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NASA/TP—2011–216300R

Evaluation of Cable Harness Post-Installation Testing: Part B

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EXECUTIVE SUMMARY

The Ares I Avionics and Software Chief Engineer and the Avionics Integration and Vehicle Systems Test Work Breakdown Structure (WBS) Manager in the Vehicle Integration Office were issued a joint action by the Ares Project Control Board (PCB) to develop the leanest set of practices for design, manufacturing, installation, and testing of electrical cable harnesses. The action was driven by a disagreement between the Ares I-X programmatic and technical communities regarding testing of electrical harnesses after they had been installed on the vehicle. The testing, which was advocated by the technical community, was eventually rescoped to a subset of the Ares I-X harnesses per the recommendation of the Ares I-X Mission Management Office and the decision of the Constellation Program Manager. An approach of how to close the action was developed and approved by the Ares PCB on May 19, 2009. The method chosen was a study of historical practices, lessons learned from Ares I-X, and benchmarking of commercial and other relevant industries.

Historically, post-installation cable harness testing has been used since the Apollo program via engineering drawing callouts, circa 1964. For the Space Shuttle, the tests began with a requirement in the Johnson Space Center (JSC) Design and Procedural Standard JPR-8080, JSC Design and Procedural Standard Requirement E-14, which has evolved to the current NASA-STD-8739.4, "Crimping, Interconnecting Cables, Harnesses, and Wiring," most recently dated November 24, 2009. For the Shuttle Program, the orbiter and propulsion elements are subject to post-installation testing. For expendable launch vehicles, one major contractor performs the tests and the other does not.

For Ares I-X, the reason post-installation testing became an issue was because it was unplanned (and therefore unsequenced) work in the integration and checkout of the vehicle. Originally, post-installation testing was a requirement on the project, but the requirement was subsequently removed. This requirement was removed prior to the Critical Design Review (CDR) to make it consistent with the processes used on the Atlas V. This requirement was relieved on the avionics Integrated Product Team (IPT) but not on the other IPTs. This meant that the ordering of long-lead parts such as mating connectors and the development of test procedures did not occur. Adding the requirement back late in the development life cycle would have had a significant impact to the Ares I-X launch date.

For this assessment, benchmarking was accomplished by developing a survey and performing either a site visit or mail-in response through the Society of Automotive Engineers (SAE) Subcommittee AE-8A, Electrical Wiring Systems Installation, a group whose focus is on aerospace wiring installation issues. Responses were received from government and private sector launch vehicle developers, military and commercial aircraft, spacecraft developers, and harness vendors. Results varied widely, as demonstrated in appendix A; however, the crewed launch vehicles and military aircraft consistently perform the post-installation tests.

Key findings were that the existing test requirements do identify manufacturing- and installation-induced damage. While the number of failures discovered by post-installation testing may be statistically insignificant, the fact is that the discovery of even one failure in a Criticality 1 circuit justifies retaining the requirement for human-rated vehicles. The team found no data supporting the claim that post-installation testing damages the harness insulation system. When properly planned in the production flow, there is relatively low overhead associated with the testing.

The recommendation is for the Ares projects to retain the value-added practice of post-fabrication and post-installation cable harness testing, including insulation resistance (IR) and dielectric withstanding voltage (DWV) tests. Human factors should be emphasized in harness design including ease of access, harness routing, interfacing structures, and routing near obstructions in an effort to eliminate the manipulation required to install and test these harnesses. To ensure the lowest life-cycle cost, several preparation steps should be taken. These steps include ensuring that the electrical integration deliverables to NASA (harness diagrams and wiring tables) are in an electronic format compatible with commercial automated test equipment and ensuring that the production contractor is required to produce and deliver cable mating adapters. NASA should also ensure that proper test and verification requirements are in place to ensure that the production and operations contractors derive the proper work instructions and workflows.

The authorization, signature page, and team memberships for the original Ares Cable Harness Post-Installation Testing Report document are presented in Appendix B.

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LIST OF ACRONYMS AND SYMBOLS

AC	alternating current
AC-1	alternating current bus-1
AF	Air Force
AST	Avionics and Software Team
CDR	Critical Design Review
CSO	Chief Safety Officer
DWV	dielectric withstanding voltage
ET	external tank
FAA	Federal Aviation Administration
FOR	Findings, Observations, and Recommendations
GSFC	Goddard Space Flight Center
HDBK	handbook
IPC	Institute of Printed Circuits
IPT	Integrated Product Team
IR	insulation resistance
IUA	instrument unit assembly
JCM	Johnson Space Center Manual
JPL	Jet Propulsion Laboratory
JPR	Johnson Space Center Procedural Requirements
JSC	Johnson Space Center

LIST OF ACRONYMS AND SYMBOLS (Continued)

KSC	Kennedy Space Center
LM	Lockheed Martin
MAF	Michoud Assembly Facility
MDA	Missile Defense Agency
MSFC	Marshall Space Flight Center
NDT	NASA Design Team
NESC	NASA Engineering and Safety Center
NHB	NASA Handbook
NPD	NASA Policy Directive
NSI	NASA Standard Initiator
NSTS	National Space Transportation System
NWTC	NASA Workmanship Technical Committee
OEM	Original Equipment Manufacturer
OMB	Office of Management and Budget
PCB	Project Control Board
PR	Problem Report
PRACA	Problem Reporting and Corrective Action
S&MA	Safety and Mission Assurance
SAE	Society of Automotive Engineers
SMDC	Space and Missile Defense Command
SRB	solid rocket booster

LIST OF ACRONYMS AND SYMBOLS (Continued)

SSME	Space Shuttle Main Engine
START	Standards and Technical Assistant Research Tool
STS	Space Transportation System
TBD	To Be Determined
TIM	Technical Interchange Meeting
TVRO	Test and Verification Requirements Operation
ULA	United Launch Alliance
USA	United Space Alliance
USP	upper stage production
VAB	Vehicle Assembly Building
VCS	Voluntary Consensus Standard
WBS	Work Breakdown Structure
WHMA	Wire Harness Manufacturers Association

TECHNICAL PUBLICATION

EVALUATION OF CABLE HARNESS POST-INSTALLATION TESTING: PART B

1. INTRODUCTION

The Ares Project Control Board (PCB) issued an action to develop the leanest set of practices for design, manufacturing, installation, and testing of electrical cable harnesses. To address the action item, a plan was developed that consisted of a review of historical practices, lessons learned from Ares 1-X, and benchmarking of commercial and other relevant industries. From this information, Findings and Observations were documented, and Recommendations for the design and operation of the crew launch vehicle were developed and presented for consideration by the Ares PCB.

2. ASSESSMENT PLAN

A plan was developed by Chris Iannello and Mark King and was endorsed by the Harness Team members. The assessment method chosen was a study of historical practices, lessons learned from Ares I-X, and benchmarking of commercial and other relevant industries. The original plan is shown in figure 1.

Note: Due to time constraints, many of the sites originally planned for benchmarking were not visited. A mail-in survey was used to collect additional information. Appendices A and C contain some of the responses of the mail-in surveys.

Cable/Harness Action Item Plan

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Task	Start	End	Mar'09 Apr'09 May'09 Jun'09 Jul'09 Aug'09 Sep'09 Oct'09
Ares Cable/Harness Action Assigned	3/24/09	3/24/09	3/24 ◆
Review NASA-STD-8739.4 (Mandatory Standard)	3/25/09	4/8/09	
Review Ares 1-X Harness Lessons Learned (M. Bangham material)	3/30/09	5/29/09	
KSC/Ops experience for Shuttle, ELV's, Ground Processing (Shuttle,	4/15/09	4/17/09	
Solicit team members	4/1/09	5/15/09	
First team meeting	4/14/09	4/14/09	4/14 ◆
Review of MSFC (or NASA) Cable Installation HDBK	4/14/09	5/29/09	
Assess Orion approach	4/22/09	5/29/09	
Interim brief at AST	4/30/09	4/30/09	4/30 ◆
Recommendation for study approach (trade, benchmark, etc)	4/27/09	5/15/09	
Develop Survey Questionaire	5/6/09	5/22/09	
STUDY APPROACH TO PCB	5/18/09	5/18/09	5/18 ◇
Develop Report Outline	5/21/09	5/29/09	
NESC Wiring & Connector Discipline Input to Study	5/5/09	5/29/09	
Boeing - Delta benchmark (Delta IV - Decatur)	5/26/09	5/28/09	
Lockheed Martin - Atlas benchmark	6/25/09	6/29/09	
Air Force - Colorado	6/30/09	7/2/09	
Robotic Space (JPL/GSFC)	7/23/09	7/27/09	
SpaceX - Falcon benchmark	7/27/09	7/29/09	
Air Force Space & Missile Systems Center - Los Angeles	7/30/09	8/3/09	
Car mfr (TBD) benchmark	8/4/09	8/7/09	
Dept of Defense (MDA, AF, and/or SMDC) benchmark	8/10/09	8/13/09	
Write summary report of observations.	8/17/09	9/4/09	
Review baseline mfr, assy, test, and checkout process.	9/7/09	9/18/09	
Incorporate observations into Ares mfr, assy, test, and checkout via	9/21/09	10/2/09	
Schedule Reserve	10/5/09	10/29/0	
Action Item Complete	10/30/0	10/30/0	10/30 ◇

Figure 1. Closure plan.

