Managing Electrical Connection Systems and Wire Integrity on Legacy Aerospace Vehicles

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Abstract

Aging wiring has become a high interest item, yet the term is not well understood by many in the aerospace community. For the purposes of this paper, aging wiring is defined as degraded performance due to accumulated damage from long-term exposure to chemical, thermal, electrical, and mechanical stresses. These stresses are often induced by the operational environment, installation and maintenance practices. Wiring failures often appear as broken conductors and damaged insulation, which can disrupt electrical signals or lead to arcing. The aging issues associated with the electrical interconnection system of an aerospace vehicle will be discussed with wiring being a significant part of this system.

The National Aeronautics and Space Administration (NASA) has recently dealt with some of these issues. During the space shuttle flight of Columbia STS-93, an Alternating Current (AC) short circuit occurred five seconds after liftoff causing loss of power redundancy for two engine controllers. The investigation of this short circuit initiated an intensive wire analysis and inspection of cables within the vehicle. This presentation provides insight into the process, analysis and findings of the space shuttle wire investigation.

Introduction

The increased emphasis and reliance on electronic systems for modern aerospace vehicles has resulted in wiring becoming a critical safety-of-flight system. Aerospace systems now routinely use fly-by-wire technology and avionics to control and manage many of critical vehicle sub-systems. According to a recent Air Force Research Lab (AFRL/MLSA) (??MLSA) study on Air Force mishaps, 43% of mishaps related to electrical systems were due to connectors and wiring (Ref. 1). The types of failures included hydraulic and fuel fires initiated by electrical arcing or degraded interconnections that caused malfunctions in flight control systems and in other critical systems. These failures included over 271 separate incidents over the last ten years. NASA has also recently dealt with wiring issues. During the 1999 July space shuttle flight of Columbia (OV-102) STS-93 an Alternating Current (AC) short circuit occurred five seconds after liftoff, causing loss of one string of redundancy for two engine controllers. Unlike other anomalies that occur during launch, this incident ultimately resulted in grounding the entire shuttle fleet and performing a complex and detailed investigation of the shuttle's wiring systems. The investigation of this short circuit initiated an intensive wire analysis and inspection of cables within the vehicle(s). Inspections on the space shuttle fleet revealed numerous wiring issues, which were corrected over several months and a heightened awareness through training in place.

Identifying Aging Wiring Issues

To address aging wiring, a working definition is needed. For the purposes of this discussion, aging wiring is defined as degraded performance due to accumulated damage from long-term exposure to chemical, thermal, electrical, and mechanical stresses. The operational environment, installation, and/or maintenance practices often induce these stresses. Wiring failures often appear as broken conductors and damaged insulation, which can disrupt electrical signals or lead to arcing. A study funded by AFRL/MLSA in 1995 suggests most wire damage occur within one or two feet of a connector [Ref. 3]. This location is where wiring will most likely be flexed or chafed during operational use or when undergoing maintenance. Examples where wire chafing led to arcing, a fire, and an aircraft mishap are shown in Figures 1 and 2 [Ref. 2]

A review of maintenance records on fighter aircraft shows that chafed or damaged insulation is the most common mode of wire failure [Ref. 3]. This is shown below in Table 1. Note that over 30% of the time no fault was found. This is consistent with the intermittent nature of wiring faults.

Table 1: Wire problem areas according to aircraft maintenance

Failure Description	**Percent of Problems (%)**
Chaffed/Damaged Insulation	44
Broken Wire	12
Open Conductor	3
Shorted Conductors	5
Missing wire	2.5
No Defect Found	24
No Determination	9.5

Note: This data collected during June 1993 through May 1994 on Air Force fighter aircraft (Ref. 3).

Most commercial and military aircraft produced over the last twenty years use a wire insulation construction based on either military specification MIL-W-81381 or MIL-W-22759. The insulation materials used are principally aromatic polyimide, polytetrafluoroethylene (PTFE), or cross-linked ethylene tetrafluoroethylene (XLETFE). Each wire construction has unique properties and will be susceptible to different stress levels and combination of stresses. These stresses can be categorized as electrical, mechanical, chemical, or thermal processes. Examples of failures related to these stresses are given in Figure 3. Once an insulation or conductor is damaged, degradation or loss of a sub-system may not occur until the system's electrical integrity is compromised. The appearance of an electrical failure will be dependent on the electrical sensitivity of the system and external environmental factors such as moisture, thermal excursions, vibration, or mechanical shock.

