R&D 100 AWARD ENTRY 2007

ArcSafe®

with Pulsed Arrested Spark Discharge

Sandia National Laboratories

ASTRONICS
ADVANCED ELECTRONIC SYSTEMS

ARCSAFE®
WITH PULSED ARRESTED SPARK DISCHARGE

Submitting Organization

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AFFIRMATION: I affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product.

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Product Name

ArcSafe®

ARCSAFE®

WITH PULSED ARRESTED SPARK DISCHARGE

Briefly Descibe Entry

The world's only advanced electrical wiring diagnostic capable of detecting insulation defects in complex wiring systems such as commercial aircraft.

Product First Marketed or Available for Order

December 2006

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Product Price

Initially $30,000. We anticipate commercial sales greater than 1,000 units within 12 months.

Patents or Patents Pending

Patent Number No. US6853196, "Method and apparatus for Electrical Cable Testing by Pulsed Arrested Spark Discharge", Feb. 8, 2005, Sandia Corporation, Albuquerque, New Mexico.

ARCSAFE®
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Product's Primary Function

PASD is effective in detecting and locating a variety of wiring insulation defects in complex wiring geometries, including commercial aircraft which represent a severe challenge because of loosely bound single-wire bundles, multiple-wire types, and branching of the wiring harnesses.

Pulsed Arrested Spark Discharge (PASD) is a patented electrical wiring diagnostic with revolutionary capabilities. PASD is effective in detecting and locating a variety of wiring insulation defects in complex wiring geometries, including commercial aircraft, which represent a severe challenge because of loosely bound single-wire bundles, multiple-wire types, and branching of the wiring harnesses. PASD is highly immune to line impedance variations, an important property for aircraft applications, and it is nondestructive. The effectiveness of PASD has been demonstrated at a Federal Aviation Administration (FAA) wiring testbed and during its first use in an accident investigation for the National Transportation Safety Board. PASD has unparalleled capabilities that will transform the future of electrical wiring inspection and maintenance.

Because of the simplicity of the PASD concept, the low-energy PASD pulser and diagnostics have been incorporated into a portable diagnostic system by Astronics-Advanced Electronic Systems, Inc. PASD shows tremendous promise as the world's only effective diagnostic that is capable of detecting and accurately locating such hard to find insulation defects as breached insulation, chaffing, and insulation cracks. PASD is capable of making a significant near-term impact on the ability of inspection and maintenance organizations to detect and locate hazardous insulation defects in wiring systems in new installations and during inspection and maintenance in the aging commercial aircraft fleet and other less challenging applications. PASD could greatly reduce the time required to track down wiring defects in the 25–200 miles of electrical wiring found in a commercial aircraft, as it can typically locate defects within inches.

The PASD technique uses a high-voltage (approximately 10 kilovolts), low-energy (few millijoule), short pulse to induce an electrical spark breakdown at the site of an insulation defect. The pulse energy is similar in magnitude to the static discharge generated when walking across a synthetic carpet and is insufficient to damage insulation or the conductors within wiring

Product's Primary Function

PASD shows tremendous promise as the world's only effective diagnostic that is capable of detecting and accurately locating such hard to find insulation defects as breached insulation, chaffing, and insulation cracks.

systems. The discharge occurs from the conductor in the wire under test to an adjacent return path, which typically is another wire or ground plane (e.g., aircraft skin). The development of an arc occurs within a few nanoseconds to produce a momentary short circuit that reflects energy back to the sensors at the injection point. Conventional Time Domain Reflectometry (TDR) techniques can then be used to accurately locate the defect site. This technique is a direct test of the dielectric strength of the insulation system. Since the PASD voltage is insufficient to break down any significant amount of bulk insulation, only potentially hazardous defects with exposed center conductors are targeted. PASD has been demonstrated to be effective in several challenging environments that other competing technologies cannot address.

