

NOVEL TECHNOLOGIES FOR IMPROVING WIRE SYSTEM INTEGRITY

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Abstract

The Federal Aviation Administration (FAA) and the U.S. Air Force recognizes the importance in shifting from a reactive to proactive mode in improving aircraft wire system integrity and in transforming the maintenance approach in the inspection and repair of aging aerospace systems. The wire “system” includes the wire conductor, insulation, splices, connectors, relays, circuit protection, sensors, power distribution panels, motors, actuators, and generators. For the last five years, a consortium of government agencies, academia, and industry have conducted a combination of basic and applied research to achieve higher levels of wire system integrity. Research areas have included advanced diagnostics, advanced circuit protection technologies, and advanced wire insulation and conductor materials. This paper will report on the most promising of these efforts. We will also propose novel approaches for achieving revolutionary improvements in wire system integrity levels with the use of carbon nano-tube materials as conductors, self-healing wire insulations, and a self-reconfiguring wire distribution system.

Introduction

The Federal Aviation Administration (FAA) and U.S. Air Force recognizes the importance in shifting from a reactive to proactive mode in improving aircraft wire system integrity and in transforming the maintenance approach in the inspection and repair of aging aerospace systems. Electrical wire distribution in aircraft has become a critical and vital system, as aircraft performance and actual flight stability become dependent upon avionics (Ref 1). 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 Laboratory study on Air Force mishaps, 43% of mishaps related to electrical systems were due to connectors and wiring (Ref 2). 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 a ten year period. Detailed examination of mishap reports revealed that most electrical failures resulted in the crew aborting a mission or declaring an emergency and landing the aircraft. In very isolated cases (4% of mishaps), the crew lost control while responding to an electrical failure or the electrical failure caused catastrophic damage to the aircraft.

In a recent search of the National Transportation and Safety Board (NTSB) incident and FAA Service Difficulty Reports (SDR) databases, 233 events were recorded from the years 1999 to 2004. This search was based on wire arcing and smoke incidents that resulted in an aircraft turn back, diversion or an emergency landing. While the degree of damage varied from loss of aircraft to loss, of several wires, the safety and economic impacts are acutely felt throughout the aviation industry.

Wiring on an aircraft is no longer just a commodity but a complex system. It not only distributes electrical power, but also provides control and information links between multiple systems and sub-systems. Components that make-up the wiring system include power and control conductors, signal and instrumentation conductors, fiber optic cables, connectors, circuit breakers, relays, power distribution and control panels, and generators. Failure of any of these components can disable an aircraft or compromise an aircrew's ability to control the aircraft.

Discussion

New aircraft continue to increase in wire system complexity and volume as traditionally mechanical systems such as flight controls and flight surface control actuators are converted to all electric systems. A modern transport aircraft contains over 200 miles of wire most of which is typically 20 gauge or smaller single conductor wire. An example of wire systems used on commercial aircraft is shown in Figure 1.



Figure 1. Typical wiring from the back of the electronics rack of an in-service transport aircraft.

Maintaining wire system integrity over extended operational time continues to be a challenge. While aging and degradation of materials is a concern, the most serious failures typically occur when proper installation protocols are not followed. This is best illustrated by describing an in-flight electrical/hydraulic fire that caused extensive damage to an aircraft wing and could have led to loss of the aircraft.

Fortunately the aircrew was able to make a successful landing and damage was confined to the internal wing components and structure (Figure 2).



Figure 2. In-flight electrical/hydraulic fire in an aircraft wing area. The fire caused extensive wiring damage, a fire extinguisher system to rupture, and damage to the wing structure.

A wire bundle containing 115 VAC power and various aircraft functions chafed to a high pressure titanium hydraulic line in a location that is rarely accessed by maintenance personnel (Figure 3).

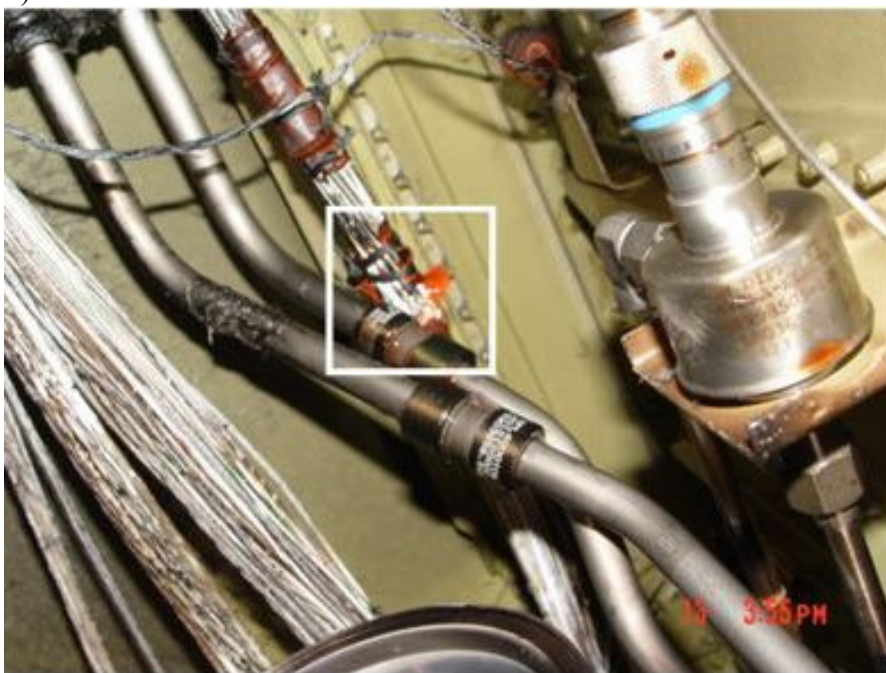


Figure 3. Failure initiation site is shown in the white box. Note that the wire bundle is lying on the hydraulic line. Red anti-chafe tape was used to protect the wiring.

The wire bundle was laying on the hydraulic line and over time, the hydraulic line couple chafed through the wire insulation. Exposed conductors arced to the titanium hydraulic line. Arcing was sufficient to breach the titanium tube, releasing high pressure hydraulic fluid that was

subsequently ignited by the continued arcing. Most damage to the remaining wiring and loss of multiple systems was due to external heating by a flame front fueled by the spraying hydraulic fluid. Temperatures in excess of 600°C were reached, as evidenced by the degradation of the Kapton[®] wire insulation. Arc tracking was minimized by the use of MIL-W-22759/87 wire insulation, a composite construction of Kapton[®] and Teflon[®] layers. The Teflon[®] layer interrupted the conductive path created by charred Kapton[®] film. The hydraulic fire also caused a fire suppression line to rupture, damaging

part of the wing structure. Only three 115 VAC three phase 12 gage wires actually arced to the hydraulic line. The 15 ampere thermal circuit breakers protecting the wires tripped at some point during the failure. A close-up of the wires that arced to the hydraulic line is shown in Figure 4.

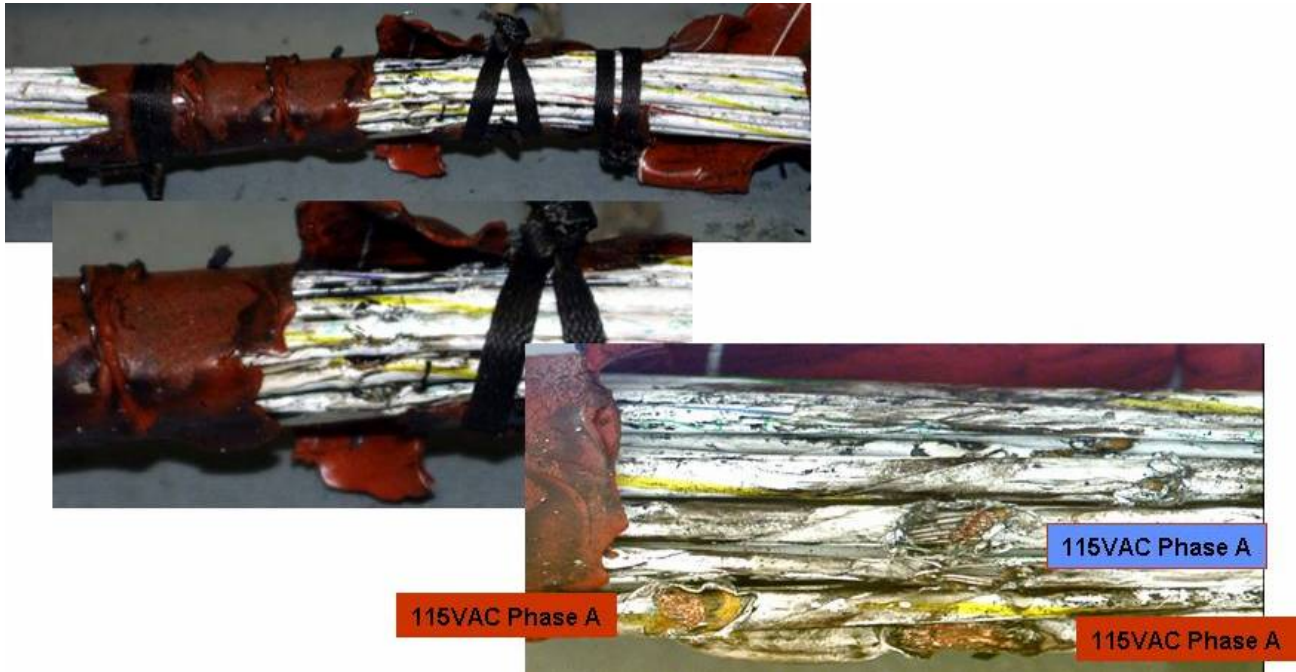


Figure 4. Close-up of wire bundle and wires that arced to the hydraulic line. The insulation was M22759/87, a composite wire construction that has excellent arc track resistance properties.

