOS for which a nominal condition is least likely. Other AOS have a possibility of finding a nominal condition, albeit one not currently understood, as the source. The lack of comparative nominal condition data precludes any conclusion to the one hundred percent certainty level. If all ten AOS are compared, five provide for the possibility of an event occurring relating to the left wing.

Recommendations for the future, in the event such imagery is requested, would require that higher resolution video be obtained at high magnification, such as that taken through a telescope that is capable of tracking an object with a high angular velocity. The digital stills proved useful, but a greater number would be desired, with minimal saturation. Nominal condition re-entry imagery is deemed necessary for future studies of this type of orbiter condition analysis upon re-entry.



1.0 INTRODUCTION

The Starfire Team was formed in support of the Orbiter Vehicle Engineering Working Group (OVEWG) to aid the NASA community in the investigation of the STS-107 accident. The team was formed with members of various organizations, some associated with NASA, some not. A short biography of each member can be found in Appendix B of this report.

The Starfire Optical Range (SOR), a part of the Air Force Research Lab, acquired three still digital photographs and four videos of the Columbia as it passed over Albuquerque, New Mexico on re-entry. This was the first attempt by SOR to capture imagery of a shuttle on reentry. SOR acquired color video through a handheld digital camera operated in movie mode, one video through a camera mounted on the elevation gimbal of the coelostat used to track the orbiter and two videos with different fields of view obtained with two telescopes looking through the 1.0-m clear aperture coelostat consisting of two flat mirrors that rotate to view different parts of the sky. Three still digital photographs were also acquired with a 3.5-inch telescope and CCD camera, also looking through the coelostat, though one of the stills imaged only a small fraction of the orbiter/plasma trail.

These images were obtained by engineers at SOR volunteering their time and using available equipment. The data collection was not an official tasking. Tracking of the orbiter had never before been attempted with this equipment. The degree of potential object brightness was unknown and that, coupled with a brightening sky due to imminent sunrise, made gain adjustments (to prevent saturation) on the instruments difficult. There was no opportunity to compensate for errors in the supplied vectors of the orbiter as the orbiter was obscured by cloud during the first 20 degrees of the pass; this compounded the difficulty of tracking a rapidly moving object in a small field of view (FOV).

The Starfire Team was formed to process and evaluate the resulting imagery for indications of the orbiter condition at that time in the re-entry path. The Starfire Team reviewed all images and identified those stills or frames of the videos that appeared most probable to achieve this goal. The team focused on the identified video frames and stills and performed various levels of image processing and analysis.

The Starfire Team provided regular status briefings to the OVEWG.

2.0 PURPOSE & SCOPE

This report defines and documents the Starfire Team investigation: determination of important stills and video frames, problems encountered, data analysis techniques, and data interpretation results.

The scope of the data interpretation included a limited number of the available video frames and two of the three stills. While other video frames were available, those of the orbiter with AOS were judged the most potentially revealing and only those were examined in detail.

Classification of priority resulted in four categories:

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- 1) High potential of information return from analyses
- 2) Moderate potential of information return from analyses
- 3) Low potential of information return from analyses
- 4) No expected information return from analyses

After review of all available data, two of the three stills and one set of frames from the 5-millirad field-of-view (FOV) video were considered to be Category 1. A set of frames here is defined as a sequential subset of video frames extracted from the complete video, wherein the number of frames in a set varies according to the content. The remaining still, one set of frames from the 5-millirad FOV video, and one set of frames from the 700-microrad FOV video were classified to be Category 2. The remaining video frames that contained views of the orbiter, as well as the two remaining videos were considered to be Category 3. Any set of video frames that failed to capture the orbiter in its field of view was classified to be Category 4.

Several problems were encountered. The primary difficulty with analysis was the lack of nominal-condition comparative data. Other problems were unknown plate scales (i.e. size of objects), motion blurring, saturated images, unknown orientation (rotation), and resolution. Techniques for analyzing this type of imagery existed only in a limited fashion; this specific type of data did not previously exist.

Plate scales and orientation of a few images were determined by imaging starfields at the known elevation and azimuth of the image and calculating the scale and degree of rotation.

Data analysis techniques and interpretation required drawing on assorted personnel with backgrounds in image data reduction and analysis, astronomical data reduction and analysis, wire cad modeling, aerothermal modeling, and extrapolation of aerothermal conditions to visual results.

3.0 DATA

All video and stills were reviewed by the Starfire Team as well as independently reviewed by the STS-107 Image Analysis Team creating the timeline for the Columbia's re-entry. The review by the timeline team was used as a metric against category classification. The approximate Greenwich Mean Time (GMT) coverage encompassing all of the videos and stills wherein the orbiter is visible is 13:56:31 – 13:58:12.

The two videos that were not acquired through a telescope were considered of no value for the purpose of this team's work other than to confirm or deny possible changes in appearance of the orbiter's luminosity. These were videos EOC2-4-148-2 and EOC2-4-148-6. They were reviewed for possible changes in luminosity and no changes were seen that correlated with any AOS.

Video EOC2-4-148-4 is a 5 millirad FOV (~1/3 degree) digital video taken through a 14" Celestron telescope looking off two 1.5-m diameter flat mirrors positioned at 45 degrees to the line of sight that rotate about vertical and horizontal axes: a configuration known as a 1-m clear aperture coelostat. This arrangement causes images in the focal plane of a camera

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to rotate as the mount tracks objects across the sky. Sets of frames ranged from Category 1 through Category 4. The orbiter was in the FOV intermittently.

Video EOC2-4-148-3 is a 700 microrad FOV video taken through a 7" Questar telescope also looking through the 1-m coelostat. Sets of frames ranged from Category 2 through Category 4. The orbiter was in the FOV infrequently.

Digital stills consist of JSC2003e03394 (GMT 13:57:14) and JSC2003e03395 (GMT 13:57:59). These were acquired with a 3.5-inch telescope and CCD camera, also looking through the coelostat. Both of these stills were classified Category 1. The third still (GMT 13:57:51) has been submitted for inclusion in the JSC Columbia Accident stills database, but as of yet has no JSC number. It was classified a Category 2. All three stills were taken with a CCD camera attached to a 3.5-inch Questar telescope looking through the 1.0-m coeleostat.

Appendix C identifies categorization of this data in both pre- and post- analysis status.

4.0 DATA ANALYSIS

After preliminary review and classification, those stills or sets of video frames in Categories 1 and 2 were examined. Sets of video frames were captured via two different programs ISEE & DPS Reality. Late in the analysis it was recognized that some small degree of signal was lost if video frames were taken from a second-generation copy rather than a digital clone or digital copy of the original. Video frames taken from a digital copy were examined and while slightly higher in quality, appeared to add no significance to the final results, thus the data were not reprocessed.

Adobe Photoshop was used to enhance contrasts, rotate images as required to correct to proper orientation due to the rotation of the mirror, and crop images. (Adobe resamples an image when it rotates an image; resampled images were not used in for final analysis.) Preliminary interpretation was performed. Stills and some single frames of video were processed with an iterative blind deconvolution method (Center for Adaptive Optics, Christou). Two of the stills were also processed using a regularized maximum likelihood method (Veridian, Thelen). Only the stills and frames processed by the blind deconvolution method were interpreted and then reviewed by the entire team.

After a detailed review, many images were reclassified. See Appendix C for details regarding classification/reclassification and a brief summary of results.

5.0 RESULTS

The Starfire Team reviewed about 18,800 frames of video and three digital stills. Ten possible AOS were identified and investigated. Due to the lack of comparative nominal condition imagery, in no case can an apparent AOS be confirmed to the one hundred percent level of certainty. One event not addressed here is Debris 16, a debris event noted

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Anomaly	NASA # Video/Still	Conclusion
Turbulence near the nose/left	EOC2-4-0148-3	Unknown if off-nominal
wing, WLE		
Asymmetric gas trail	JSC2003e03394	Nominal
WLE "bulges"	JSC2003e03394	Off-nominal
Asymmetric bulge at nose	JSC2003e03394	Nominal
Asymmetric streaming of gas	EOC2-4-0148-4	Unknown if off-nominal
from aft of orbiter		
Flare 1	EOC2-4-0148-4	Off-nominal
Flare 2	EOC2-4-0148-4	Off-nominal
Flaring/Streaming	EOC2-4-0148-4	Off-nominal
Brightening of left wing	JSC2003e03395	Off-nominal
	EOC2-4-0148-4	
Nose or Tail brightening	JSC2003e03395	Off-nominal
	EOC2-4-0148-4	

Table 1 – Anomalous Optical Signature (AOS) Results

by the STS-107 Image Analysis Team constructing the timeline. The debris event is difficult to see and was not part of the scope of this task. Of all the AOS identified as off nominal, the Wing Leading Edge (WLE) "bulge(s)" is the AOS for which a nominal condition is least likely. Other AOS have a greater possibility of finding a nominal condition, albeit one not currently understood, as the source. See Table 1 for a list of the ten AOS, video/still the AOS is associated with, and conclusions. A brief discussion follows, identifying possible causes of the AOS identified and the conclusions drawn. Some additional information is contained in Appendix D.

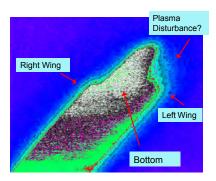


Fig. 1: Turbulence near the nose/left wing/WLE. NASA video EOC2-4-0148-3. It is unknown what a nominal optical signature of the flowfield at these specific conditions (speed, orientation, etc.) would look like. The signature is not overt nor does telemetry provide additional insight. No conclusion can be drawn regarding a nominal or off nominal condition.

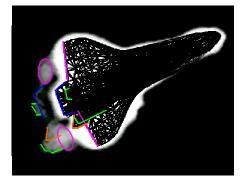


Fig. 2: Asymmetric Gas Trail. NASA Image JSC2003e03394. The processed image revealed structure in the gas trail. This structure could be correlated to specific source locations on the orbiter. Damage to the left wing could create additional enhancement of the gas trail that could not be distinguished from known sources. This optical signature is considered to represent a nominal condition with the caveat that an off-nominal condition could not be identified as such with this image.

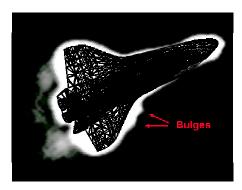


Fig. 3: WLE "Bulges". No currently understood nominal condition can support this optical signature. Possibilities for sources of this optical signature are: localized increase in temperatures (hot spots), local increase in reflectivity (unlikely), tile damage (unlikely), and damage to WLE. Viewing geometry and refraction could contribute. See Appendix D for some additional explanation. This is considered to represent an offnominal condition.



Fig. 4: Asymmetric Bulge at Nose. The nose is known to be the hottest spot and could produce an optical signature representative of a localized intensity increase. As the image displays the bottom of the orbiter (the wirecad model is "see-through" and somewhat misleading due to that), orientation and viewing angle is considered the most likely source of this optical signature. This is not inconsistent with Sandia's Plasma models. This is considered to represent a nominal condition.

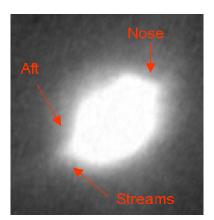


Fig. 5: Asymmetric Streaming of Gas from Aft of Orbiter. NASA video EOC2-4-0148-4. This is apparent in the video and not well represented by a still image. In the video, the image of the orbiter is highly saturated and is "lemon-shaped" in appearance. The image shown at the left has been rotated into its approximate correct orientation and would appear similar to the above digital still were it not so badly saturated. A "tail" of gas/plasma is evident at the aft of the orbiter (identified as "streams"). This tail appears to stream and pulse over time. One of the three digital stills is acquired during this period of time and shows an asymmetric gas trail (see Fig. 2). This streaming is likely related to the

asymmetric gas trail seen in the still and the explanation for the asymmetric gas trail potentially applies to this streaming/pulsing tail. The asymmetric gas trail in the still is thought to be nominal (with consideration of the caveats mentioned in Fig. 2) and this suggests that this streaming effect may also represent a nominal case. Without nominal comparative data, no conclusion can be drawn regarding if this is a nominal or off nominal condition.

The last five AOS are to some degree interrelated. The five signatures are Flare 1, Flare 2, Flaring/Streaming, Brightening of Left Wing, and Nose or Tail Brightening. The Brightening of the Left Wing and Nose or Tail Brightening occurs simultaneously with Flare 1 and visually may help create the optical signature of Flare 1. Flare 1 shows brightening of the

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left wing, the nose/tail, and a streaming signature (hot gas?) possibly located around the tail region. This does not imply tail damage, but rather one possibility presented is that normal tail interaction with the flowfield generates this optical signature. The general optical signature of Flare 1 persists (in time) and Flaring/Streaming is seen. The orbiter passes out of the FOV, then returns. As it leaves the FOV again, Flare 2 is seen. Flare 2 is merely a brightening with no significant change in the general optical signature associated with Flare 1, other than the increase in brightness. Only the imagery of Flare 1 is shown as all five optical signatures are essentially represented by the three images shown below.





Fig. 6: Flare 1. **NASA** video EOC2-4-0148-4. Flare 1 is noted on the timeline Columbia's reentry and its AOS may in part be a brightening of the upper portion of the canopy and left wing of the orbiter. Images taken from

the video are shown. To the left is the pre-flare appearance of the orbiter; to the right is Flare 1. The checkerboard pattern to the left of both images is the edge of the FOV. These images are approximately half a second apart in time. They have not been rotated to the proper orientation. Diffraction was considered as a possibility; diffraction is an effect of the optics seen as a brightening of an object as an object leaves the FOV of the telescope. This was tested for by SOR. Jupiter was used to represent the orbiter, as Jupiter was approximately the same visual size as the orbiter; the telescope was moved rapidly to simulate the orbiter's motion through the FOV. No similar brightening was noted. Although phase angle cannot be simulated (the orbiter was in daylight at the time), diffraction as the source of brightening is considered unlikely. The streaming of what is thought to be hot gas is not well represented by a still, but the aspect of the elongation of what may be hot gas can be seen in the digital still (Fig 6A), and contributes to the optical signature of Flare 1. Viewing angle may contribute to the signature seen in that the camera is viewing the aft of the orbiter. It is unknown to what degree the view is looking through a plasma trail, the opacity of the plasma trail, and if the plasma trail contributes to the "flare" signature. Additionally, shadowing due to phase angle of the sun may contribute to the signature.

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Fig. 6A: Flare 1. NASA image JSC2003e03395. The second digital still analyzed was taken at about the same time as the right-hand image in Figure 6. The still is shown here after a blind deconvolution has been applied to the image and its contrast enhanced. It has been properly oriented and displays a wireframe overlay of the orbiter. The wireframe overlay has been approximately scaled. Exact placement relative to the image is unknown. See Appendix D for more details regarding these images and others. The flare image and the digital still are considered to represent an off-nominal condition, and all five AOS listed in the paragraph above Fig. 6 are considered off nominal.

6.0 CONCLUSIONS

Of the ten AOS identified in the Starfire datasets, two were classified as nominal, two were inconclusive and six were considered potentially off-nominal, with one of those six having no currently identifiable possibility of a nominal condition. If all ten AOS are compared, five provide for the possibility of an event occurring relating to the left wing. Based upon the AOS with no currently identifiable possibility of a nominal condition, the left wing WLE appears to be in an off-nominal state.

7.0 RECOMMENDATIONS

Recommendations for the future, in the event such imagery is requested, would require that higher resolution video is obtained at high magnification, such as that taken through a telescope that is capable of tracking an object with a high angular velocity. Resolution, saturation, and tracking were three keys issues that reduced the usefulness of the videos. An additional issue was that, due to the rotating coelostat, the orientation (rotation) of each frame of video was unknown and each processed frame's rotation had to be determined by acquiring starfield images at a later date. The digital stills proved useful, but a greater number would be desired, with minimal saturation.

Nominal condition re-entry imagery is deemed necessary if future comparative studies of this type of orbiter condition upon re-entry analysis is requested or planned.

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APPENDICES

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APPENDIX A ACRONYMS AND ABBREVIATIONS

AOS Anomalous Optical Signature
FOV Field of View (telescope)
GMT Greenwich Mean Time
OVE Orbiter Vehicle Engineering

OVEWG Orbiter Vehicle Engineering Working Group

SOR Starfire Optical Range WLE Wing Leading Edge

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APPENDIX B TEAM MEMBER BIOGRAPHIES

Starfire Team Biographies

Julian Christou

Dr. Christou has over twenty years experience with image processing of both astronomical and artificial satellites. He obtained a Ph.D. in Astronomy from New Mexico State University and has worked at the National Optical Astronomy Observatories and Steward Observatory both in Tucson, Az., as well as the Starfire Optical Range. He is presently a research scientist with the Center for Adaptive Optics at the University of California, Santa Cruz.

Rick Cleis

Mr. Cleis works at the SOR. No Bio provided.

Robert Q. Fugate

Dr. Fugate is the Air Force Senior Scientist for Atmospheric Compensation and serves as the Technical Director, Starfire Optical Range, Directed Energy Directorate, Air Force Research Laboratory, Kirtland Air Force Base, N.M. The Range operates 1.5- and 3.5-meter telescopes, and a 1.0-meter beam director. Dr. Fugate conducts a research program on atmospheric propagation physics; atmospheric compensation using laser guide star adaptive optics; the acquisition, tracking and pointing of lasers to earth-orbiting satellites; and the development of sensors, instrumentation and mount control of large-aperture, ground-based telescopes. He has worked for the U.S. Air Force since 1970 in the fields of atmospheric propagation, electro-optical sensors and detection, space surveillance and adaptive optics.

Dewey Houck

Mr. Houck is currently a Senior Technical Fellow working in the Space and Intelligence Systems Division of IDS for Boeing/Autometric. He chairs Boeing/Autometric's Engineering Review Board that acts in an oversight capacity for Product Development and Program initiatives. He also chairs the Technology Steering Group responsible for commercial product investment decisions. Prior to the Boeing acquisition (of Autometric), he served as a member of the senior management team as Vice President for Technology development for Autometric. During that time, he administered all Research and Development activities including several geospatial, photogrammetric and visualization initiatives. Mr. Houck has Master's and Undergraduate degrees in Civil Engineering from Virginia Tech with specialization in Photogrammetry and Geodesy.

Kandy Jarvis

Ms. Jarvis has seven years experience at NASA, all with Lockheed Martin Space Operations. Her position is Senior Research Scientist as Lead for the Planetary Astronomy Group and Optical Lead for the Orbital Debris Program Office. In both positions she works with a variety of telescopic data, including the acquisition, data reduction, analysis, and interpretation of spectrophotometry and video and short exposure (5 – 20 seconds) images of starfields containing orbital debris.

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Robert Johnson

Major Johnson is with the USAF and has a PhD. He works with cameras and optics. No Bio provided.

Roger Petty

Mr. Petty works at the SOR. He is an optical engineer. He performed as outdoor spotter and operated the handheld camera. No Bio provided.

Rich Rast

As an Air Force civilian, Mr. Rast served as chief orbital analyst at NORAD before coming to JSC in 1986. He left JSC after six years to become operations manager of SOR. He now works at AFRL's Satellite Assessment Center. He proposed that SOR image Columbia's reentry to JSC-DM4's Gilman on December 9, 2002.

Karen Watts

Ms. Watts has six years of experience in the Space Shuttle Program, all with the United Space Alliance. Her current position is Pointing Operations Engineer in the Attitude and Pointing Office. The Pointing Office is responsible for manned spacecraft attitude determination and line-of-sight analysis.

R. Douglas White

Mr. White is currently the Director for Operations Requirements in the United Space Alliance Orbiter Element department. He began work on the space shuttle program in 1979 as an employee for Rockwell International in Downey, California. Mr. White has held increasingly responsible positions within the space shuttle program focusing on the areas of turnaround test requirements, engineering flight support, anomaly resolution, and Orbiter certification of flight readiness preparation. He joined United Space Alliance as a director in 1996. He holds a BS and MS in physics from UCLA.

Other Contributors:

Gil Carman: JSC NASA

Sina Farsiu: Engineering Department, Univ. of CA, Santa Cruz

Dr. Peyman Milanfar: Electrical Engineering Department, Univ. of CA, Santa Cruz

Scott Murray: JSC NASA

Dr. Brian J. Thelen: Veridian Systems Ann Arbor Research and Development Center

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APPENDIX C CATEGORY CLASSIFICATION AND SUMMARY

Type: Digital Still Photograph

NASA Number: JSC2003e03394

GMT Time: 13:57:14

<u>Initial Classification</u>: Category 1 <u>Post Analysis</u>: Category 1

Description: Saturated image of the underside of the orbiter.

Results: Image was analyzed, interpreted, and results presented. See Appendix D.

NASA Number: JSC2003e03395

GMT Time: 13:57:59

<u>Initial Classification</u>: Category 1 <u>Post Analysis</u>: Category 1

<u>Description</u>: Partially saturated image of the orbiter looking at the aft end.

Results: Image was analyzed, interpreted, and results presented. See Appendix D.

NASA Number: JSC2003exxxx (Still #3)

GMT Time: 13:57:51

<u>Initial Classification</u>: Category 2 Post Analysis: Category 3-4

Description: Plasma trail directly aft of orbiter.

Results: Image was analyzed and interpreted. Little to no information obtained.

Type: Video

NASA Number: EOC2-4-0148-2

Field of View: 5 degree

<u>Frame Subset or Full Video?</u>: Full Video <u>GMT Timespan</u>: 13:56:47.22 – 13:58:11.29

<u>Initial Classification</u>: Category 3 Post Analysis: Category 3

Results: Video was reviewed. No significant anomalies seen other than those identified by the STS-107 Image Analysis Team. One piece of debris identified by the STS-107 Image Analysis Team: Debris 16. No further processing performed. Possibility of identifying additional debris with extensive processing of video.

NASA Number: EOC2-4-0148-6
Field of View: ~5 degree, RGB (color)
Frame Subset or Full Video?: Full Video
GMT Timespan: ~13:56:47 – 13:58:12

<u>Initial Classification</u>: Category 3 <u>Post Analysis</u>: Category 4

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Results: Video was reviewed. No anomalies seen. No further processing performed.

Type: Video (cont.)

NASA Number: EOC2-4-0148-3

Field of View: 700 µrad

<u>Frame Subset or Full Video?</u>: Frame Subset <u>GMT Timespan</u>: 13:57:23.0 – 13:57:23.3

Initial Classification: Category 2
Post Analysis: Category 2

<u>Results</u>: Video frame set = 7 fields (2 fields per frame, 29 frames per second). Video frames show motion-blurred orbiter. Effort was made to re-integrate images but relative velocity of orbiter and movement of camera prevented this effort. Field b, at GMT 13:57:23.1 was analyzed and interpreted. Results presented. See Appendix D.

NASA Number: EOC2-4-0148-3

Field of View: 700 µrad

Frame Subset or Full Video?: Full Video

GMT Timespan: 13:56:45.29 – 13:58:57.5 (excluding previously listed times)

Initial Classification: Category 3

Post Analysis: (Predominantly) Category 4

<u>Results</u>: Video was reviewed. In most frames, orbiter is not in the FOV. Occasional streaks of light suggest orbiter presence in or near the FOV. No further processing performed.

NASA Number: EOC2-4-0148-4

Field of View: 5 mrad

<u>Frame Subset or Full Video?</u>: Frame Subset <u>GMT Timespan</u>: 13:57:11.14 – 13:57:18.3

<u>Initial Classification</u>: Category 2 Post Analysis: Category 3

<u>Results</u>: Video was reviewed. Includes time coverage of still JSC2003e03394. Orbiter is badly over-saturated; orbiter appears "lemon-shaped". An undefined asymmetric streaming is seen at aft of orbiter; may relate to tail of orbiter; unknown if nominal or off nominal. Severe saturation prevents further analysis at this time. No further processing performed.

NASA Number: EOC2-4-0148-4

Field of View: 5 mrad

Frame Subset or Full Video?: Frame Subset GMT Timespan: 13:57:49.23 – 13:58:01.11

<u>Initial Classification</u>: Category 1 <u>Post Analysis</u>: Category 2-3

Results: Video was reviewed. Includes time coverage of still JSC2003e03395. Orbiter is partially over-saturated; orbiter appears "horseshoe-shaped". Aft of orbiter is toward camera. Two brightening events are seen to occur; these events are termed "Flare 1" and "Flare 2" in the timeline. Three hundred plus frames were extracted and processed with various methods by the CFAO. The orbiter is in and out of the FOV during this timespan. Two frames (13:57:54.14, 13:57:54.22) at the beginning of Flare 1 and peak of Flare 1 were analyzed and results presented; see Appendix D. No significant improvement was achieved

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on most processed frames. Possibility of determining if the Flares are an optical effect related to the tail or nose with further study.

Type: Video (cont.)

NASA Number: EOC2-4-0148-4

Field of View: 5 mrad

Frame Subset or Full Video?: Full Video

GMT Timespan: 13:56:48.26 – 13:58:01.11 (excluding previously listed times)

<u>Initial Classification</u>: Category 2-4 <u>Post Analysis</u>: Category 3-4

Results: Video was reviewed. Orbiter is in the FOV intermittently. Excluding previously noted framesets, orbiter is motion blurred due to relative velocity of orbiter and motion of

camera. No further processing performed.