3. DESCRIPTION OF THE ACTION AND APPROACH

3.1 Action Description

3.1.1 Action From Ares Project

In light of the recent issues on Ares I-X related to cable/harness installation and testing, Ares must develop its own lean approach to the manufacture, installation, test, and checkout of cables/harnesses across the integrated launch vehicle stack. The team must assess the Ares I-X for on-going lessons being learned, conduct an end-to-end assessment (cable manufacture to flight) of current cable/harness practices and standards in NASA and the commercial launch industry and any other relevant industries, and develop a recommended set of practices for Ares that will result in the lowest life-cycle cost with a high reliability approach. The goal should be to develop the leanest set of practices for Ares designers, assemblers, and operators to use in laying out, manufacturing, installing, and testing cables/harnesses for Ares I and V rather than relying on NASA-STD-8739.4. The team should include project, engineering, Safety and Mission Assurance (S&MA), original equipment manufacturers (OEMs), and operators.

3.2 Action Approach

In order to complete this action, the team decomposed the action given into several smaller and more manageable activities that are listed below. Beneath each item, the team has listed the activities performed to address this portion of the action. Actions taken to assess lessons learned from Ares I-X are as follows:

- Assess lessons learned from Ares I-X.
  - Interviewed participants, collected lessons learned, and assessed testing regime during site visit.

- Conduct an assessment of cable/harness practices in NASA, commercial launch industry, and other relevant industries.
  - Performed benchmarking site visits of NASA and commercial space industry, surveyed broader industries, and interviewed SAE subcommittee with wide cross section of industrial participants.

- Problem Reporting and Corrective Action (PRACA).

- Develop a recommended set of practices for Ares I and V resulting in a balance of lowest life-cycle cost with high reliability.
  - Provided as findings, observations, recommendations, and lessons learned in the subsequent report.

- Integrate these practices in Ares I and V design, manufacturing, assembly/installation, test, and operations.
  - Implementation of recommendations by Ares Elements.

The activities are further described below.

3.2.1 Ares I-X Assessment

The team reviewed Ares I-X summary reports related to the issues with post-installation cable testing. In addition, Mike Bangham, a team member on this assessment, was an active participant representing the Ares I-X project during the team's assessment of the testing. Ares I-X summaries and their proposed lessons learned with respect to cable testing are included in the appendices. Experience from Ares I-X points to the need to consider this kind of post-installation testing during design and during production/integration flow planning. In particular, with regard to design, Ares I-X suggests design rules to avoid installation-induced problems, effectively designing for operations (i.e., How can the cable and harness designs best accommodate operations?). In addition, I-X points to the need for a reevaluation of how harnesses are routed. The team points out that consideration for how to develop a test to avoid damage is also an important step.

3.2.2 Benchmarking Activities

The Ares project action included the action to "...conduct an end-to-end assessment (cable manufacture to flight) of current cable/harness practices and standards in NASA and the commercial launch industry and any other relevant industries..." To accomplish this, the team used several methods to benchmark other's activities with respect to cable testing. These included the following:

- Benchmarking field facility visits.
- Emailed surveys.
- Open discussion/interviews with technical committees on pertinent standards.

To further expand on the team's benchmarking activities, the team visited several facilities including the United Launch Alliance (ULA) facility producing Delta II/V (and future home of Atlas) in Decatur, AL; a prominent commercial space contractor's production facility; Shuttle's Wire and Test Facility (Kennedy Space Center (KSC), FL); and the Interplanetary Rover Cable Facilities (Jet Propulsion Laboratory (JPL), Pasadena, CA). For facilities that the team was unable to visit due to time or access constraints, an emailed survey was used. In total, although relatively few emailed responses were received on the survey (<10), those responses offered an interesting and pertinent cross section of the aircraft manufacturers and added a new perspective to the dataset. In addition to these activities, the members of the SAE Subcommittee AE-8A were also interviewed at their Portland, OR, meeting in October 2009. Participants in the SAE AE-8A committee included OEMs, airframe manufacturers, airline and other aircraft operators, systems suppliers, the military, NASA, government agencies (e.g., the Federal Aviation Administration (FAA)), component manufacturers, consulting firms, and academia. The participants represented a diverse cross section of industries and, hence, perspectives on post-installation cable testing varied.

3.2.3 Problem Reporting and Corrective Action and Significant Problem Searches

PRACA and significant problem searches were conducted (see Appendix D). In addition to the original planned actions, the PCB also requested (Ares PCB 80, Oct. 2009) that the team collect known failures and determine if the testing in question would be capable of screening for such failures. To that end, three main data collection activities ensued. The first was a collection of significant wiring related anomalies in NASA history that resulted in a list of high-profile failures attributed to wire latent defects or induced damage to wire by handling. Second, previously compiled studies of Orbiter Wiring Problem Reports were reviewed and pertinent data were excerpted for this report. Finally, the Ares Avionics and Software Chief Safety Officer (CSO) commissioned a data collection activity in order to find any instances where the post-installation cable testing was able to catch failures with the potential for a critical failure (i.e., loss of life or loss of mission).

3.3 Background and Status of Current Requirements

3.3.1 Background

Document searches using the NASA Standards and Technical Assistant Research Tool (START) found that the earliest reference to post-installation requirements for harnesses is in JSC Design and Procedural Standard 133, dated July 27, 1970, cited in National Space Transportation System (NSTS) 08080-1, Manned Spacecraft Criteria and Standards. The Space Shuttle Program released a similar document, JSC Manual (JCM) 8080 on April 01, 1991, which has evolved into JSC Procedural Requirements (JPR) 8080.5, JSC Design and Procedural Standards. The applicable test requirement is found in Standard Number E-14, dated April 01, 1991, and reaffirmed on March 08, 2005.

The earliest Agency-wide document citing post-installation requirements for harnesses is May 1996 in NASA Handbook (NHB) 5300.4(3G-1), Workmanship Standard for Interconnecting Cables, Harnesses, and Wiring, paragraph 3G1401.8. This document has evolved into NASA-STD-8739.4, where the post-installation test requirement is in paragraph 18.2.8 and was reaffirmed in the latest release dated November 24, 2009.

Post-installation tests were imposed on the Apollo via engineering drawings dated circa 1964.

Various military standards had requirements for testing, but the responsibility for documenting specifications for the types and frequencies of tests was assigned to the individual programs.

3.3.2 Current Status

Per NASA Policy Directive (NPD) 8730.5, NASA Quality Assurance Program Policy, NASA-STD-8739.4 (Change 4) is the current workmanship standard that is to be imposed on programs fabricating space flight or mission critical ground support cables and harnesses. NASA-STD-8739.4 is maintained by the NASA Workmanship Technical Committee (NWTC).

A separate task of the NWTC is to support NASA's responsibility to comply with Office of Management and Budget (OMB) Circular A-119. This Circular directs government agencies to use voluntary consensus standards (VCSs) in lieu of government-unique standards except where inconsistent with law or otherwise impractical. To meet that goal, the NWTC participates in several organizations that maintain VCSs.

For electronics fabrication, the predominant VCS organization is the Institute of Printed Circuits (IPC), Association Connecting Electronics Industries. IPC/Wire Harness Manufacturer's Association (WHMA) A-620A, Requirements and Acceptance for Cable and Wire Harness Assemblies is considered the primary industry standard for cables and harnesses. Along with many electronics manufacturing companies (many of which are large NASA and Department of Defense suppliers), the NWTC supports the committee that maintains this standard and a subcommittee that is generating IPC A-620AS, Space Applications Hardware Addendum to IPC/WHMA A-620A. The scope of the space addendum is to "provide additional requirements over those published in IPC/WHMA A-620A to ensure the performance of cable and wire harness assemblies that must survive the vibration and thermal cyclic environments getting to and operating in space." The NWTC plans to recommend Agency adoption of this document to replace NASA-STD-8739.4 upon the release of the space addendum and its associated training program. This is expected to occur before the end of calendar year 2010.

The electrical test requirements in IPC/WHMA A-620A require post-installation tests of cable and harness assemblies. It is not expected that the space addendum subcommittee will change that requirement for the space addendum.

4. DATA ANALYSIS

The results of the benchmarking activities described above are summarized to the entries listed in table 1. Company names are generalized to their respective industries to protect proprietary contractor data.