Note the exposed conductors that resulted from chafing to the hydraulic line couple and melted copper conductors that arced to the hydraulic line. An example of a chafed wire that did not arc and a wire that was rubbed several times across the hydraulic line couple is shown in Figure 5.

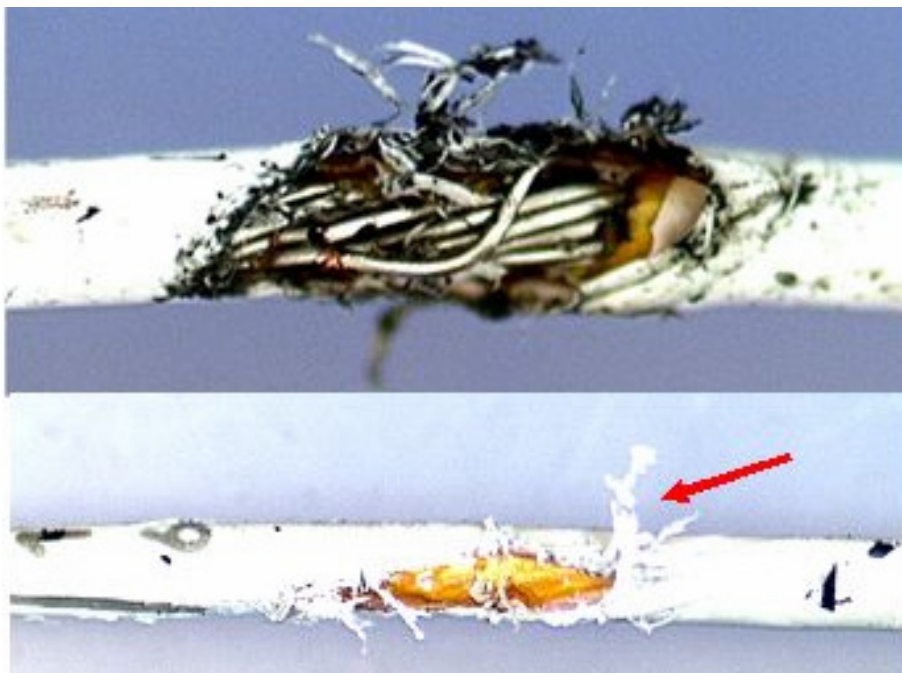


Figure 5. Top photo shows wire from incident which exhibits chafing and exposed conductor damage. An undamaged wire from the incident bundle was manually chafed against the coupling of the 'good' hydraulic line. The bottom photo shows abrasion damage created by lab personnel for comparison.

The arc initiation site on the hydraulic line is shown in Figure 6. A close-up of the damage site (Figure 6) shows the pinhole location in the hydraulic line and chafe areas on the composite couple. Note the broken composite fibers near the tube-couple interface. Scratching through a thin layer on the composite couple material revealed it was conductive.

The hydraulic line pinhole location exhibited molten titanium on the surface with rich areas of copper from the arced wires (see Figures 6 and 7).

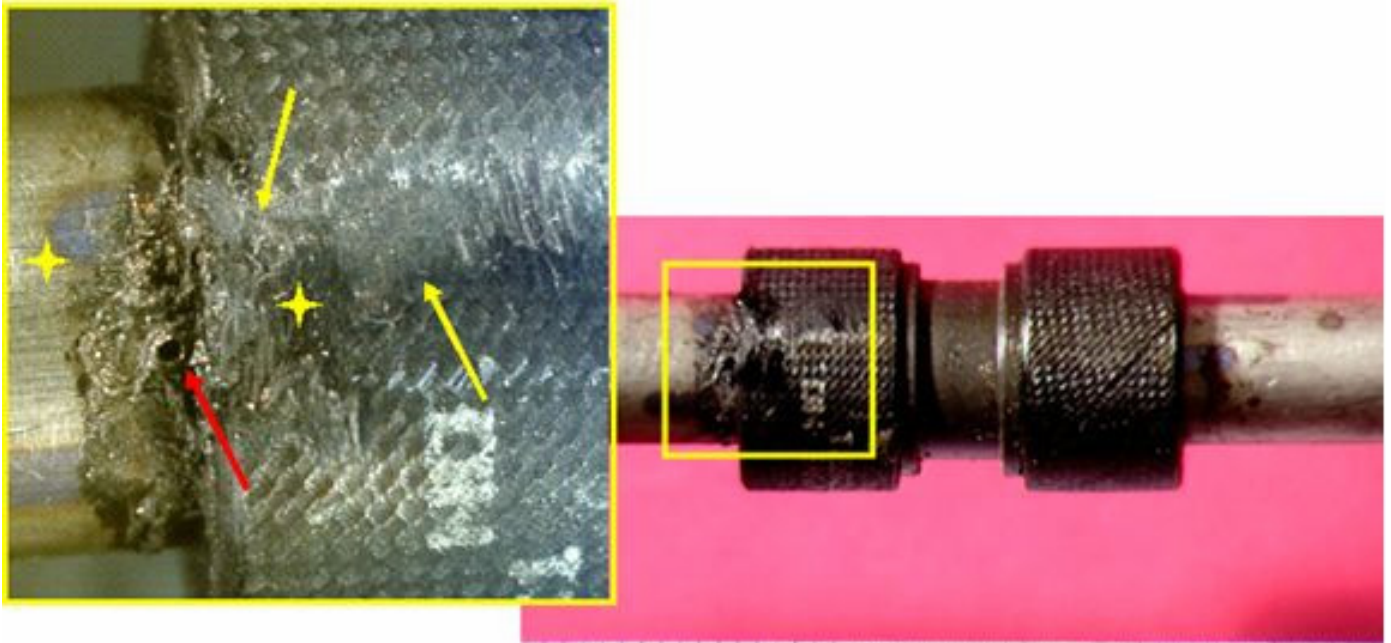


Figure 6. Arc initiation site on hydraulic line is shown in the yellow box. Red arrow in close-up photo highlights pinhole location; yellow arrows highlight chafing of coupling composite. Note the broken composite fibers near the tube-couple interface. A conductive path was measured between the yellow stars.

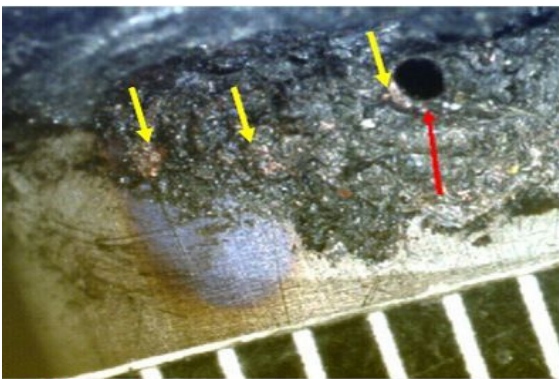
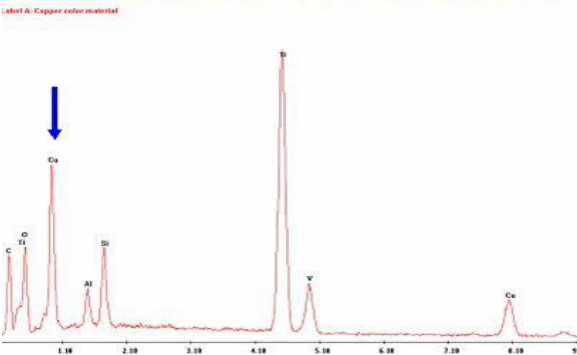


Figure 7. High magnification of hydraulic line pinhole location with surrounding molten material (red arrow). Note copper-colored areas (yellow arrows) that were verified as being copper rich using a scanning electron microscope with energy dispersive analysis (lower image). These characteristics confirm arcing occurred between several wires (see Figure 4) and the hydraulic line.



Inspection of the incident hydraulic line on operational aircraft revealed there was inadequate separation between the wiring and hydraulic line on several vehicles (Figure 8).