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APPENDIX D

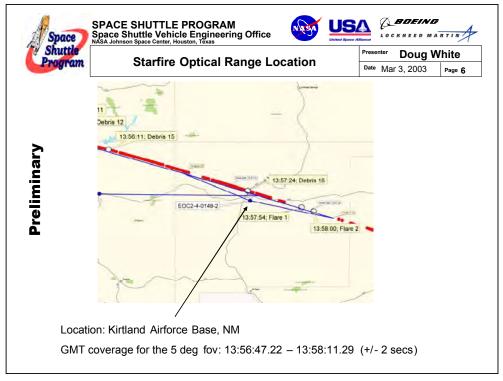
Presentation 1: Select slides taken from first presentation to OVEWG

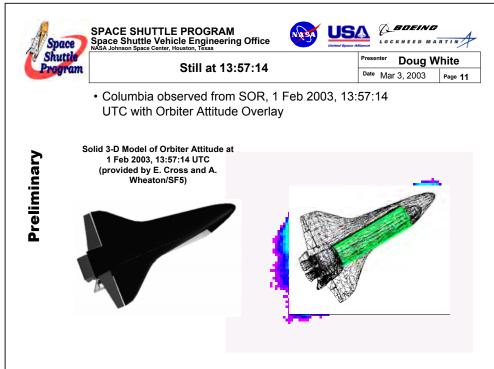
Presentation 2: Second presentation to OVEWG

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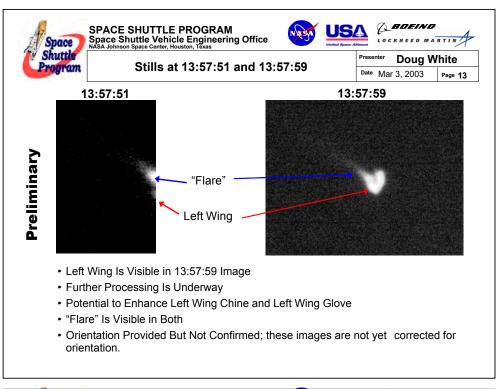
Presentation 1

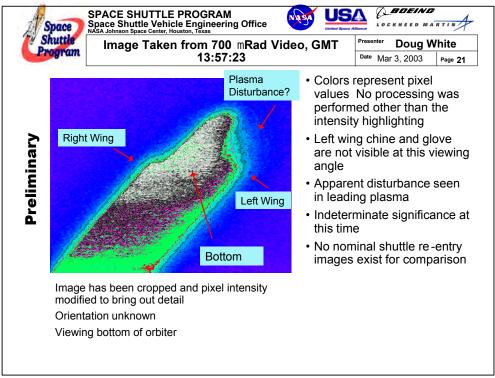




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Presentation 2





STS-107 Investigation **Kirtland Photo Tiger Team** 4/21/03



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Objective and Team Members

Kandy Jarvis Date April 21, 2003 Page 2

The Objective of This Tiger Team Was to Analyze the Still and Vi deo Images Taken at the Starfire Optical Range (Kirtland AFB, NM) During the STS-107 Entry

- · Tiger Team Members
 - · Doug White, USA
 - · Kandy Jarvis, Lockheed Martin
 - · Dewey Houck, Boeing
 - · Karen Watts, USA
 - · John Neer, Lockheed Martin
 - · Scott Murray, NASA

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Starfire Optical Range Team and Media

Kandy Jarvis Date April 21, 2003 Page 3

- Starfire Optical Range Team
 - · Major Robert Johnson, PhD, camera and optics
 - Mr. Rick Cleis, software and coelostat control
 - · Mr. Roger Petty, optical engineer, outdoor spotter and handheld camera operator
 - · Mr. Rich Rast, liaison with NASA to get vectors
 - Dr. Robert Q. Fugate, Senior Scientist and Technical Director, S OR (Unable to be there during the event)
- Media
 - · 4 videos
 - 3 stills
 - · A total of 5 cameras were used, some utilizing telescopes, some not



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Images Analyzed

Kandy Jarvis Date April 21, 2003 Page 4

Revised Analyses of Starfire Optical Range Stills

Preliminary

13:57:14

13:57:59

Two Frames Taken from 5-mRad Video for Analyses

13:57:54.14

13:57:54.22

Stills and frames have been processed by Dr. J. Christou, Center for Adaptive Optics, UCSC using a blind deconvolution technique

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Starfire Optical Range Stills & Frames

Presenter Kandy Jarvis
Date April 21, 2003 Page 5

- · Stills:
 - 3.5" telescope looking through a computer controlled 1.0 -m coelostat (rotating mirror)
 - · The plate scale is known for these images
 - ~ Measurements of object can be done
 - · Re-processing has altered plate scale
 - · Orientation (rotation) is known
 - The stills have an ~5 mRad (~1/3 degree) field of view (fov)
- Video Frames:
 - 5 mRad fov: intensified CCD camera attached to a 14" telescope, looking through the 1.0-m coelostat
 - · Orientation for every frame will change
 - Approximate Orientation known
 - · Plate scales have been estimated
 - · Re-processing has changed the plate scale



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Still at 13:57:14

Presenter Kandy Jarvis

Date April 21, 2003 Page 6

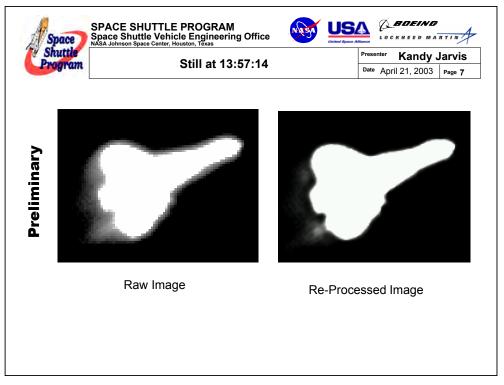
 Notes Regarding Attitude Comparison at Time: 1 Feb 2003, 13:57:1 4 UTC

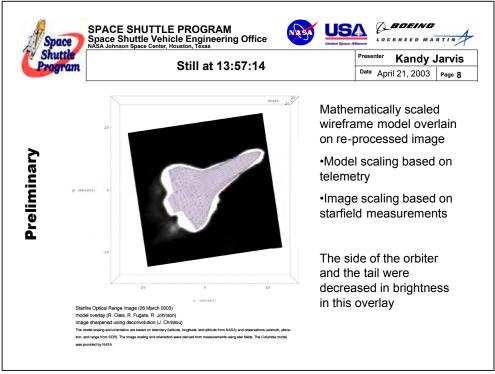
minary

- Models account for 8 degree rotation (per 24 -Feb. SOR e-mail)
- Elevons, body flap, and engines are modeled in neutral position
- Groundsite observer viewing from slightly port, slightly forward of normal to orbiter belly
- · Model scales were done visually
 - Approximations were calculated based on wingtip to wingtip dista nce and nose to tail distance
 - Plate scale of original known; compared to deconvolved image and plate scale approximated
 - Model fit visually based upon approximated scale and compared ag ainst SOR's model

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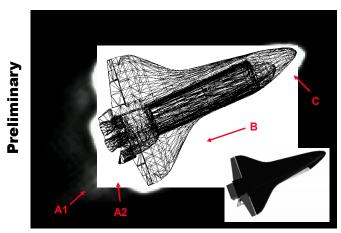






Still at 13:57:14

Presenter Kandy Jarvis
Date April 21, 2003 Page 9



Wire frame 3-D Model of Orbiter Attitude at 1 Feb 2003, 13:57:14 UTC overlaid on still Solid 3-D model provided as inset

3 Areas of Interest

- Asymmetric (A) Gas Flow Pattern
 - Left wing more elongated in vertical wake (A1)
 - Greater area brightened in aft wing area (A2)
- Asymmetry (B) of Wing (Left vs. Right)
 - Convex in region (Xo-1100, Yo-256), leading edge of left wing
- Asymmetry (C) of Nose



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BOEING

Still at 13:57:14

Presenter Kandy Jarvis

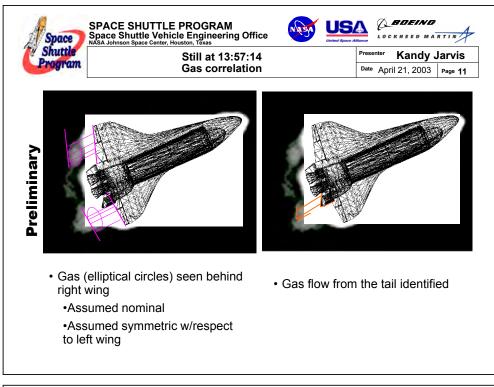
Date April 21, 2003 Page 10

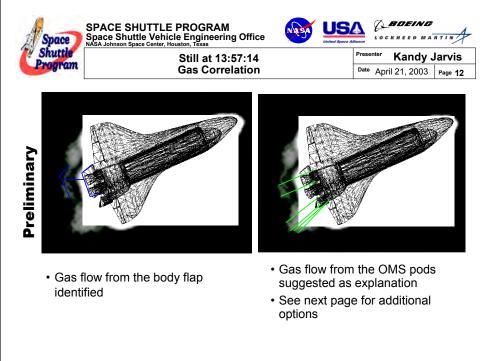
Asymmetric Gas Flow (A1)

- When the re-processed image is adjusted to brighten the fainter pixels, details of the asymmetric gas are definable
 - Correlation between portions of the orbiter and the gas are possible
- · The most probable correlations are presented
 - Other possibilities are not precluded and should be investigated by
 - Modeling
 - Wind tunnel testing
- · Specifics of correlations follow

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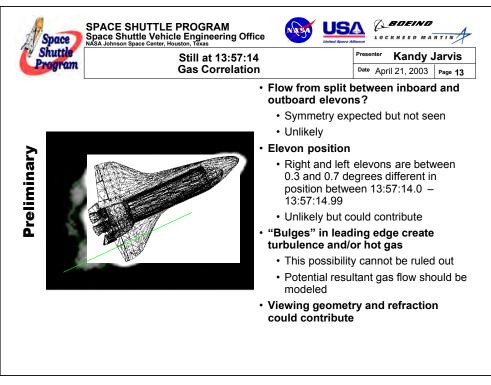


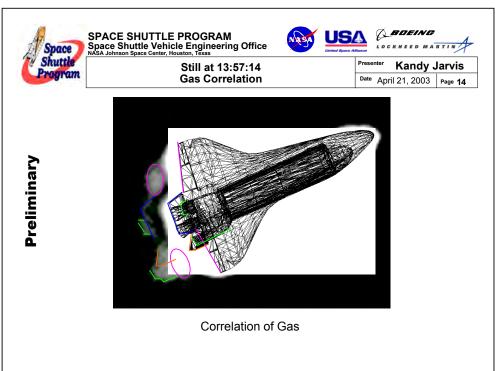




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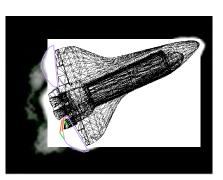




Still at 13:57:14

Kandy Jarvis Date April 21, 2003 | Page 15

Preliminary



Greater area is brighter behind trailing edge of left wing (A2)

- · Both wings show a gas flow pattern that is rounded; however, left wing has an additional bulge in area near elevon gap
- This brightened zone appears to correlate with the tail and left OMS pod/stinger
 - Some contribution could be from either the elevon, or from the "bulges" along the leading edge of the wing



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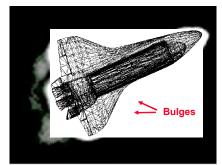




Still at 13:57:14

Kandy Jarvis Date April 21, 2003 Page 16

Preliminary



Two Bulges on Wing (B)

- · Clearly outboard of wing structure
- · Shape is inconsistent with wing leading edge
- · Inconsistent with flow pattern on right wing

Possible Causes

- · Localized intensity increase
- · Anomalous gas flow pattern

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Still at 13:57:14

Kandy Jarvis Date April 21, 2003 Page 17

Localized intensity increase

- · Local increase in temperature; hot spots
- Local increase in reflectivity (orbiter is in sunlight at this t ime)
 - · Exposure of metal
 - · This is considered unlikely, but is possible

Anomalous gas flow pattern in front of wing

- Tile damage?
 - · Possible, but unlikely to change bow shock and wing shock shape (per aerothermo team)
- Damage to wing leading edge?
 - Could change local bow shock and wing shock shape (per aerothermo
- · Viewing geometry and refraction could contribute



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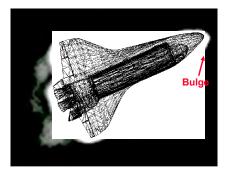




Still at 13:57:14

Kandy Jarvis Date April 21, 2003 Page 18

Preliminary



Asymmetry of Nose (C)

- · Unknown if nominal
- · Localized intensity increase
- Could be normal canopy shock seen from this angle
- · Viewing geometry could hide symmetry

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Still at 13:57:14

Kandy Jarvis Date April 21, 2003 Page 19

Final Conclusions

- · Asymmetric gas behind left wing (A1)/brightened aft region(A2)
 - · Can be accounted for with structure of Orbiter
 - · Contribution from leading edge "bulges" can not be ruled out
 - · Contribution from elevon can not be ruled out
- · Bulges (B)
 - · Caused by either local increase in intensity or anomalous gas fl ow
 - · Some possible causes of anomalous gas flow presented
 - » Modeling and wind tunnel testing investigations should aid in understanding and/or
 - » Some measurements of angles of bulges in relation to orbiter may be possible if so requested by other teams
- · Nose asymmetry (C)
 - · Likely nominal condition
 - Flight data (OI and OEX) show no anomalous readings at the chin panel or vent nozzles at this time

Analyses of This Still is Considered Complete Unless Otherwise I nstructed



Preliminary

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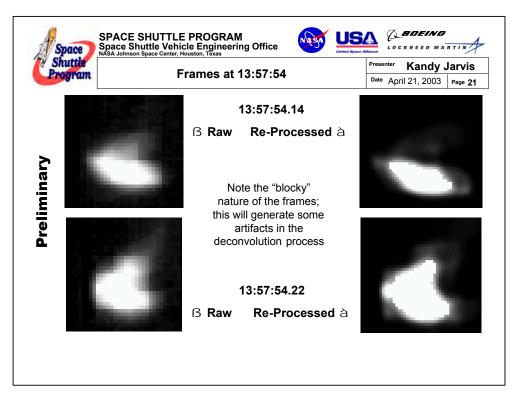
Frames at 13:57:54.14 & 13:57:54.22

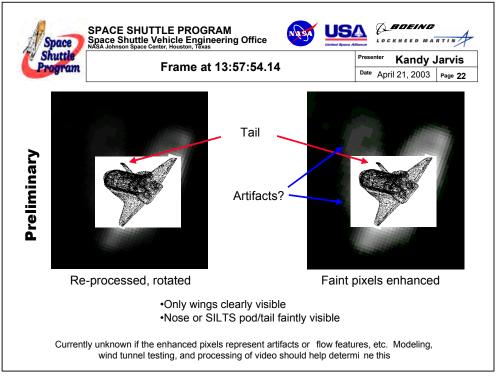
Kandy Jarvis Date April 21, 2003 Page 20

- Notes Regarding Attitude Comparison at Time: 1 Feb 2003, 13:57:5 4 UTC
 - Telemetry exists for 13:57:54.14 UTC; 13:57:54.22 was interpolat ed.
 - Elevons, body flap, and engines are modeled in neutral position
 - · Ground observer viewing from vertical tail and slightly to port
 - · Model scales were done visually
 - · Approximations were calculated based on wingtip to wingtip dista nce
 - Plate scale of still (5 secs later) known; compared to deconvolved image and plate scale approximated
 - · Model fit visually based upon approximated scale.
 - · Orientation (rotation) of frames with overlays were estimated ba sed upon known orientation of wireframe.

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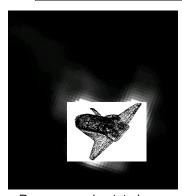


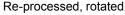


Frame at 13:57:54.22 (Flare Event #1)

Kandy Jarvis Date April 21, 2003 Page 23

Preliminary







Faint pixels enhanced

 Increased intensity/visual blooming of nose or SILTS pod/tail Increased intensity/visual blooming of left wing

There are still multiple questions regarding the event seen here ; See discussion



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Frames at 13:57:54.14 & 13:57:54.22

Kandy Jarvis Date April 21, 2003 Page 24

Current understanding of video images

- The left wing appears to brighten
- The nose/tail then appears to brighten
 - · Possible causes
 - · Changes in the flow field for the left wing and tail
 - An event in the left wing generates a flow field that, at this v isual aspect, appears to intersect with the tail
 - Flow field is generally too faint to see but when additive with nose/tail brightness, appears to cause an overall brightening of the nose/ tail
 - · The tail passes through the flow field as the orbiter moves forw ard and this enhances the brightening
 - · An illumination of the wing illuminates area(s) previously in sh adow (nose or tail)
 - There are no overt indications in information from the orbiter t hat suggests the tail underwent any change at this moment in time. Newly acq uired MADS data has not yet been compared against these times.
 - Diffraction (see next page)

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Frames at 13:57:54.14 & 13:57:54.22

Kandy Jarvis Date April 21, 2003 Page 25

Diffraction:

- · As a bright object exits the field of view of a telescope, diffr action of the optics can create a brightening of that object
 - · Both "flare events" in the time line occur at the edge of the fi eld of view
 - SOR has taken video of Jupiter at the same angular size as the o rbiter, and moved the telescope so Jupiter left the field of view at the sam e approximate location as the orbiter
 - · No flash or flare was seen to occur
 - Can not re-create phase angle of the sun at that time (no stars in
 - There does appear to be a distinct visual change in the orbiter between preflare and post flare. Still at 13:57:59 shows brightened nose/t ail region
- This suggests diffraction is not a cause of the events seen



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Still at 13:57:59

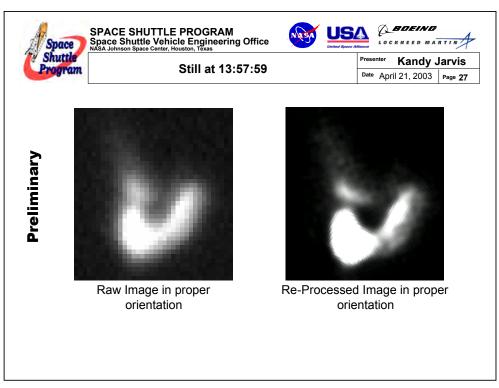
Kandy Jarvis Date April 21, 2003 Page 26

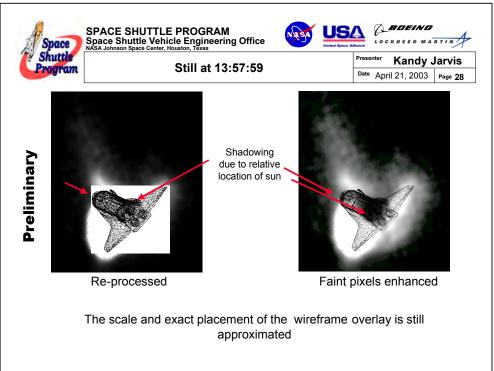
Notes Regarding Attitude Comparison at Time: 1 Feb 2003, 13:57:5 9

- Telemetry unavailable for 13:57:59 UTC; interpolated. Orientation known (rotation)
 - Elevons, body flap, and engines are modeled in neutral position
 - · Ground observer viewing from vertical tail and slightly to port
 - Model scales were done visually
 - · Approximations were calculated based on wingtip to wingtip dista nce
 - · Plate scale of original known; compared to deconvolved image and plate scale approximated
 - Model fit visually based upon approximated scale

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Photo Still at 13:57:59

Kandy Jarvis Date April 21, 2003 Page 29

Current understanding of still

- · The left wing has increased intensity
- · The nose/tail has increased intensity
 - Improved resolution (vs. video frames) suggests
 - An event in the left wing generates a flow field that, at this v isual aspect, appears to intersect with the tail
 - Flow field is generally too faint to see but when additive with nose/tail brightness, appears to cause an overall brightening of the nose/ tail region
 - · An illumination of the wing illuminates area(s) previously in sh adow (nose or tail)
 - · There are no overt indications in information from the orbiter t hat suggests the tail underwent any change at this moment in time



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Next Steps

Kandy Jarvis Date April 21, 2003 Page 30

- SOR-AFRL Will
 - · Provide video for plate scaling
 - · Determine orientation of video frames of interest

Preliminary

- · Acquiring Slightly Better Resolution Video Frames from Digital R ecording for Deconvolution
 - · First set of frames have been acquired and will soon be processe d
- Continue Interpretation of Still 13:57:59 and Video Frames from 5 mRad
- Video Processing Will Search for Additional Signs of Debris
- · Events Will Be Submitted for Entry Event Timeline as Confirmed

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APPENDIX E DEFINITIONS

Anomalous Optical Signature –A visual appearance of the orbiter containing a characteristic that appears irregular such as a lack of expected symmetry, pulsation of signal, or outline not matching the expected configuration.

Frames, Set of –A sequential subset of video frames extracted from the complete video, wherein the number of frames in a set varies according to the content.

Nominal -All conditions within normal expected parameters.

Off Nominal –A condition or conditions outside of normal expected parameters.

Orientation –The known compass direction of an image. This may be unknown due to the rotation of the imaging apparatus.

Pixel –A contraction of "picture elements"; a single energy flux detector.

Plate Scale –The ratio of a measurement on an image to the equivalent measurement of the imaged object.

Resample –An averaging of nearby values to generate a new value.

Resolution –The ability to separate closely spaced objects on an image.

Saturation –When the energy flux exceeds the sensitivity range of a detector or set of pixels. This overflow can also spread to adjoining pixels, altering their values.

Starfield –An image of a collection of identifiable stars at a known time that permits calculation of plate scale and compass orientation of an image.

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C0-000031

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Volume V Appendix G.8

Using the Data and Observations from Flight STS-107... Exec Summary

This Appendix contains the report <u>Using the Data and Observations From Flight STS-107 to Explain the Fatal Reentry of the Columbia Orbiter OV-102, Bertin, John J., Smiley, James W.</u> This report develops possible scenarios that were considered by the Columbia Accident Investigation Board.



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IAST-JWS/JJB-1

USING THE DATA AND OBSERVATIONS FROM FLIGHT STS-107 TO EXPLAIN THE FATAL REENTRY OF THE COLUMBIA ORBITER OV-102

By
DR. JOHN J. BERTIN
DR. JAMES W. SMILEY
CONSULTANTS, CAIB SUPPORT GROUP

EXECUTIVE SUMMARY

In our role as Aerothermodynamic Consultants to the Columbia Accident Investigation Board (CAIB), we are documenting our interpretation of the key events, which led to the demise of OV-102 during Flight STS-107. In order to develop an understanding of aerothermodynamic environment and of the sequence of critical events that led to the demise of the Orbiter, meetings were held with NASA personnel and their contractors and with other consultants to Group 3 (Engineering and Technical Analysis) of the Columbia Accident Investigation Board (CAIB). During these meetings, we obtained film clips, timelines, basic data, interpretations of the data, and figures from power-point presentations. In these meetings, we exchanged ideas on what we thought were key events, about what was possible, what was likely, what was not possible, and what was not likely.

The authors would like to acknowledge the inputs (verbal and written) that we received from Rick Barton, Charles Campbell, Joe Caram, Ray Gomez, Dave Kanipe, Steve Labbe, Gerald J. Lebeau, Chris Madden, Fred Martin, Scott Murray, et al. [all of the Johnson Space Center (NASA)]; Stan Bouslog of Lockheed-Martin; and Jim Arnold, Howard Goldstein, Pat Goodman, Robert Hammond, Jim Mosquera, and Donald J. Rigali from the CAIB Technical Support Team. The authors have benefited from discussions with and from presentations made by the Group 3 members of the CAIB, Dr. James Hallock, G. Scott Hubbard, Dr. Doug Osherhoff, Roger Tetrault, and Dr. Sheila Widnall. The following text offers our interpretation of the significance of and the relationship between data and observations that are currently "known" about the fatal aerothermodynamic environment of flight STS-107 for the Columbia Orbiter, OV-102.

It is the intent of the authors to document a summary of key data and provide a realistic scenario that would explain the aerothermodynamic environment during the demise of Columbia OV-102. In this effort, we have attempted to match what we consider to be twelve critical events or observations that were determined from "data" gathered from the persons mentioned in the previous paragraph. The word "data" has been placed in quotes, since some "data" represent flight measurements whose time and magnitude are well known, other "data" represent debris whose origin and timing is somewhat subjective, and still other "data" are from computations and wind-tunnel tests and, thus, are dependent on the simulation models (numerical or experimental) used. Therefore, some of the observations based on our interpretation of the "data" may differ from the demise scenarios proposed by others using the same "data". For instance, some of the information gleaned from the recovered debris may be in error, because the debris was misidentified or because the damage to the recovered debris may have occurred at a different time during the reentry. Furthermore, new information (in the form of additional recovered debris, analysis, etc.) may become available at some point in the future. For instance, data from the MADS recorder that was recovered after initial



investigations provided information over a longer time frame and from additional sensors. To allow for such uncertainties in the existing "data" and for the probability of new, additional data providing an improved understanding of the aerothermodynamic environment, most of the observations that the authors deem to be "critical" represent several pieces of information rather than a single datum point.

Furthermore, by matching the information from twelve "critical data/events", it is hoped that a reasonably accurate and coherent description of the evolving damage will be presented in this report. We will describe how the following sequence of events can be used to define a demise scenario, which is judged to be consistent with all of the "data".