The columns represent different industries and are generally the result of a single representative respondent in order to maintain the intent of this chart to provide a summary of the benchmarking activity. The rows represent electrical tests grouped by production/installation phase. Specifically, after the harness is manufactured, the post-fabrication testing occurs after a supplier or a respondent's in-house fabrication facility fabricates the cable. Preinstallation at system integration refers to the process by which a subset of respondents assemble all the electronics (avionics) and operation harnesses as a preliminary testing opportunity before final installation into the structure/chassis. Finally, the post-installation rows refer to testing after the cable harness is fully integrated in the vehicle or structure. Tests across the rows include the testing required by NASA-STD-8739.4, which includes continuity, DWV, IR, and other pertinent testing such as functional tests or safe-to-mate testing. In some cases, these other pertinent tests are listed because the respondent cited them as alternatives that mitigate or lessen the need for a NASA-STD-8739.4 test not being performed. As an example, the safe-to-mate test, a test performed by JPL as a channelization test, also verifies expected electrical parameters done as a precursor to mate. Notes on the bottom of the table explain key aspects of the data. Note 1 refers to interview responses from cable engineering at JPL and their concern that DWV testing has the potential to cause latent damage to the cable system. As a result, JPL intentionally does no DWV testing. It should be noted that studies performed by the Marshall Space Flight Center (MSFC) and KSC on the effects of DWV show no adverse effects on the insulation systems (see Appendix E). Notes 3 and 4 speak to the relatively new practice of cable testing and cable test facilities at the commercial space contractor. This vendor is just getting up to speed on how to incorporate the full test regime required by NASA-STD-8739.4 but, at the time of the team's visit, had not done so. Notes 5 and 6 refer to the team's initial contact with the Orion project on the NASA and contractor sides. The initial response was that Orion would follow the policy of no post-installation IR or DWV once avionics are installed. However, this response was revised by NASA engineering supporting the Orion Project, who will hold the contractor to their contractual requirement to perform such testing.

The Orion project documentation calls for post-installation DWV in CEV-T-031212 CEV Subsystem Requirements Specification Crew Module and Service Module/Spacecraft Adapter Wiring Subsystem under WIRE-0684 (included as Appendix F).

Data collection on this activity began by evaluating NASA's own experience on wiring anomalies and practice of post-installation cable testing within its major programs.

Table 1. Benchmarking result.

Cable Test		Shuttle Orbiter	Shuttle Payload	Shuttle SRB	ELV	EELV 1	EELV 2	Commercial Space Co.	JPL Interplanetary	Orion	Commercial Aircraft Maker	Military Aircraft Maker	Harness Manufacturer
Post-fabrication	Continuity												
	Insulation Resistance (Megger)												
	Dielectric Withstand Voltage (Hi-Pot)							(4)	(1)				
Preinstallation at System Integration	Continuity	Optional											(7)
	Insulation Resistance (Megger)	Optional						(3)					(7)
	Dielectric Withstand Voltage (Hi-Pot)	Optional						(3)					(7)
	Functional												(7)
Post-installation w/ Avionics Boxes Installed	Continuity									(6)			
	Insulation Resistance (Megger)						(5)	(3)		(6)	(8)		
	Dielectric Withstand Voltage (Hi-Pot)						(5)	(3)		(6)	(8)		
	Safe to Mate							(3)	(2)				
	Functional												(7)

(1) JPL does no DWV testing whatsoever.
(2) A channelization test that also verifies expected electrical parameters is done as precurser to mate.
(3) Commercial Space Co. does no cable testing once installed.
(4) Commercial Space Co. is working to get DWV testing incorporated post-fabrication.
(5) The contractor does not do Megger with electronics installed in spacecraft regardless of whether harnesses are mated or not.
(6) Orion project documents do require the contractor to do full suite of post install cable testing regardless of avionics installed.
(7) When manufactured harness gets integrated into Next Higher Assembly by harness manufacturer.
(8) Rarely perform DWV or IR post-fabrication unless functional failure occurs.

- Test Not Performed
- Test Performed
- N/A

A first step was a review of the databases and anomaly logs of the major manned programs including the Shuttle's PRACA Database, KSC's Shuttle Problem Report Tallies, and a review of significant wiring anomalies in the Shuttle and Apollo.

Figure 2 shows the relationship between the number of wire problem reports (PRs) per year and flights per year. Note that the flight rate data are erroneously shifted to the right one year. From the data, there is no indication that wiring PRs decrease with vehicle maturity in the case of the Orbiter (although Ares' single-use, ship-and-shoot strategy makes this not directly comparable to Ares). Also, per the Orbiter electrical team, there are two major reasons that Orbiter wiring PRs increase during low flight-rate years. First, inspections of wiring go up during those years. Second, as the flight rate decreases, there is more traffic in the ship resulting in an increase in collateral damage.

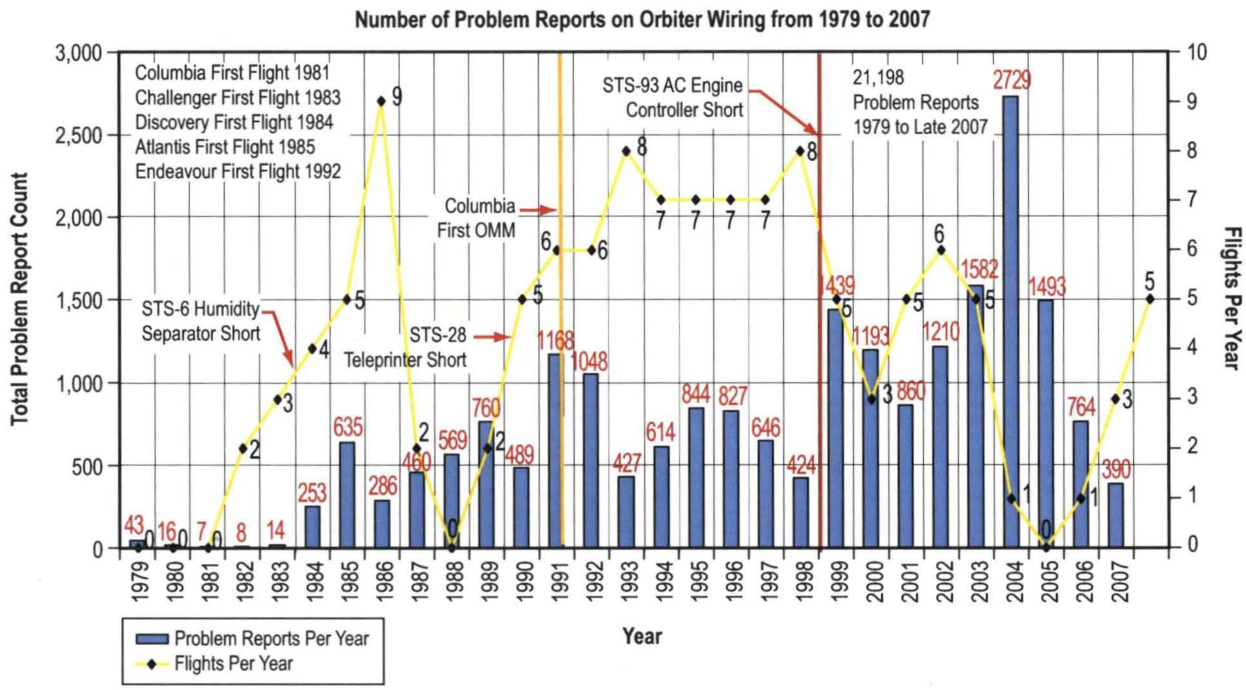
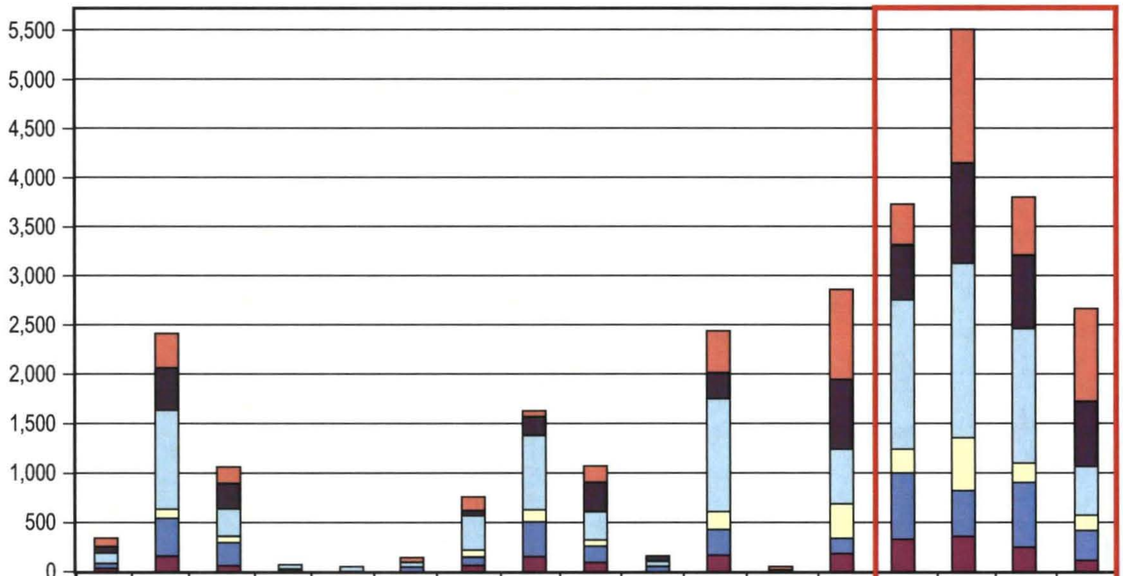


Figure 2. Shuttle (Orbiter) wiring problem reports and flight rate from 1979–2000.