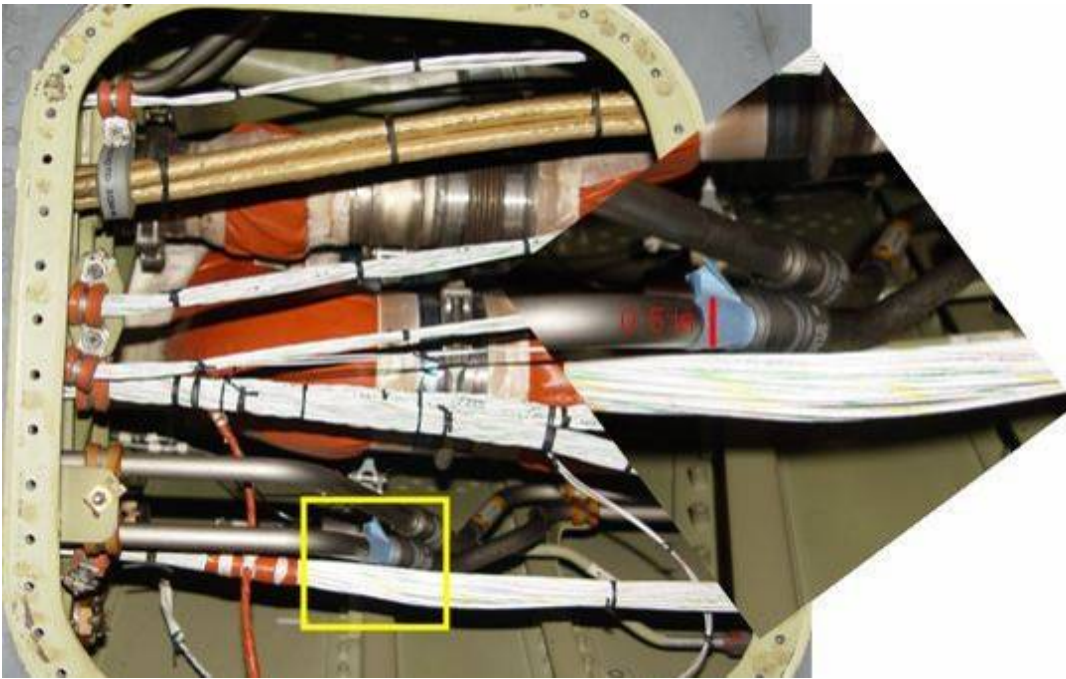


Figure 8. Inspection of the incident area on another aircraft shows there is inadequate separation between the incident wire bundle and hydraulic line (yellow box).

A number of lessons learned can be gleaned from this overall incident. First, this again demonstrates that current visual inspection practices are insufficient for maintaining overall wire system integrity. The best prevention is following proper installation guidelines for separation of wiring and hydraulic lines as outlined in SAE AS 50881B, which addresses installation of wiring systems in aerospace vehicles, (section 3.11.11) and SAE AS 5440, Aircraft, Design and Installation Requirements For Hydraulic Systems, (Section 3.11.28.7). These documents would have required the bundle to be above the hydraulic line and have a positive separation of at least 0.5 inches. Both these requirements are violated in the example shown in Figure 8. Identifying the causes of wire system failures and using the information to mitigate future failures can be an effective method to improve wire system integrity. Another possible mitigation approach would be the use of arc fault circuit breakers. This technology will be discussed in a later section.

From an inspection and design standpoint the FAA Electrical Wiring Interconnection System (EWIS) addresses wire separation, yet wiring still is not being fully considered as part of an overall reliability analysis. Wires are treated as a component with a fixed failure rate that does not take into consideration environmental, aging and maintenance factors. With increased awareness of how wires age and fail, new risk analysis tools are being developed. The FAA is developing a risk analysis software tool in a contract with Lectromech Corporation (Ref 8). The tool developed under the contract uses the latest wire insulation aging models, environmental and maintenance effects on failure prediction. The risk analysis tool (EWIS RAT™) developed during this study facilitates just this function, permitting a more realistic evaluation of the in-service performance and reliability of a particular wiring layout. Based on historical data as well as expert judgment, the tool can be used during aircraft design to assure adequate separation and segregation of aircraft wiring, thereby minimizing the potential for single-point failures. The tool can also be applied for assessing the safety of modifications to the original layout, as might be entertained in the Supplemental Type Certificate (STC) process. A more long term and comprehensive approach would be to address wire integrity

through the use of diagnostics, advanced circuit protection technologies, development more robust and self healing wire insulations, and development of fault tolerate power and signal distribution systems.

The investigation of the TWA Flight 800 fuel tank explosion, which caused the loss of a 747 aircraft and 230 passengers and crew, brought attention to damaged and degraded wiring. The National Transportation Safety Board (NTSB) identified wire damage as part of the probable cause (final report) (Ref 3). Following this mishap, the Federal Aviation Administration (FAA) initiated a study on the condition of aged aircraft wiring under the guidance of the Air Transport Systems Rulemaking Advisory Committee (ATSRAC), Ref 4. The intrusive inspection phase of the ATSRAC study evaluated the condition of wiring on five different recently retired commercial aircraft models (A100, L1011, B747, DC-9, DC 10), each with over 20 years of service. A review of the data in the Intrusive Inspection Final Report clearly indicated visual inspection is not able to identify many types of wire system damage and degradation. Some examples of what may be visually undetectable are: damage or degradation hidden inside wire bundles; high resistance connections (connectors, splices, terminal blocks, nicked conductors/broken strands, etc.), damage and degradation hidden under accumulated lint and other contaminants commonly observed on all six aircraft studied; damage inside protective wrap materials, conduit, or in inaccessible zones; small cracks and other insulation breaches. As an aircraft ages, these types of defects tend to increase as a result of long-term exposure to stresses and through exposure to the operational and maintenance environment. Aged or degraded wiring can be defined as wire exhibiting degraded performance due to accumulated damage from long-term exposure to chemical, thermal, electrical, and mechanical stresses. Aircraft wiring maintenance occurs in one of three levels: phase, field, and depot. Depot activities are focused towards maintenance modifications. Phase-level activities are focused towards scheduled maintenance inspections. Field-level maintenance activities are more reactive in nature with the objective to keep the aircraft mission capable. Typically there are scheduled wiring inspections during maintenance actions. Field-level maintenance is the area with the greatest need for advanced diagnostic and inspection systems.

A portable wiring diagnostic system would be most useful for locating a wiring fault and to a lesser extent evaluation of wire system integrity. Visual inspection or General Visual Inspection (GVI) is the current method for ensuring wire integrity for military and commercial aircraft wire systems and is also used to locate wire damage in known problem areas. As already discussed above, visual inspection is not an effective technique for finding many types of wire damage. Wiring fault detection is typically accomplished using a combination of visual inspection and a multimeter. Highly skilled technicians can obtain good results, although it can be a time consuming process. The multimeter is preferred because of its ease of use and quick interpretation of results. In the past several years the FAA and DoD have sponsored research programs that have investigated over thirty technologies for Non Destructive Inspection (NDI) of wire systems. Technologies that have shown promise continue to be developed through coordination with multiple government agencies. Two hand held diagnostic technologies have shown significant promise and are similar in size and ease of use to the multimeter. They are based on Standing Wave Reflectometry (SWR) and Time Domain Reflectometry (TDR). Laboratory testing has shown these two technologies can identify and locate opens and shorts in twisted pair wiring and in some cases, with less accuracy, single wire conductors (Ref. 5 and 6). Both TDR and SWR technologies rely on reflected signals that detect an impedance change located between the meter's signal source and some location on the wire under test. A typical TDR measurement employs a step generator and an oscilloscope in a system. A voltage step is injected into the wire under test, and the incident and reflected voltage waves are monitored by the oscilloscope at a particular point on the wire. TDR reveals at a glance the distributed characteristic impedance of the wire, and it shows both the position and the nature (i.e., resistive, capacitive, or inductive) of each discontinuity, or defect, within the wire. While this technique has been very successful on controlled

impedance wires such as coax and twisted pair it has limited use on single conductors with uncontrolled impedance and variable ground plane proximities.

The objectives of the Air Force evaluation program is to develop a standardized diagnostic test bed and identify equipment capable of locating electrical shorts or opens in a wire bundle within 24 inches of the fault. Additional requirements are an equipment setup time of 30 minutes or less and an overall equipment weight of less than 50 pounds.

In Air Force evaluations we have defined an electrical short as less than 10 ohms @ ≥ 100 milliamps and an open as greater than 1×10^6 ohms @ 100 volts DC. A test bed developed at the Air Force Reach Laboratory is shown in Figure 8. This test bed allows connector or pin to pin testing of various wire configurations with removable test patches using wire types, interconnections, and electrical faults commonly found on a military fighter aircraft (Figures 9 and 10).