- 1. The observation that foam particles from the external tanks impinged on the wing leading edge during the launch.
- 2. Radar signatures from the second day of the mission that showed a piece of debris drifting away from the Orbiter.
- 3. The strain-gage reading (beginning at EI + 270) and the temperature rise at two thermocouples located in the vicinity of RCC Panel 9 (beginning at EI + 290), as indicated by MADS data.
- 4. The perturbations to the heating and to the surface pressures due to the interaction between the bow shock wave and the wing-leading-edge shock wave are most severe in the region of RCC Panels 8 and 9.
- 5. Start of off nominal temperature histories at four sensors on left OMS Pod (beginning with lower than expected temperatures at EI + 340, followed by higher than expected temperatures at EI + 460).
- 6. The anomalous temperature increases that occurred at various locations in the main left-landing-gear wheel well (beginning at EI + 488).
- 7. The increase in temperatures at points located on the vertical side of the fuselage, as indicated both in thermocouples on the Orbiter itself and in the temperature sensitive coatings on the wind-tunnel models tested at the Langley Research Center (beginning at EI + 493).
- 8. Loss of all measurements from the wire bundle running along the backside of the wing spar (beginning at EI + 487) followed by the loss of measurements from the wire bundle running along the left main-landing gear wheel well, which included elevon measurements (beginning at EI + 527)
- 9. The observations regarding the damage to the wing leading edge, as determined from the recovered debris.
- 10. The modifications to the shock/shock interaction flow field that was described in "critical data/event" #4, as developed based on the developing damage scenario and correlated against the Kirtland photograph, i. e., observations by personnel from the Starfire Optical Range (at EI + 830.5/832.5).

2



- 11. Comparing selected histories showing that the actual flight was close to the planned flight up to EI + 900.
- 12. Using the rolling-moment-coefficient history to support findings for some of the previous eleven points.

It is recognized that there are other data (facts) and that some of these facts may become critical as an improved and more complete understanding of the demise is achieved. However, based on our understanding at this time, we believe that these twelve "critical data/events" are very important and that a demise scenario that incorporates all twelve has some credibility. The time-dependence of these twelve events will be based on the "Relation of Reentry Parameters" that are contained in the table presented in Table 1 and in Appendix A. Entry Interface (EI) occurred at GMT 13:44:09. Referring to Table 1, the reader can identify three, related early "events" that indicate anomalous behavior: the strain gage reading and the high temperatures for two thermocouples on the spar behind RCC Panel 9 (one on the clevis and one on the back face of the spar. These foreboding signs occurred by 13:49:00, with the Orbiter still approximately 1000 miles west of the California coast. The Orbiter was flying at altitudes in excess of 260,000 feet, where non-continuum effects are important in modeling the flow field and the peak convective heating has not been reached. Thus, it is believed that the initial damage that compromised the thermal protection system and that led to the demise of OV-102 was in place at the EI.

To readily access the figures and appendices of this report click on the hyperlinks located on the last page of this document.



GENERAL DISCUSSION

(1) The observation that foam particles from the external tanks impinged on the wing leading edge during launch.

A large piece of foam (debris) from the bipod area of the external tank (ET) is evident in the film of the STS-107 during launch. The trajectory of the debris, which is shown in Figure 1, indicates that the ET foam debris struck the wing leading edge 82 seconds after launch. Based on this trajectory, the likeliest area of impact was on RCC Panel 6, or slightly downstream. See Figure 2. As shown in Figure 3, RCC Panels 1 through 4 are located on the glove, which has a sweep angle of 81°. RCC Panels 5 through 7 are located on the intermediate spar, a. k. a., the transition spar. RCC Panels 8 through 19 are located on the wing spar, which is swept 45°,

Post-flight analysis of the MADS data indicated a small temperature rise in the measurement from a temperature sensor that was located behind the wing spar of RCC Panel 9. This is a possible additional piece of evidence that the damage occurred during the launch phase.

The authors believe that significant damage to the RCC panels in the vicinity RCC Panel 6 is consistent with the early thermal anomalies that were observed both in the sensors on and/or near the spar at the back of RCC Panel 9 and in some of the sensors in the left main-landing-gear wheel well. The anomalies that occurred in these two regions did not occur simultaneously, but were close in time. Thus, damage somewhere in the vicinity of RCC Panel 6 would be strategically placed to deliver hot gases that could both damage the wires on the back of the wing spar near these RCC panels and the wires on the main left-landing-gear wheel well. The hot gases from the breech in the wing leading edge would also flow down the chunnel (channel/tunnel) that exists between the RCC panels and the spar that follows the wing leading edge, producing the anomalous readings on the sensors at the spar at RCC Panel 9.

The wing-leading-edge subsystem (LESS) is shown in the sketch of Figure 4. The impact of the debris with a leading-edge RCC panel could have removed (all or part of) a T-seal or produced a hole or a crack in the RCC panel itself. In an attempt to further define the location and the extent of the debris-induced damage, NASA personnel and their contractors have been using computational fluid dynamic (CFD) codes. Additional work is needed to complete and to validate the analysis efforts, e. g., use the direct simulation Monte Carlo (DSMC) computational tools to provide an independent validation of the flow field at these low-density gas conditions. The modeling of the internal flow through the chunnel, starting with a breech of the leadingedge TPS (using the location and the nature of the breech to define the boundary conditions for a few likely initial conditions), and proceeding into the wing is a very complex task that should be completed. Of special interest is matching the computed results to the observed times for (1) the burn through of the MADS wires behind the spars. (2) the burn through of the bundle of wires that ran along the wall of the main leftlanding-gear, and (3) the anomalous temperatures measured at various points inside the left main-landing-gear wheel well.



(2) Radar signatures from the second day of the mission that showed a piece of debris drifting away from the Orbiter.

Radar signatures from the second day of the STS-107 mission indicated that there was an object drifting away from the Orbiter, disappearing after a few orbits. The radar signature and the ballistic coefficient of the object were analyzed to determine what the object might be. Recent communications from personnel from the Lincoln Lab (as provided to Dr. Sheila Widnall) indicate that, in their judgment, the best match to the "data" would be a piece of a T-seal. However, the possibility exists that the impinging ET foam caused a piece of an RCC panel to be broken off. The exact configuration of the initial damage is not known.

(3) The strain-gage reading (beginning at EI + 270) and the temperature rise at two thermocouples located in the vicinity of RCC Panel 9 (beginning at EI + 290), as indicated by MADS data.

As shown in Figure 5, three sensors were located in the vicinity of RCC Panel 9: two thermocouples and a strain gage. AT GMT 13:48:39, the strain gage on the left wing spar at RCC Panel 9 starts an off-nominal increase, as indicated in Appendix A. This is only 270 seconds after EI. At this point in time, the Orbiter is located about 1000 miles west of the California coast, flying at 23,000 feet/second at an altitude in excess of 270,000 feet. Refer to Table 1. Referring to Table 1 and to Figure 6, the temperature sensed by the thermocouple on the Spar 9 Clevis starts to increase by (approximately) GMT 13:49:00, which is less than 300 seconds after EI. According to Table 1, the temperature sensed by the thermocouple on the back of Spar 9 starts to increase very rapidly with time beginning at GMT 13:51:09. Refer now to Figure 7. Signal is lost from the thermocouple on the clevis at (approximately) 55 deg F, 490 seconds after EI. At approximately 522 seconds after EI, signal is lost from the thermocouple on the back face of the spar at a temperature exceeding 240 deg F.

The authors believe that the increase in temperature of the two thermocouples that are located on or near Spar 9 was caused by hot gases entering through a breech in the thermal protection system (TPS), which occurred when the impingement of the ET foam debris damaged the leading-edge TPS. Based on the information currently available to the authors, the critical, it is their opinion that the initial damage probably occurred in the vicinity of RCC Panel 6. Hot gases from the shock layer entered through the breech in the TPS and flowed down the chunnel. Although the density of these gases is relatively low, their temperature is very high. If this is indeed the case, then these hot gases flowing through the chunnel also were destroying the intermediate spar, a. k. a., the transition spar, and parts of the wing spar. Assuming this model to be correct, the hot gases would flow through the gaps and around the edges of the insulative wrap that surrounds the sensors. Thus, convection would be added to conduction and radiation, as mechanisms contributing to the rate at which the measured temperature increases.

Based on the computed flow-field solutions by NASA and on the engineering experiences of the authors, the flow path of the ingested hot gases depends on the location and on the shape of the breech in the thermal protection system. If the initial damage were a hole in the RCC panel itself, there would be a strong component of flow outward along the chunnel and parallel to the wing leading edge, following the external streamlines. If the initial damage were a piece of T-seal, the ribs of the bounding RCC



panels would constrain the flow to the channel bounded by the ribs. This flow path is initially perpendicular to the wing leading edge. However, the high temperature gases flowing in this channel could quickly ablate the downstream rib, at which time the damage would function as a hole.

Some Observations at This Point (A)

The destruction of the spar is not the only problem caused by the hot gases flowing down the chunnel. Under normal circumstances, the locally high convective heating rates to the external surface of the RCC panels along the wing leading edge are balanced by radiation into the relatively cool cavity behind the curved RCC panels, i. e., into the chunnel volume. In addition, under normal circumstances, some energy is conducted away from the leading edge through the high temperature gradients in the reinforced carbon/carbon shell. But this is no longer possible. These hot gases flowing in the chunnel not only prevent the mechanisms for relief of the energy from the RCC panels, they create a situation where the panels are being heated from both sides. The hot gases in the chunnel prevent the energy relief from the high convective heating rates to the external surface of the RCC panels. This will strike first at the RCC panel where the convective heating from the flow in the shock layer is the greatest. As will be discussed, the shock/shock interaction pattern produced the highest convective heating rates in the vicinity of RCC Panel 9. This will be discussed in "critical data/event" #4.

The destruction of the intermediate (or transition) spar somewhere behind RCC Panels 6 through 8 provides a source for the problems soon to affect objects in the left main-landing-gear wheel well ("critical data/event" #6) and the early loss of the elevon signals, which is attributed to the wire burn through ("critical data/event" #8).

(4) The perturbations to the heating and to the surface pressures due to the interaction between the bow shock wave and the wing-leading-edge shock wave are most severe in the region of RCC Panels 8 and 9.

The bow shock wave intersects the wing-leading-edge shock wave, creating a shock/shock interaction, such as shown in Figure 8 [Ref. 1]. The interaction between the bow shock wave and the wing-leading-edge shock wave depends (among other parameters) on the gas chemistry, on the angle-of-attack, and on the sweep angle of the wing. The bow shock wave is relatively weak, so that flow in the shock layer near the wing root is supersonic and the pressure is relatively low. Far outboard, the wingleading-edge shock wave depends on the sweep of the wing leading edge. If the leading edge is only slightly swept (as was the case for some of the early Orbiter concepts), the wing-leading-edge bow shock wave will be strong with high pressures in the downstream, subsonic flow. The low-pressure, supersonic flow inboard of the interaction adjusts to the high pressure, subsonic flow outboard of the interaction through a complex flow that contains regions of subsonic flow, of supersonic flow, impinging jets, and imbedded shock waves. See Figure 8(b). The surface of the wing leading edge that is subject to the impingement of this strong viscous/inviscid interaction may see heating rates more than an order-of-magnitude greater than the heating rates that would exist if there were no shock/shock interaction. However, in actuality, the wing-leading-edge sweep angle (for RCC Panels 8 through 18) is 45°. See Figure 3. Since the wing is highly swept, the wing-leading-edge shock wave will be relatively weak with low pressures in the downstream, supersonic flow. See Figure 8(c). Both the jet and the free-shear layer that are contained in the shock/shock interaction diffuse rapidly.



As a result, the shock/shock-induced perturbation to the heating in the region affected by impinging flow is relatively small for the current Orbiter configuration, i. e., approximately twice the heating that would exist if no shock/shock interaction were present.

Convective heating rates in the interaction region of the wing leading edge have been computed for the Shuttle Orbiter. The computed heat-transfer rates that are presented in Figure 9 indicate that the interaction between bow shock wave and the wing-leading-edge shock wave causes the heating to the surface in the interaction to be approximately twice the undisturbed value and that RCC Panel 9 experiences the highest heating. Because the Orbiter is operating at an angle-of-attack of 40-degrees, the stagnation line is on the windward surface just below the apex of the leading edge. Thus, the highest convective heating to the wing-leading-edge region affects RCC Panel 9, on the lower surface, just below the leading edge. As noted in the previous paragraphs, under normal circumstances, these incident heating rates would be accommodated by radiation from the back surface of the RCC panel into the cavity and by conduction through the reinforced carbon/carbon shell, away from the stagnation line. However, as shown in the sketch of Figure 10, the hot gases flowing up the chunnel not only eliminate the ability to transfer energy away from the wing leading edge, but they produce a situation where energy is added to the RCC panel from the inside as well as from the outside. It doesn't take long before the material near the stagnation line (on the lower surface) fails, leaving relatively sharp RCC plates, exposed to the flow. Thus, the authors believe that a second breech of the thermal protection system has occurred. The authors believe that this one is most likely to be on the lower surface of RCC Panel $9 \pm$ one panel. The authors' belief that there are two breeches to the RCC panels along the wing-leading edge is based upon not only the sensor data, but upon the Kirtland photograph, which will be discussed as "critical data/event" #10. Gases quickly flow from the high pressure region in the shock layer near the stagnation line into the chunnel, causing the destruction of the lower surface of the panel. The authors believe that this is a significant change in the Orbiter Mold Line (OML). The changes in the OML of the wing leading edge modify the vortices that emanate from this region and that impinge on the leeward fuselage. Therefore, it is associated with the start of off-nominal temperature histories at the four sensors on the left OMS Pod, which are described in "critical data/event" #5.

(5) Start of off nominal temperature histories at four sensors on left OMS Pod (beginning with lower than expected temperatures at EI + 340, followed by higher than expected temperatures at EI + 460).

Refer to "The STS-107 Mishap Investigation – Combined Master Timeline, - Baseline Corrected" that is presented in Appendix A. It is noted that, at GMT 13:49:49, which is EI + 340, "Start of off-nominal temperature trends" for "4 Left OMS Pod Surface Temps". Initially, the rise rate is cooler, when compared to previous flights of the same inclination. That is followed by a warmer-than-expected temperature trend, beginning at EI + 460. It is noted in Appendix A that the "Sensor sees a sharp increase at EI + 910 and goes erratic at EI + 940."

Even for the baseline configuration, i. e., for the configuration without any damage to wing leading edge, free-vortex-layer types of separation are produced by the flow around the fuselage chine, around the highly swept glove (sweep angle of 81°) and around the transition section from the glove to the majority of the wing, which is swept 45°. The resultant viscous/inviscid interactions cause locally high heating rates and high



shear forces to act on the orbital maneuvering system (OMS) pod. However, as is evident in the data presented by Neumann [Ref. 2] and reproduced in Figure 11, the heating to the OMS Pod is a function of the angle-of-attack. The correlation between the local heating and the angle-of-attack is important, since the Space Shuttle Orbiter employs ramping during entry. That is, the angle-of-attack of the Orbiter during entry is initially high, i. e., approximately 40-deg. until Mach twelve is reached. Then, it is ramped down, reaching approximately 20-deg., when the flight Mach number is four. The reader should note that there are significant differences between the heat-transfer correlation based on the wind-tunnel data and that based on the flight data. These differences can be traced, at least in part, to real-gas effects, to Reynolds-number-related effects, and/or to low-density effects.

The first author had a similar experience involving a difference between viscous/inviscid correlations based on wind-tunnel data and those based on flight-test data from the Gemini program. During the design phase of the Gemini capsule, it was assumed that the reentry aerothermodynamic environment for Gemini capsule was similar to that for the Mercury capsule. Thus, the wind-tunnel test program that was conducted during the design phase of the Gemini was somewhat limited. However, the Mercury capsule flew at an angle-of-attack of zero degrees, while the Gemini capsule reentered at an angle-of-attack of approximately 20-deg. Because the Gemini capsule flew at non-zero angle-of-attack, a vortex-induced viscous/inviscid interaction produced locally high heating rates on the conical surface in the vicinity of the umbilical fairing. The locally high heating rates produced numerous, small holes in the surface of the conical frustum of the capsule that was made of Rene 41. Once the inspection of the recovered capsule revealed the damage, a post-flight wind-tunnel test was conducted with instrumentation specifically located to obtain information about the aerothermodynamic environment in the region of perturbed flow. The wind-tunnel data revealed that locally high heating rates due to the viscous/inviscid interaction caused by the presence of the flow over the umbilical fairing. Although the wind-tunnel tests revealed the presence of and the approximate strength of the perturbations, there were considerable differences between the severity and the locations of the flight-observed damage and those based on the wind-tunnel tests. The results were similar to those of Figure 11.

By EI + 290, anomalous readings have occurred at the three sensors near Spar 9, as discussed in section relating to "critical data/event" #3. By EI + 493, anomalous data will be evident in the data from sensors in the left main-landing-gear wheel well and on the vertical side of the Orbiter. There will be a loss of the measurements from wire bundles at various locations in the wing box, beginning at EI + 487. These anomalous data indicate there was a considerable mass flow of hot gases through a large fraction of the internal wing volume.

The off-nominal temperature trends that were discussed in the first paragraph of this section (first slightly below the expected values, then above the expected values) are attributed to changes in the free-vortex shear-layer pattern that dominates the leeward flow field. The changes in the vortex pattern are due to the changes in the Outer Mold Line and to hot gases that are flowing from the internal wing volume through the vents that are located on the upper surface of the wing. The specific location of the perturbations to the surface heat-transfer and surface pressure are sensitive to the angle-of-attack, to the Reynolds number, to the density ratio across the shock wave, etc.



Flow-field computations for an Orbiter with RCC Panel 6 removed that were presented by Labbe et al. [Ref. 3] are reproduced in Figure 12. The computations that were made with the FELISA code at the Langley Research Center (NASA) assume an inviscid flow with equilibrium air in a Mach 23.8 stream. Three principal observations are associated with the removal of RCC Panel 6:

- "(1) Produces negative roll and yaw moments w/small magnitude
- (2) Streamlines for the damaged vehicle track inboard of baseline
- (3) Resultant shock raises pressures in proximity to temp measurements".

(6) The anomalous temperature increases that occurred at various locations in the main left-landing-gear wheel well (beginning at EI + 488).

The first sign that hot gases had reached the main left-landing-gear wheel well showed up in the brake-line temperature measurements. A "bit flip" in the "LMG Brake-Line Temp D" occurred at GMT 13:52:17 [Ref. 3]. This is temperature trace M in Figure 13. Thus, this event occurred 488 seconds after EI, which is approximately three minutes after the anomalous readings in the vicinity of Spar 9 ("critical data/event" #3). While a "bit flip" may well be within the experimental uncertainty and, therefore, will not be truly indicative of a problem, the LMG Brake-Line temp D was only one of many anomalous measurements that occurred in this time frame at sensors in the vicinity of the left main-landing-gear wheel well. Referring to Table 3, three "LMG Brake Line Temps" began unusual temperature increases in the time frame GMT 13:52:17 to GMT 13:52:41. Both the temperature measurement for LMG Brake-Line Temp C, which is trace I in Figure 13, and the temperature measurement for LMG Brake-Line Temp A, which is trace G in Figure 14, exhibit anomalous increases starting at GMT 13:52:41. These three gages cover X₀ coordinates from approximately 1100 through 1200. Thus, all three sensors are aft of the tires of the LMG. Because the rate of increase for the temperatures sensed in the wheel well was relatively slow, the hot gases didn't impinge directly on these sensors. Instead, the authors believe that the hot gases entered the cavity away from the sensors and gradually heated the volume of air that resided in the wheel well. Because of the severe damage on the tire and of the aluminum residue splattered on a door latch, the authors believe that the plume of hot gases could have entered that area through a breech near RCC Panel 6.

(7) The increase in temperatures at points located on the vertical side of the fuselage, as indicated both in thermocouples on the Orbiter itself and in the temperature sensitive coatings on the wind-tunnel models tested at the Langley Research Center (beginning at EI + 493).

It is noted in Appendix A that, by GMT 13:52:52, i. e., EI + 493, unusual temperature shifts were observed in five thermocouples on the fuselage and on the upper left wing. It is noted in Table 1 that "Mid fuse bond temp starts up" at GMT 13:54:22. The location of this sensor is noted in Table 3 as X_0 = 1410. Hasselback [Ref. 4] reports that, at GMT 13:53:29, "Fuselage side surface temp increase at X_0 1000.7". Because these anomalous fuselage side-wall temperatures were given a separate mention in the time line of Appendix A, it is given a separate data/event number in this report. However, the flow phenomena that cause these anomalous are essentially those associated with the anomalous heating to the left OMS Pod, i. e., "critical data/event" #5.

Wind-tunnel data from the 20-inch Mach 6 (Air Wind Tunnel) at the Langley Research Center (NASA) that are reproduced in Figure 15 show increased heating rates



on the side of the Orbiter fuselage both for only RCC Panel 6 removed and for only RCC Panel 9 removed.

(8) Loss of all measurements from the wire bundle running along the backside of the wing spar (beginning at EI + 487) followed by the loss of measurements from the wire bundle running along the left main-landing gear wheel well, which included elevon measurements (beginning at EI + 527).

Several of the wires carrying signals from the MADS sensors (including the two temperature measurements behind RCC Panel 9, one on the clevis and one behind the spar) run behind the RCC Panel 9 area wing spar along the back of the spar, forward to the front of the wheel well (about RCC Panel 5). See Figures 16 and 17. At EI + 487, the sensors whose wires run on the back of the left wing front spar begin going off-line, indicating a burn through of the spar. Over the next 10 seconds most of these signals go off line. The last one, the bottom-most wire, goes off-line at EI + 522. Since these wires are separated by about eighteen inches in most locations, the breech, at least its vertical dimension, had to be quite large. Beginning at approximately GMT 13:52:59, which is equivalent to EI + 530, the wires in the large bundles that run along the top of the wheel well (See Figure 17 and 18) begin to go off line. The first signal to go off line was the elevon lower skin temperature. Over the next minute or so most of the signals in these wire bundles go off line. See Figure 19. This would indicate a significant amount of heat was impinging on the wires and wheel well wall. NASA has performed a number of tests to investigate the burning of wire bundles. These test demonstrated that the rapid loss of the entire wire bundle requires very hot gases, with local heat rates of 80 to 90 Btu/ft²-sec. It is likely that the wheel well wall had been penetrated at this time, since anomalies were showing up in the temperature measurements in the left mainlanding-gear wheel well. Recall that the first observed "bit flip" in the wheel well was at EI + 488. While this single "bit flip" may or may not be significant by itself, within the next one to two minutes most of the temperature sensors on the landing gear in the wheel well began to increase. Refer to the discussion of "critical data/event" #6.

This sequence raises some dilemmas that need to be addressed. First, how do we get enough heat on the wheel well to burn the wires, but yet the sensors in the wheel well stay on line until the loss of the Orbiter and the temperatures only go up about 40°F. Second, the hole through the spar has to be large enough (> 18 inches tall) to take out all the wires, creating a large path for the hot gases to go into the wing interior, yet much of the aluminum wing structure stays intact for another 8 minutes. One explanation could be that a T-seal (or portion of a T-seal) missing. With a T-seal the impinging jet would be narrow, but tall enough to cut all the MADS wires. It could take out the vertical array of wires without the massive heat a "circular hole" would deliver. Also, it would seem that the breech in the spar should be near where the wire bundles (MADS and OI) are close together so the required heat would be minimized. This would favor a breech through a lower number RCC panel. However two strain gages on the front of the wheel well did not go off-line (See Figure 18). This would tend to rule out RCC Panel 5, which is ahead of the front wheel well wall. If the initial damage were to a T-seal (or maybe created a hole just upstream of an RCC rib), the hole through the spar could be smaller and still burn a vertical array of wires. Interestingly enough, such a damage configuration would result in initial flow perpendicular to the spar and cut wires. After 2 to 3 minutes, the very hot gases impinging on the downstream edge of the slot would burn through the RCC rib. At this point the hot gases would tend to flow down the chunnel, damaging the downstream RCC panels and the spar.



(9) The observations regarding the damage to the wing leading edge, as determined from the recovered debris.

Many members of the Board and support staff have spent considerable time in Florida examining the recovered debris. Experts such as Jim Arnold, Howard Goldstein, Pat Goodman, Greg Kovacs, Mark Tanner, and Don Rigali have spent considerable time and effort analyzing the recovered debris. The present authors are not as knowledgeable as many others on the detailed interpretation of the reconstructed wing leading edge. Therefore, our conclusions rely on the photographs, reports, and oral feedback from these experts. Photographs of the reconstructed wing-leading-edge panels, RCC Panels 5 through 11, are presented in Figures 20(a), 20(b), and 20(c). Note that very little of the bottoms (windward surfaces) of RCC Panels 6 through 9 have been recovered. The authors interpret the damage pattern to RCC Panels 6 through 9, as supporting their belief that the foam-induced damage was centered on RCC Panel 6 and the subsequent damage caused by the blockage-of-relief/additional-heating from the chunnel gases led to the loss of most of RCC Panel 9. Because RCC Panel 9 is in the most severe region of the baseline shock/shock interaction region, it would be expected to suffer the most damage. Thus, we believe that the subsequent loss of RCC Panel 9 left two regions where substantial damage had occurred to the wing-leading-edge RCC panels relatively early. Of course, the absence of debris could mean simply that the debris has not been found. It appears that significant fractions of the upper section of RCC Panels 7 and 8 have been recovered. Thus, it appears that there was a surviving section of RCC panel(s) between the two gaps. This is consistent with the authors' belief that, by the time of the Kirtland photograph, there were two distinct notches in the wing leading edge, which were caused by the loss of a substantial amount of RCC Panel 6 (+/- one panel) and RCC Panel 9 (+/- one panel). Between these "missing" panels, a piece of the wing leading edge (what we believe to be the surviving pieces of RCC Panels 7 and 8) remains in place.

The experts report that there is a lot of unique damage in the vicinity of RCC Panels 8 and 9, noting that there is considerable slag deposited on the inner surfaces of the upper portions of the recovered panels. The relative metallic deposition on left wing materials is presented in Figure 21. Note that the metallic deposition is "heavy" to "very heavy" behind RCC Panels 7, 8, 9, and 10. Since the predominate flow stream will be up and out along the chunnel, this pattern would be consistent with an initial breech in the vicinity of RCC Panel 6 +/-1 panel with the hot gas plume impinging on the spar behind RCC Panels 7 and 8, causing splatter on the material in this area.