Figure 3 shows a breakdown of the types of wire-related problems encountered in the Orbiter fleet. Note that some of the most significant categories include damaged conductor and exposed conductor.

Clearly, handling-induced damage or damage resulting from work in close proximity is a primary source of wiring anomalies. The question is: Of the total set of wiring problems, how many, if any, can the post-installation testing in question screen? To answer this question, the team took a different approach on data collection. The idea was to generate a very narrow search criteria with the intent of finding instances where the post-installation testing described in this report uncovered



	105 UMP Total	105 J2	105 Stnd-Dwn/Subs	103 STS-120	103 STS-116	103 STS-121	103 STS-114	OV-103 J3	103 Stnd-Dwn/Subs	104 UMP STS-117	104 STS-115	104 RTF (ECLSS)	104 Stnd-Dwn/Subs	103 Grand Total	104 Grand Total	105 Grand Total	OV-102 J3
Total	340	2,400	1,053	72	47	150	750	1,628	1,677	163	2,442	49	1,844	4,324	4,498	3,793	2,666
Chafe Protection	80	344	155	9	3	41	124	60	161	7	425	25	915	398	1,372	579	954
Kapton Damage	75	423	261	7	3	10	53	185	300	57	256	2	687	558	1,002	759	654
Jacket Damage	81	997	285	28	28	47	362	760	298	44	1,162	11	566	1,523	1,783	1,363	483
Shield Damage	21	106	53	5	4	6	63	114	53	6	165	8	344	245	523	180	168
Exposed Conductor	45	367	236	10	4	34	90	364	168	42	258	0	153	670	453	648	293
Conductor Damage	38	162	63	13	5	12	58	145	95	7	176	3	187	328	373	263	114

Figure 3. Orbiter wiring problem breakdown.

failures that, had they gone unnoticed, had the potential to result in a critical effect. To this end, a keyword search was generated on the MSFC Shuttle PRACA Reportable database on keywords "POST," "INSTALLATION," "DWV," "IR," "MEGGER," "HI-POT," and "CONTINUITY." The results were further screened to ensure all the resulting entries were, in fact, instances where post-installation testing caught a potential problem. PRACA search results for the MSFC/Shuttle are presented in table 2.

The 11 entries found suggest that this sort of testing does uncover potential issues, but the number of entries suggest that these types of significant finds are rare. In fact, each survey and interview respondent indicated uncovered failure rates of less than 1–2%.

As such, the team's conclusion here was even though IR and DWV usually uncover a low failure rate (often less than 1%), the data presented herein show cable testing of this sort does identify cable damage that could result in loss of life or loss of mission, albeit rare, and that data alone is sufficient justification to conduct this testing.

Table 2. MSFC/Shuttle PRACA search results.

MSFC Report #	Problem Title	Element	System	Functional Criticality	Hardware Criticality	Test Operation	Fail Mode	Cause	FMEA #	Fail Date	NCA Part #
A16814	O.I. CABLE X21W5R PIN A (switch 51) failed DWV test.	SRB	E&I	1R	–	A	EL	UK	50-04-X21/B05	3/25/1996	10400-0050-501
A17039	IW20 harness failed megger check post test 904297.	SSME	Harnesses	1R	1R	D	EL	ETE	H120-01	2/7/1997	R0018420-51
A17040	IW16 harness failed megger check post test 904297.	SSME	Harnesses	1R	1R	D	EL	ETE	H116-01	2/7/1997	RS008116-101
A17271	Wire harness failed post-installation DWV test.	ET	Electrical	1R	1	A	EL	ES	3.12.7.2	4/25/1998	80931003714-229
A17395	AFT SRB/orbiter wire harness (303W04) failed dielectric withstand voltage (1,500) test.	ET	Electrical	1R	–	A	EL	M	3.12.4.2	4/20/1999	80931003714-160
A17537	Wire harness (303W07) failed post-installation TM04 dielectric withstand voltage (1,500 V) test.	ET	Electrical	1R	–	A	EL	MM	3.12.7.2	12/20/1999	80931003714-229
A17616	Wire harness 303W07 did not pass TM04 dielectric withstand voltage test (1,500 V) at MAF.	ET	Electrical	1R	1	A	EL	MAW	3.12.7.2	9/14/2000	80931003714-179
A17632	FASCOS Cable FID/In-family.	SSME	Harnesses	3	3	Q	Mf	ET	H150-01	11/1/2000	R0014030-201
A18030	Harness failed continuity check.	SSME	Harnesses	1R	1	Q	EN	DHA	H102-01	2/7/2005	RS008102-041
A18080	BIPOD WEB temperature sensor harness 311W09P1 failed post-installation isolation resistance test.	ET	Electrical	3	3	AI	EL	MW	3.8.14.2	4/27/2005	80931023704-099
A18544	THE 303W01 wire harness failed the post-installation TM04 dielectric withstand voltage (1,500 V) test on ET-129 at MAF.	ET	Electrical	1R	1R	AS	EL	MW	3.12.1.2	7/16/2008	80931003714-209

The team also wanted to understand what strategies could be employed to reduce the overhead associated with these tests. To that end, the team referred to Ares I-X lessons learned, the returned surveys, and the interview responses to questions related to testing overhead.

Ares I-X lessons learned are included in Appendix G. These lessons can be summarized as follows:

- Risk to your avionics when doing DWV.
- Design for accessibility.
- Preplan for testing.

On Ares I-X, the lessons learned underscore design for accessibility and preplanning for post-installation testing. On the Ares I-X solid rocket booster (SRB) (first stage) structure, harness failures, in general, have occurred in the last 12 inches or so of the harness. The team makes the following two observations on this:

- First, most manipulation to install these harnesses occurs near the end.
- Second, many of the installations have the smallest bend radii at the box connection point.

On testing the harnesses, the requirement is that the harnesses be tested after installation. So when does installation end? The team maintains that it ends when the harnesses are either installed at the end plate or very near it. Today on the SRB program, testers must take the harness end and bend it to allow connection to the test harness. In some cases, the harness is then completely out of the installation area. This is done very carefully and the harness is supported (usually by ropes), but there is manipulation of the harness to get it into a test configuration and then back into the installation configuration.

In figure 4, the harnesses are draped over the cylinder to allow the technicians to connect to the harness. Given most of the failures have occurred in the last 12 inches, and those last 12 inches are being manipulated after the test, in addition to when the cables are finally mated, this design is not optimal with respect to cable testing.

Suggestions for improvement include improving the ways tests are set up and performed from a design perspective. These include the following:

- Selecting easily mated/demated connectors.
- Designing for special test connectors that allow technicians to leave the harness in the near final location for testing.
- Considering a common connector.
- Developing a common method to hold the test connectors and harness in place during the testing process.

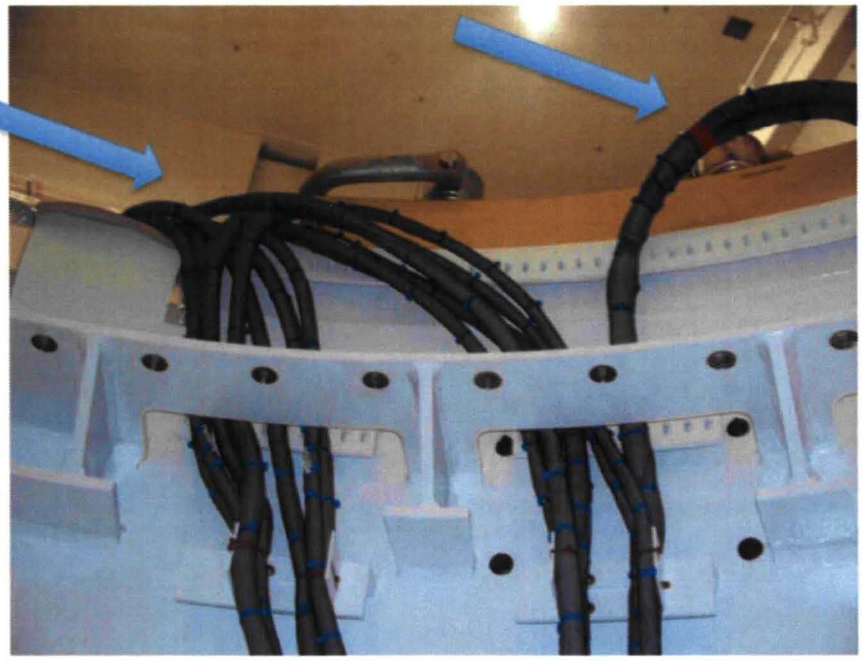


Figure 4. Ares I-X cable harness test configuration.