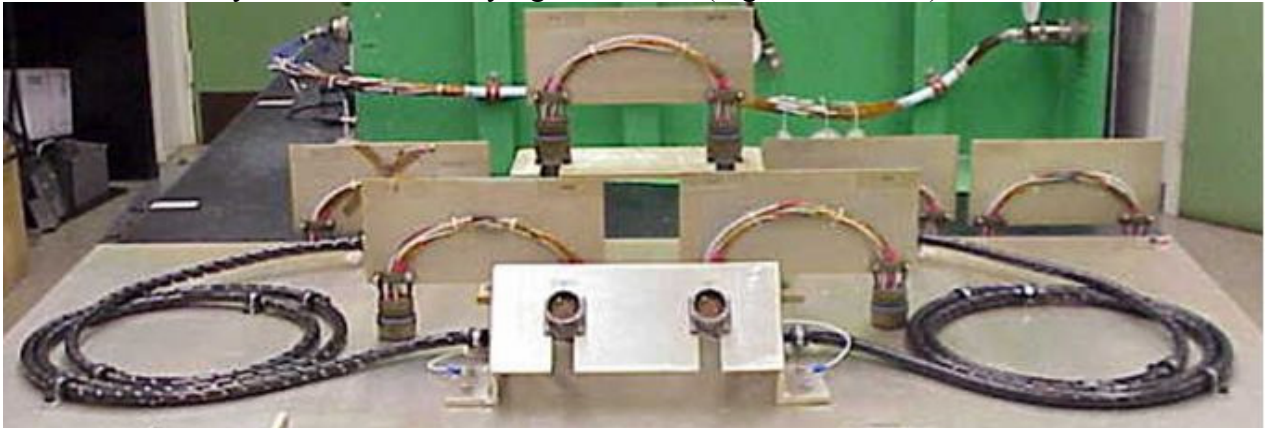


Figure 9. Test bed for evaluating wiring diagnostic systems. The system was fabricated with parts used on a military fighter aircraft and has removable test patches in the center that introduce wiring faults.

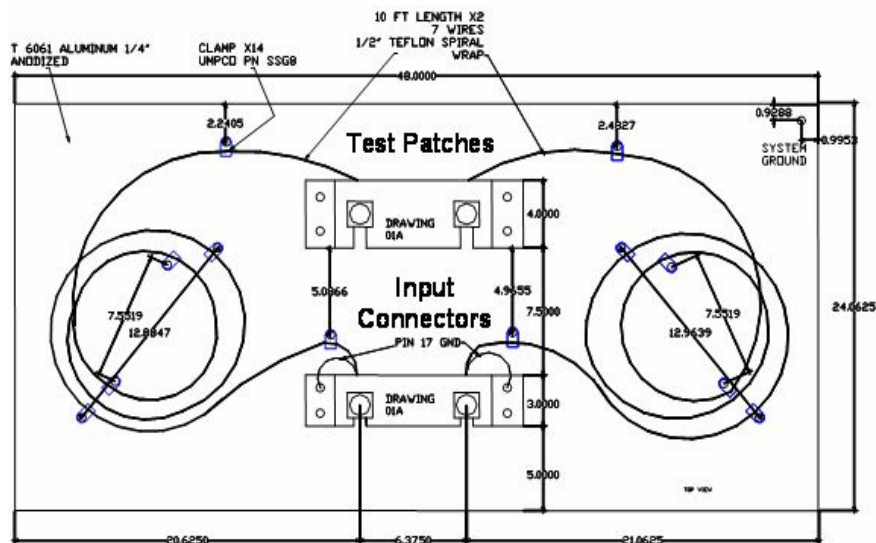


Figure 10. Engineering drawing of the test bed showing construction details and wire bundle lengths. The distance between input connectors is 21 feet or 252 inches. Distance from the connector to test patch faults is approximately 10.5 feet or 126 inches.

	WIRE TYPE #1	WIRE TYPE #2	WIRE TYPE #3	WIRE TYPE #4	WIRE TYPE #5	WIRE TYPE #6
TEST PATCH 1	NO DAMAGE	NO DAMAGE	NO DAMAGE	NO DAMAGE	NO DAMAGE	NO DAMAGE
TEST PATCH 2	One Conductor to Shield Short between pin 2&4	Short between pins 5&7 and to Ground	Conductor Short (pin 8) to Ground Plane	2 Wires Shorted Together (pins 9&10)	Short between 14&26 w/ lead to gnd.	Conductor Short between pin 23&25
TEST PATCH 3	Electrical Open in center of TP/ 0.125in of separation	Electrical Open in center of TP/ 0.125in of separation	Electrical Open in center of TP/ 0.125in of separation	Electrical Open in center of TP/ 0.125in of separation	Electrical Open in center of TP/ 0.125in of separation	Electrical Open in center of TP/ 0.125in of separation
TEST PATCH 4	INSULATION PENETRATION	Pin 6 shorted to 7 w/ 5 MOhm	1K OHM/ COND TO GROUND	INSULATION STRIPPED .25 IN. X 360 Deg	25% DEPRESSION OF WIRE 360 Deg/ .5in Dist	DEFORM INSULATION 50%/ VISIBLE FLATNESS 0.5in Dist
TEST PATCH 5	270 DEGREE SHIELD REMOVED/ .5 IN./ HEAT SHRINK	Diode with 1KOhm resistor in parallel w/ pin 5	50% RES. INCREASE (110m Ohm of Resistance)	10% RES. INCREASE (30m Ohm of Resistance)	NO DAMAGE	CHAFE .5 IN LENGTH 1/2 THICKNESS
TEST PATCH 6	Incorrect Splice (Pin 1) needle nose crimp on 1 side. Pins 2&3 correct (Blue) splice	NO DAMAGE	(Yellow) Splice Incorrect (pin 8) Crimp	Correct Splice Size (Blue) Pin 9, Correct Splice (Red) Pin 10	NO DAMAGE	Correct Splice (Red) Pin 23

Test patches contain known good wiring and wiring faults such as opens, shorts, damaged insulation and conductors, high resistance connections, and low resistance paths between insulated wires (Figure 11).

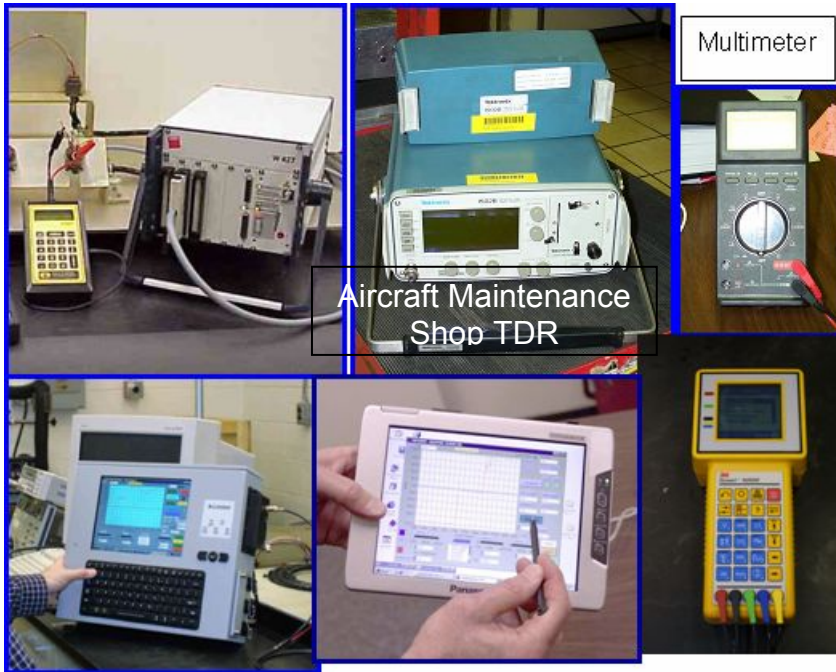
Wire Type 1: Twisted Triplet, Shielded, MIL-C-27500, M81381/11-22-5, Wire Type 2: Twisted Pair, Shielded, Wire, MIL-C-27500, MIL-W-22759/11-20, Wire Type 3: Single Wire, 22759/91-20, Wire Type 4: Twisted Pair, unshielded MIL-C-27500, M81381/11-22-5, Wire Type 5: Cable, Radio Frequency, C-17D Flexible Triaxial, 95 Ohms, Wire Type 6: Single Wire, M22759/34-22-9, Wire Type 7: Single Wire, M81381/7-20-2

Figure 11. Wire system wire types and faults selected for evaluation are given above.

Maximum location error results for nine manufacturers of hand held and bench top wire diagnostic equipment designed for on aircraft troubleshooting is given in Figure 12 (Ref 6). In many cases location accuracy varied over several readings so the worst case value is only shown in the table. As expected, the error level was highest for the single conductor wire. All equipment evaluated required less than 30 minutes to make a measurement and weighted considerably less than 50 pounds.