The authors believe the recovered portions of RCC Panels 6 through 10 are reasonably consistent with the demise history of the panels that will apply to "critical data/event" #10. Moving circumferentially around the wing leading edge in an x-y plane, the most severe convective heating occurred in the vicinity of the stagnation line in the shock/shock-interaction region, which is most severe for RCC Panel 9 \pm one panel. See Figure 9. The burn through started at the stagnation line and proceeded to eat away the RCC shell in either direction. Thus, it is not surprising that the lower surface has not been found for any of these RCC panels. The hot gases flowing through the chunnel from the original ET foam-induced breech to the thermal protection system (TPS), which occurred in the vicinity of RCC Panel 6 +/-1 panel, ate away at numerous metal surfaces, depositing the residue as slag on the surviving inner surfaces of the leading edge TPS elements.



It would be reasonable to expect that, if any portion of an RCC panel were recovered, it would be upper portion of the panel. The lower portion (which is the windward portion and, therefore subjected to the greatest convective heating) of the panel may be destroyed during the expanding destruction of the reinforced carbon/carbon shell. Referring to Table 2 and Figure 20(c), the upper portions of RCC Panels 7 and 8 on the left wing have been recovered. Only the edges of the upper portion of RCC Panel 9 have been recovered. As of the date of this writing, the lower portions of these three RCC panels have not been found.

Some Observations at this Point (B)

Referring to the timeline record presented in Table 1 for the flight STS-107 of OV-102, the first debris was seen leaving the Orbiter at GMT 13:53:44. Hot gases have been entering through a breech, or breeches, that occurred in the vicinity of RCC Panels 6 though 10. Sensor measurements on the spar behind RCC Panel 9 indicate anomalies starting at approximately GMT 13:48:39, which is 270 seconds after EI. Temperatures sensed at various points in the LMG brake line exhibit anomalous behavior, starting at GMT 13:52:17 (or slightly later). Thus, the anomalous temperature measurements from the main left-landing-gear wheel well started approximately 488 seconds after EI.

Note that "critical data/events" # 3 and #5 through #9 take place over several minutes in time, affecting first sensors at the spar behind RCC Panel 9, which is relatively close to the wing leading edge, and then, approximately three minutes later, affecting brake line temperatures in the LMG wheel well. This pattern is consistent with a damage model that starts with a foam-impact-induced breech near RCC Panel 6 ± one panel. Hot gases flowing through the chunnel not only block the path for relieving the relatively high heating rates to the external surface of the RCC panels in the vicinity of the shock/shock interaction, but cause these critical panels to be heated from both sides. Because the shock/shock interaction to the baseline configuration produces relatively high heating rates centered in the vicinity of RCC Panel 9 (refer to Figure 9), the internal flow next creates catastrophic damage to the TPS in this region. Thus, the RCC panels in this region undergo growing damage, providing a second breech to the TPS. As noted earlier, at this point in time during reentry, there has been a significant change to the Orbiter Mold Line (OML).

Note that it is the authors' opinion that the limited data available to the authors at this time does not rule out the possibility that the initial foam-impact-induced breech might have affected an RCC panel downstream of RCC Panel 6. However, the Kirtland photograph, which will be discussed in the next section, indicates to us that there are two gaps in the wing leading edge. Regardless of where the initial breech of the wing leading edge occurred, the locally high pressures due to the shock/shock interaction that exist for the baseline Orbiter configuration are greatest on the surface of RCC Panel 9 +/- one panel. These pressures drive the hot gases into the wing volume, contributing to the heating to those gages on the spar behind RCC Panel 9. Then, within a few minutes, the gases break through the spar and the LMG wheel-well wall. Damage to the Orbiter is growing rapidly. The first five debris events (refer to Table 3) occurred in the time GMT 13:53:44 to 13:54:11. The demise of one or more RCC panels changes the Orbiter Mold Line (OML) geometry of the wing leading edge. Instead of encountering a rounded leading edge with gradually changing wing-leading-edge sweep angles, the



oncoming flow sees cavities or notches in the wing leading edge, flat faces of (what is left of) the spars, metal surfaces of high catalycity, etc. See Figure 22. Locally strong shock waves that are imbedded in the viscous/inviscid interaction change the nature of the interaction to one more like that of Figure 8(b). A significant increase occurs to the perturbations in heating to the erose leading edge formed by the damage to/loss of those RCC panels in the "transition zone", e. g., RCC Panels 6 through 9. All of this, occurs with the Orbiter flying at velocities in excess of 22,000 feet/second (Mach 22.5) and at an altitude of 227,000 feet where the flow is a continuum and the aerothermodynamic environment is severe.

The scenario now becomes one in which the damage accelerates dramatically.

(10) The modifications to the shock/shock interaction flow field of "critical data/event" #4, as developed based on the developing damage scenario and correlated against the Kirtland photograph, i. e., observations by personnel from the Starfire Optical Range (at EI + 830.5/832.5).

As noted in the previous paragraphs, debris events 1 through 5 take place from GMT 13:53:44 to GMT 54:11. See Tables 1 and 3. A number of tiles and/or pieces of individual RCC panels along the leading edge have been ablated, or lost. See Figures 20(a) through 20(c) and the "The Content of Left RCC Panels" in Table 2. Consistent with our premise, let us assume that there are at two gaps due to "missing" RCC panels from the wing leading edge. Missing is in quotes because parts of the panels are probably still in place. Furthermore, each notch may represent one or more RCC panels. Recall from the previous discussion that the initial, critical, foam-impingementinduced damage possibly affected RCC Panel 6 ± one panel. The early and rapid responses of the three sensors near the spar behind RCC Panel 9 led to the postulation that hot gases were flowing through the chunnel. The significant amount of metallic deposits on left-wing materials presented in Figure 21 further supports the contention that damage to RCC Panel 6 was the initial breech. Downstream, leading edge RCC panels were being heated from both sides, with disastrous effects. The most disastrous were to the RCC panels located where the shock/shock interaction heating was the greatest, RCC Panel 9. Thus, based on the previous discussion, we will assume that the two notches are centered on RCC Panel 6 and on RCC Panel 9. Refer to Figure 22.

As shown in the sketch of Figure 23, the loss of these segments along the wing leading edge present the oncoming flow with notches that contained flat faces, forward-facing corners, etc., instead of the gradually changing sweep angle and the rounded nose of the undamaged wing leading edge of the Orbiter. Locally strong shock waves, i. e., shock waves that are perpendicular to the oncoming flow, occur for each notch. A portion of each shock wave is normal to the oncoming flow, but only for a short distance. The notch-induced shock waves quickly curve away as the flow follows the RCC surface downstream of the corner. Thus, the shock shape has a "bubble-like" appearance in the plane of the paper.

The shock-layer structure postulated for each notch in the sketch of Figure 23 is similar to that obtained during the Mach 6 wind-tunnel tests that were conducted at the Langley Research Center. See Figure 24. Consider the curved shock wave associated with the notch created by the removal of RCC Panel 9 from the wind-tunnel model. The trace of the shock wave nearest the wing root, i. e., the trace that extends into the notch produced by the missing RCC Panel 9 is normal to the oncoming flow. Thus, the flow



immediately downstream of the normal shock wave is subsonic. As the shock wave curves, it becomes weaker and the flow immediately downstream of the shock wave is supersonic. Because the shock wave is curved, there is considerable vorticity in the shock layer flow approaching the wing leading edge. The curved shock wave associated with the notch of RCC Panel 6 would exhibit similar features. Furthermore, when these two curved shock waves intersect for this high angle-of-attack configuration, they create an extremely complex flow field.

Consider next the flow of the air in the shock layer just ahead of the wing leading edge. The density of the air in the shock layer will be greatest in the shock-layer flow downstream of the normal portions of the shock wave. The large density gradients that occur in the shock layer flow would cause light rays from a distant source on the far side of the vehicle to be bent as they pass through the shock layer. Light rays would bend due to the large second derivatives in the density of the air in the shock layer, producing dark areas in a photograph of the flow. This phenomenon is similar to the shadowgraph technique, which is used to visualize the shock-wave structure in a wind-tunnel flow. The stand-off distance from the shock wave to the vehicle surface is relatively small for these hypersonic flows. Thus, the shock layer flow in the shadowgraph may appear as a dark region in the plane of the photograph. The reader should note that this is a two-dimensional trace of a three-dimensional phenomenon.

A photograph of the Orbiter in flight was taken by personnel at the Starfire Optical Range is presented in Figure 25. This is called the Kirtland photograph. It was taken at EI + 830.5/832.5, which is just less than two minutes before the loss of signal. Note the similarity between the notch-induced shock-wave structure that the authors postulate for the flow near the wing root (refer to Figure 23) and the darkened area in the Kirtland photograph (refer to Figure 25), which contains two bubbles in the darkened area near the intersection of the wing with the fuselage. Many investigators have tried to define the place of the Orbiter within the darkened area. Two examples of these attempts are presented in Figures 26 and 27. Although the present authors do not necessarily agree with the phenomenological models proposed for these two figures, they do support our belief that damage to the wing-leading edge in the form of missing RCC panels produces a multiply-curved shock structure. The existence of two notches along the wing leading edge produces a shock-layer structure, which is consistent with the present authors' interpretation of the Kirtland photograph.

Assume that the breech of the wing leading edge through the loss of "two" RCC panels occurred near GMT 13:54:00, i. e., the time of debris events one through five. "Two" is in quotes, because the possibility exists that portions of adjacent RCC panels may also be missing during this time frame. Why does the darkened region in the Kirtland photograph, which was taken at GMT 13:57:59.5, which was approximately 240 seconds later, still correlate with the authors' model of the notch-induced perturbed flow? The authors believe that, while there is a considerable mass of hot gases flowing through the wing box, there is a considerable thermal mass available to absorb the energy in these hot gases. Thus, it takes awhile for the damage to the structures in the internal wing volume to reach the critical limit, where the left wing will break off. This occurs somewhere between the time of the Kirtland photograph (EI + 830.5/832.5) and the LOS (EI + 923).



(11) Comparing selected histories showing that the actual flight was close to the planned flight up to EI + 900.

Beginning at EI + 270 and continuing through EI + 923, which corresponded to LOS, the damage to OV-102 grows continuously. Breeches along the wing leading edge allow hot gases to flow through large portions of the internal wing volume, destroying structures in its path. Venting gases and the changes to the OML modify the vortical flow over the leeward surfaces of the Orbiter. Nevertheless, the "actual, or as flown trajectory" was very close to the "planned trajectory". Referring to Figure 28, the velocity history for the actual trajectory follows closely that for the planned trajectory through EI + 923. A similar comparison for the altitude history would produce the same degree of agreement.

It is noted in Appendix A that angle-of-attack modulation becomes active at EI + 562. "Entry Guidance enables limited delta angle of attack commands from the reference angle of attack to promote improved convergence to the reference drag profile". Referring to Figure 29, the reader can see that the "actual, or as-flown" angle-of-attack history follows "reasonably well" the "planned" angle-of-attack history until after EI + 900. The actual angle-of-attack was usually within one degree of the planned flight angle-of-attack.

Thus, despite the growing damage, many of the flight performance parameters remain close to nominal up to this time. At some time after (approximately) EI + 860, with the Orbiter over Texas, a substantial portion of the left wing probably broke away. From then on, there were a plethora of indicators of trouble.

(12) Using the rolling-moment-coefficient history to support findings for some of the previous eleven points.

The delta rolling moment history is presented in Figure 30. The strong oscillatory variations of the delta rolling moments that occur before GMT 13:50:00 were attributed to experimental uncertainty from the outset, as noted by Labbe et al. [Ref. 3]. From GMT 13:50:00 through GMT 13:53:00, the delta rolling moment was relatively constant and negative. The magnitude is within the experimental uncertainty. Furthermore, additional review of these data indicated that there had been flight-to-flight variations of similar magnitude from previous flights. Winds were offered as another factor that could have affected the data in this time frame. Because of these three factors, the authors have assumed that none of the delta rolling moment data for times before GMT 13:53:00 are definitive.

From GMT 13:53:00 to GMT 13:54:00, the delta rolling moments are negative (left-wing down) and becoming more negative with time. See Figure 30. In the same time frame are the first five debris events. Recall that, for the flow field that was computed for the Orbiter with RCC Panel 6 missing, there were negative rolling moments of small magnitude. See Figure 12.

Research activities have been conducted by personnel at the Langley Research Center (NASA) to determine the flow field of the Shuttle Orbiter at an angle-of-attack of 40°. Notches in the wing leading edge simulated missing RCC panels. The Mach 24.2 flow field was computed assuming that the Orbiter was missing RCC Panel 9 and that the air was in thermochemical equilibrium. Surface pressures for this computed flow



field are presented in the lower right-hand figure of Figure 31. Streamwise streaks of high pressure are associated with the vortices from the shock interactions and from the flow around the notches. The effect of the vortices are also exhibited in the streamwise streaks of high heating that bound the large area of lower left wing surface where the notch has perturbed the heating. See the lower left-hand figure of Figure 31.

High pressures act at the notch left by the loss of RCC Panel 9. The probable loss of a good portion of the spar behind that RCC panel provides a path for the hot gases to create devastation to the structures in large areas of the internal wing volume. Although temperature measurements in the LMG wheel well have been indicating problems for over two minutes, the damage to the wing front spar and internal struts is increasing. The timeline presented in Table 1 indicates that, during the same time frame that first five debris events occur. It is likely the upper interior wing honeycomb surface is being heated above the RTV (tile bonding adhesive) failure limit and the tiles are coming off. It is also possible a larger section of the honeycomb aluminum burns or comes lose which could correspond to the flash (burning of the vaporized aluminum) observed in this time period.

As the internal wing structure (spar and struts) melts, the dynamic pressure on the lower wing surface would likely cause some wing flexure, bending up or dimpling of the lower wing. Loss of the internal wing structure would put added loading on the remaining RCC panels causing them to break, consistent with observed panel tops cracked at the apex. A bent spanner beam was also found. These phenomena also contribute to the explanation of the increasingly positive rolling moment observed.



CONCLUDING REMARKS

This document develops a plausible scenario for the demise of the Shuttle Columbia based on what the authors judge to be 12 critical pieces of data. While there is lot still unknown and much we'll never know, the authors believe there is sufficient collaborating evidence to support the following conclusions:

- 1. At 82 seconds into the launch, the ET-foam debris strikes the wing, damaging the leading edge. For reasons discussed in the main body of the report, the authors believe the initial breech was in the vicinity of RCC Panel $6 \pm$ one panel. This also would mean the breech was present at start of reentry.
- 2. Hot gases entering a breech near RCC Panel 6 have several negative effects. First, hot gases flow down the chunnel, causing the MADS sensors near spar 9 to have anomalous responses early in the entry. The slag and other melting metallic components are splattered onto the surfaces behind RCC Panels 7 through 10. See Figure 21. Second, the incoming plume impinges on the spar, eventually burning a hole. Third, the hot gases in the chunnel reduced the heat rejection capability of the RCC panels downstream (outboard) of RCC Panel 6. Since these RCC panels are in the region where the baseline shock/shock interaction pattern is most severe, a second breech in the TPS occurs near RCC Panel 9 ± one panel. Soon other RCC panels in the vicinity experience significant ablation. See Figure 20(c).
- 3. The hole through the spar has some defining characteristics. It has to burn all 4 MADS wire bundles on the back of the spar (making it about 18 inches high), yet focus enough heat on the OI (telemetry) wire bundles several feet away on the top of the wheel well to burn them quickly. A missing T-seal (or a portion thereof) near RCC Panel 6 ± one panel would allow a concentrated slit of hot gases to cut the wire bundles, without depositing heat to a large internal volume in the wheel well. Since the temperature sensors in the wheel well all increase together, but at a very slow rate (about 8 degrees per minute), the plume can't be impinging directly on these temperature sensors. Within a few minutes, the slit jet will change to a "circular" hole as the downstream rib burns through. The change in the geometry of the breech causes more of the hot gases to flow down the chunnel.
- 4. Damaged panels near RCC Panels 6 and 9 would explain the OMS-Pod heating transients because of the perturbation to the flow over the wing. This behavior is consistent with studies being conducted at the Langley Research Center (LaRC). Notches at two locations along the wing leading edge appear as a double hump in the leading edge flow field that is captured in the Kirtland photograph, which was taken when the Orbiter was visible to the Starfire Optical Range,
- 5. The debris damage shows a lot of unique damage in the region of RCC Panels 8 and 9. This is consistent with a secondary burn through in this max-heat area after hot gases get in the chunnel. The fact that much of the bottom panels in region 6 to 10 are missing would be consistent with burn through on the bottom high heat area. Probably first occurring at the shock-shock interaction centered on RCC Panel 9, but eventually affecting RCC Panels from 6 to 10. The tire in



the left wheel well shows unique burning, as does one of the main gear up-lock parts. This would be consistent with a jet originating behind RCC Panel 6 and burning through the wheel well near the tire. The tire would protect the temperature sensors in the wheel well from being directly hit and, as a good insulator, help diffuse the heat for a while giving in a more uniform heat up rate in the wheel well.

6. The small initial decrease in rolling moment is consistent with LaRC wind tunnel test with "missing" RCC panels. The hot gases will penetrate into the wing front spar region and the wing internal structure. As this wing support structure is destroyed the lower wing surface will begin to flex upward under the increasing dynamic pressure load as the atmospheric density increases. The changing shape could explain the continuing increase in roll moment up until the loss of signal at about EI + 923.

While there is much that will never be known about the demise the authors judge the scenario developed in this paper is reasonable and may best correlate with the available aero, thermal, debris, and timeline. At the time of this report, NASA has not yet completed an integrated Aerothermal-structural analysis starting with a breech in the vicinity of RCC Panel 6.



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- [1] J. J. Bertin, <u>Hypersonic Aerothermodynamics</u>, AIAA Education Series, Washington, D. C., 1994.
- [2] R. D. Neumann, "Defining the Aerothermodynamic Methodology", J. J. Bertin, R. Glowinski, and J. Periaux (eds.), <u>Hypersonics, Volume I: Defining the Hypersonic Environment</u>, Birkhaeuser Boston, Boston, 1989.
- [3] S. Labbe, J. Caram, and C. Madden, "CAIB Public Hearing", Tuesday, 18 March 2003.
- [4] M. Hasselbeck, "Preliminary Conclusions Based on MADS Data", April 2003.

To link to the figures and appendices please click on the following hyperlinks:

To see figures click on 2 Fatal Reentry of STS107 Data and Observations.ppt

To see appendix click on <u>3 Timeline-STS-107-REV17-BASELINE.xls</u>

Figures for

Using the Data and Observations from Flight STS-107 to Explain the Fatal Reentry of the Columbia Orbiter OV-102

Table 1

Time Al from El	Values from NASA briefs and lead books Prop By Jun Smiley X7545. Time Alithud Air Atmos Dynam Equiv Heat 1 from Density Press Press Sea L Rate 17 El slugskin 2 pv./VZ speed analys and min Ebel #South Mileth But 46	Prop. Bruint States and some of the states o	Atmos Dyr Press Pre	Atmos Dynam Equiv y Press Press Sea L pv'v/2 speed Esqfi #isqf Mie/br	Equiv Heat Sea L. Rate speed analys Miehr. Blu	Heat LE Rate Temp analys analys Blu deo-F	LE Maci Temp analys deo-F	Mach Vel Locatio	on Key Entry Events Rev 14	Atth Debris Number Miles Events Dens Molent3	Altitude Miles Km		Path Iambda Lambda Iambda II inches Layer Infgas reg Free spac Linda fri20	path Layer Free air > Lmda fri20	MAX KE 1/2pv*v*v per f/2 Bluff2sec	Air Flow Oxygen Flow Moxyx.2 Ibm/fi2sec Ibm/sqf-	Air Flow Oxygen Alumina Flow Burn ra Moxxx.23 if hot en thorit2sec ibmisqfi-sec Mis per sqft-sec	트 # 3	Heat of Combustion If hot enough Bhu per sqft-sec
0.4	400000	5.4E-11 -4	0		12Sec	Desc 0	0 24	24.6 23000	13:44:09 Entry interfera	Later	7.6	126	6 72	Later 1.73E+16		A.06-05	9.1E-06		000
30							100									1.7E-04			
1:00							200									3.06-04			
1:30						57	350									4.2E-04			
8	2:00 340000 7:5E-10	7.58-10		0	bs	en en	200	22820			1 19	007.0 701	00 8.405	5 2.42E+17	2.0	5.56.04	1.3E-04	10.0	1.86
30 3	2:30 327000					~	800	22900			1 29	103				1.8E-03			
00 3	3.00 314000				177	10 11	1100	22890			66	8				3.0E-03			
30 3	3.30 301000				100	15. 13	1300	22880			25	35				4.2E-03			
00 2	4:00 288000 7.4E-09		9	N	28	22 15	1500 24.7	24.7 22850			55	170.0 16	71 0.853	2.385+18	25	5.4E-03	1.3E-03	0,10	18.26
30 Z	4.30 Z74000 1.4E-08		0.01	*	38	30 17	1750	23050			25	86 0,038	38 0.461	4,42€+18	108	1,0E-02	2.3E-03	0.19	34.10
00 2	5:00 260000 2:5E-08	25E-08 0.021	121	1	25	36 20	2000 24.6	24.6 23100	RCC-9 Clevis heafing		69	82 0.021	21 0.249	8.17E+18	202	1.95-02	4.3E-03	0.35	63.27
30 2	5.30 256000 3.06-08	3.0E-08 0.030	30	100	8	42 22	2200	23050			87	81 0.017	17 0.209	9.75E+18	239	2.2E-02	5.2E-03	0.41	75.28
00 2	6.00 251500 3.7E-08	3.7E-08 0.040	140	10	23	45 24	2400	23000			48	79 0,014	14 0.171	1,196+19	290	2.7E-02	6.3E-03	0.50	91.57
30 2	47000	6.30 247000 7.4E-08 0.051	191	50	98	52 25	2550	22950			47	78 0.007	07 0.085	5 2.38E+19	925	5.4E-02	1.3E-02	1.01	182.91
00 2	7:00 243000 8	8.8E-08 0.058	95	23	88	55 27	2700 24.1	24.1 22900	Start of peak heating RCC 9 Spar heating		46	77 0.006	06 0.072	2.82E+19	629	6.4E-02	1.5E-02	1.19	216.39
30.2	7:30 239000 1 DE-07	1.0E-07 0.063	8	27	103	57 27	2750	22825			45	75 0.005	05 0.061	3.34€+19	797	7.65-02	1.8E-02	1.41	255.73
00 2	8:00 236000 13E-07	13E-07 0.080	08	33	113	58 28	2800 23.6	23.6 22750 300 w calif	51.46 inertial Beta goes neq-stays ne f 52.05 first off nominal aero signal		45	74 0.004	04 0.050	4.04€+19	983	9.2E-02	2.1E-02	1.69	307.93
30 2	8.30 234800 1.3E-07	1.35-07 0.085	98	33	114	60 28	2800	22600	52.32 Supply H2O lemp rise		4	74 0.004	04 0.049	4.18€+19	296	9.4E-02	2.2E-02	1.74	316.51
2 00	9.00 233600	1.4E-07 0.089	68	38	119	62 28	2800 23	23.3 22500	53.01 First clear Off line roll moment		**	74 0.004	04 0.044	4.57E+19	1044	1.0E-01	24E-02	1.89	344.77
30 2	9:30 231000 1,5E-07	1.5E-07 0.102	0.5	88	122	63 28	2850 23	23 22400 Calif coast	53:36 into Elevon temp OSL	4	#	73 0.003	03 0.042	4,88E+19	1099	1.1E-01	2.5E-02	2.01	366.12
00 2	10:00 229000 1.7E-07	1.7E-07 0.112	12	14	127	PR 28	2900	22250	54:10 LG brakelstrut lemp up	3	43	72 0.003	8000 00	5.32E+19	1174	125-01	2.7E-02	2.18	396.59
30 2	10.30 227000	1.8E-07 0.121	53	4	132	64 28	2800 22	22.5. 22100 CAINV Bond	54:20 Slow aleron frm change and 54:22 Mid flue bond temp starts up #6	- H	43	72 0.003	03 0.035	5,79E+19	1253	1.36-01	2 9E-02	236	428 95
00 2	11.00 224800	1.9E-07 0.133	33	46	134	64 28	2900	21700	CHICAGO DIAGRANDA SOCIALI MOSO	#7 to	43	71 0.003	03 0.033	6 23€+19	1276	1.36-01	3.1E-02	2.49	453.10
1355.30 11.30 Z 1355.45 Z 1356.00 12.00 Z	13:55:30 11:30 223500 13:55:45 222800 13:55:45 222800 12:00 222000 13:55:00 12:00 222000 13:55:00 13:5	2,1E-07 0,144 2,1E-07 0,150 2,3E-07 0,158	488	2 8	135	2 2 2	2900 21.6	21.6 21000 20.650	rd 55.41 Mid Fus sill T start off N 56.03 Wing temp trend down	#15	222	71 0.003 70 0.002 70 0.002	03 0.031 02 0.030 02 0.027	6.86E+19 6.86E+19 7.41E+19	1273	1.46-01	32E-02 33E-02 35E-02	258	471.86 482.68 517.47
30.2	12:30 220000 3	2.4E-07 0.171	11	15	142	64 28	2900	20780	56.30 Roll Reversal Inibated		42	69 0.002	02 0,027	7,60€+19	1367	1.6E-01	3.6E-02	2.91	529,13
2 00	13:56:45 13:57:00 13:00 218000 2:6E-07	2.6E-07 0.185	88	98	148	64 29	2900 201	20.7 20700 AZINM bo	cord 56:55 Roll reversal comp		14	2000 69	02 0.024	8.36€+19	1486	1.7E-01	4.0E-02	3.19	579.80
30 2	13:57:15	2 9E-07 0 190	8	19	155	64 28	2900	20350	57.28 Wing temp off line	910	41	58 0.00Z	02 0.022	9.42E+19	1592	1.96-01	4.4E-02	3.53	842.54
2 00	13:57:45	3.4E-07 0.233	33	69	164	63 29	2900 19.5	19.9 20000 NM	58:09 Sign chang e yaw and roll	Flare 2	40	57 0.002	02 0.018	1,10E+20	1767	2.2E-01	5.1E-02	4.06	738.44
30.2	13:58:30 14:30 208000 3	3.9E-07 0.296	96	73	169	62 28	2850 19.3	19.3 19400 Littlefield	58:32 Tire femp and press OSL		88	96 0,001	0,016	1.24E+20	1818	24E-01	5.5E-02	4.44	807.58
00 3	13.58.45	4.5E-07 0.341	77	20	178	60 28	2800 186	18.6 18900 Lubbock	59:06 LMG Down lock indication		39	64 0.001	01 0.014	1,45E+20	1960	2.7E-01	6.3E-02	5.04	917.09
30 2	13.59.30 15.30 200700 4	4.8E-07 0.381	181	83	180	59 28	2800	18600	59.33 Two yaw lets firing		88	63 0.001	0.013	1.54E+20	1985	2.9E-01	6.6E-02	527	959 23
13:59:45																			