The team concurred with all of the Ares I-X lessons learned. Lessons learned are incorporated in section 5, Findings, Observations, and Recommendations (FOR), with the exception of the first concern related to performing DWV testing with avionics installed (cables/connectors demated).

Even though DWV testing of harnesses requires disconnecting them from their associated avionics boxes pretest, Ares I-X brought forward a concern that modern avionics should be assessed against possible damage when cables under DWV test fault to chassis. The question raised was that projects should ensure that the avionics box can withstand any variations in its chassis voltage should a harness under test short to the chassis nearby. The team did not share this Ares I-X concern for a number of reasons. First, with proper bonding and grounding it is virtually impossible to develop any potential difference across the avionics box chassis. Further, modern test equipment is designed to protect the device under test to the greatest extent possible. This includes current limiting features and incremental voltage test regimes. It is likely that these are the reasons the team could find no documented cases of testing-induced damage.

With regard to the survey and interview responses, in all cases where the vendor was performing testing comparable to the post-installation testing in NASA-STD-8739.4, each vendor indicated that such testing was low overhead. In each of these cases, it was noteworthy that these organizations had well-developed test procedures. The wire harness pin outs were in an electronic format consumable by their particular brand of cable tester; they had racks of cable adapters for each flight or vehicle harness suitable for interconnect with the tester, and the test was planned into the assembly workflow so as to minimize effort. These responses were developed into the recommendations found in section 5.3.

Finally, it should be noted that a number of high-profile failures in NASA history have listed wiring faults and handling-induced damage as related causes. Included in these are the Apollo 1 and Apollo 13 incidents and a number of Shuttle anomalies. The Apollo 1 fire shown in figure 5 (as excerpted from The Apollo 204 Report) occurred during a full-up launch simulation on January 28, 1967. A momentary increase in alternating current (AC) Bus 2 voltage on all three phases was noted at ≈9 seconds before the report of fire, and at the same time telemetry data from equipment powered from AC Bus 2 showed abnormalities. All communications were lost 18 seconds later. The rapid spread of fire within the pure oxygen atmosphere caused an increase in pressure and temperature that resulted in rupture of the Command Module and creation of a toxic atmosphere. Death of the crew was from asphyxia due to inhalation of toxic gases due to fire.

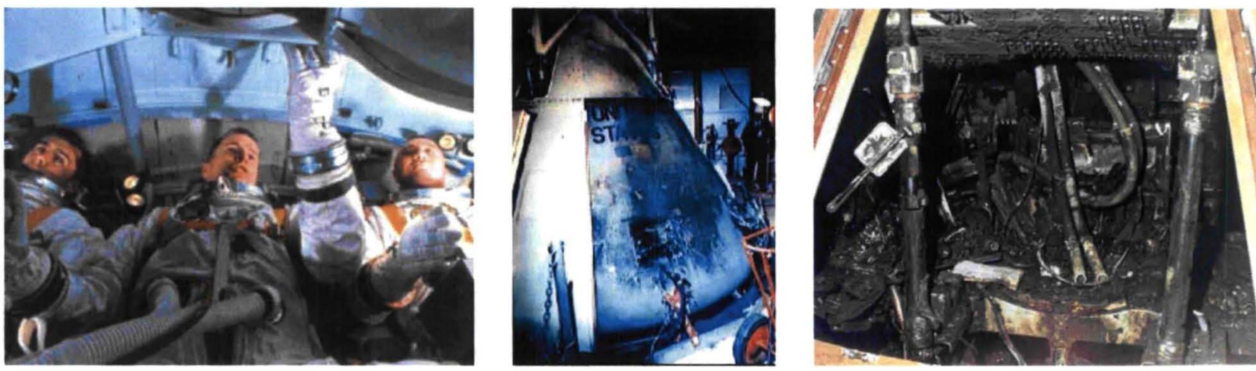


Figure 5. Apollo I fire (crew, capsule, and damage).

Listed in the Apollo 1 findings was that it is most probable that the fire was initiated by an electric arc and was most probably brought about by some minor malfunction or failure of equipment or wire insulation. Components of the Environmental Control System installed in Command Module 012 had a history of many removals and of technical difficulties that included regulator failures, line failures, and environmental control unit failures. The design and installation features of the environmental control unit made removal or repair difficult. In addition, deficiencies in design, manufacture, installation, rework, and quality control existed in the Teflon® electrical wiring. The report conclusion included a recommendation that rigid inspection at all stages of wiring design, manufacture, and installation be enforced.

Similarly, on Apollo 13 (fig. 6), as excerpted from the Apollo 13 Review Board Cortright Commission's report, the No. 2 oxygen tank had been previously installed in the service module of Apollo 10, but was removed for modification (and was damaged in the process of removal). At 55 hours, 55 minutes, oxygen tank No. 2 exploded, causing No. 1 tank also to fail. The Apollo 13 command module's normal supply of electricity, light, and water was lost, at a distance of 200,000 miles from Earth. Subsequent investigation of the accident determined the cause of the combustion was most probably the ignition of Teflon wire insulation on the fan motors' wires, caused by electric arcs in this wiring. In both cases, handling-induced damage and wire insulation failure were contributors.

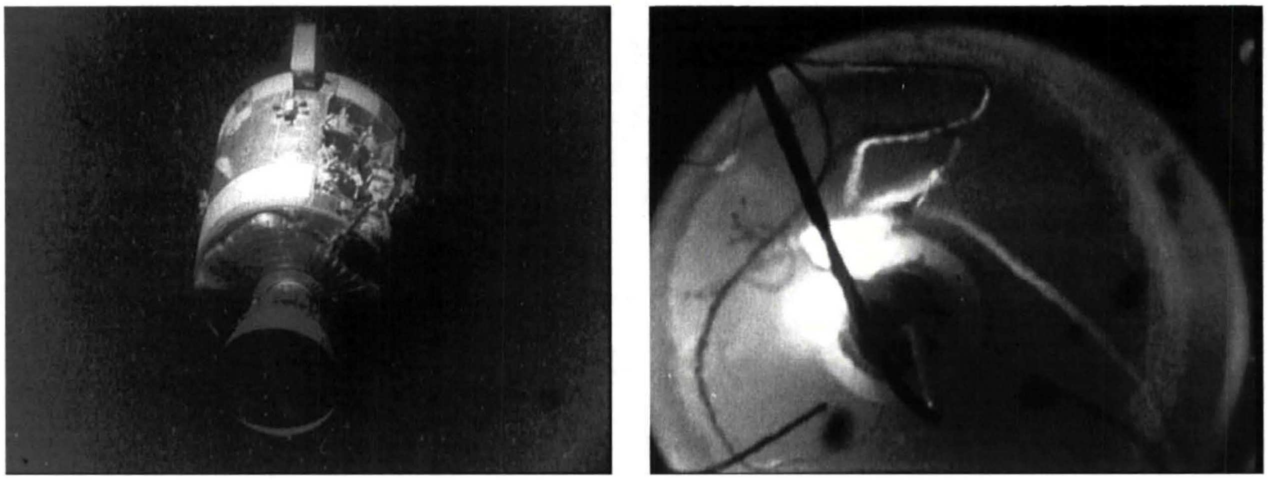


Figure 6. Apollo 13.

Other examples of notable failures within the Space Shuttle Program are depicted in figures 7 through 10. Figure 7 shows damage to Orbiter wiring caused by work in close proximity to the wire bundle shown. Note that the outer color coating is damaged in several areas, exposing the Kapton® insulation layer. Also note that in several areas, the outer Kapton layer has also been damaged. This type of damage can exist undetected with no outward indication that the system function can be compromised. In these cases, ascent thermal and/or vibration environments can move the harness, increasing the potential for bare conductor to short to chassis or other exposed wires. Figures 8 and 9 show a closeup of the insulation damage and figure 10 shows a closeup of the teleprinter short.