Equipment Evaluated	Stage 2A Performance - (Long Bed)					
	Test Patch 2 - Shorts			Test Patch 3 - Opens		
	Wire Type 2: Twisted Pair Shielded	Wire Types 3,6,7: Single Conductor	Wire Type 4: Twisted Pair Unshielded	Wire Type 2: Twisted Pair Shielded	Wire Types 3,6,7: Single Conductor	Wire Type 4: Twisted Pair Unshielded
fault ID % max. error						
Handheld Units						
A	100% within 6"	100% within 18"	100% within 4"	100% within 54"	100% within 3"	100% within 4"
B	100% within 6"	100% within 18"	100% within 6"	100% within 30"	100% within 30"	100% within 6"
C	100% within 12.9"	100% within 1.4"	100% within 42"	100% within 19"	100% within 45"	100% within 8.6"
D	100% within 2"	100% within 22"	100% within 2"	100% within 3"	100% within 9"	100% within 1"
E	100% within 2.4"	75% within 169.3"	100% within 14.5"	100% within 12.1"	100% within 36.8"	100% within 10.1"
F	100% within 3.6"	100% within 126"	100% within 1.9"	100% within 10.3"	100% within 5.5"	100% within 5.1"
Benchtop Units						
G	100% within 7.1"	100% within 11.2"	100% within 29.4"	100% within 4.2"	100% within 6.98"	100% within 2.5"
H	100% within 3"	100% within 18"	100% within 3"	100% within 5"	100% within 10"	100% within 3"
I	100% within 3.8"	100% within 13.8"	100% within 14"	100% within 6.1"	100% within 12"	100% within 2.3"
Manual TDR	100% within 4"	100% within 8"	100% within 2"	100% within 3"	100% within 1"	100% within 1"

Figure 12. Maximum location measurement error results for nine manufacturers of wire diagnostic equipment and a manual TDR.



Examples of the evaluated equipment are given in Figure 13. *Figure 13. Wire diagnostic equipment evaluated. Aircraft maintenance shops currently use a multimeter and a manual TDR (upper center) to locate wiring faults.*

Distances to fault calculations were based on either velocity of propagation or a resistance or capacitive ratio. Velocity of propagation (Vop) is the ratio of the velocity of a wave in a transmission line to the speed of light in vacuum; the number is 1 or less. A reasonable Vop value for a wire is 0.67, also known as the Kuzniar number. Each unit was first calibrated on a known

length of wire using the test bed (approximately 252 inches). After calibration, a test patch with a short or open was placed in the test bed. Faults were approximately 126 inches from the input connector. Analysis of the test results show most of the evaluated equipment could correctly identify an electrical short or open and give an approximate distance to the fault. As a reference, distances to fault readings were made with a TDR from an aircraft avionics maintenance shop (see Figures 12 and 13). This is the authorized equipment for locating an electrical fault in an aircraft wire system. Only a limited number of maintenance personnel have been trained to use this equipment. Equipment under this evaluation is automated and requires far less training than the manual TDR system. Most diagnostic systems were capable of consistently measuring a short or open in an unshielded twisted pair wire within 12 inches. Faults that were associated with an electrical ground (shielded twisted pair in Figure 12) did produce larger errors than 12 inches. Fault distance measurements to single wires shorted or open (single wire in Figure 12) varied considerably between evaluated equipment. This was expected for equipment that uses waveform reflections (vendors A-F) since the measurements are being made on wires with uncontrolled impedance. Of particular note was equipment that could display a waveform. An experienced user could determine if a reading had a high confidence level based on observing where the fault was placed on the displayed waveform (see Figures 14 and 15).

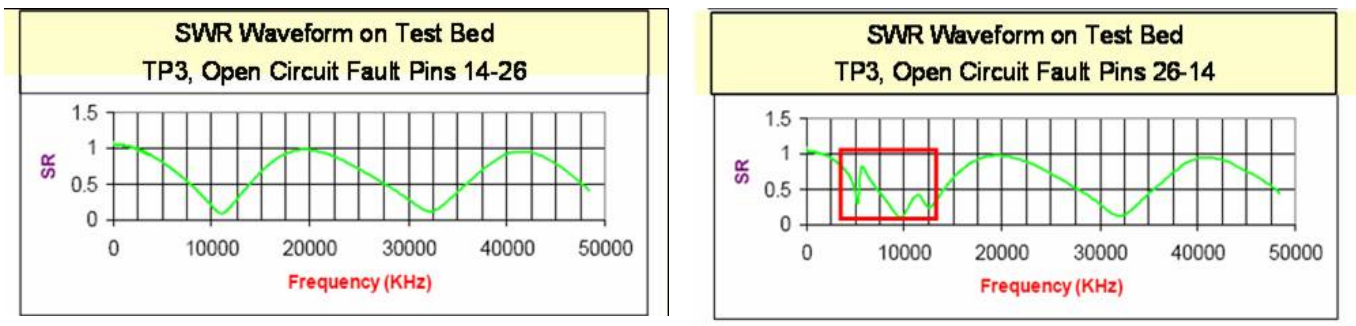


Figure 14. Display on the left shows a SWR waveform of a Triax shielded wire. The system detected an open fault within 3 inches for the actual fault location. Display on the right is a SWR waveform of the same triax shielded wire with the input pins reversed. In this case the system detected an open fault within 245 inches of

the actual fault. The error was due to waveform distortion in bottom waveform (red box), which is a strong indication that the measurement is suspect.

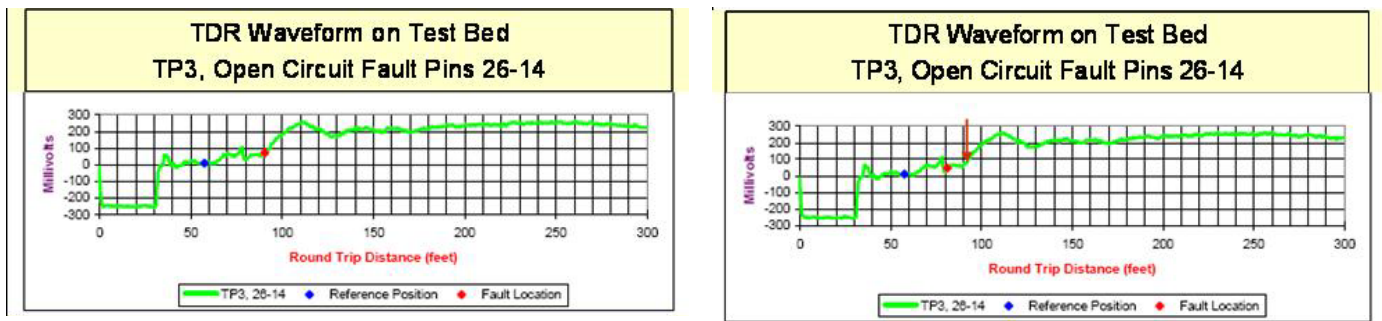


Figure 15. Display on the left shows a TDR waveform of a Triax shielded wire. The system detected an open fault within 14 inches of the actual fault location. Display on the right is a TDR waveform of the same Triax shielded wire. In this case the system detected an open fault within 44 inches of the actual fault. The error is due to a false trigger on the electrical open location. The open should have been triggered at the arrow location. This visually shows there will be an error in the measurement location.

An important feature of equipment is the ability to zero out or electrically remove the influence of test leads when making a measurement. Another limitation noted on SWR and TDR based equipment, is the difficulty in locating a fault less than 3 feet from the input source. This issue is being addressed by several equipment vendors, and recent testing has shown significant improvement in this area.

Recently, a new test bed has been built which will more accurately simulate wiring installed on an aircraft. Most of the equipment being evaluated are prototype systems. Several are now commercially available and being used to successfully locate wiring faults on operational aircraft. A number of alternative approaches for detecting wiring faults have been evaluated and show promise for detecting subtle electrical faults, such as insulation damage or degraded connections. These systems have used acoustic properties, voltage breakdown characteristics, or capacitive and resistive properties of wire systems.

One of the more successful technologies sponsored by the FAA is Arc Safe[®] by Astronics Corporation. This tester combines two technologies developed by the FAA NDI program Pulse Arrested Spark Discharge (PASD) develop by Sandia National Labs and the Micro Energy Tool developed by Astronics. This technology uses a high voltage, yet low energy source to test wire insulation integrity. If the insulation breaks down, a small energy controlled arc is created, and the reflection is analyzed to determine the distance to the fault.

An output screen from a prototype system is shown in Figure 16. Two single wires were abraded next to each other to expose conductors 40 ft. from the input source.