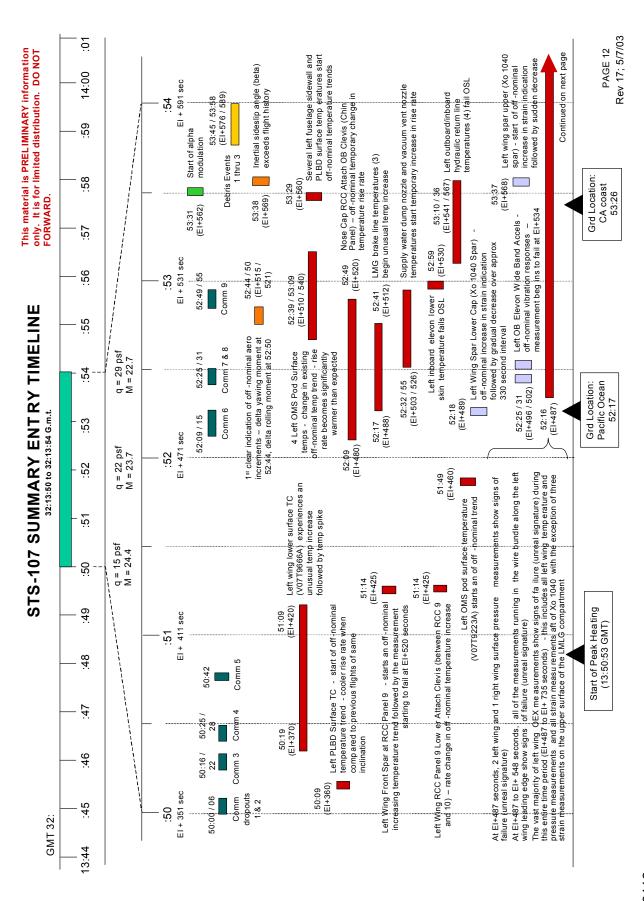
2 Fatal Reentry of STS107 Data and Observations.ppt

Content of Left RCC Panels

	Lower Closeout Panel	Lower RCC Panel		Upper RCC Panel Upper Closeout Panel
_	×	×	×	×
2	×	×	×	
က	×		×	×
4	×		×	
2			×	×
9	×			×
7	×		×	
∞	X Tiles Only		×	
6	X Tiles Only		X Edges Only	
10	×			
17	×			
12				
13		×		×
14		×	×	×
15	×	×	×	×
16	×	×	×	
17			×	
18		×		
19		×		
20				
21		×		
22	×	×		

CA-000112

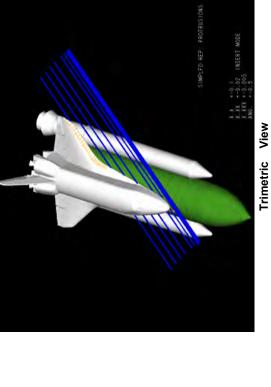
Table 3

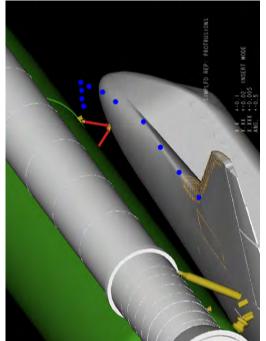


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Ascent Debris Trajectory

 Solid cylindrical protrusions were created through the debris locations in each view





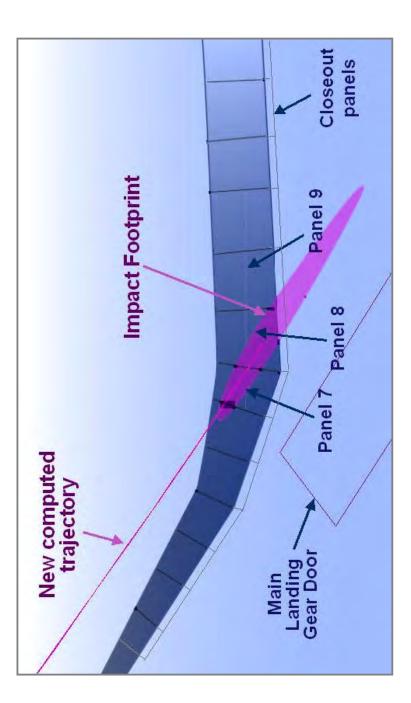
ET208 Camera View



CA-000112

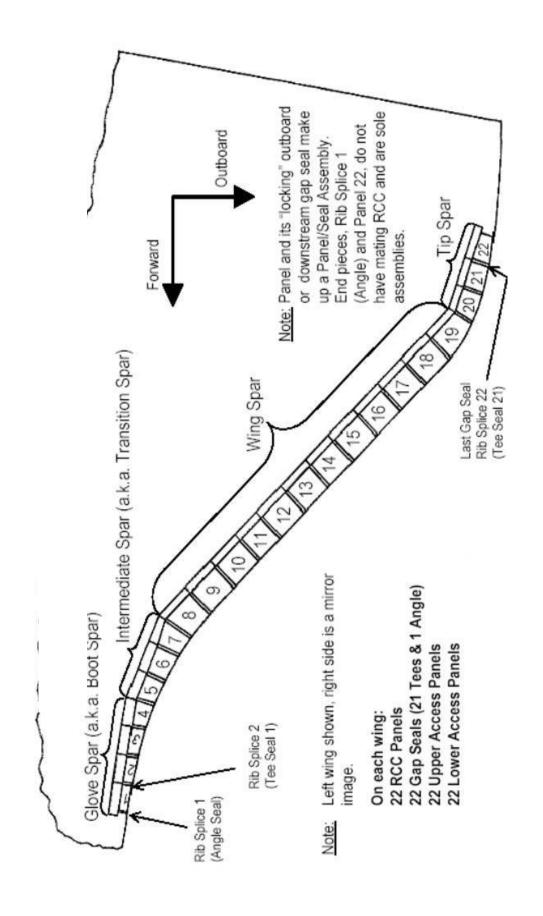
Projection of Debris Trajectory onto Left Wing

Figure 2



approximately RCC panel 8, with the most likely foam impact predicted Centerline of one-foot diameter trajectory "pipe" intersects the wing at along panels 7 and 8

Left Wing Orientation

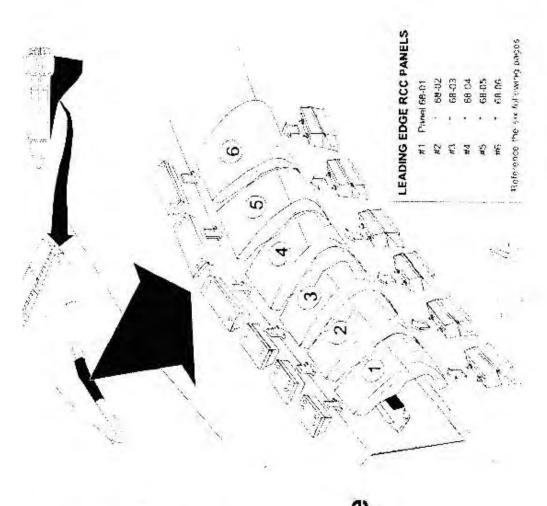


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Left Wing Leading Edge

Figure 4

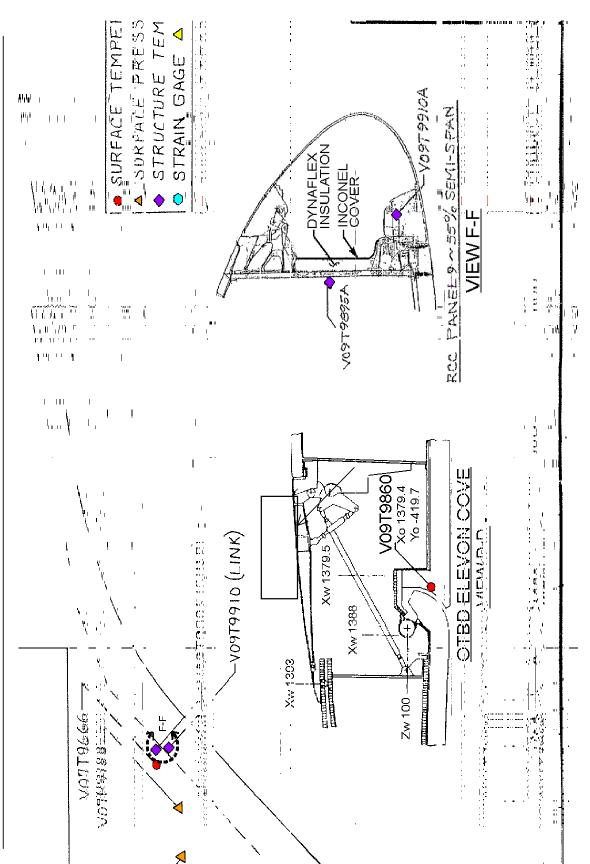
mounting hardware (LESS) comprised of RCC panels, T-Edge Subsystem Seals, Upper and · Wing Leading Lower Thermal Barriers, and associated



3/14/03

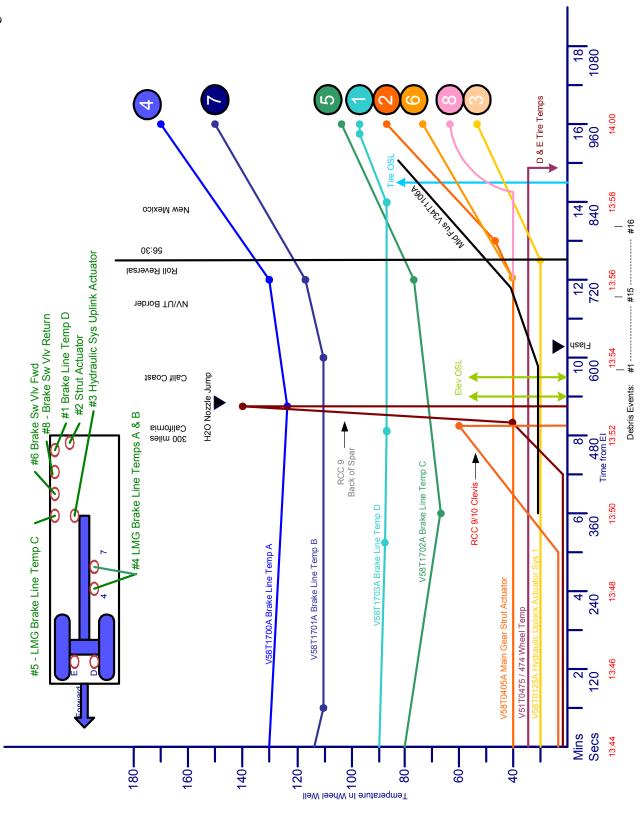
CA-000112

RCC Panel 9 Sensor Locations



CA-000112

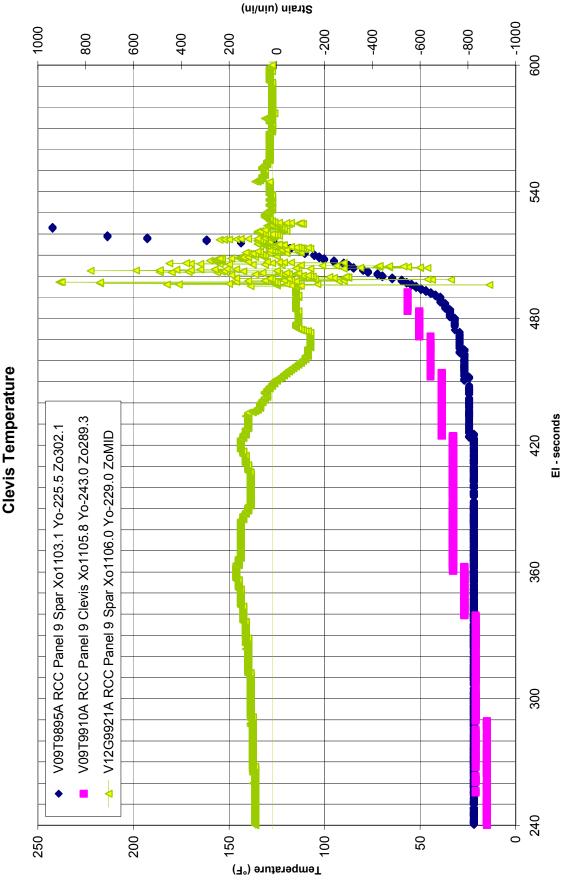
2 Fatal Reentry of STS107 Data and Observations.ppt



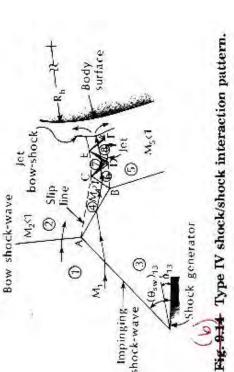
2 Fatal Reentry of STS107 Data and Observations.ppt

Figure 7

STS-107 RCC Panel 9 Spar Temperature & Strain



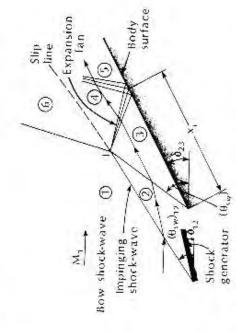
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ž

Impinging shock-waye

Figure 8



(a) Self 3 Interactions between the bow shock wave and the

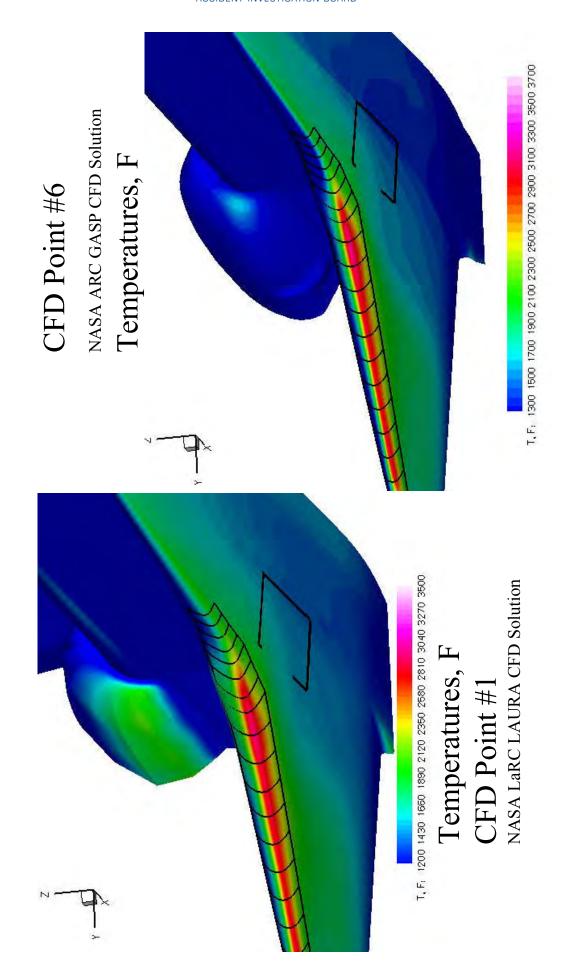
wing leading edge shock were

Fig. 949 Type VI shock/shock interaction pattern,

2 Fatal Reentry of STS107 Data and Observations.ppt

Surface Temperatures Radiation Equilibrium

Figure 9



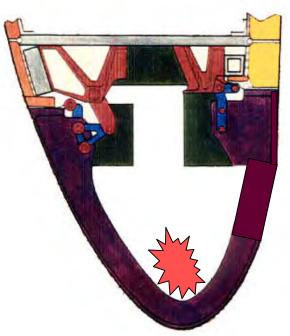
CA-000112

Hot gases enter the chunnel

Figure 10

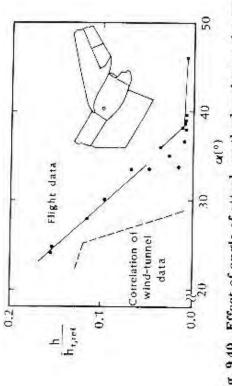
- Flow behind RCC
- Outward through Chunnel





Jet of hot gases coming down the chunnel

Inconel 718 A-286 steel Inconel-Dynaflex RCC Aluminum L12200



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Fig. 9.40 Effect of angle-of-attack on the heating to the OMS pod, as taken from Ref. 38.

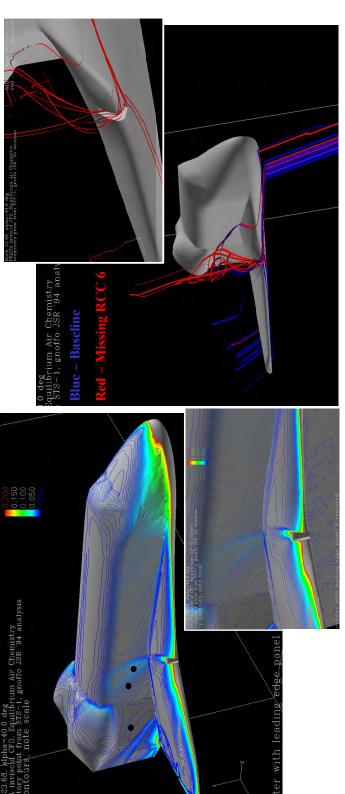
2 Fatal Reentry of STS107 Data and Observations.ppt

Figure 11

Orbiter OML Sensitivity CFD Analysis

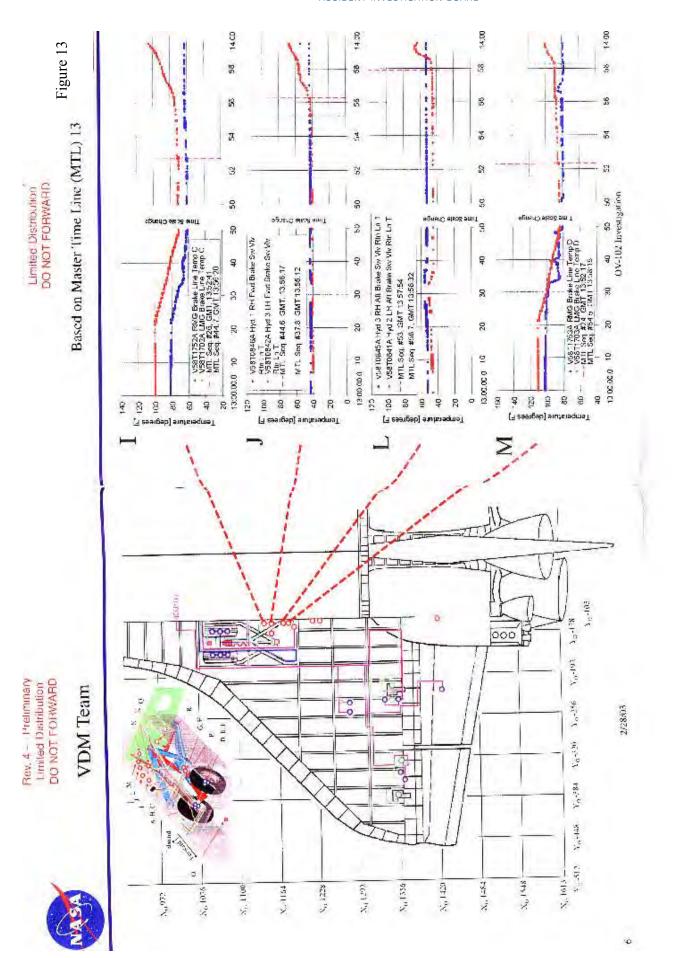
Figure 12

Orbiter with RCC Panel 6 Removed – Mach 23.8



Results and Observations (CFD analysis)

- Produces negative roll and yaw moments w/small magnitude
- Streamlines for damaged vehicle track inboard of baseline
- Resultant shock raises pressure in proximity to temp measurements



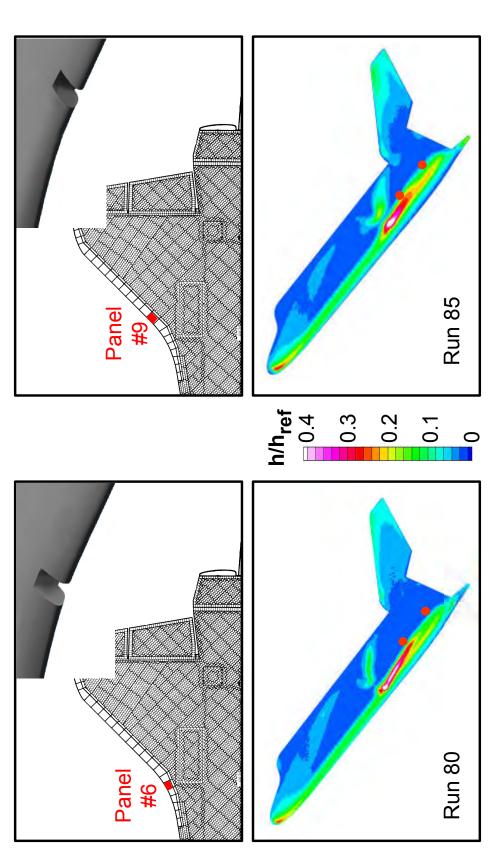
2 Fatal Reentry of STS107 Data and Observations.ppt

2 Fatal Reentry of STS107 Data and Observations.ppt

Figure 15

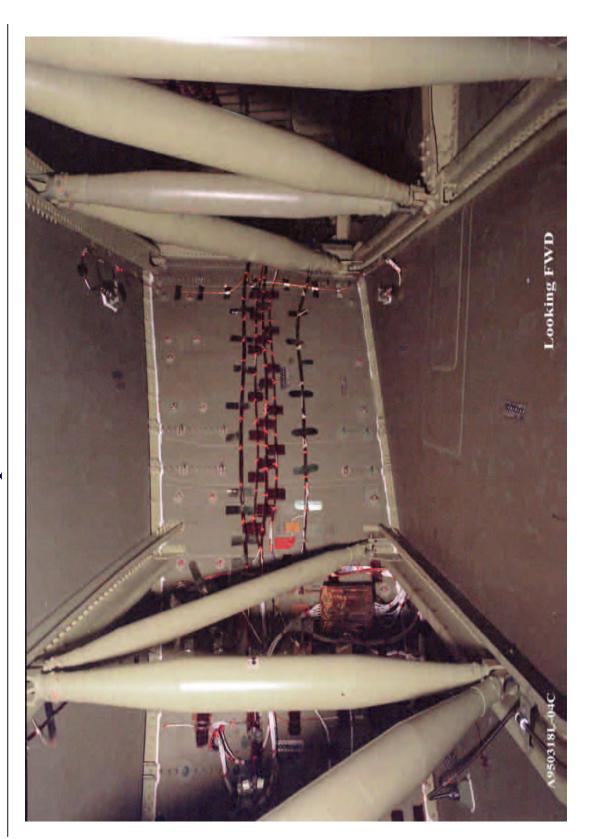
Effect of RCC Panel Cutout Position on Orbiter Fuselage Nondimensional Heating, Wind Tunnel Testing of Orbiter OML Deltas Panel 6 vs. Panel 9

Side fuselage heating 2 to 10 times nominal configuration heating.