During Space Transportation System (STS)-28, a short circuit occurred between the +28V and return wire segments inside a power cable for a teleprinter (fig. 10). Suspect Cause: Kapton wiring was subjected to a severe bend over the top of the straight backshell when routed during use. The design was changed to incorporate the use of Teflon wiring and a 90-degree backshell.

During STS-93, an electrical short circuit on AC Bus-1 (AC-1), Phase-A (fig. 11), resulted in loss of the primary controller for Space Shuttle Main Engine (SSME)-1 and the secondary controller for SSME-3. The suspected cause was that a torque set screw head with burred edges likely damaged the wire insulation before launch, resulting in the exposed conductor, which made contact during the vibration environment of launch, resulting in the short.

Another anomaly occurred during STS-97 that, after postflight analysis, drove a rollback of STS-98 for assessment. The anomaly was that System "A" NASA Standard Initiator (NSI) Pressure Cartridge in the left aft lower strut did not fire, resulting in a Criticality 1R failure of the SRB separation system, shown in figures 12 and 13. The assessment team confirmed that the Orbiter and external tank (ET) cabling performed nominally as did the pyrotechnic NSI. The failure was attributed to the watertight reusable strut ordnance cable. Gross shield damage was noted. The most probable cause was identified as handling damage unique to the ET attach-ring strut reusable strut cables.

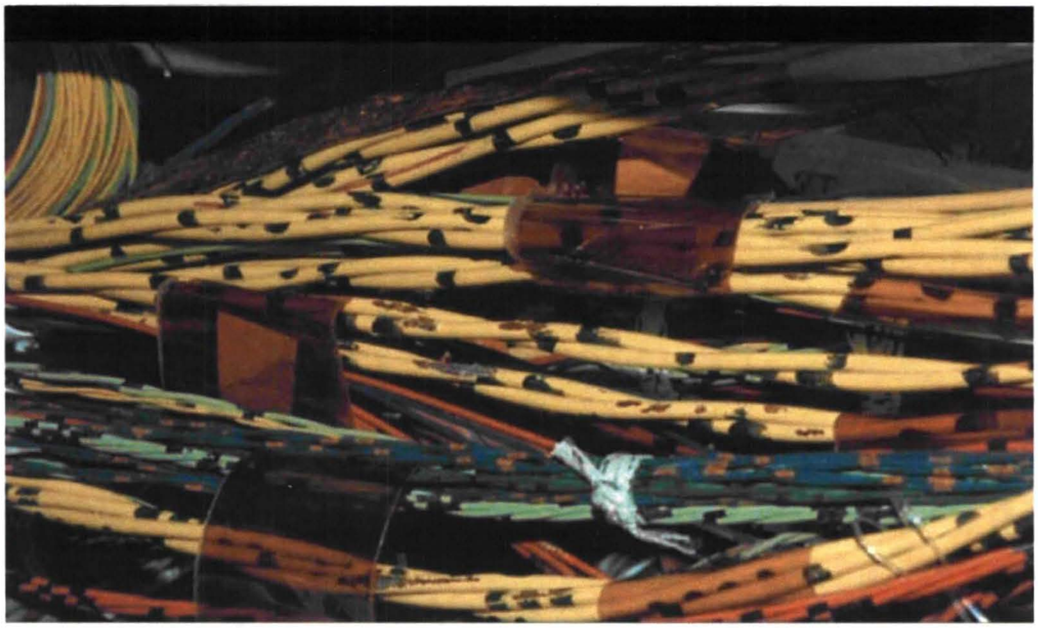


Figure 7. Orbiter wiring damage.

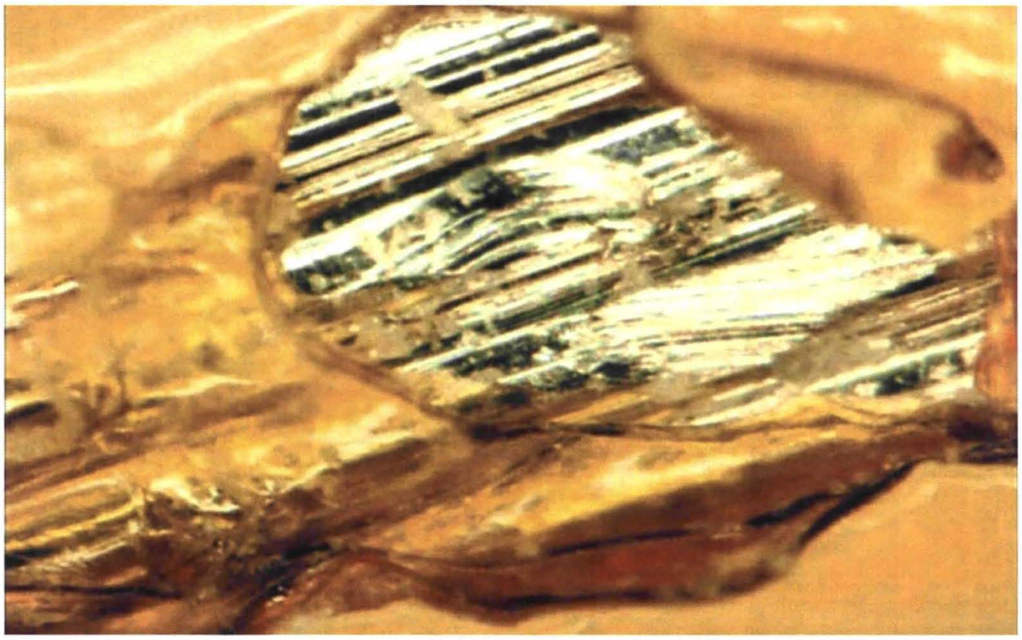


Figure 8. Closeup of Orbiter wiring damage.

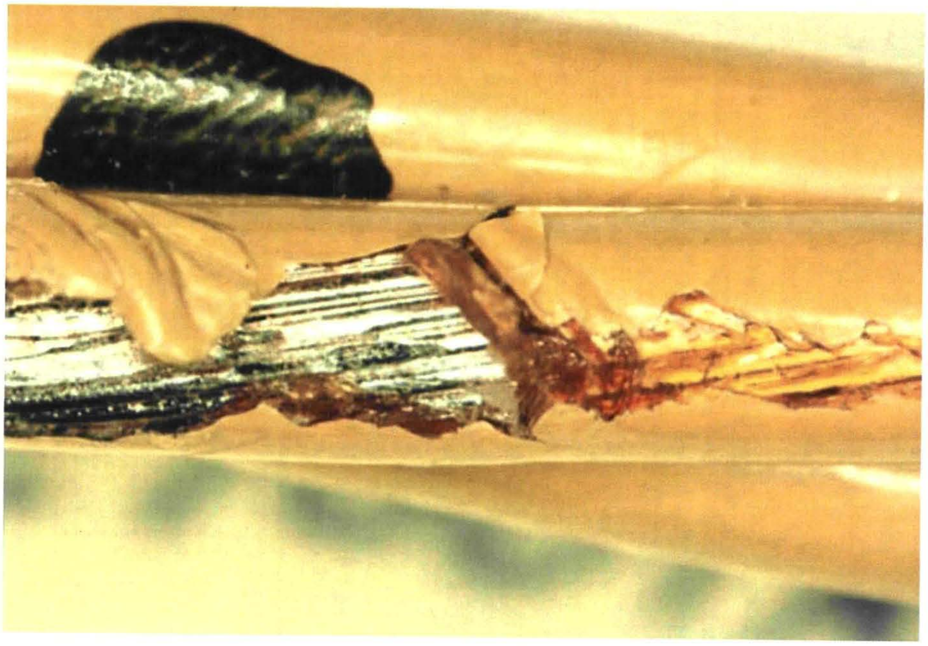


Figure 9. Closeup of Orbiter wiring damage.

Figure 10. Closeup of Orbiter teleprinter short.

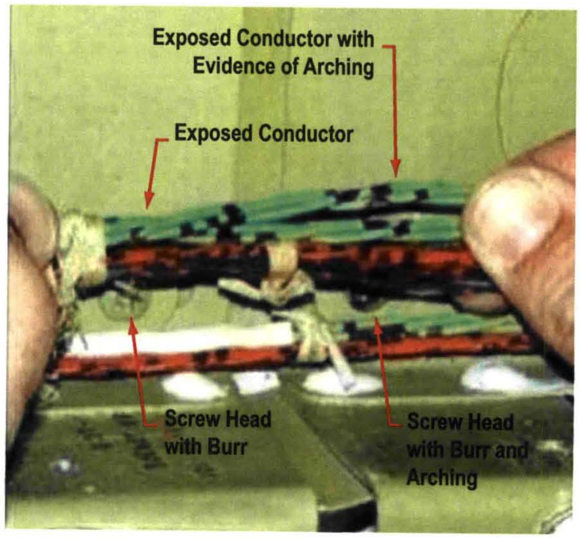


Figure 11. STS-93 AC Bus short to structure.