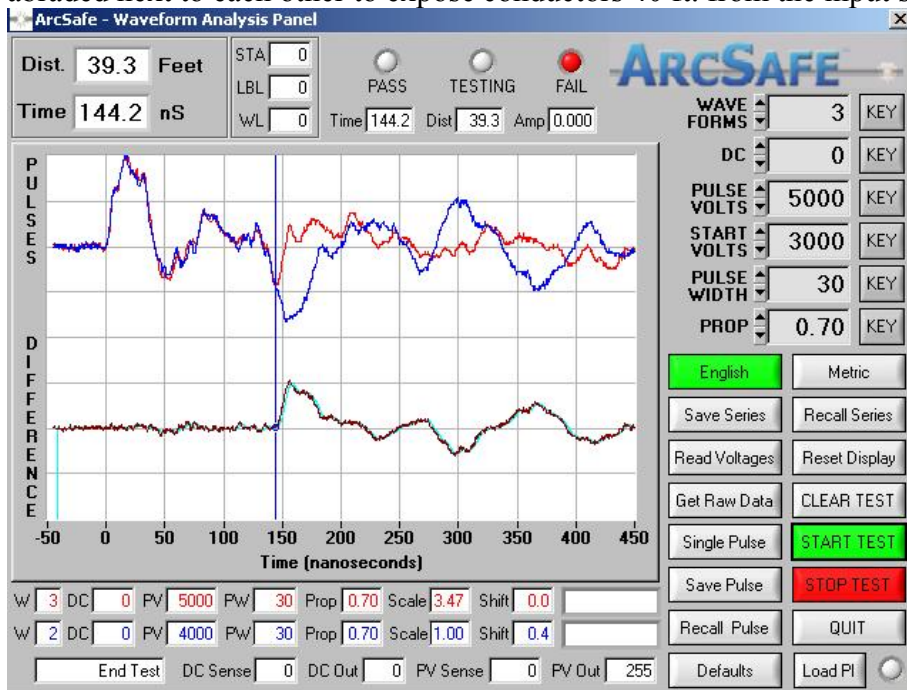


Figure 16. Screen output of system that imposes a high voltage, yet low energy pulse of wires to create a spark gap. In this case of fault was detected as 39.3 feet from the source. The actual fault was 40 feet from the input source.

Circuit Protection Technologies. In the past, thermal circuit breakers and differential current sensors were used to protect the aircraft wiring system. Recently arc and ground fault technologies have been successfully integrated into

aircraft circuit protection in the form of advanced circuit breakers. In addition to circuit breakers, which primarily protect the wiring associated with the downstream loads, many other power control devices upstream in the power distribution also provide safe distribution of electrical energy. Contactors, remote controlled circuit breakers, and power control relays, are a sampling of devices that perform critical power control functions. These devices need to be updated to include arc fault interruption, ground fault interruption, or other suitable technologies in order to afford increased levels of wire protection. Cost will be a consideration in applying these technologies. As an example, Arc Fault Circuit Breakers (AFCBs) devices are 5 to 10 times the cost of current thermal circuit breakers.

With the recent development of AFCBs and solid state circuit breakers, electronics are supplementing, and in some cases replacing, the circuit protection role of thermal breakers. The introduction of electronics into the circuit protection devices of aircraft has created many opportunities to advance circuit protection and safety. An additional benefit of the electronics would be to gather in-circuit real time data. Electronic enhanced circuit breakers could be used as sensors to monitor the health and safety of the aircraft power distribution system. The new power control systems, used by Boeing and Airbus, are the first step in advanced power distribution and protection. These systems have programmable trip curves and advanced protection algorithms to detect intermittent faults. They also possess an ultimate trip value. All of these functions are programmable, so one device can operate over a wide current range and also be ganged together to work as a single or three-phase unit. Another advantage to the new electronics protection is the devices no longer need to be located near a primary or secondary distribution panel. The device will report to a maintenance screen which can be accessed in today's glass cockpits. The breaker can show open, closed, or tripped conditions and could be remotely reset from the same panel.

In a recent study conducted at the FAA's Arc Fault Evaluation Lab (AFEL) tests were conducted to evaluate arc mitigation techniques (Ref7). One test simulated the electrical/hydraulic fire described earlier in this paper as shown in Figure 17 below.

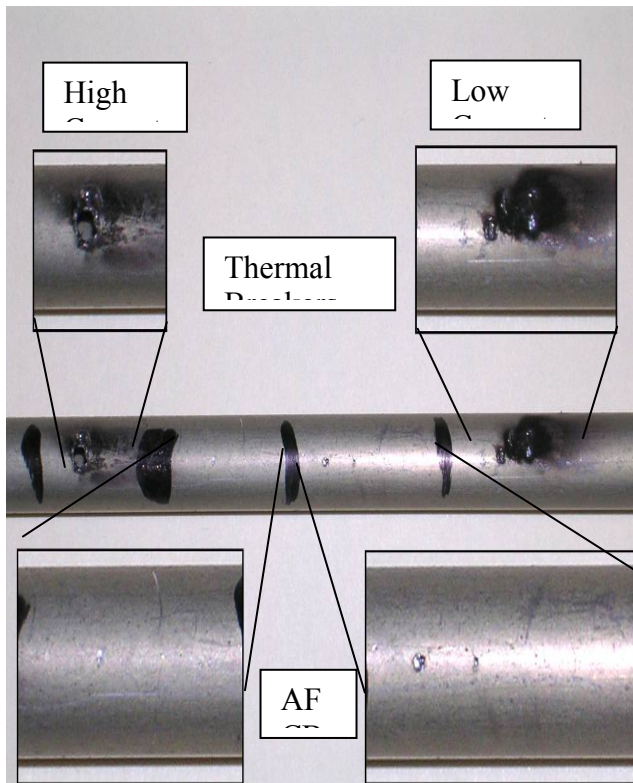


Figure 17. Examples of three phase 115 VAC arcing to a hydraulic line. AFCB devices and current limited thermal breakers effectively protected the aluminum hydraulic line.

This ongoing study showed the benefits of arc fault circuit breakers, wire insulation materials and fault current reduction on reducing damage from wires arcing to transport aircraft hydraulic line. The main purpose for the FAA study is to establish a guideline for the separation and segregation of critical fly-by-wire circuits.

New Wire Constructions: For the last twenty years, advances in aerospace wire insulations have been through engineering enhancements. Development of new materials and construction approaches will be required to result in revolutionary improvements in wiring performance. Three areas being investigated are conductive polymers, as a replacement for metallic conductors, self-healing wire insulation, and smart wiring with a self-configuring capability.

Conductive Polymers/Carbon Nano-tubes. Stringent weight and space requirements of advanced aerospace systems have led to a need for stronger, lighter, smaller, and more flexible wire and shield conductors. Wire conductors continue to be down-sized for weight and volume savings. Many aerospace wiring designs start with 24 gauge conductor as the minimum size and quickly move to a 26 gauge size for weight savings. These small diameter wires have limited break strength and flex life. A conductive polymer wire with conductivity in the range of copper could offer lower weight, higher break strength, and longer flex life. Considerable research has been conducted on conductive polymers for electronics and optoelectronic applications. Polymers such as polyacetylene, polyaniline, polythiophene, and polypyrrole have reached electrical conductivity levels up to 10^5S-cm^{-1} by chemical and electrochemical doping. This is near the conductivity of copper, $6 \times 10^5 \text{S-cm}^{-1}$ (Ref 9). These intrinsically conductive polymers have advantages over metals in weight reduction, tailoring of properties, and low-temperature processing. However, they have limited applications due to their cost, environmental instability, and poor mechanical properties. Alternate approaches are loading high strength polymer fibers with conductive particles or plating the fibers with metal. This has been successfully accomplished by DuPont. Their plated polymer fiber, Aracon[®], has been used as a braided shield on aircraft wire systems. A recent Air Force program compared high strength 26 gauge copper beryllium wire (CS95) with a candidate plated polymer fiber. Syscom Technology, Inc. (STI) developed and evaluated a plated, high-strength, and high-modulus polymer for power and signal transfer and electromagnetic interference (EMI) shielding applications under a USAF small business contract (Ref 10).

The polymer fiber was made from poly(*p*-phenylene benzobisoxazole) (PBO) material. The wire test methods in SAE AS 4373 were used to evaluate the polymer wire properties. A detailed review of the program is given in reference 10. Results are summarized below in Table 1.

Table 1. Summary of Test PBO Program Results.