In addition to loss of an electrical system due to a wiring failure, identifying and resolving wiring faults can also cause extensive downtimes for aerospace vehicles. Most troubleshooting systems currently available assume failures occur in the avionics equipment, not the interconnections. Wiring failures also tend to be intermittent in nature and can take considerable time to isolate. Ultimately, there is a need to develop techniques and processes to manage the aging wiring and interconnection systems on legacy aerospace systems.

Space Shuttle Wiring

NASA's oldest orbiter, Columbia, was built during the 1970's and flew its first mission in 1981. Like commercial aircraft, NASA's shuttles adhere to strict operational and maintenance routines in order to continue flying, however, unlike commercial aircraft NASA's orbiters are developmental in nature and are unlike any other vehicle in the world. For example, each shuttle vehicle has over 200 miles of wiring, 103,000 cables, over 3000 electrical connectors, and thousands of wire splices and terminal boards. Each and every launch mission and landing result in new challenges that must be investigated and resolved before the next launch can take place. The space shuttle requires an aggressive maintenance program and as with modern aircraft, shuttle wiring is a critical system since multiple failures can affect vehicle operation. Even with an active wire management program failures can still occur due to the complexity of the interconnection system (Figure 4).

One recent failure in particular has placed additional emphasis on shuttle wiring. As discussed earlier, five seconds after the STS-93 launch of Columbia, a primary and back-up main engine controller on separate engines dropped off-line. The controllers were automatically dropped off line when a power fluctuation was detected. This left single engine controllers on two of the three engines (each main shuttle engine has redundant controllers). The mission continued uneventfully and after the mission, inspection revealed a single 14 gauge twisted three-wire polyimide insulated conductor wire had arced to a burred screw head located in the aft left-hand midbody bay #11 lower tray (Figure 5). A single three amp circuit breaker had tripped, with no electrical damage to adjacent wiring or arc propagation. The wire provided 115 VAC power to each of the controllers that were dropped off line. Inspection of the wires in the adjacent area revealed insulation and conductor damage at the short location (Figures 6 and 7). Additional inspections performed on Columbia's wire tray dividers revealed wire damage at other locations.

A team of malfunction analysis experts was assembled to assess the wiring damage that was detected during Columbia's inspections. The primary goal of the assessment team was to determine whether the damage represented a mechanical failure or if the damage was due to vibrations that occur regularly during launches. Several of Columbia's wire segments were removed and submitted for laboratory analysis. To illustrate the difficulties in understanding wiring failures, it is helpful to review the failure analysis on the arced wire from the above failure event. Arcing was established with evidence of material transfer and melting (Figure 6) on the failed wire. Gouges in the conductor were also noted (Figure 8). Surface analysis revealed oxides in the wire strand gouge sites that suggested the damage may have occurred several years earlier. The wiring in the midbody payload bay is normally covered and records did not indicate the cover had been removed since the last Orbiter Maintenance Down Period (OMDP). Secondary damage caused by the arcing destroyed most of the insulation and wire damage that was present before the arcing began at the primary failure site. Evidence surrounding the failure suggests the wire may have initially been damaged by an impact and then subsequent chafing/vibration during the launch sequence most likely led to the electrical failure aboard STS-93. [Ref 4]

The failure did not appear to be related to properties unique to polyimide insulation; any thin walled insulation would be susceptible to this type of failure. When an arc event occurs, polyimide can carbonize and propagate damage into adjacent wiring. Outer edges of the arced polyimide wire appeared to be carbonized, this would have created a low resistance path between the conductor and another metallic surface. During the arc event a three ampere circuit breaker "popped", suggesting there was a hard short. The presence of a hard short is also supported by evidence that the wire and screw head were welded together and separated after the arc had cooled. This was supported by the presence of ductile dimples, characteristic of overload, in the weld area. Polyimide failures that propagate or arc track tend to be resistive or "soft shorts". This type of fault would appear as an intermittent load. Insulation damage was noted under and near the screw head. Normal inspection procedures may have missed this type of damage since it was hidden underneath the wire harness bundle.