CA-000112

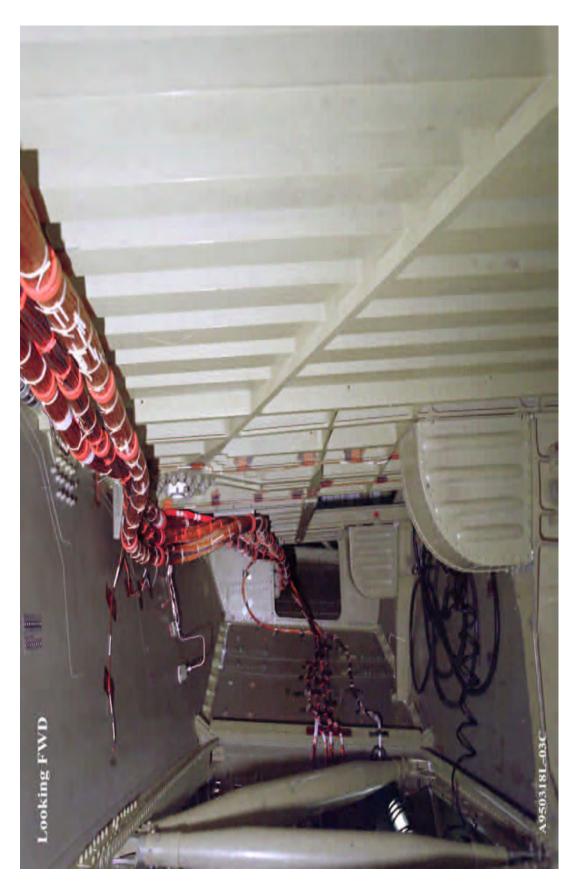
MADDS Wires on Back of Spar RCC 9 and 8



MADDS Wires on Back of Spar RCC 7 and 6 and

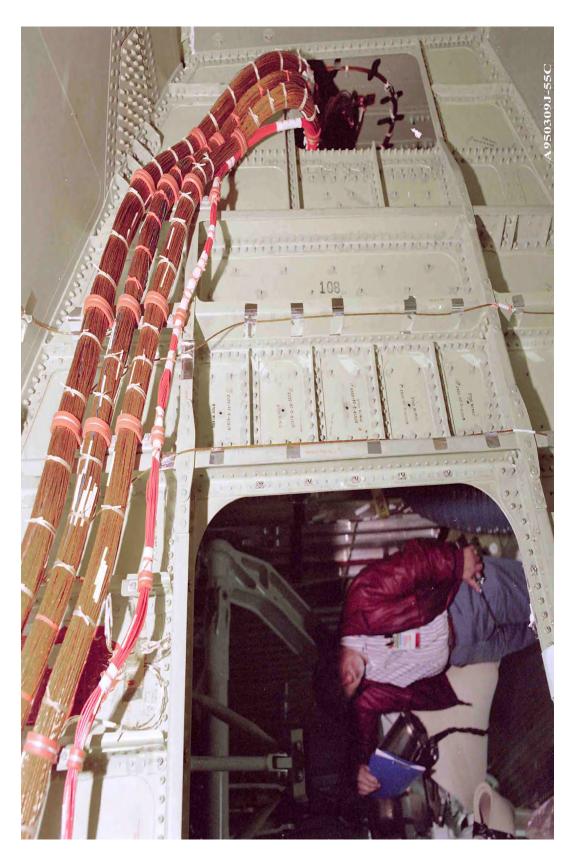
Figure 17

IO Wires on Wheel Well

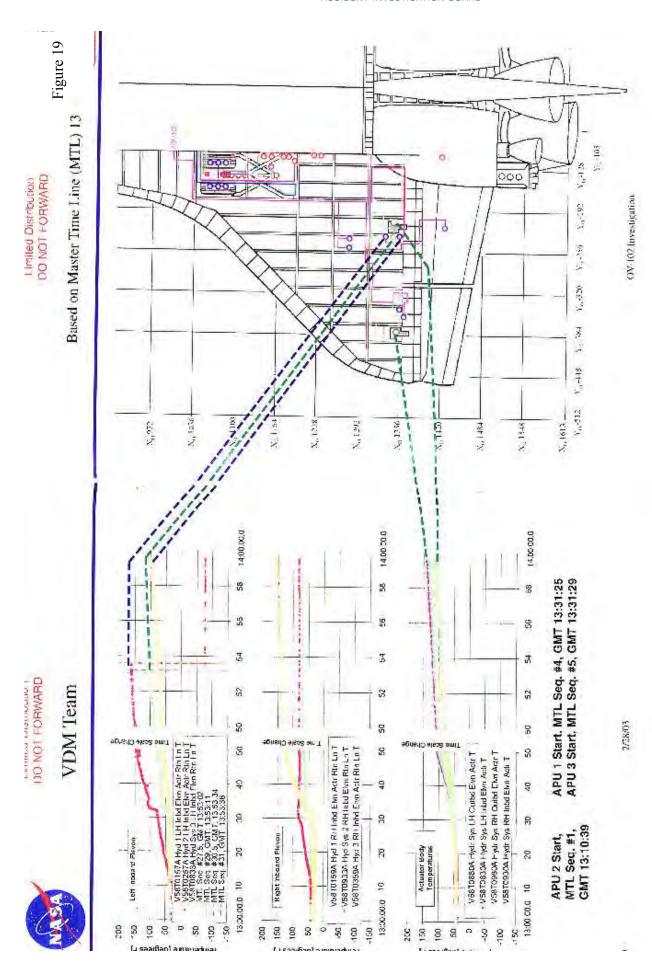


CA-000112

RCC Spar 5 on MADDS and OI Wires on Front of Wheel Well



CA-000112



2 Fatal Reentry of STS107 Data and Observations.ppt

Left RCC Panels 5-8

Figure 20a

• There is no RCC from panel 6

Only upper RCC sections of 5, 7, and 8
 Interesting T Seal between 5 and 6

Panel 6 Panel 7 Panel 8

Panel 5

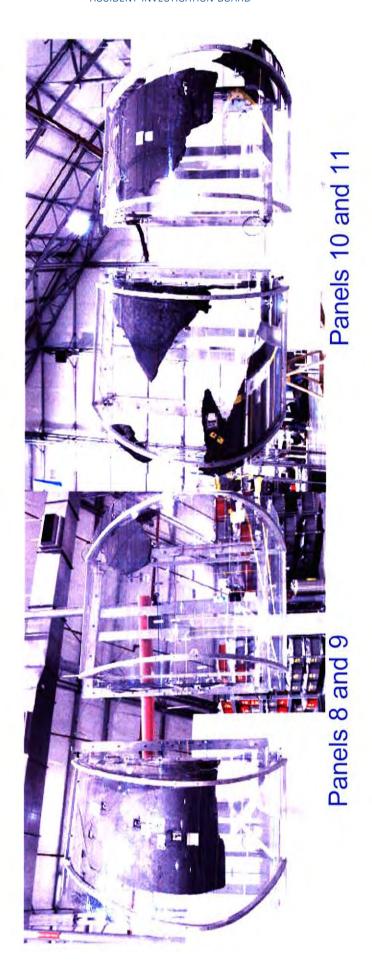
Predecisional Working Draft

2 Fatal Reentry of STS107 Data and Observations.ppt

Left RCC Panels 7-11 Exhibit Unique Characteristics

Figure 20b

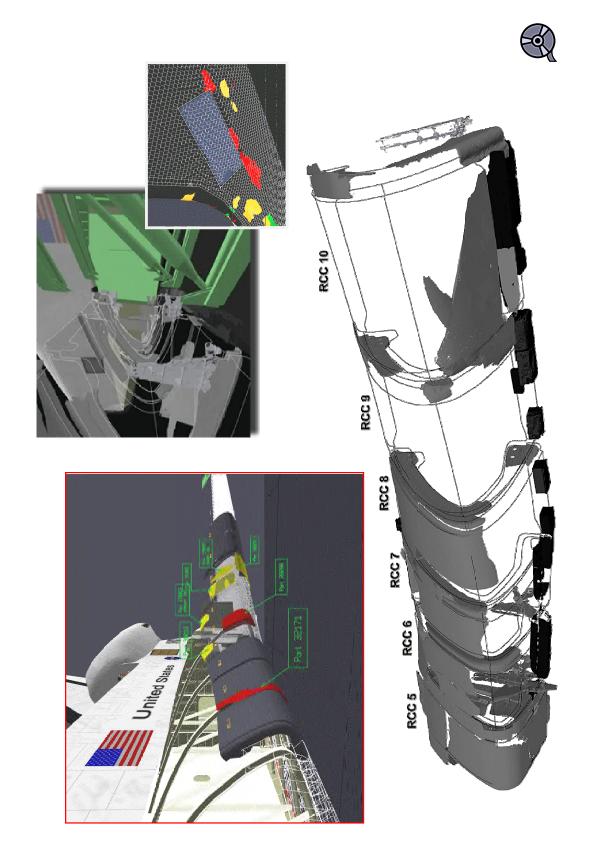
Deposits and Erosion Indicate an Outboard Flow Substantially Less RCC Material



CA-000112

Virtual 3-D Reconstruction of Debris

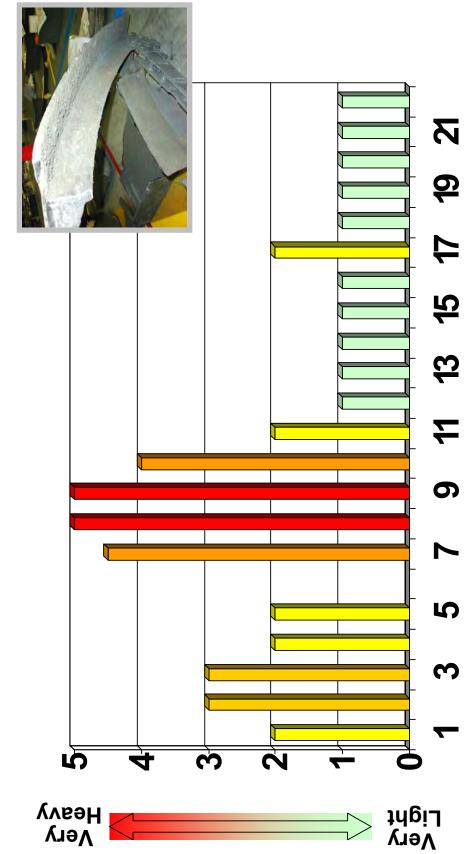
Figure 20c



COLUMBIA ACCIDENT INVESTIGATION BOARD

CA-000112

Relative Metallic Deposition on Left Wing Materials



Panel Number

Distribution of metallic deposition volume was centered around panels 8 & 9

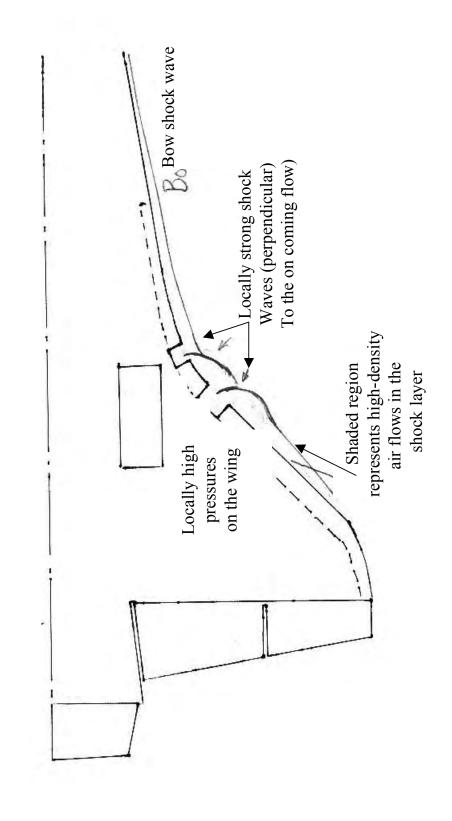
CA-000112

View From Bottom of Left-Wing (Similar to Kirtland Photography)

Figure 15, View from bottom of left-wing (similar to Kirtland whotograph) - RCC Panel 6 "Missing" RCC Pinel 9

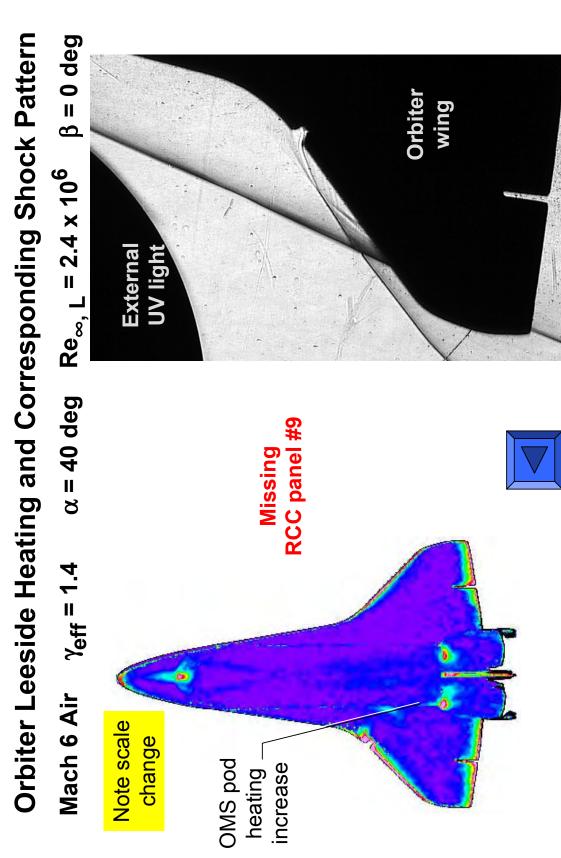
CA-000112

Shock-Shock Interaction for Left Wing, as Modified by Missing RCC Panels (RCC Panel 6 and RCC Panel 9)



CA-000112

(path integrated) Shock patterns



2 Fatal Reentry of STS107 Data and Observations.ppt

Leeside heating

pattern

Kirtland Image

Image straight overhead from Albuquerque Approximately 13:57:24 GMT Gregg Byrne's team thinks this apparent feature is real

Are RCC panels hinged up?

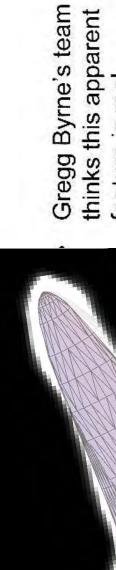
Predecisional Working Draft

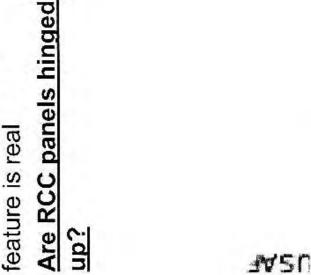
AV5N

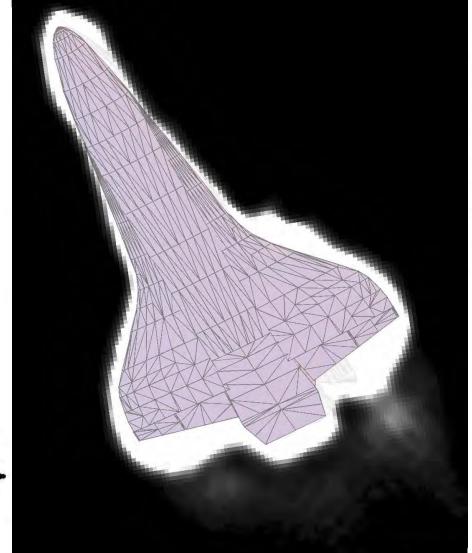
CA-000112

Kirtland Image

Image straight overhead from Albuquerque Approximately 13:57:24 GMT

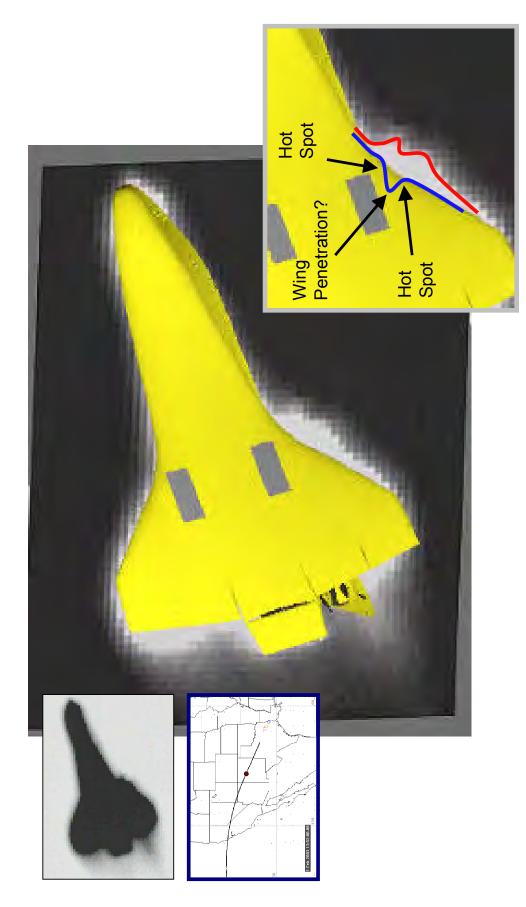




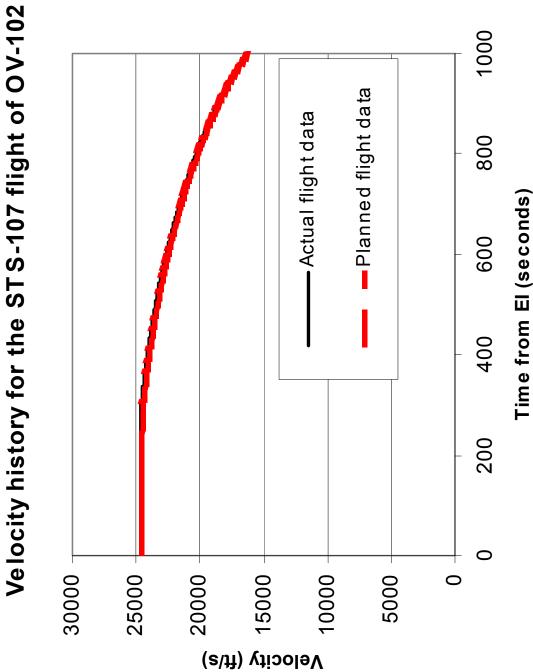


CA-000112

Kirtland AFB Photo at 13:57:19

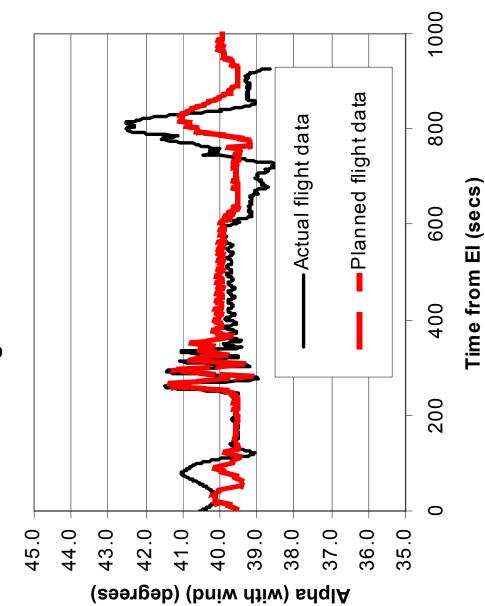


CA-000112



2 Fatal Reentry of STS107 Data and Observations.ppt

Angle-of-attack (with wind) history for the STS-107 flight of the OV-102

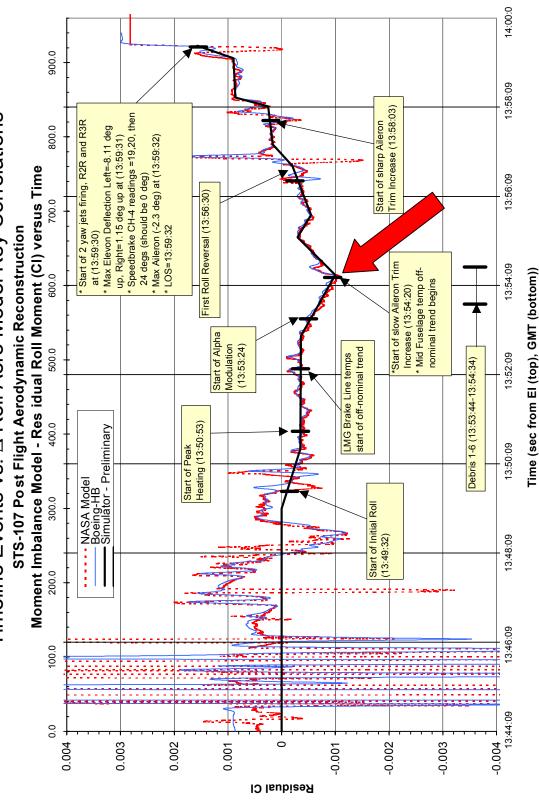


2 Fatal Reentry of STS107 Data and Observations.ppt

Sharp Change in Rolling Moment

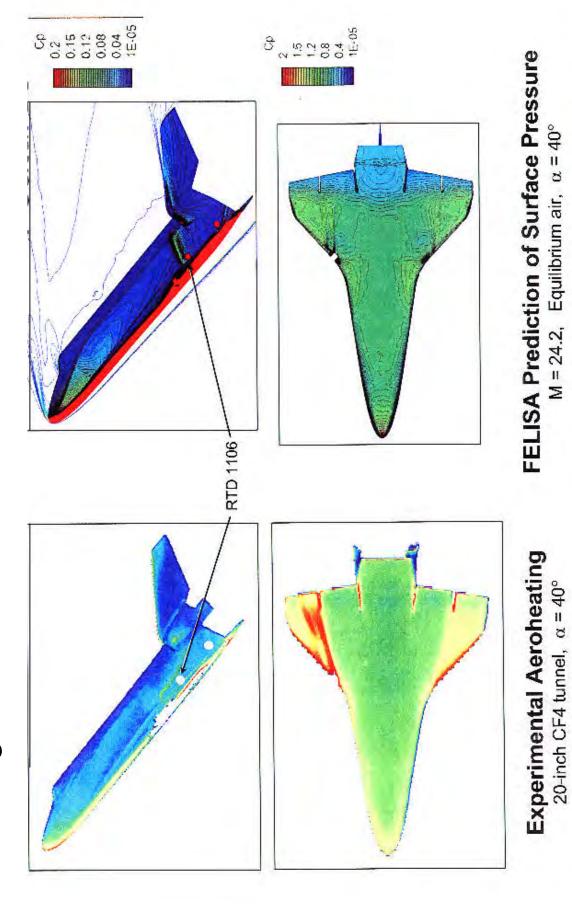
Figure 30





CA-000112

Missing RCC Panel 9 – Surface Flow Features



CA-000112

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Integ Time Line Team - REV 17 BASELINE

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Note: Rev 17 BASE integrates the OEX data timeline with the Baselined Rev 16 timeline plus IEE aero event changes (accounted for wind effects in aero increment derivation process). Rev 17 was baselined by the OVE Working Group Team as of 5/7/03.

Sum	GMT	II 8	OEX	OEX Milestone E	Entry Event	Remarks	MSID
- 2 c 4 c c c c c c c c c c c c c c c c c	13:10:39 13:10:39 13:18:30 13:31:25 13:31:29 13:39:28:559 13:34:09	E1+2010 E1-1719 E1-1561 E1-764 E1-760 E1-280.4		HIG-5 C C C C C C C C C C C C C C C C C C C	APU 2 Start OMS TIG OMS End of Burn APU 1 Start APU 3 Start APU 3 Start Ent of OEX PCM Data Block Entry interface (400,000 ft)	Mach 24.57	
1.9	13:45:39 / 48:59	EI+90 / EI+290	×	- Ψ υ	16 Temperature Sensors on the lower surface to the left of or at the centerline experience off-nominal early temperature frends (warmer temperature rise rate compared to previous flights of OV-102 at the same inclination)		
6.15	13:48:39	EI+270	×	<u> </u>	Left Wing Front Spar at RCC Panel 9 - initiation of off-nominal trend in strain (small nocease) followed by a more significant off-nominal signature to failure at EI+495 secs	The measurement began to fail at approximately EI+495 sec	VUS 19231A VOLT 9489A V12G9921A X1106.0 Y-229.0 ZMID
6.2	13:48:59	EI+290	×	_ 0 ∉	Left Wing RCC Panel 9 Lower Attach Clevis (between RCC 9 and 10) - initiation of an off-nominal temperature trend (early temperature increase compared to previous flights of same inclination)	The measurement began to fail at approximately El+492 sec	V09T9910A X1112.0 Y-239.0 Z289.0
6.4	~13:49:39*	~EH333	×	<u>v</u> =	Start of Initial roll Left Wing Front Spar Caps Strain Gage shows early off nominal downward trend	*Note: PCM3 entry data is in snapshot format (not continuous). Time indicated is at start of data segment where off-nominal signature is first observed, therefore event may have started earlier than noted.	//2G9169A X107 Y232 Z?
6.45	13:49:49 / 49:59	EI+340 / EI+350	×	4 4	4 Left OMS Pod Surface temps - Start of off-nominal temperature trend - cooler rise rate when compared to previous flights of same inclination	Followed by the start of a warmer-than-expected temperature trend \\ \\ beginning in the Ei+510 to EI+540 sec range	V07T9976A V07T9978A V07T9220A V07T9972A
QBAR = ~	QBAR = ~15 psf (~0.10 psi); Mach 24.4	Mach 24.4			32:13:50:00	E1+351 sec; WLE Stagnation Temp: ~2520 F (STS-107 Nom EOM Design Pred)	(STS-107 Nom EOM Design Pred)
6.5	13:50:00 / 43	EI+351 / EI+394 EI+360	×	<u> </u>	Five events of unexpected return link comm drop-out (Comm events 1-5) Left PLBD Surface TC BP3703T - Start of off-nominal temperature trend - cooler rise	On upper left aft anterna (TDRS 171/W). Appears off-nominal based on previous fit data. Comm loss not continuous thru period indicated. Followed by large increase in temperature at El + 570 seconds	V07T9925A
;		i					X1138.5 YLH Z441.4
6.9	13:50:19	EI+370	×		Left Wing Lower Surface Thermocouple BP2510T begins off-nominal temp increase from ~2000 deg F to ~2200 deg F over approx 50 seconds followed by a momentary 100 deg F temperature spike	requently fails at approximately E1+496 sec	V07T9666A X1121.1 Y-235.5 ZLWR
7	7 13:50:53 EI+4	EI+404		Start of Peak Heating	00.17.00.00	Determined by analysis	El + 411 sec. WI E Stanistics Town: ~2650 E
7.2	13:51:14	EI+425	×	1	Left Wing Front Spar at RCC Panel 9 - start of off-nominal increasing temperature	Increasing trend continues until the measurement starts to fail at	(09T9895A
7.25	13:51:14	EI+425	×		anel 9 Lower Attach Clevis (between RCC 9 and 10) - start of a ominal increasing temperature frend	፱	X1102.2 Y-239.0 Z- 239.0 V09T991.0A X1112.0 Y-239.0
7.3	deleted					Rationale for deletion: Upon further evaluation of the data, it was determined that the remote sensor signatures had been seen in previous flights and/or could be explained by known events.	0.8027
7.35	deleted 13:51:49	E1+460	×		OMS-L. Pod HRS1 Surf T3-AFT - Start of off-nominal higher-than-expected temperature trend when compared to previous flights of same inclination	d to seq # 11.37 after further analysis. imp increase at EI+910 and goes erratic at	V07T9223A X1437.2 Y-126 Z422
QBAR = ~	QBAR = ~22 psf (~0.15 psi); Mach 23.7	Mach 23.7			32:13:52:00	EI + 471 Sei	EI + 471 sec; WLE Stagnation Temp: ~2700 F
7.45	deleted 13:52:09 / 52:55	EI+480 / EI+486		ш.	Four events of unexpected return lirk comm drop-out (Comm events 6-9)	Rationale for deletion: Moved to seq # 8.75 after further analysis. On upper left aft antierna (TDRS 171/M). Appears off-nominal based on previous fit data. Comm loss not continuous thru period indicated.	