The PASD concept has been incorporated into an advanced commercial platform called ArcSafe®, which includes a 40-circuit sequencer for automatic cycling through multi-pin aircraft connectors, an advanced GUI-data management system, wireless data upload and download, and 3-dimensional fault mapping.

The ArcSafe® product line was developed in cooperation with the FAA to address safety concerns about the state of wiring in the aging commercial aircraft fleet—specifically the health of the wire dielectric material—as it degrades over the life of the aircraft. The well-publicized TWA-800 crash provided the impetus for numerous FAA funded study contracts to investigate novel new technologies that could identify and locate "cracks in wires." The objective has been to "push the design envelope" of non-destructive inspection (NDI) techniques, to a capability where these tools are more adept at assessing the **true** hazard potential of wire faults, typical of those found on aircraft flying today.

ArcSafe®
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Product's Primary Function

Numerous surveys have been conducted to gather the aviation industry's input and recommendations concerning these emerging technologies. The need for enhancing safety has always been well supported; however, the fear exists of exposing a plethora of faults on aircraft, that may not have caused immediate system failures. Once exposed, existing maintenance procedures would require timely resolution. Potential lost revenue, associated with aircraft downtime and the costs for this repair, could be staggering. The goal is to develop smart diagnostic tools, that can help the user assess the severity of the defect. This would then allow a reasonable determination of the need for repair. PASD has the capability to address these needs.

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Product's Competitors by Manufacturer, Brand Name, and Model Number

ArcSafe® with PASD is the only non-destructive test (NDT) diagnostic available that is capable of detecting and locating insulation defects and providing diagnosis of intermittent faults. Other significant diagnostic manufactures are:

- Cable Test—MPT5000L
- CK Technologies—Model 1175-10
- DIT-MCO—Model 2135
- Northrop Grumman—AMWIT 1000
- Eclypse International—ESP Plus
- Jovial Test Equipment—Shortstop
- Phoenix Aviation—ARCMAS
- 3M Company—900AST

Comparison Matrix

Technology	Company	Detects & Locates intermittent faults	Detects & Locates insulation defects
ArcSafe with PASD	Astronics Advanced Electronics	YES	YES
Time domain reflectometry	3M, Northrop Grumman, Jovial Test Equip., Phoenix	NO	NO
High pot testing	Cable Test, CK Technologies, DIT-MCO	NO	NO
Resistive-Capacitive analysis	Cable Test, CK Technologies, DIT-MCO	NO	NO
Standing wave reflectometry	Eclypse International	NO	NO

Vendor	Equipment	Size	Weight	Cost (US $)
Cable Test	MPT5000L	Table Top	70 lb	$14,672
CK Tech	1175-10	Table Top	48 lb	$22,650
DITMCO	2135	Table Top	30 lb	$21,830
Eclypse	ESP Plus	Hand Held	1.2 lb	$5500
JTE	Shortstop	Hand Held	1 lb	$349
Northrop Grumman	AMWIT	Table Top	28 lb	$unknown
Phoenix Aviation	ARCMAS	Hand Held	2 lb	$7000
3M	900 AST	Hand Held	2.5 lb	$4800
Astronics	PASD	Briefcase	20 lb	$30,000

How Product Improves Upon Competition

ArcSafe® with PASD is the only technology capable of detecting and locating intermittent faults or wiring insulation defects. PASD can also detect defects which cannot be seen through visual inspection. This is a profound result when considering that visual wiring inspection is a routine practice in the commercial aircraft fleet due to the lack of an effective insulation diagnostic.

Table 1 below contains data supporting the location accuracy that can be realized with the PASD technology. These insulation type defects were all detected and subsequently located within 3% of their actual location. These insulation defects, which are invisible to other commercially available wiring diagnostics, are detected by PASD and located very efficiently.