Finished Product	Metallized PBO	Beryllium Copper
Weight—12 Inch Specimen (Grams)	0.3179	0.4332
Conductivity (S-cm ⁻¹)	387	544
Resistance (ohms/1000 ft.)	78.7	56
The Fusing Time at 9 amp (seconds)	>300	>300
Tensile Breaking Strength (lbs) Requirement for 26ga.: 21.5 lbs	60.3	29.47
Dynamic Cut Through Force (lbs)	Ambient: 43.7 to 114.2 200 °C: 22.7 to 49.3	Ambient: 10.5 to 13.7 200 °C: 3.6 to 6.4
Shielding Effectiveness (dB) (0.1 to 10GHz)		
100 - 500 MHZ	32.2	35.4
500 - 1,000 MHz	39.5	41.1
1 - 2 GHz	40.0	39.0
2 - 4 GHz	42.4	41.7
4 - 8 GHz	42.5	43.0
8 - 10 GHz	42.2	39.8

Recent research activities have focused on using carbon nano-tubes as the conductive media. Carbon nanotubes (CNTs) were first described by S. Iijima in 1991 (Ref 11). The two types of carbon nanotubes most commonly studied are Single-Walled Nanotubes (SWNTs) and Multi-Walled Nanotubes (MWNTs). SWNTs are single layer hollow tubes of graphitic carbon on the order of 1 nanometer in diameter, while MWNTs are made up of multiple layers of SWNTs typically in the range of 100 nanometers (Ref 12). MWNT's are easier to manufacture and have metallic conductor properties which make them good candidates as conductors. Tensile strength for a narrow for a MWNT fiber is reported to be 150 GPa (a typical value for steel is 1.5 GPa), Ref 13. MWNT fibers have been added to composite material to increase strength and conductivity. Conductivities of 0.1 S-cm⁻¹ have been reported with 5% loading. Recent research has shown up to 12% of loading will be needed to reach conductivity levels for a polymer wire.

Self Healing Wire Insulation. Several programs are investigating polymers capable of flowing into and resealing exposed conductors. One approach is to microencapsulate a polymer that would flow and cure when heated using a self contained chemical heater. This technology is being developed by NASA and under a NASA contract with Arctic Slope Regional Corporation (ASRC) Aerospace.

Preliminary testing has demonstrated the concept and the first application may be a wire repair kit for existing wire constructions. A meltable polyimide based polymer that bonds to existing M81381 wire insulation is shown in Figure. 18.

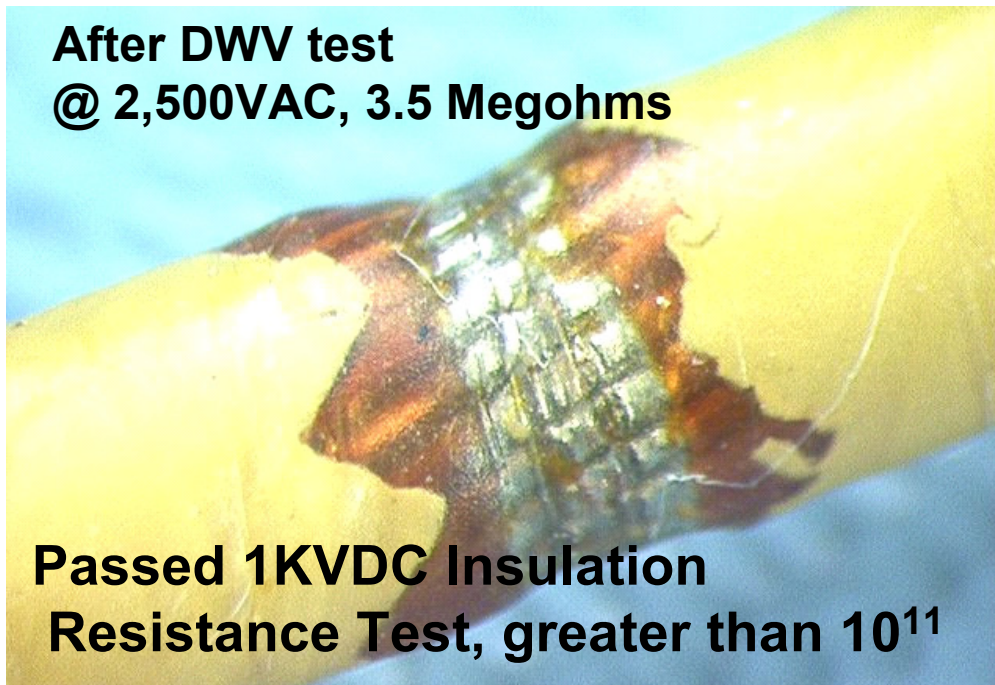


Figure 18. M81381 wire repaired with a meltable polyimide which passed insulation resistance and Dielectric Withstand Voltage(DWV) testing after immersion in a conductive solution.

Self-Configuring Wiring Systems with Integrated Health Monitoring Systems. Several Integrated Health Monitoring Systems (IHMS) approaches are being developed by the FAA, NASA and

DoD. Embedded diagnostics research includes remotely controlled and in-circuit sensors for monitoring the electrical integrity of wiring distribution systems. The desired product will be the system requirements for a sensor capable of monitoring signal integrity by detecting shorts, opens, intermittent, and degraded electrical connections on an aircraft. It is anticipated that micro-electromechanical (MEM) devices will be used to improve sensor reliability and reduce component costs. Initial systems could be added temporarily to fault isolate intermittent wire failures. Intermittent faults on aircraft are among the most time-consuming and frustrating for aircraft maintainers. IHMS systems would monitor circuits under “live conditions” in a non-interfering basis and would operate under dynamic conditions. These systems should be capable of detecting wet arc tracking, dry arc tracking, and loose connections.

The data gathered by these devices can be used to create and improve predictive models to provide better maintenance and safety routine for aircraft. Having data from the aircraft in electronic format will also enhance the ability of maintenance troubleshooting programs. The goal of the program is to develop a prototype health monitor system for aircraft electrical power system capable of incorporating generator prognostics and interfacing with aircraft maintenance and troubleshooting systems. The benefits of this system will be realized in reduced unscheduled maintenance events and reduced damage to power system components.

All of these new features do not come with out cost, both economic and performance tradeoffs must be assessed. New protection devices must qualify to the same rigor as current avionics devices and must also adhere to all of the new software and complex hardware specifications. These devices will have to be able to distinguish between normal, abnormal operation, and faults while operating in harsh environments. Data retrieved from these devices will only be useful when it can be used by other systems and databases. An approach to realize the maximum benefit of these systems would be to define data protocol and power requirements similar to the computer industry. Not all data captured from these devices will be useful. Until noise sources and normal operating conditions are established, a great deal of the data may prove insignificant.

A promising IHMS system is being developed by Live Wire Test Labs, Inc and the University of Utah as part of a DoD and FAA effort (Ref 14). The monitoring system would initially be inserted into

a wire system as a pass through connector so that an intermittent condition could be captured and down loaded after an aircraft flight.

A low level Pseudo-Noise (PN) code is sent down the wire and it is reflected when an open, short, or large impedance change is encountered. The PN code is a set of 1's and 0's that appears random but is actually a defined pattern well below the allowed noise margin of most systems. This is expected to prevent interference with the aircraft electrical system (Figure 19).

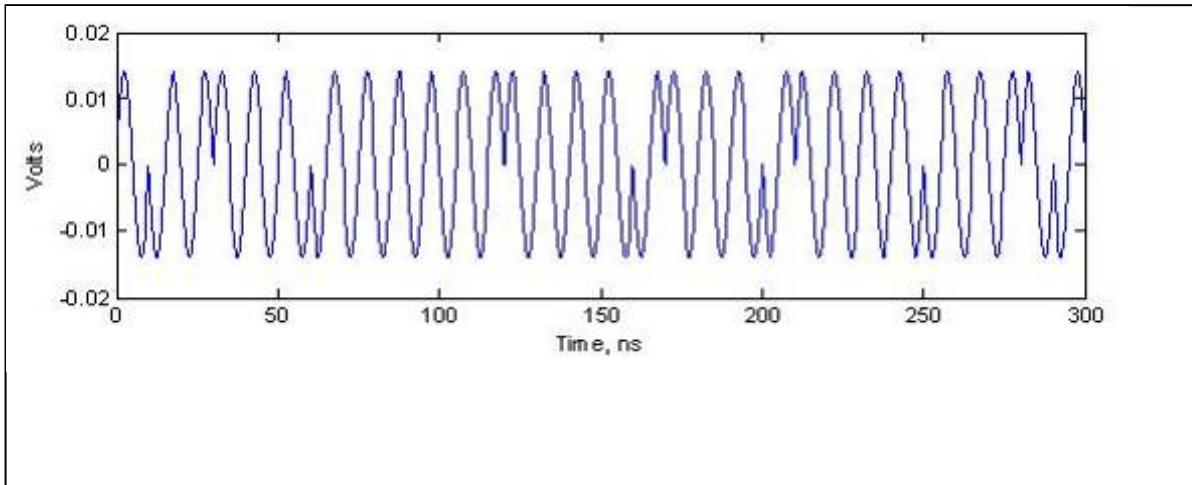


Figure 19: Typical PN code appears random to the aircraft but is a well-defined pattern as small as 10 millivolts.

A Spread Spectrum Time Domain Reflectometry (SSTDR) system detects the monitoring signal by correlating the reflected PN code with the original PN code. SSTDR technology operates on live aircraft wires carrying DC power, 400 Hz power or MIL-STD-1553 data signals (Ref 14). Initial testing has shown that the injected monitoring signal is below MIL-STD EMI/RFI emissions tests for in-flight systems.