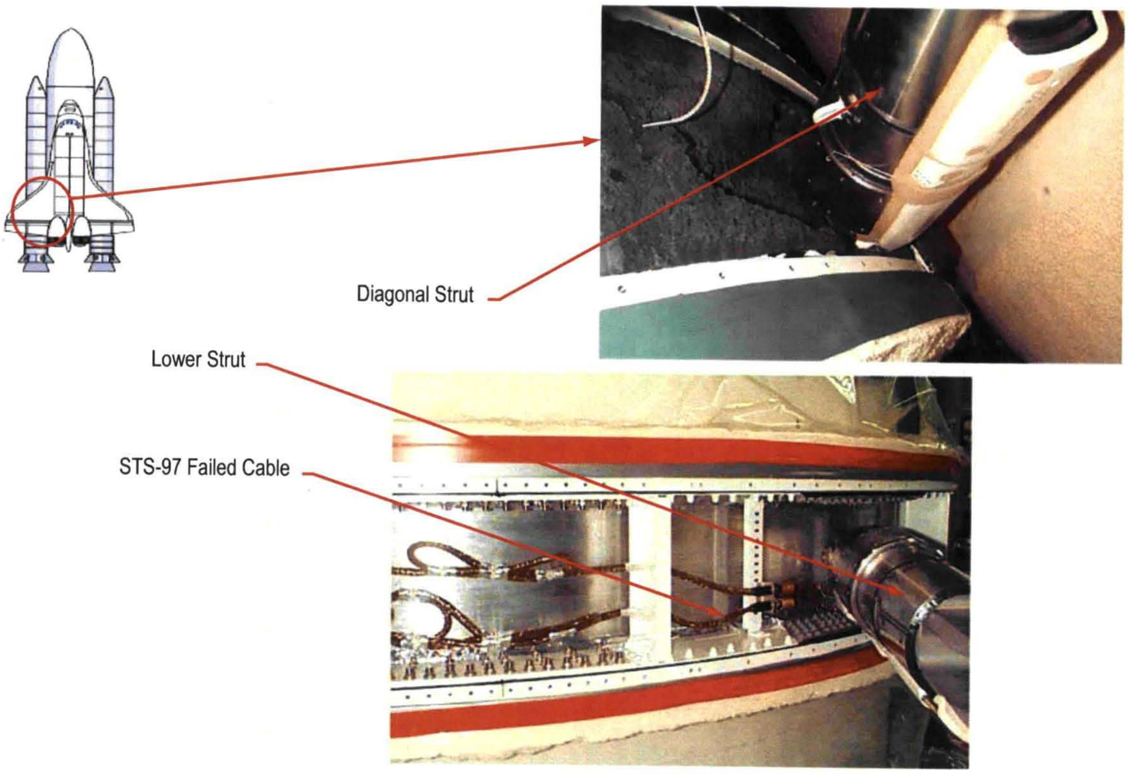


Figure 12. STS-97 NSI cable failure.

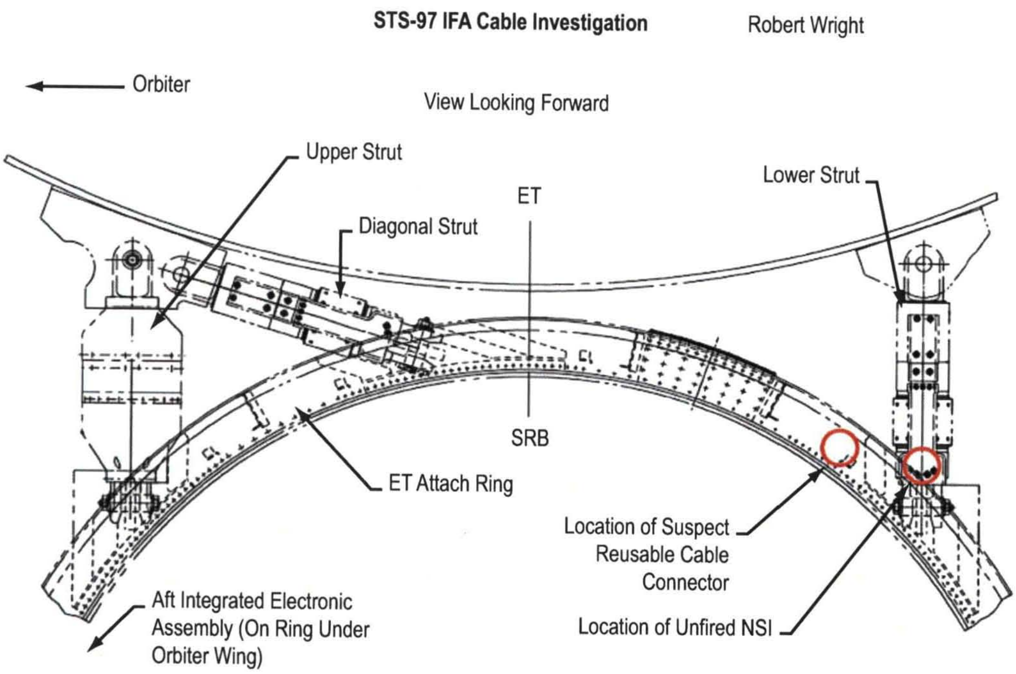


Figure 13. STS-97 failure location.

Technicians performed x-ray inspection and electrical tests of the STS-98 reusable strut ordnance cables and replaced one suspect upper strut reusable ordnance cable and also reterminated one suspect lower strut reusable ordnance cable. The team replaced one suspect forward separation bolt ordnance cable. An effort was also kicked off to perform x-ray inspections and electrical tests of additional cables from inventory. The x-ray inspection and electrical tests of 223 flight cables from inventory was completed and four cables were identified with a break in a conductor. Analyses concluded conductor breaks were not recent occurrences. Corrective actions were implemented for the STS-98 mission, which entailed rollback to the Vehicle Assembly Building (VAB) for inspection and testing of system tunnel cables. The team completed x-ray inspections and electrical tests of 36 of the 38 system tunnel cables with no anomalies noted. This anomaly shows the impact that problems like these can have when discovered late in the flow.

4.1 Ares I First Stage Concept of Operations

The first stage will actually be integrated as a stage in the KSC VAB, similar to how the Space Shuttle SRBs are stacked today. The KSC contractor, working under Constellation Program's Ground Operations Project, will develop the assembly and checkout procedures from the information provided by the Ares I first stage. This information is in the form of Test & Verification Requirements Operations (TVROs), which are being developed for the first stage CDR. Presently, the heritage Shuttle SRB and Ares I-X are being used as a starting point for TVRO development.

4.2 Ares I Upper Stage Concept of Operations

The upper stage will be fully integrated and checked out at the Michoud Assembly Facility (MAF) before shipment to KSC. In the current concept of operations production flow, the instrument unit structure is handed over from the upper stage production (USP) contractor to the instrument unit assembly (IUA) contractor for integration and checkout, and then the IUA is handed back to the USP for integration onto the rest of the upper stage. The upper stage manufacturing and assembly subsystem team is responsible for overall stage integration.

The USP contractor is responsible for development of the in-process work instructions, which contain the details of how the stage is assembled and checked out. The prime driver to the work instructions is the upper stage assembly drawings.

Work instruction development has begun for a ground vibration test article, but this test article does not need the full suite of flight unit work instructions. Per the master schedule, no instrument unit work instructions are being developed. Once development begins, the NASA Design Team (NDT) will be responsible for ensuring that the appropriate Ares I requirements and processes are captured.

4.3 Shuttle Concept of Operations

Shuttle production flow differs for each of the three elements. For Orbiter, although complete post-installation cable testing was performed after all harness installations, it is rarely repeated onboard the Orbiter after individual wiring anomalies are identified. For the SRB and ET, since each are built up each flow, a number of post-installation cable tests are performed. For the ET, these tests are performed at MAF as each cable is installed into the ET. For the SRB, since the segments are integrated in the VAB and system tunnel cables installed there, a post-installation test is performed by KSC.

5. FINDINGS, OBSERVATIONS, AND RECOMMENDATIONS

5.1 Findings

The following team findings were identified:

F-1. Data show that the testing regime required by existing Ares cable harness testing requirements is capable of identifying typical cable system manufacturing defects and installation-induced damage.

F-2. In NASA programs, the number of failures identified by harness testing is relatively low in both the build and installation processes.

F-3. The incidence of testing-induced failures is extremely low.

F-4. The Ares I-X production flow was designed without the requirement for post-installation cable testing and, as a result, did not account for all the necessary preplanning to facilitate post-installation cable testing, which is the root cause of the issues on Ares I-X with respect to cable testing.

F-5. NASA programs that do incorporate the full suite of NASA-STD-8739.4 required testing demonstrate a value-added step in their production flow with relatively low overhead associated with the testing.