Table 1: PASD defect location accuracy

Cable Type and Damage	Cable Length (ft)	Damage/Defect Location (Actual) (ft)	PASD Reported Location (ft)
RG-174 Break in shield	24	19.2	19.2
RG-214 Break in shield	30	22.9	22.8
Alpha 2473 (TP) insulation damage	30.3	24.2	24.6
RG-214 abraded shield & insulation	25.8	10.5	10.8
RG-174 abraded shield & insulation	24.3	13.8	13.4
RG-214 pin-in-Shield (1.2 mm)	30.3	8.4	8.5
RG-214 pin hole only (1 mm)	30.3	22.2	22.2
Non-uniform impedance (TP)	15.6	12	12.3

ArcSafe®

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How Product Improves Upon Competition

The formula for PASD's impact in the wiring community is simple: **minimum aircraft downtime = maximum revenue**. Fault chasing, via manual inspection or rudimentary tools (i.e., digital multimeter [DMM]), is very time consuming. Wire testers involving flying leads (wire-to-wire check) lack robustness when the task is to identify faulty conductors within a complex harness. ArcSafe®, as a single portable automatic system, is capable of identifying and locating intermittent faults, shorts, and opens and has real value. A simple user interface without need to interpret TDR waveforms allows use by a technician with a minimal amount of training. Advanced three-dimensional fault locating capability minimizes the time to isolate faults within a complex aircraft spatial environment. ArcSafe®'s paired fault-finding capability identifies and locates critical faults only, minimizing concern about nuisance faults/trips.

Product's Principal Applications

Commercial Aviation Industry

Other Applications

ArcSafe® with PASD is the only technology capable of detecting intermittent faults or wiring insulation defects.

ArcSafe® with PASD can be used in any application where the manufacturer or end user cares about the quality of the electrical insulation in their products. This has enormous potential to be used as a manufacturing quality test for verifying the integrity of new wiring installations in aircraft, automobiles, rockets, ships, etc. PASD can detect manufacturing defects in the wiring or damage introduced during the installation process. PASD could also detect cable connector defects.

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Summary

PASD and its implementation into the sophisticated ArcSafe® diagnostic platform will revolutionize wiring inspection by providing, for the first time, a means to detect wiring insulation defects caused by improper installation, damage introduced by maintenance procedures, or defects developed during the normal aging process. The degrading of wiring insulation in the aging commercial aircraft fleet is a well documented and significant issue in United States. ArcSafe® with PASD has demonstrated capabilities unmatched by other diagnostic concepts developed over the last several decades. It is simple, highly effective, and capable of transforming the wiring diagnostic community.

PASD is the world's first diagnostic capability that can see and then locate a broad range of critical insulation defects in highly complex wiring configurations. Nowhere is this more important than in the aging commercial aircraft fleet in the United States. The PASD technique will find its way into a myriad of applications wherever the integrity of wiring insulation is of critical importance. This technique could dominate the wiring diagnostic community in the years to come, contributing desperately needed capabilities to verify the reliability and security of electrical wiring infrastructures in the United States.