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Integ Time Line Team - REV 17 BASELINE

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Note: Rev 17 BASE integrates the OEX data timeline with the Baselined Rev 16 timeline plus IEE aero event changes (accounted for wind effects in aero increment derivation process). Rev 17 was baselined by the OVE Working Group Team as of 5/7/03.

Sum	GMT	В	OEX	Milestone	Entry Event	Remarks	MSID
No.	GMT Day 32	sec	_				
7.46	13:52:09 / 52:49	EI+480 / EI+520	×		Nose Cap RCC Attach OutBoard Clevis (Chin Panel) - Temporary change in slope, then returns to "homina" and other school of Nore' Adjacent esnery ViORT988 (on centerline) does not show this signature.		V09T9889A X262.0 Y-23.0 LWR
7.47	13:52:16	E1+487	×		Two Left Wing and 1 Right Wing Surface Pressure measurements show signs of failure	First OEX data to show signs of failure	V07P8038A V07P8086A V07P8151A
7.48	13:52:16 / 53:17	EI+487 / EI+522	×		All of the measurements running in the wire bundle along the left wing leading edge show signs of failure		15 of 15 measure-
7.49	13:52:16 / 56:24	EI+487 / EI+735	×		The vast majority of left wing OEX measurements show signs of failure during this time period - this includes all left wing temperature and pressure measurements and all strain measurements aft of Xo 1040 with the exception of three strain measurements on the upper surface of the LMLG compartment		mens Multiple measurements
					Additionally, 30 right wing pressure measurements show signs of failure		
7.5	13:52:17	EI+488		Approx Vehicle Ground Location: 39.0 N / -129.2 W	Altitude 238,800 ft / Mach 23.6 - Over the Pacific Ocean, approx 300 miles West of California Coastline	Approx vehicle position when first off-nominal data was seen; Data source: STS-107 GPS Trajedory Data	
7.7	13:52:17	EI+488			LMG Brake Line Temps (D) - small increase in temperature ("bit flip up")	Initiation of temp rise ("bit flip up") - may be nominal based on rise	V58T1703A
7.75	13:52:18	EI+489	×		Left Wing Spar Cap Lwr L103 (Xo 1040 Spar - Lower Cap) - off-nominal increase in strain indication followed by gradual decrease over approx 330 seconds interval until measurement failure at ~El+935	ומני כסוויף מואי ווקוו באליומו אי	V12G9048A
7.77	13:52:24	EI+495	×		Left Wing Front Spar at RCC Panel 9 - strain gage goes erratic for approximatly 20 second - measurement appears to be failing	Subsequent data is suspect	V12G9921A X1106.0 Y-229.0
7.8	13:52:25	E1+496	×		Left Outboard Elevon Wide Band Accelerometers - off-nominal vibration response (approximately 2G petak-to-peak). An Antiva Ch. 2)		V08D9729A
7.85	13:52:29	EI+500	×		off-nominal erratic trend when	Followed by drop in temperature at EI + 570 seconds and subsequent erratic temperature changes	V07T9219A X1507.1 Y-126.0 2422.0
7.9	13:52:31	EI+502	×		Left Outboard Elevon Wide Band Accelerometers - off-nominal vibration response (approximately 3G peak-to-peak) V08D9729A - L OB Elevon Z-Vib (MUX1B Ch 2)		V08D9729A
8.5	deleted 13:52:32/55	EI+503		. -	Supply H2O Dump Nozzle Temps (A, B) (2) and Vacuum Vent Temp (1) - transient (15 and 23 seconds, respectively) increase in typical rise rates.	Rationale for deletion: moved to seq #8.7 GMT shown indicates initial rise duration. Supply H2O Dump Nozzle V62T0440A temps took additional 48 secs to return to nominal temp rise, vacuum V62T0551A vert temps took additional 40 secs to return to nominal rise.	V62T0440A V62T0439A V62T0551A
8.6	13:52:34	EI+505	×		OMS-L Pod HRS1 Surf T2-AFT - Start of off-nominal lower-than-expected temperature trend (comparing the previous flights of same inclination) until sensor sees the previous trends on the previous flights of same inclination.		V07T9222A X1486.9 Y-126 Z422.0
8.65	13:52:39 / 53:09	EI+510 / EI+540	×		a such prompting each carry of any goes entered and agreement of the carry of the c		V07T9976A V07T9978A V07T9220A V07T9972A
8.7	13:52:41	EI+512			LMG Brake Line Temps (A, C) (2) - start of off nominal trend	Unusual Temperature Increase	V58T1700A V58T1702A
8.75	13:52:44 / 52:50	EI+515 / FI+521			First clear indication of off-nominal aero increments	Delta yawing and rolling moment coefficients indicate off-nominal trends. Derived by analysis	n/a
8.8	13:52:49.5 / 52:51.4	EI+520.5 / EI+522.4	×	3	2 Left Wing temperature sensors begin an off-nominal (typically erratic) response that appears to be an indication of the measurements (sensors/wiring) failing		V09T9895A V09T9849A
9	deleted 13:52:59	E1+530			Left INBD Elevon Lower Skin Temp (1) - OSL	Began trending down 3 secs earlier	V09T1006A
11	~25.5); Mach 23.2			32:13:53:00		EI + 531 sec; WLE Stagnation Temp: ~2800 F
10.5	deleted 13:53:03	EI+534	×		Left Outboard Elevon Wide Band Accelerometers - onset of signal saturation indicating likely measurement failure (approximately 10G peak-to-peak - off-scale)	Kationale for deletion, Werged with seq #8.7.5 after further analysis.	V08D9729A
7	13:53:10 / 36	EI+541/EI+567			Hydraulic System Left Outbd / Inbd Elevon Return Line Temps (4) - OSL	OSL was preceded by Nominal Temp rise.	V58T0394A V58T0193A V58T0157A V58T0257A
				1			

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Note: Rev 17 BASE integrates the OEX data timeline with the Baselined Rev 16 timeline plus IEE aero event changes (accounted for wind effects in aero increment derivation process). Rev 17 was baselined by the OVE Working Group Team as of 5/7/03.

Sum	m GMT		OEX	Milestone	Entry Event	Remarks	MSID
Š	Ö	sec Sec	data				1
11.	.1 deleted					Rationale for deletion: alpha modulation time tag updated - moved to seq #11.25	
11.2	.2 13:53:26	EI+557		Approx Veh Grd Location: 38.7 N / -123.5 W	Atttude 231600 ft / Mach 23.0 - Crossing the California Coastline	Data source: STS-107 GPS Trajectory Data	
11.21	21 13:53:29	EI+560	×		Left Fuselage Side Surface Temp BP3605T - start of off-nominal increasing temperature trend from ~180 deg F to 400 deg F	Trend followed by temperature drop and rise	V07T9253A X1000.7 Y-105 Z354.5
11.22	13:53:29	EI+560	×		Left PLBD Surface TC BP3603T - Start of slightly off-nominal erratic temperature trend when compared to previous flights of same inclination		V07T9913A X1003.8 YLH 2441.3
11.23	13:53:29	EI+560	×		Left PLBD Surface TC BP3703T - start of off-nominal temperature rise, peaking at EI+625, followed by temperature drop and subsequent off-nominal higher-than-expected temperature signature		V07T9925A X1138.5 YLH Z441.4
11.24		EI+560	×		Left Fuselage Side Surface TC BP3604T - Start of slightly off-nominal erratic temperature trend when compared to previous flights of same inclination		V07T9903A X1006 Y-105 Z398.4
11.25		EI+562		Alpha Modulation	Angle of attack (alpha) modulation active		V90H0803C
11.3	.3 13:53:32 / 54:22	EI+563 / EI+565	ω Ω		Two events of unexpected return link comm drop-out (Comm events 10-11)	On upper left aft anterna (TDRS 171M). Appears off-nominal based on previous fit data. Comm loss not continuous thru period indicated.	
11.35	35 13:53:37	EI+568	×		Xo 1040 Spar (MLG Forward Wall Spar) Strain Gage - Upper Cap - start of off- nominal increase in strain indication (over an approximate 115 second interval) followed by sudden decrease		V12G9049A X1040 Y-135 ZUPR
11.37	13:53:38	EI+269			Inertial sideslip angle (Beta) exceeds flight history.	The steady state navigation derived sideslip angle becomes out-of- family as compared to previous flight data at this point in the trajectory.	V90H2249C
4.11.	.4 13:53:44	EI+575	×		OMS-L Pod HRSI Surf T1-AFT - Start of off-nominal lower-than-expected temperature Sensor goes erratic at E1+940 trend when compared to previous flights of same inclination		V07T9219A X1507.1 Y-126.0 Z422.0
11.5		EI+576 / EI+602	2		1st reported debris (5) observed leaving the Orbiter just aft of Orbiter envelope (Debris # 1 thru 5)	EOC video # EOC2-4-0055, 0056, 0064, 00136 & 0201. No evidence of jet firings near events.	n/a
QBAR	R = ~29 psf (~0.20 psi); Mach 22.	Mach 22.7			32:13:54:00	EI + 591 s	EI + 591 sec; WLE Stagnation Temp: ~2850 F
13		EI+601/EI+663	ღ		Left Main Gear Brake Line Temp B (1) / Strut Actuator Temp (1) / Sys 3 LMG Brake Sw Viv Ret Line Temp (FWD) (1) - start of off nominal trend	Unusual Temperature Increase	V58T1701A V58T0842A V58T0405A
4	4 13:54:20	EI+611			Start of slow alleron trim change. Reversal in trend of derived rolling moment coefficient.	The alleron trim setting observed in flight first deviates from the predicted trim setting at this pt in trajectory (GMT is approximate (+/- 10 sec) for alleron). Also, observed roll moment changed from a negative to positive slope (derived by analysis).	V90H1500C n/a (alleron trim) (roll moment)
15	13:54:22	EI+613			Mid Fuselage LT BondLine Temp at x1215 (1) & LH Aft Fus Sidewall Temp at x1410 (1) - start of off nominal trend	Unusual increase in temperature rise rate	V34T1106A V09T1724A
15.2	.2 13:54:29	EI+620	×		Left Fuselage Side Surface temp BP3605T peaks and starts downward trend		V07T9253A X1000.7 Y-105 2354.5
15.3	54:37	EI+624.3 / EI+628			Flash #1 - Orbiter envelope suddenly brightened (duration 0.3 sec), leaving noticeably luminescent signature in plasma trail; plus Debris # 6 - report of very bright debris observed leaving the Orbiter just aft of the Orbiter envelope.	EOC video # EOC2.4-0026, 0034, & 0009B. R3R and R2R jet firings occurred near events. Debris events 6 & 14 are visually the biggest, brightest events & therefore may indicate the most significant changes to the Orbiter of the western debris events.	n/a
15.32	32 13:54:34	EI+625	×		Left Fuselage Side Surface temp BP3703T peaks and starts downward trend		V07T9925A X1138.5 YLH Z441.5
13.33	13:54:39	~EI+630	×		Strain Gages Centered on the Upper Surface of the Left MLC Wheel Wheel - Higher-than-expected strain indications observed in these gages	Note: PCM3 entry data is in snapshot format (not continuous), therefore event may have occurred earlier than noted	V12G9156A, V12G9157A, V12G9158A

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Note: Rev 17 BASE integrates the OEX data timeline with the Baselined Rev 16 timeline plus IEE aero event changes (accounted for wind effects in aero increment derivation process). Rev 17 was baselined by the OVE Working Group Team as of 517103.

	Nds Daseilleu by	THE OVE WORKIN	o io	s of 5/7/03.			
No.	GMT Day 32	sec	OEA data	data Milestone	Entry Event	Neligins	UISIN
13.34	13:54:39	~El+630	×		Leff Wing X1040 Spar Web - shows increase in strain	Note: Adjacent sensor V12G9165A did not show similar "off-nominar" vigorature at this time, also, PCM3 entry data is in snapshof format vigorature at this time, also, PCM3 entry data is in snapshof format vigorature at this time, also, PCM3 entry data is in snapshof format vigorature at this first provided in the provided and provided in the provided p	V12G9166A V12G9167A (V12G9165A- nominal)
QBAR = ~	QBAR = ~34.5 psf (~0.24 psi); Mach 22.1	; Mach 22.1			32:13:55:00	EI + 651 se	EI + 651 sec; WLE Stagnation Temp: ~2900 F
15.35	13:55:04 / 55:29	EI+655 / EI+680			Debris # 7, 7A, & 8 thru 10 observed leaving the Orbiter just aft of Orbiter envelope. Debris 8, 9, & 10 were seen aft of the Orbiter envelope inside Debris Shower A (next event listed).	EOC video # EOC2-4-0005, 0017, 0021, 0028, 0030, 0098 & 0161. No evidence of jet firings near events except 7A where analysis still pending.	n/a
15.37	13:55:22 / 55:28	El+673 / El +679			Debris Shower A - Report of debris shower seen just aft of Orbiter envelope.	Seen just aft of Orbiter envelope. Over the course of these four seconds a luminsecent section of plasma trail is observed which appears to contain a shower of indefinite particles and multiple, larger discrete debris that includes Debris 8, 9, and 10.	Saw debris: EOC24-0098, 0161, 0005, 0030 Saw shower: EOC24-0017, 0021, 0028
15.4	deleted					Rationale for deletion: Upon further evaluation of the data, it was determined that the remote sensor signatures had been seen in previous flights and/or could be exchanged by known events.	
15.43	13:55:33 / 56:03	EI+684 / EI+714		,	Two events of return lirk comm drop-outs (Comm events 12 & 13)	On upper right aft antenna (TDRS 171/W). Uncertain if off-nominal based on previous flight data. Comm loss not continuous thru period indicated.	
15.44	13:55:34	EI+685	×		Xo 1040 Spar (MLG Forward Wall Spar) Strain Gage - Upper Cap - sudden drop in strain followed by gradual increase until erratic signature at approximately EI+930	~ ~ ~	V12G9049A X1040 Y-135 ZUPR
15.45	13:55:35 / 56:13	EI+686 / EI +724			Debris # 11, 11A, 11B, 11C & 12 thru 15 observed leaving the Orbiter just aft of Orbiter envelope. Debris #11B & #11C events were both seen at the head of a parallel plasmar trail aft of the Orbiter envelope. Debris #12 event was preceded and followed by secondary plasma trails. Debris #13 event was followed by momentary brightening of plasma trail adjacent to debris. Debris #14 event consisted of very bright debris observed leaving the Orbiter.	EOC video # EOC2-4-0005, 0017, 0021, 0028, 0030, 0050, & 0038. No evidence of jet firings near events. (Nearest jet firings occur at 56:17). Debrie sensits & 4 thera visually the biggest, brightest events & 4 therefore may indicate the most significant changes to the Orbiter of the western debris events.	n/a
15.5	13:55:41	EI+692			Mid Fuselage Port (Left) Sill Longeron Temp at X1215 - start of off nominal trend	Unusual Temperature Increase	V34T1118A
QBAR = ~	~40 psf (~0.28 psi); N	Mach 21.4			32:13:56:00	EI + 711 se	EI + 711 sec; WLE Stagnation Temp: ~2900 F
16	13:56:03 / 56:24	El+714 / El+735		<u></u>	Left Lower/Upper Wing Skin Temps - Trending down (2)	Indication of potential measurement failures	V09T1002A V09T1024A
16.5	13:56:16 / 56:53	EI+727 / EI+764			Hyd Sys 1 LMG Upbock Actuator Unlock Line Temp; Sys 3 LMG Brake Sw VIv Ret Line Temp (FWD); LMG Brake Line Temp C; LMG Brake Line Temp B; Sys 3 Left Main Gear Strut Actuator Temp - all show a temp rise rate change.	Significant increase in temp rise rate on all four lines	V88T0125A V58T1701A V58T0842A V58T0405A V58T1702A
16.55	13:56:30 / 56:55	EI+741 / EI+766			First Roll Reversal initiation/ completion		V90H1044C
16.6	deleted					Rationale for deletion: Comm dropout (event 14) is deleted since probably nominal due to competion of roll reversal resulting in elevation angle nearing 60 deg's (vertical tail interfence w/comm).	
QBAR = ~	QBAR = ~42 psf (~0.29 psi); Mach 20.7	Mach 20.7 FI+780	×		Elicelane Side Surf Thermond RP3078T - start of off-nominal trend (farm increase	EI + 771 Sei	EI + 771 sec; WLE Stagnation Temp: ~2900 F
16.67	13:57:09	E1+780	< ×	_ +- 4-	roseage size sur intermoch broszer i saar orominimarteno (temp increase followed by temp drop / rise) Fuselage Lower Surface BF Thermoch BP220T - start of off-nominal frend (shallow		VOT 1921 0A X1486.1 Y-124.8 2307.1 VOT 19508A
16.7	13:57:19 / 24	EI+790 / EI+795			temp drop) MLG LH Outbd Tire Pressures 1 & 2 - start of small increase in pressures) Not seen in previous flights	X1560 Y-111.1 Z LWR V51P0570A V51P0572A

OVE 05-07

5/8/2003 11 AM

Integ Time Line Team - REV 17 BASELINE

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Note: Rev 17 BASE integrates the OEX data timeline with the Baselined Rev 16 timeline plus IEE aero event changes (accounted for wind effects in aero increment derivation process). Rev 17 was baselined by the OVE Working Group Team as of 5/7/03.

Sum	was baselined by the OVE W		OEX I	Torking Group Team as of 5/703.	Entry Event	Remarks	MSID	
No.	GMT Day 32	sec	data					
16.8	13:57:19 / 58:01.5	EI+790 / EI+832.5			Debris # 16 (very faint debris) observed leaving just aft of Orbiter followed by two levents of assymmetrcial brightening of the Orbiter shape (Flares 1 and 2). (Occurred over eastern AZ and NM.)	Debris #16: EOC video # EOC2.4-00148-2. Flares #1 & 2: EOC2.4-00148-4. Observations by personnel from the Starfire Optical Range (Kirtland Air Force Base, NM).	n/a	
17	13:57:28 / 57:43	EI+799 / EI+814			Left Lower/Upper Wing Skin Temps (2) - OSL		V09T1002A	V09T1024A
18	deleted 13:57:54			-2	Sys 2 LH Brake Sw Vlv Return Temp (1)	Unusual Temperature Increase	V58T0841A	
11	~52.5	; Mach 19.8			32:13:58:00		El + 831 sec; WLE Stagnation Temp:	Temp: ~2880 F
20 20.3	13:58:04	EI+835	×		Start of sharp alleron trim Increase Left fuselage side surface temp BP3605T starts off-nominal temperature increase	GMT is approximate (+/- 10 sec)	V90H1500C V07T9253A X1000.7 Y-105 Z354.5	
20.5	13:58:04 / 58:19	EI+835 / EI+850			increase in off-nominal aero increments.	Substantial increase in rate of change of rolling and yawing moment increments and initial indication of off-nominal pitching moment increment. Derived by analysis.	n/a	
21	deleted deleted							
22.5 23	13:58:16 13:58:32 / 58:54	EI+847 EI+863 / EI+885		-	LMG Brake Line Temp D - Temp rise rate change MLG LH Inbd / Outbd Tire Pressures (4) - Decay to OSL	Significant increase in temp rise rate.	V58T1703A V51P0570A	V51P0573A
24 25	36.34 deleted 13:58:39 /	EI+870 / EI+879			MLG LH Inbd/Outbd Wheel Temps (2) - OSL			V51T0575A
25.5 26	58:48 13:58:40 13:58:56	EI+871 EI+887			BFS Faut Msg (4) - Tire Pressures - 1st Message BFS Faut Msg (4) - Tire Pressures - Last Message			
lii I	~63.5 psf (~0.44 psi); Mach 18.7	; Mach 18.7			32:13:59:00	EI + 891 se	EI + 891 sec; WLE Stagnation Temp: ~2850 F	Temp: ~2850 F
27.3	13:59:06 13:59:09 / 59:39	EI+900 / EI+930	×		Left Main Gear Downlocked Indication - Transferred ON Several left side temperature measurements show a rapid increase in temperature followed by erratic behavior and subsequent loss of the measurements at approximately EH-940		V51X0125E V07T9925A V07T9972A V07T9976A V07T9903A V07T9913A	V07T9976A V07T9978A V07T9222A V07T9223A
27.7	13:59:23 13:59:26 / 59:28	EI+914 EI+917 / EI+919		-	Loss of MCC rear-time data to the workstations in the FCK and MEK Abrupt increase in off-nominal aero increments.	Abrupt increase in rate of change of pitching, rolling, and yawing increments. Magnitude of aero increments starting to exceed ability of aileron to laterally trim the vehicle. Derived by analysis.	n/a	
28	13:59:30.66 / 59:30 68	E1+921.66 / E1+921.68		*	Start of two yaw jets firing (R2R and R3R)	Fired continuously until end of data at 13:59:37.4	V79X2634X	V79X2638X
29 29.3	13:59:31 13:59:31.4 / 59:34.5	EI+922 EI+922.4/ EI+925.5			at LOS d BFS FSM messages during this time period all indicate	Left8.11 deg (up) Right1.15 deg (up) ASAs responded appropriately. However, signature is indicative of allure of ASA 4.	V57H0253A (5 Hz)	
29.5 30 31 32	13:59:32 deleted deleted deleted	E1+923			Observed alleron frim at LOS	-2.3 degrees		
32.5	13:59:32	E1+923	~ <u> </u>	Approx Veh Grd Location:	Altitude ~200700 ft / Mach ~18.1 - Near Dallas TX	Approximate Vehicle Ground Location at Loss of Signal based on GMT; Data source: STS-107 GPS Trajectory Data	n/a	
33	13:59:32.136	EI+923.136			Last valid downlink frame accepted by ODRC - OI / BFS / PASS. Start of reconstructed data.	Nominal loss of comm at this GMT (for ~15 sec max based on previous fit data)		
35	deleted 13:59:35/36	EI+926 / EI+927		*	Sideslip on vehide changes sign.	The event occurred between the two times listed. Aerodynamic forces due to sideslip are now reinforcing aerodynamic asymmetry.	n/a	
36	13:59:36	EI+927			Growth in Bank attitude error	Up until this time the flight control had been able to maintain the Bank error around 5 deg.		
37	13:59:36.8	EI+927.8		-	Aerojet DAP Requests Third Right Yaw RCS Jet (R4R)	This additional jet is required to counteract the increasing aerodynamic moments on the vehicle. Fired continuously until end of data at 13:59:37.4		
38	13:59:37.3	EI+928.3		-	Aerojet DAP Requests Third Right Yaw RCS Jet (R1R)	This additional jet is required to counteract the increasing aerodynamic moments on the vehicle. Fired continuously until end of data at 13:59:37.4		

Integ Time Line Team - REV 17 BASELINE

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Note: Rev 17 BASE integrates the OEX data timeline with the Baselined Rev 16 timeline plus IEE aero event changes (accounted for wind effects in aero increment derivation process). Rev 17 was baselined by the OVE Working Group Team as of 5/7/03.