F-6. The effort to perform cable testing is strongly a function test preparation including the formulation of cable pin-out tables, the compatibility of the electronic format of these tables with the automated tester, and the availability of tester mating adapter cables.

5.2 Team Observations

The following team observations were identified:

O-1. There is a perception within some NASA programs and program contractors that high-voltage cable testing can result in damage to the cable's insulation system, but this assertion is not supported by MSFC and KSC testing, which show no measureable adverse effects.

O-2. The degree to which NASA programs follow NASA-STD-8739.4 varies when it comes to cable testing and, in particular, post-installation cable testing.

O-3. Cable testing practices vary in NASA programs and in industry based on a number of factors that include the reliability required in the application, the maturity of the operation, the nature of the assembly process, and the cultural heritage of the workforce.

5.3 Recommendations

The following team recommendations were identified:

R-1. The Ares project should retain the value-added practice of post-fabrication and post-installation cable testing including IR testing and DWV testing.

R-2. The Ares project should emphasize human factors in cable harness design including redesigning the harness routing, interfacing structures, routing near obstructions, etc., in an effort to eliminate the manipulation required to install these harnesses.

R-3. The Ares project should ensure the lowest life-cycle cost to implement recurring cable testing by incorporating the following necessary preparation steps into the production contractor's workflow:

- Ensure the electrical integration deliverables to NASA from the production contractor include harness diagrams and wiring tables in an electronic format compatible with commercial automated cable testers (such as Cirrus).
- Ensure the production contractor is required to produce and deliver cable mating adapters suitable for interconnecting each Ares cable harness to the automated cable tester for post-fabrication and post-installation testing.
- The selection of the cable tester's mating connector, which makes up one end of each and every adapter cable, should be chosen such that it is standard, easily obtainable, of necessary contact density, and consistently employed on each adapter cable.
- Ensure documentation that initiates the creation of post-installation test procedures is adequately addressed during workflow development.
- Ensure the assembly sequence accounts for planned post-installation cable testing. This is particularly true for areas with difficult access.

6. ALTERNATE VIEWPOINTS

The review team offered no dissenting opinions· The team is in concurrence with all findings· observations· and recommendations·

7. ADDITIONAL INFORMATION

A Science and Technology Technical Interchange Meeting (TIM) pdf is found in Appendix H and the NASA Electrical Presentation Final Ares PCB Presentation is presented in Appendix I.

APPENDIX A — SURVEY RESPONSE SUMMARY/INTERPRETATION MATRIX

Information for this appendix is classified SBU and can be found in Part A of this TP. Information needed to access Part A of this TP can be obtained on the NASA Technical Reports Server (NTRS) using <http://ntrs.nasa.gov/search.jsp>.

APPENDIX B—STUDY AUTHORIZATIONS AND TEAM MEMBERS

B.1 Approval and Document Revision History

Table 3. Approval and document revision history.

Version	Description of Revision	Author	Effective Date
1.0	Initial Release	Mark S. King, Chris Iannello	

B.2 Authorization and Notification

This report was generated as the result of an action item assigned by the Ares Project Manager at the March 24, 2009, Ares Project Control Board (PCB). Authorization for the action closure plan, which is included this report, was sanctioned at the May 19, 2009, Ares PCB.

B.3 Team Members

Table 4. List of team members.

Name	Function
Mark S. King	Lead for WBS 5.2.6/Avionics Integration & Vehicle Systems Test
Chris Iannello	Lead for Avionics & Software Chief Engineer
Garry McGuire	Electrical Integration, Workmanship
Andy Gamble	S&MA/Ares Avionics & Software Chief Safety Officer
Mike Bangham	Ares I-X Consultant/Advisor
William (Art) Davis	Harness Design & First Stage Representative
Joe Schuh	Ares I Airborne & Orbiter Electrical Engineering
Ronald (Ron) Hodge	EEE Parts Engineering
Tammy Owens	Technical Editing and Coordination

In addition to the team members listed above, a host of others were significant contributors to the data provided and conclusions derived in this report. These individuals, although not formally listed as team members, supported the activity extensively by providing consultation services, facilitating demonstrations, supporting data collection, and in many cases helping write this report. The team leads would also like to thank Hung Nguyen, NASA Kennedy Space Center (KSC); Angel Garnica, NASA Jet Propulsion Laboratory (JPL); Pat Dillon, NASA JPL; and George Slenski, NESC consultant, for their expert advice and dedicated support to this action. Finally, data provided in this report was collected with the help of a variety of sources including the NASA Johnson Space Center (JSC), Boeing, and United Space Alliance (USA) Shuttle wiring teams.

B.4 Signature Page

8/6/2010

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Avionics Integration and Vehicle Systems Test

8/9/10

Chris Iannello, Date
Lead for Avionics and Software
Chief Engineer

8/6/2010

Garry McGuire, Date
Electrical Integration, Workmanship

8/6/10

Andy Gamble, Date
S&MA/Ares Avionics and Software
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8/9/10

Mike Bangham, Date
Ares I-X Consultant/Advisor

8/13/10

William (Art) Davis, Date
Harness Design and First Stage
Representative

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Joe Schuh, Date
Ares I Airborne and Orbiter Electrical
Engineering

8/5/2010

Ronald Hodge Date
EEE Parts Engineering

8/6/10

Tammy Owens Date
Technical Editing & Coordination

APPENDIX C—SURVEY RESPONSES

Information for this appendix is classified SBU and can be found in Part A of this TP. Information needed to access Part A of this TP can be obtained on the NTRS using <http://ntrs.nasa.gov/search.jsp>.

APPENDIX D—PROBLEM REPORTING AND CORRECTIVE ACTION DATA AND ASSESSMENT OF ARES AVIONICS AND SOFTWARE CHIEF SAFETY OFFICER

Information for this appendix is classified SBU and can be found in Part A of this TP. Information needed to access Part A of this TP can be obtained on the NTRS using <http://ntrs.nasa.gov/search.jsp>.

APPENDIX E—ELECTRICAL HARNESS TEST DATA

Information for this appendix is classified SBU and can be found in Part A of this TP. Information needed to access Part A of this TP can be obtained on the NTRS using <http://ntrs.nasa.gov/search.jsp>.

APPENDIX F—ORION PROJECT REQUIREMENT EXCERPT ON POST-INSTALLATION CABLE TESTING

Information for this appendix is classified SBU and can be found in Part A of this TP. Information needed to access Part A of this TP can be obtained on the NTRS using <http://ntrs.nasa.gov/search.jsp>.

APPENDIX G—ARES I-X PRELIMINARY LESSONS LEARNED ON POST-INSTALLATION CABLE TESTING

Information for this appendix is classified SBU and can be found in Part A of this TP. Information needed to access Part A of this TP can be obtained on the NTRS using <http://ntrs.nasa.gov/search.jsp>.

APPENDIX H—SCIENCE AND TECHNOLOGY TECHNICAL INTERCHANGE MEETING NASA ELECTRICAL PRESENTATION

Information for this appendix is classified SBU and can be found in Part A of this TP. Information needed to access Part A of this TP can be obtained on the NTRS using <http://ntrs.nasa.gov/search.jsp>.

APPENDIX I — FINAL ARES PROJECT CONTROL BOARD PRESENTATION

Information for this appendix is classified SBU and can be found in Part A of this TP. Information needed to Part A of this TP can be obtained on the NTRS using <http://ntrs.nasa.gov/search.jsp>.

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Prepared by the Science and Exploration Vehicle Office, Science and Mission Systems Office
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14. ABSTRACT
The Cable Harness Post-Installation Testing Report was written in response to an action issued by the Ares Project Control Board (PCB). The action for the Ares I Avionics & Software Chief Engineer and the Avionics Integration and Vehicle Systems Test Work Breakdown Structure (WBS) Manager in the Vehicle Integration Office was to develop a set of guidelines for electrical cable harnesses. Research showed that post-installation tests have been done since the Apollo era. For Ares I-X, the requirement for post-installation testing was removed to make it consistent with the avionics processes used on the Atlas V expendable launch vehicle. Further research for the report involved surveying government and private sector launch vehicle developers, military and commercial aircraft, spacecraft developers, and harness vendors. Responses indicated crewed launch vehicles and military aircraft perform post-installation tests. Key findings in the report were as follows: Test requirements identify damage, human-rated vehicles should be tested despite the identification of statistically few failures, data does not support the claim that post-installation testing damages the harness insulation system, and proper planning can reduce overhead associated with testing. The primary recommendation of the report is for the Ares projects to retain the practice of post-fabrication and post-installation cable harness testing.

15. SUBJECT TERMS
electrical cable harnesses, post-installation testing, test requirements, crew launch vehicle, megger, hi-pot

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(Include area code)*
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