It is helpful to understand why an exposed conductor could exist without causing an electrical malfunction for an extended period of time or not be found during routine functional, isolation, continuity and Dielectric Withstand Voltage (DWV) testing. All these tests are performed while the vehicle is static. Insulation confidence testing using DWV at 1500 Vdc with no leakage current above 0.5 millamperes between individual wires and ground is very limited. This test will only detect flaws in insulation at distances of 0.02 inch. (Figure X) The screw head associated with the arced wire exhibited a raised burr, which may have been formed during initial installation or when the screw was removed and then replaced (Figure 5). Most of the screw heads appeared to be coated with an insulating material (Koropon). The coating apparently protected the exposed wire in previous launches. At 115 volts, the exposed wire would have to touch a bare part of the screw head to arc since the breakdown in air is above this level. Vibration during the launch sequence was apparently sufficient to result in movement and contact between the exposed conductor and an exposed metal area on the screw head.

The primary wiring used in the shuttle is a stranded nickel-plated copper conductor with 6 mil thick polyimide/FEP (Spell out FEP)? insulation (similar to MIL-W-81381), a wire construction used extensively in aviation since the early 1970's. There are known maintenance and design issues to this type of insulation related to arc track propagation (carbonization of polyimide and rapid collateral damage to adjacent wiring), mechanical degradation when exposed to certain environments (ultra-violet radiation, atomic oxygen, high pH materials - above 10, and sustained long term exposure at elevated temperatures to moisture while under mechanical stress), and nick propagation from insulation cracking when nicked and placed under tensile stresses. Polyimide wire insulation performs best in straight runs with minimal bending and flexing. Examination of the shuttle midbody would seem to be the ideal application for this type of wiring (Figure 4).

Shuttle Wiring

Aging with respect to wiring can be divided into general degradation (chemical in nature) or specific, or isolated degradation from a single event or cumulative effects from several stress factors. A major difference between wiring on the shuttle and on aircraft is the high touch labor level and intensity of maintenance actions on and near wiring. Using the definition of aging wiring given earlier in this paper, it is apparent a certain level of aging has occurred primarily as a result of these maintenance actions and to some extent, exposure to mechanical stresses.

After determining that pre-existent wire damage was present, an aggressive inspection program was conducted on the shuttle fleet. A team of engineers, quality inspectors, and technicians was assembled to establish inspection criteria and to develop corrective actions that would prevent reoccurrence of wiring damage. This team recommended that the inspections focus primarily on identifying damaged insulation, exposed conductors and/or wire harness crossovers; however, any and all types of damage detected during inspection was to be noted and logged into reports.

A thorough analysis of work stands around the midbody wire trays and other areas was performed. Wire inspectors used flashlights, mirrors, and 10X magnification to examine midbody wiring and other normally accessible areas (Figure 9). This typically requires damage to be visible from the top (outer circumference) of the wire bundle or in an area known to be susceptible to damage (Figure 10). Two independent inspector teams were required to utilize mirrors to inspect all sides of the wire harness throughout the entire inspection. Minimal movement and handling of the wiring was emphasized to reduce additional collateral damage. The overall goal of the wiring review was to inspect and examine the surface of 100% of the wire harnesses on each vehicle. The wiring was reviewed and four criteria were applied to wiring that required immediate inspection by the Kennedy Space Center (KSC) team. The following criteria were used: (1) history of wire damage, (2) high electrical modification, (3) high traffic of personnel during processing, and (4) presence of critical circuit redundancies. Feedback from these inspections identified any areas of significant damage that would require closer scrutiny and repair. A graphical representation of the inspection and repair process is given in Figure 11.[Ref 5]

Meanwhile, wiring areas that fell outside of the “four critical areas” were to be inspected at NASA’s Palmdale, California facility during each of the vehicle’s scheduled major modification periods. Again the most intense inspection was conducted in the shuttle midbody bays and aft compartments at KSC. It is expected that at least 98% of entire wire harnesses will have been inspected by the completion of the OMDP for each vehicle. A summary of the areas inspected in the midbody and aft areas is shown graphically in figures 12 and 13. An examination of wiring data, prior to the most recent ongoing inspection process shows the midbody area to be the fourth highest area with wire damage (Figures 4 and 9). A summary of the wiring anomalies found in three of the shuttle vehicles is given below in Table 2.