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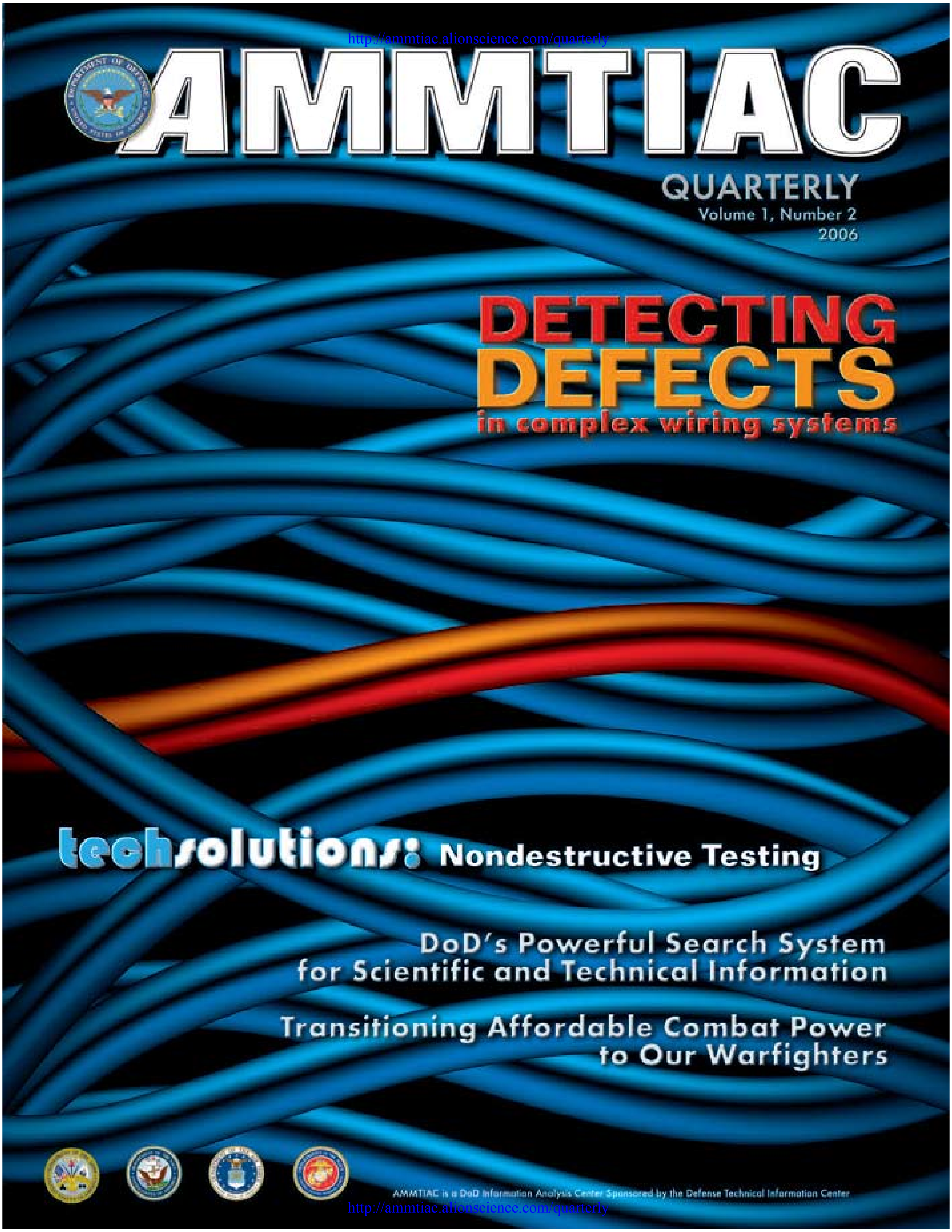
Appendix A

Articles Describing PASD

A NEW CAPABILITY TO DETECT AND LOCATE INSULATION DEFECTS IN COMPLEX WIRING SYSTEMS,
L. X. Schneider, *AMMTAIC Quarterly Magazine*, Oct. 2006.

A NEW CAPABILITY TO DETECT AND LOCATE INSULATION DEFECTS IN COMPLEX WIRING SYSTEMS,
L. X. Schneider, Kevin Howard, Steve Glover, Mike Dinallo, and Gary Pena, *IEEE Electrical Insulation Magazine*, July/August 2005.

Appendix A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AMMTIAC
QUARTERLY
Volume 1, Number 2
2006
DETECTING
DEFECTS
in complex wiring systems
techsolutions: Nondestructive Testing
DoD's Powerful Search System
for Scientific and Technical Information
Transitioning Affordable Combat Power
to Our Warfighters
AMMTIAC is a DoD Information Analysis Center Sponsored by the Defense Technical Information Center
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AMMTIAC's Expanded Role in the Area of Testing

In the first issue of the *AMMTIAC Quarterly* we introduced AMMTIAC as the newest of the nine Defense Technical Information Center (DTIC) sponsored Information Analysis Centers (IACs). In that issue we discussed how the basic functions of three predecessor IACs, namely AMPTIAC, MTIAC and NTIAC, were merged into a single new entity, AMMTIAC. We also mentioned that the new center was in many ways more than the sum of its parts. One of the significant changes of the new center, as compared to its predecessors, is a general extension and broadening of our scope in the area of testing. No longer are we restricted to the field of traditional nondestructive testing (NDT). The expanded scope includes all aspects related to the physical, mechanical, and functional testing of materials, components, and items. Within this, nondestructive testing is only one element, albeit, a critical one.