0	TRO		2	Milostono	Enders Estand	Domonto	Giom
ġ	B		data				<u>.</u>
39	13:59:37.n	EI+928.n			Last aileron data	The alleron position is now approx -5.2 deg with approx -2.5 deg of alleron trim. The rate of change of alleron trim had reached the maximum allowed by the flight control system.	
40	13:59:37.396	EI+928.396		End of 5-second period of reconstructed data	End of first 5-seconds of the 32-second period of post-LOS data. Start of approximately 25 seconds of no data available	GMT derived by MER data personnel	n/a
40.5	13:59:39 / 14:00:19	EI+930 / EI+970	×		Beginning at EI+930 and continuing until the loss of sync on OEX data (EI+964.4 for PCM and EI+970.4 for FDM), essentially all of the OEX data for the entire vehicle becomes erratic and falls		
4	13:59:46.347 / 14:00:01.900*	El+937.347 / El+952.900			PASS Fault Message annunciation - ROLL REF PASS Fault Message annunciation - L RCS LEAK BFS Fault Message annunciations - L RCS LEAK (2)	*Time info corrupted on some of the events.	
QBAR =	QBAR = nn psf; Mach nn				32:14:00:00	EI + 951 sec;	EI + 951 sec; WLE Stagnation Temp: ~2800 F
42	14:00:02/06	EI+953 / EI+957			Debris A observed leaving the Orbiter - Large debris seen falling away from the Orbiter envelope.	EOC videos # EOC2-4-0024, EOC2-4-0018 & EOC2 4-0118	n/a
43	14:00:02.654	EI+953.654			PASS Fault Message annunciation - L RCS LJET		
4	14:00:02.660	EI+953.660		Beginning of 2-second period of	Beginning of 2-second Start of last 2-seconds of the 32 second period of post-LOS data. The second second Start of last 2-seconds of the 32 second period of post-LOS data. The second		
					During this final 2 second period of reconstructed data, the data indicates the following systems were nominal: APUs were running and WSB cooling was evident. MPS integrity was still evident. Fuel cells were generating power and the PRSD tanks/lines were infact. Comm and navaids systems in the forward fuselage were performing nominally. RSB, Body Flap, main engine, and right wing temps appeared active. ECLSS performance was nominal.	systems were nominal: APUs were running and WSB cooling was SD tanks/lines were intact. Comm and navaids systems in the wing temps appeared active. ECLSS performance was nominal.	
					During this final 2 second period of reconstructed data, the data indicates the following systems were off-nominal: All three Hyd systems were lost. The left inbd/outbd eleven actuator temps were either OSL or no data exists. Alajority of left OMS pod sensors were either OSH or OSL or no data exists. Elevated temps at bottom bondline centerline skin forward and aft of the wheel wells and at the port side structure over left wing were observed. EPDC shows general upward shift in Main Bus amps and downward shift in Main Bus volts. AC3 phase A inverter appeared disconnected from the AC Bus.	systems were off-nominal: All three Hyd systems were lost. The left MMS pod sensors were either OSH or OSL or no data exists. Elevated port side structure over left wing were observed. EPDC shows ase A inverter appeared disconnected from the AC Bus.	
					GNC data suggests vehicle was in an uncommanded attitude and was exhibiting uncontrolled rates. Yaw rate was at the sensor maximum of 20 deg/sec. The flight control mode was in AUTO. (Note that all Nav-derived parameters (e.g., alpha) are suspect due to high rates corrupting the IMU state.)	ntrolled rates. Yaw rate was at the sensor maximum of 20 deg/sec. sha) are suspect due to high rates corrupting the IMU state.)	
45	14:00:03.470 / 14:00:03.637*	EI+954.470 / EI+954.637			BFS Fault Message annunciation - LOMS TK P BFS Fault Message annunciation - Indeterminant BFS Fault Message annunciation - SM1 AC VOLTS PASS Fault Message annunciation - LRCS PVT	* Time info corrupted on some of the events.	
46	14:00:03.637	EI+954.637			PASS Fault Message annunciation - DAP DOWNMODE RHC	The s/w process which logs the PASS message runs every 1.92 seconds, so this event could have occurred as early as 14:00:01.717 GMT. However, during the 2 sec period, available vehicle data indicates RHC was in detent and DAP was in AUTO.	
47	14:00:04.826	EI+955.826		End of 2-second period of	Last identifiable OI Downlink frame	c	n/a
47.5	14:00:13.439	EI+964.439	×	reconstructed data	OEX PCM loss of sync		
48	14:00:17 /	EI+968 / EI+973			Debris B and C observed leaving the Orbiter	EOC videos # EOC2-4-0024 & -0118 (for both B and C)	n/a
48.5	<u> </u>	EI+970.44 EI+972 / EI+976	×		FDM1 A end of data Vehicle Main Body break-up	EOC videos # EOC2-4-0024, -0018 &-0118	n/a
20	14:00:53	EI+1004		End of Peak Heating		Determined by analysis	

Timeline-STS-107-REV17-BASELINE.xls



Volume V Appendix G.9

Contracts, Incentives, and Safety/Technical Excellence

This Appendix contains a Report to Columbia Accident Investigation Board: Contracts, Incentives, and Safety/Technical Excellence, Olson, Gary, Foster, Tim; 27 May 2003.



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Report to CAIB:

Contracts, Incentives, and Safety / Technical Excellence

Submitted by: Gary Olson and Tim Foster - 27 May2003



Summary

NASA efforts to enhance contractor performance have resulted in complex contracts with multiple incentives. The assumptions are:

- The opportunity to increase corporate profits motivates management and workers more than devotion to astronaut safety, to program success, and to their own livelihood;
- Contractors so motivated will act always in the government's interest with minimal oversight;
- These incentives enhance NASA leverage with sole source, non-competitive, costreimbursement contractors.

The extensive use of incentives, particularly award fees (the principal one) detracts from technical excellence and safety. For example, they:

- Make fee dollars, not technical excellence and safety, the primary focus for program oversight and review.
- Encourage complacency through high scores, emphasis on contractor strengths, and loophole-ridden "metrics" that often stipulate tolerance for errors and lateness.
- Devalue the contributions of many by assigning relative weights to work areas.

Because the outcome of incentive fee processes has become predictable – high fees (near or above the normal limit) –NASA probably will be unable to regain leverage and avoid contractor complacency absent competition. "Conventional wisdom" in NASA presumes that only aerospace firms can manage shuttle work.

The people and facilities at NASA sites, not corporate logos, are critical to program requirements. NASA's shuttle work is based on NASA-owned technology, done for the most part at NASA-owned facilities by a workforce trained by NASA and dedicated to the facility. Department of Energy, in similar situation, has had no shortage of reputable bidders for management and operating contact work.

The U.S. Naval Nuclear Propulsion Program is evidence that a technical program of comparable complexity and risk can be managed successfully without extensive reliance on contract financial incentives and without being beholden to incumbent contractors.

Recommendation: Rather than hoping to motivate contractors to manage the NASA shuttle program through cumbersome financial incentives, NASA should:

- Develop a strong, stable, self-sufficient Shuttle Program Office of experienced, expert technical personnel capable of effective program management and oversight.
- Establish leverage over contractors by opening to competition by aerospace and non-aerospace companies what are in effect management and operating contracts.

Contract Environment

The NASA Space Shuttle Program relies predominantly on Lockheed Martin and Boeing, either as direct component suppliers or, for operations, through their joint venture creation, United Space Alliance (USA). Lockheed Martin and Boeing formed USA as a



limited liability corporation in 1996 in response to NASA desires to consolidate work under the Space Flight Operations Contract (SFOC).

For SFOC and for major shuttle component work, which NASA decided not to incorporate into SFOC as originally planned, NASA has relied on sole source, noncompetitive, cost-reimbursement contracts since shuttle program inception in the early 1970s. These contracts indemnify the contractors against third party claims for injury, loss of life, and property damage arising from shuttle operations. Progress payments ensure these contractors substantial, positive cash flow.² In addition, the contractors are realizing fees for this work averaging about 10% of incurred cost, the limit prescribed by the Federal Acquisition Regulation for cost-reimbursement contracts.³

Without the discipline of competition or fixed priced contracting, NASA provides multiple contract financial incentives to motivate shuttle program contractors. The theory is that since contractors are in business to make money, the best way to promote excellence is to tie fee payments to performance.

The emphasis on contract financial incentives extends beyond NASA; it tends to be government-wide. When the budget process generates fewer dollar and manpower resources than program managers request, the differences are often attributed to "inefficiencies" and lead to calls for better forms of contracting. The goal is to so effectively structure contract incentives that contractors, looking to their own financial interests, will act in the Government's best interest with little need for oversight.

In evaluating the NASA financial incentives and possible impact on safety, the following sections discuss each contract financial incentive that NASA uses in major shuttle program contracts as they pertain to technical excellence and therefore safety.

Cost Incentive Fees

All major shuttle program contracts are, in part, cost-plus-incentive-fee contracts. From a negotiated target cost and target fee, contractors get more fee dollars if costs at completion underrun the negotiated target cost, but less fee if they overrun the negotiated target cost. The percentages of underrun and overrun sharing are defined in the contract.

Cost-plus-incentive contracts may or may not significantly motivate contractors to reduce cost, depending on the situation:

- In the case of the reusable solid rocket motor contract, NASA program managers became concerned that the contract provisions overly motivated contractor management to reduce personnel, potentially to the program's detriment. NASA officials, therefore, eliminated the contract underrun sharing provision.⁴
- Cost incentives, on the other hand, can equally motivate contractors to negotiate higher target costs and higher prices for contract changes, or to submit claims for contract price adjustments in the case of potential overruns.

¹ Boeing and Lockheed Martin each put up \$1M to form USA. They appoint top USA management and share profits 50/50.

² Contractor billings, submitted every two weeks and paid within seven days, include incurred costs, accrued costs, and provisional fees.

³ FAR 15.903

⁴ NASA and the contractor agreed to redirect the equivalent fee potential to other areas.



• For repetitive, non-competitive contracts, a contractor might conclude that the long-term benefits of sustaining a high cost base for future contract negotiations outweigh the near-term advantages of driving down costs.

Determining whether these cost incentive contract provisions actually save money is difficult. However, to outsiders they seem to satisfy the feeling that contractors that spend less should get more fee.

On the plus side, cost-plus-incentive-fee provisions generate little, if any, additional effort or distraction for workforce or management. Beyond a possible tendency towards more aggressive contract price negotiations, these provisions should involve little, if any, additional administrative effort beyond that required for any other cost reimbursement contract; i.e., Government validation of costs incurred.

Conclusion - Cost Incentive Fees

Regardless of the extent to which they may or may not actually reduce costs, cost incentives as used in major shuttle program contracts do not seem likely to detract significantly from technical excellence and safety.

Performance Incentive Fees

Performance incentive arrangements pay fixed sums for meeting prescribed program milestones and impose penalties for failure to meet selected milestones. Performance-based contracting is not uniquely a NASA concept. Rather, the approach arose government-wide as a way to motivate contractors.

NASA policy ties performance incentive fees to objective milestones, either schedular or successful completion of specific tasks or events; e.g., delivery of a product, successful launch, or successful flight. Since successful completion often demonstrates safe operation, these performance standards also fall into the category of safety incentives.

These performance incentive fees are "all-or-nothing" payments. A contractor either earns the performance fee for that event or gets nothing – or may have to pay a penalty.

Whether tying fee payments to performance milestones provides any additional motivation to workers and management is not clear. These performance incentives did not preclude USA from missing milestones that resulted in fee forfeiture of from \$1M to \$3M each on five different occasions. Moreover, shuttle program managers note that contractor / customer relations become more contentious when a contractor might miss an incentivized milestone. In such situations, fee forfeiture can be avoided if the contractor can successfully blame the delay on others.

Whether or not these performance incentives provide added incentive, administration of performance-incentive-fee contract provisions does not seem to impose substantial additional workload on management and workers. The contract milestones tend to be ones that would be the focus of any effective program management system.

Conclusion—Performance Incentive Fees

There appears to be little evidence, one way or the other, that performance incentive fees enhance shuttle program contractor performance. However, they seem to pose little risk of burdening or distracting technical effort from primary functions beyond the possibility of inserting contractor financial and contract specialists more deeply into technical and production work.



Award fees

Background

In addition to having cost-plus-incentive-fee provisions, all major shuttle program contracts also have cost-plus-award-fee provisions. This means that every six months a performance evaluation board subjectively evaluates contractor performance, assigns a numeric performance grade, and recommends to a fee-determining official an award fee as a percentage of available fee assigned for that period.

Award Fee Process and Scoring

The purpose of the award fee is to make contractors more responsive to customer needs. Since contractors are in business to make money, the theory is people who actually manage and execute the work can best be motivated if they see a connection between their work and corporate profits. According to NASA policy, the award fee process is designed to promote "... more effective communications among Government and contractor personnel, at management levels where decisions can be made and results achieved."

The award fee process seems inevitably to result in high scores and realized fee levels near or above the normal 10 percent maximum limit for cost reimbursement contracts.⁶ The question is whether the high scores actually reflect exceptional performance across the board or are they largely a predictable outcome. Also, if the performance is as good as indicated, should the success be attributed primarily to the award fee process?

NASA policy specifies a contractor that satisfactorily meets contractual commitments will fall into the "good" range (score: 71-80). However, overall ratings for shuttle program contractors tend always to fall in the mid-80s to low-90s on a scale of 100. For the period preceding the Columbia accident, all major shuttle program contractors rated "excellent", which NASA policy defines as "exceptional performance".

The complexity of the performance evaluation process varies by contract. For SFOC, NASA contract monitors, called Technical Manufacturing Representatives, assess contractor strengths and weaknesses against nearly 400 elements grouped within thirteen functional areas. Some eighty of these elements are stated in the SFOC along with measures of performance, referred to as "metrics", for each one.

Each monitor assigns a numerical grade for his or her area of oversight. These scores, after weighting for relative importance and budget significance, determine the recommended overall contractor performance rating. Interestingly, the grades assigned by three of the twelve monitors determine 75 percent of the proposed SFOC award fee score.

For major shuttle program contracts other than SFOC, NASA managers also list strengths and weaknesses, and assign weights to perhaps a dozen areas of performance. However, the award-fee provisions are much simpler than the elaborate process followed in the SFOC. In essence, program managers for these contracts are not so constrained by metrics in arriving at their subjective evaluations of contractor performance.

⁵ NASA Award Fee Contracting Guide section 3.7.1

⁶ Under the Federal Acquisition Regulation, NASA may approve individual and class deviations from this limit.



The award fee process, occurring every six months with interim assessments at the midpoint, seems to have become the principal forum for reviewing work. But the process differs from more traditional reviews in that issues are translated into fee dollars.

To reduce performance evaluation to a score, the award fee process compares contractor strengths and weaknesses. This balancing of good with bad might be useful for rationalizing performance scores, but is of little value in accomplishing work. In the absence of these incentives, traditional reviews would emphasize problems, potential problems, actions needed on critical path items, and areas that need management attention.

Overall performance scores vary within a relatively small range from period to period.

There are reasons, aside from possible performance, why ratings tend to be much higher than "good".

- NASA policy encourages high awards, stating: "...an award fee contract should provide the contractor with a reasonable opportunity to earn the maximum award fee available".
- The NASA managers who have day-to-day responsibility for each area assign grades for contractor performance in that area. Poor contractor grades might reflect adversely on their own performance.
- Poor contractor performance scores could strengthen the hand of program critics and jeopardize program support for the budget arena.
- When contractors respond to a customer-identified area of emphasis, performance evaluators may feel obliged to increase the score, which over time can lead to rising grades.
- Higher grades are less subject to contractor rebuttal in front of the performance evaluation board.

Corporate Profit Maximization Is Not The Best Focus and Motivator for Those Who Actually Do the Work

The risk with award fees is that both customers and contractors begin focusing on the award fee process rather than on the work itself.

It is hard to imagine that, for all those involved in shuttle program work, the prospect of influencing in some small way corporate profits could surpass the incentives inherent in the work itself. They are contributing to a nationally recognized, prestigious program the fate of which (not to mention their own livelihood) depends upon public confidence and safety. The importance of their work to the safety of the astronauts they see working around them is certainly well recognized and to suggest the opportunity to earn the company a little extra fee would enhance their concern would be to do them a great disservice.

NASA policy requires grading based on evaluation factors weighted as to relative importance. This is not conducive to technical excellence. For example, does it promote technical excellence to assign, as NASA has in the SFOC, a 20 percent weight factor to "Operational Safety", which includes industrial safety? Or, does it inspire technical excellence to assign "Quality" the same 15 percent weighting as contractor performance in awarding contracts to small, minority, or disadvantaged business?



In a similar vein, the SFOC, as previously noted, defines more than 80 performance elements with associated "metrics", the apparent result of a procurement initiative to demonstrate commitment to performance-based contracting. From a practical standpoint, the metrics run counter to the pursuit of excellence.

Many of the contract metrics stipulate customer tolerance for errors or lateness. Others include loopholes that render them largely irrelevant. The following are examples of "expected" levels of performance. The contract also identifies for many items an even lower level of acceptable performance called maximum error rate.

• Safety, Mission Assurance, and Product Assurance:

"Expectation: 85% of risk packages presented to the Government are accepted."

"Expectation: 85% of items correctly assessed as no increased risk validated through use, Government audit, or Government surveillance."

"Expectation: 15 mishaps per year." ("Mishaps" are injury to non-SFOC contractor personnel or damage to NASA property by accidents / incidents during processing.)

- Quality Assurance: "Expectation: 95% of all mandatory Government inspections are accepted.... Success rate of SFOC work volume greater than 90%."
- **Orbiter Logistics:** "Expectation: 96% of all reparable Orbiter hardware requirements satisfied by the negotiated need dates."
- Backup Flight System (and Pass Flight Software): "Slips or redelivery caused by BFS not meeting negotiated schedules or due to a redelivery to correct an error are allowed if no additional resource impact to outside organizations is incurred."
- Launch Readiness: "Expectation: 97% of all items on the initial launch countdown constraints list completed and closed prior to Launch Countdown Call-to-Stations."
- Engineering, Maintenance, and Operations Support for Flight Operations System: "Expectation: 5% late, but in no case impact safety, mission success, or major program schedule milestones."

Finally, the award fee process tends to result in making engineering and other technical personnel more accountable to financial and contracting people whose job is to try to win as large an award fee as possible. The rewards for portraying contractor performance in its best light are inconsistent with prompt and candid problem reporting and performance self-assessment, which is vital to successful management of complex technical programs.

Conclusions -- Award-fee contracts:

Continued reliance on award-fee provisions would significantly detract from emphasis on technical substance and problem resolution. An environment that, in effect, tries to make engineers and technical people their own corporate profit centers is not conducive to technical excellence.

Other Contract Financial Incentives

Major shuttle program contracts include other, less significant, financial incentives. These include:

• "Performance Plus" incentives. These are relatively small amounts program managers are able to use at their discretion to focus contractor attention on near-term actions.



- "Value Engineering" incentives. These are standard government contract provisions
 designed to encourage contractors to recommend cost-saving modifications to
 specification requirements. If accepted by the government, the contractor shares in
 the estimated savings.
- "Employee Incentives". USA, for example, makes a flat payment to all non-supervisory employees each year depending on USA success in earning award fee.
 NASA, however, is not involved in these incentive payments except that NASA, not USA, bears the full cost of this program.

Conclusion – Other Contract Financial Incentives.

Whether or not these incentives are effective, they seem to impose little or no additional effort or adverse impact on those who perform the work. The Program Plus incentive, however, further reinforces the notion that the customer, in effect, must "tip" the contractor to get its work done.

Fee Reduction for Catastrophic Loss.

The most prominent, safety-related contract financial incentive in all current major shuttle program contracts is a clause entitled "Fee Reduction for Catastrophic Loss".

As explained earlier, the government indemnifies shuttle program contractors from liability for such loss, whether loss of life, damage to government property, or other third party liability. The Catastrophic Loss clause, however, allows NASA to reduce contractor fee by a prescribed amount if NASA determines that the accident was due to that contractor's actions or failure to act. The clause requires the NASA finding to be based on an accident board's finding.

Interestingly, only the most recent external tank contract contains the Catastrophic Loss clause. The contract under which Lockheed Martin delivered the external tank used on the last Columbia flight has no such clause. 8

From a practical standpoint, the Catastrophic Loss clause – or any other clause of that sort, regardless of amount – is unlikely to enhance contractor management or workforce attention to safety. Even at \$10M or more in forfeited fees, the damage to the corporate image due to loss of life and technical failure in such a highly visible program would be incomparably greater. Nor is there reason to believe the clause would stimulate managers and workers to apply higher standards than they would otherwise apply. Their connection to the program, to the astronauts, and to their own jobs is no doubt stronger than their devotion to corporate finance.

Conclusion – Catastrophic Accident Penalty.

The effect of the Catastrophic Accident clause on contract performance seems minimal – certainly not negative. However, having the provision is helpful to demonstrate a measure of recompense where a contractor is responsible. This provision, which

⁷ The SFOC specifies no fee for the six-month period in which the accident occurred. The most recent external tank contract stipulates a \$10M penalty. The Space Shuttle Main Engine and Reuseable Solid Rocket Motor contracts specify a \$10M penalty and forfeiture of all fees for the six-month period in which the accident occurred.

⁸ According to NASA officials, Lockheed Martin was unwilling to accept the clause without a corresponding increase in contract fee.



predetermines the forfeiture amount, is preferable to leaving the question open for possible litigation.

Overall Conclusion

NASA relies very extensively on contract financial incentives to motivate major shuttle program contractors. There is no evidence these contract provisions directly contributed to the Columbia accident. Nor is there evidence they actually motivate contractors and enhance excellence.

To the extent financial incentives might help focus additional attention on cost reduction and key milestones, they can be positive. If instead financial incentives encourage contractor personnel to try to game the system by initially inflating contract prices or by setting the stage constantly to be able to blame others for missed milestones, they can be counterproductive. Overall, however, the cost incentive and performance incentive processes demand little, if any, additional effort or distraction on the part of those actually doing the work. The cost incentive is based on incurred costs; the performance incentives on events or tasks most likely to be tracked in any event.

In contrast to the cost and performance incentives, the contract award fee provisions are cumbersome and counterproductive.

- The award fee process in practice results almost inevitably in high grades and near
 maximum fees for major shuttle program contractors. These high grades, together
 with an award fee process that emphasizes contractor strengths as well as weaknesses,
 can encourage complacency.
- The assignment of relative weights to elements of contract performance based on several factors, including budget share, although required for award fee purposes, can do more harm than good. It tends to diminish the importance of the contributions that all must make in contract execution.
- The award fee process now seems to be the primary forum for program oversight and review. That this forum must translate technical and production issues into fee dollars sends a message that money, not technical excellence, is the important objective.
- The "metrics", which the NASA procurement community apparently required to be included in SFOC, tend to undermine excellence, not encourage it. The standards are filled with loopholes that make many of them useless. They concede customer tolerance for errors and late deliveries.

The Catastrophic Loss contract provision bears most directly on safety by prescribing that a contractor must forfeit \$10M or more in cases where NASA determines that contractor is responsible for the accident. However, that management and the workforce would view this forfeiture of corporate fee as a more powerful incentive for safety than their inherent commitment to the safety of the astronauts, to the well being of the program, and their own livelihoods is unlikely.

Overall, the extensive use of contract financial incentives in the space shuttle program seems more a reaction to government-wide procurement policies than something NASA managers invented as an important program management tool. The award fee structure in the SFOC seems to have been primarily the work of procurement personnel, not technical program managers.



In a budget-constrained environment and under pressure to reduce its federal payrolls, NASA contracting efforts focus on trying to structure incentives so effective that the contractor, pursuing its own financial interests, will automatically work to the government's benefit – with limited NASA oversight. Consequently, management attention on both sides tends to focus on dollars vice technical excellence. Financial incentives are no substitute for oversight by experienced, expert technical customer representatives. To this end, NASA should ensure that the Space Shuttle Program Office becomes a strong, stable, and self-sufficient entity capable of performing that function.

Contract financial incentives, such as NASA uses for shuttle program work, are not the only path to technical excellence and safety. NASA's Administrator has characterized the highly successful Naval Nuclear Propulsion Program as perhaps the most similar to NASA's space shuttle program in terms of engineering challenge. Both must apply complex and demanding technologies in a hostile environment with the lives of crewmembers as well as National interests at stake. The Naval Nuclear Propulsion Program, however, goes about the task much differently insofar as contracting.

The Naval Nuclear Propulsion Program avoids financial incentives in contracts with its major prime contractors – opting instead for close oversight by relatively small, but technically competent, headquarters and field organizations. Naval Nuclear Propulsion Program prime contractors operate under low-fee, cost-plus-fixed-fee contracts that include no contract financial incentives.

The theory behind this approach is that the best way to sustain an environment conducive to technical excellence and objectivity is to free those doing the work from corporate pressures to maximize profits. Program decisions with respect to assigning work and whether to extend or re-compete management and operating contracts provide ample business leverage to ensure contractor responsiveness to program needs. NASA, in efforts to focus more clearly on technical substance, might be well advised to consider the Naval Nuclear Propulsion Program approach.

With nearly 30 years of cost-plus-award-fee contracting tradition for major shuttle program work, incumbent contractors have no doubt become accustomed to high profit, no-risk, no investment, and generous cash flow associated with these contracts. With this background, effecting any substantive change in contracting approach through sole source negotiations with incumbent contractors may be impossible.

Should NASA consider significant change, it should reevaluate "conventional NASA wisdom" that only aerospace firms are candidates to compete for what in most cases amounts to management and operating contracts similar to the contracts the Department of Energy uses for nuclear weapons and naval nuclear propulsion work. As with the Department of Energy, to a large extent, critical NASA resources are government-financed technology, government-owned facilities, and workforces largely acquired, trained, and supported for decades at government expense.

NASA has historically concluded that only aerospace firms can be considered for NASA shuttle program work – a conclusion most recently reinforced by the NASA Space Shuttle Competitive Sourcing Task Force study published last fall. In contrast, the Department of Energy solicits competitive bids for management and operating contracts with the result that nationally know construction firms, component manufacturers, non profit institutions, universities, and even aerospace firms regularly vie for the work at a fraction of the fee NASA pays for these services. If they can design nuclear weapons and



naval nuclear propulsion plants for the Department of Energy – why cannot NASA overcome its attachment to the aerospace industry to seek management and operating support from a broader base?

The transition of SFOC work to USA demonstrated that change of operating contractors at NASA -sites could be effected with minimum impact without adverse effect on personnel retention or on pensions. Under the circumstances, no valid reason seems to exist beyond tradition that NASA should remain principally beholden to two contractors, or to the aerospace industry, for work at NASA sites. Department of Energy experience suggests no shortage of firms willing to assume responsibility for managing and operating complex work at its government sites.

The challenge to NASA in effecting significant change may be less formidable once the agency realizes that the people and facilities at NASA sites, not corporate logos, are critical to program requirements.