After the PN code signal has been sent, the reflections are analyzed. When the reflections have been processed, a waveform similar to that shown in Figure 20 is presented for further analysis and fault location calculations.

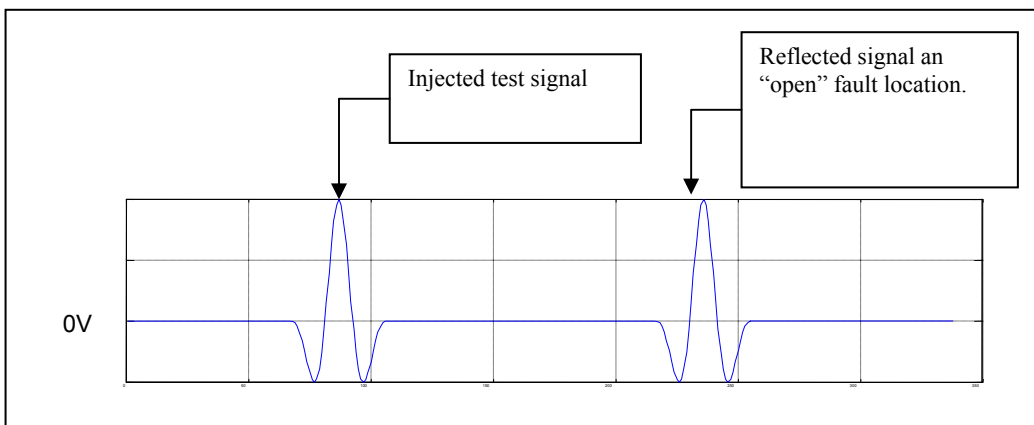


Figure 20: Ideal SSTDR correlation signal showing the reflection at the start of the board (left) and end of the line (right).

An example of an SSTDR signal operating on a wire system with a “short” fault is shown in Figure 21. There are three parts to the waveform: the test signal, miscellaneous reflections, and the

fault. The large pulse on the left is the test signal being sent by the monitoring unit. Moving right on Figure 21 is a series of ripples representing reflected signals that will be filtered out in normal use. The next part of the waveform is the fault information; it appears to be upside down from the test signal, indicating there is a short on the wire being tested. The fault was detected approximately 60 feet from the monitoring system.

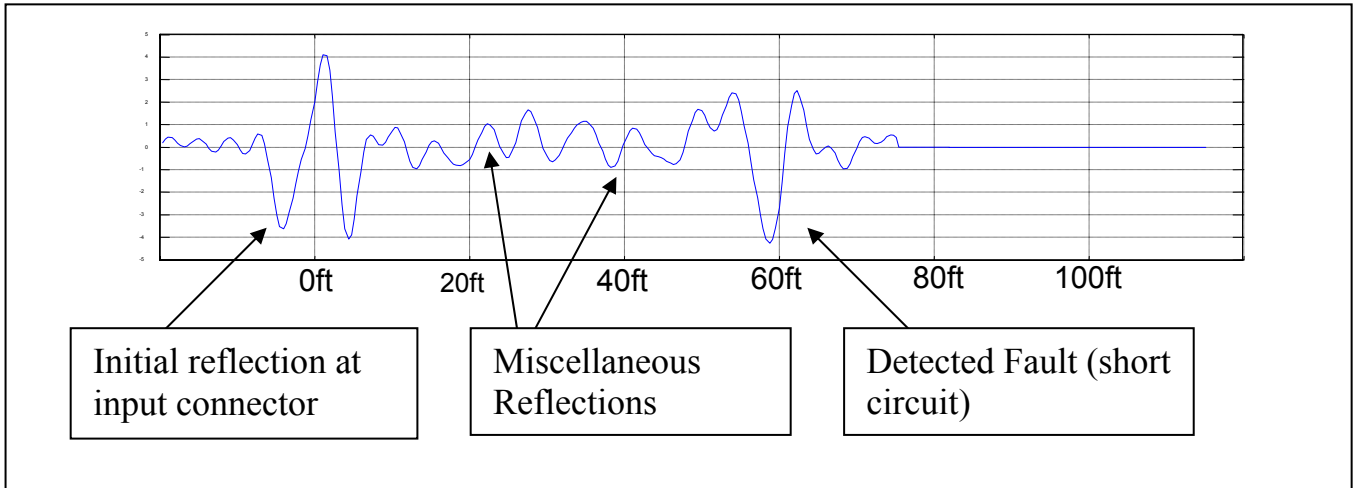


Figure 21: Measured SSTDR waveform for a short circuit approximately 60 feet from the start of the wire

Aerospace wire systems that are self-healing and reconfigurable are being developed by NASA, as part of next generation wiring materials for the new manned space exploration initiative. This system would use an IHMS connected to an active matrix that would switch wire paths based on a failure condition or a change in mission profile (Ref 15). These systems would detect a circuit anomaly and allow active circuit switching to an alternate path. The active switching matrix would consist of a reconfigurable connector and Microelectronic Machine (MEMs) switches. A concept is shown in Figure 22. Once this system is developed, wire systems could be embedded in composite structure using conductive polymers. This would protect the wires for damage and reduce the overall weight and volume of the wire system.

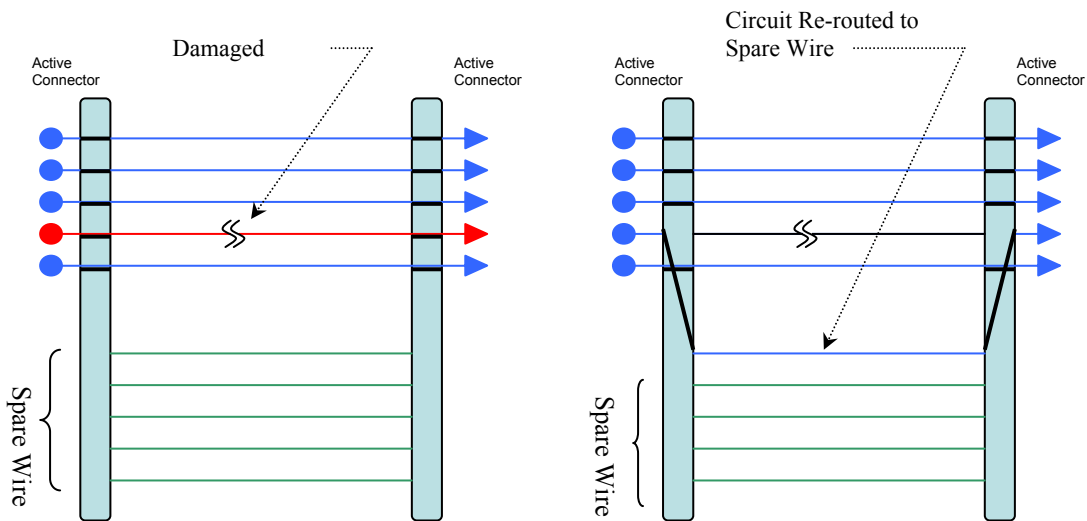


Figure 22. Self configuring wire system using an active connector for switching.

Summary

Many of the interconnection technologies currently in use today are the result of incremental improvements over the last 30 years. There have been few revolutionary changes. New design approaches and materials will be needed to achieve significant improvements in wiring integrity. For the last five years, a consortium of government agencies, academia, and industry have conducted a combination of basic and applied research to achieve higher levels of wire system integrity. Research areas have included advanced diagnostics, advanced circuit protection technologies, and advanced wire insulation and conductor materials. We have attempted to highlight the most promising of these technologies and approaches. These technologies could lead to revolutionary improvements in wire system integrity and to systems with extended failure free operating periods. Further research could lead to wire system designs that are truly fault tolerant. A focused effort between government agencies, academia, and industry will be needed to fully develop these wire system technologies and transition them to aerospace systems.

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GEORGE A. SLENSKI, Principal Technologist for the Electronic Materials Evaluation Group in the Air Force Research Laboratory's Materials Directorate. He holds a 1980 Bachelor of Science in Electrical Engineering from University of Florida and a 1994 Master of Science in Materials Engineering from University of Dayton. Mr. Slenski holds Certificates as a level three DOD Acquisition Official for Science and Engineering and a private pilot license. For the past 24 years, he has worked in the area of electronic failure analysis for the United States Air Force.

Mr. Slenski is an Air Force subject matter expert in the areas of electronic/electrical failure analysis and aerospace accident investigations. Mr. Slenski has managed efforts that have developed new aerospace wire insulations, a handbook for conducting electrically related mishap investigations, and a program for developing a life prediction system for aging wiring systems. He is also the Air Force representative to the SAE aerospace committees on wire and cable and electrical and electronic distribution systems. Mr. Slenski's current emphasis area is on developing new research initiatives to improve wire system integrity.

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