TABLE 2: Summary of Orbiter Wire Damage Inspection at KSC

Area Examined	**Total Anomalies**	**Insulation Damage**	**Exposed Conductor**	**Other**
Vehicle OV-103				
Forward	34	25	4	6
Midbody	160	84	26	52
Aft	164	87	28	52
Vehicle OV-105				
Forward	21	16	1	4
Midbody	169	93	43	34
Aft	57	24	2	31
Vehicle OV-104				
Forward	11	0	0	0
Midbody	156	137	46	17
Aft	60	0	0	0

Other” category includes discrepancies on items other than wiring such as safety wire, clamps, and other miscellaneous conditions. Numbers may not total across because each anomaly can document more than one discrepant condition. Columbia’s (OV102) inspection in-work at Palmdale.

Red tags were used to identify wire damage, potential chafe points, and potential wire harness cross-overs. If significant wire damage was found, the wire harness spot-ties were removed and the wire harness was separated, for a closer more detailed inspection. Wire harness cross-overs were a concern to protect critical circuit redundancies from touching each other. Established standard wire repair practices were used to repair any damage that was found. Examples of the type of wire damage found are given in Figures 14 and 15. Note that in Figure 15 the conductor is severed.

As part of corrective actions and improved wire protection within areas of potential high traffic, convoluted Teflon tubing was installed over wire harnesses to provide additional protection. Eventually over 150 pounds of black tubing were installed within each orbiter. Extruded rubber grommets, Teflon tape wrap, and silicone tape wrap were also used where applicable (Figure 16). In addition, wiring was rerouted to reduce damage potential. Numerous ground processing enhancements were also initiated such as providing temporary protective covers for midbody wire trays, enhancing access platforms, increasing training and awareness on wiring, providing a more rigorous wiring inspection certification process and enhancing inspection criteria.

Conclusions

In summary, managing the wiring and overall interconnection system of legacy aerospace vehicles can be accomplished with a program that monitors wiring failures with a balanced inspection effort. As occurred with STS-93's unique and intensive wiring review effort, it is recommended that technicians, quality controllers, operations engineers and design engineers all participate in wire monitoring and inspection programs. The inspection team that NASA assembled to investigate the STS-93 failure continues to review wiring anomalies and continues to update inspection criteria. This "team" effort helps ensure that all aspects of wire monitoring and inspection are addressed by experts within their field, whether it be "hands on" or theoretical / research-related. Additionally, it is a great benefit to have a pre-assembled team to turn to resolve issues that arise during daily shuttle processing or launch activities.

The wiring review that resulted from the short circuiting event during STS-93's launch was the first of its kind to be performed on the shuttle fleet. Numerous lessons were learned on how to optimize inspection efforts. A few examples are listed as follows:

- Clearly defining the inspection criteria and methods for wire inspection proved critical to the success
- Concurrent engineering with design – operations – shop – quality inspectors that on a "daily" basis resolve issues and concerns with wiring as a separate system.
- Establish optimal conditions for technicians and inspectors such as proper lighting and ample workstands to improve access.
- Require all personnel that work on the vehicle to be aware of the potential hazards with working around wire harnesses.
- Minimize wire handling by using mirrors and other inspection tools.
- Ensure that temporary covers are used to protect exposed wire harnesses during modifications or maintenance.
- Maintain good historical records of damage and it's precise location for comprehensive corrective action reviews.
- Train and certify quality inspectors regarding updated techniques, specifications, and inspection criteria.
- Establish good lines of communication between technicians, quality inspectors, and engineers.

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Since 1990, Mr. Slenski has been the lead engineer in the electronic materials evaluation group that is responsible for planning, organizing, and conducting Air Force electronic failure analysis and materials evaluations on fielded and new systems. He has personally conducted several hundred failure investigations, with many supporting aircraft mishap boards.

Mr. Slenski’s current emphasis area is on characterizing and assessing aging electronic systems, specifically dealing with wiring, connectors, and other types of interconnection technologies

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