The AMMTIAC Team retained the assets and expertise from the Nondestructive Testing IAC (NTIAC), and because NDT has evolved over the years into a sophisticated and often very effective solution to many challenges, we wanted to leverage this established knowledge and talent for the ultimate benefit of the warfighter. However, it is also important that we emphasize that our legacy of knowledge and expertise is not limited to nondestructive methods. From the Advanced Materials and Processes Technology IAC (AMMTIAC) we retained a vast amount of information and expert knowledge on conventional materials testing techniques as well; including fatigue testing, corrosion testing, accelerated testing, and many other testing methods. From the Manufacturing Technology IAC (MTIAC) we retained the knowledge and expertise of in-process manufacturing testing and evaluation. Combining these three focused areas of testing, while expanding the scope to incorporate testing of materials, components, and items in general, has enabled DTIC to provide a comprehensive resource for the acquisition, operations, and sustainment communities.

For the first several issues of the *AMMTIAC Quarterly*, we are focusing a lot of attention on the area of NDT, because as mentioned earlier, it is a critical technology area that enables the safe operation of many Defense assets. In this issue of the *AMMTIAC Quarterly*, for instance, we have two articles relevant to nondestructive testing. The first is a new technology used to inspect complex wiring systems for defects and damage. Secondly, in the inaugural edition of *TechSolutions*, which is our tutorial-styled feature dedicated to solving problems through technologies and technical methods, we give an overview and introduction to the area of NDT. In issues to follow we will delve deeper into the specific NDT methods to teach non-experts how the various methods work, how they are applied, and where they can be used. Ultimately, when we finish covering all of the eight common NDT methods, we will combine the articles into a desk reference, similar to the one we did on material failure modes (see http://ammtiac.alionscience.com/pdf/deskref.pdf).

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A New Method for Detecting and Locating Insulation Defects in Complex Wiring Systems

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The article entitled "Wired for Success: Ensuring Aircraft Wiring Integrity Requires a Proactive Systems Approach", which was published in Vol. 8, No. 3 of the AMPTIAC Quarterly *(a predecessor to the* AMMTIAC Quarterly*), established the importance of maintaining wiring integrity, especially in aging aircraft. The article also emphasized the need for nondestructive approaches for evaluating the integrity of wiring systems and components. The current article answers the mail in terms of providing a nondestructive inspection (NDI) method to proactively ensure wiring integrity.* – Editor

INTRODUCTION

Detecting and locating insulation defects in wiring systems is a non-trivial challenge. Ideally, the diagnostic should be nondestructive, capable of detecting a variety of insulation defects, such as cracking, chaffing, and abrasion, and be able to locate the defect accurately to reduce potential inspection and maintenance costs. The diagnostic should also have a low rate of false detection. Complicating this quest is the nature of complex wiring systems. For example, aircraft wiring systems are comprised of harnesses containing periodically bound single wire pairs* which create highly non-uniform impedance characteristics due to the varying distance between wire pairs. Insulation defects may also be physically small, resulting in an immeasurable change in the impedance at the defect site. These characteristics tend to render impedance measuring or conventional time-domain-reflectometry (TDR)† concepts ineffective. Other approaches such as partial discharge or DC breakdown techniques may detect some types of insulation defects, but cannot locate them in complex impedance wiring systems (Figure 1).

PULSE ARRESTED SPARK DISCHARGE

Pulse Arrested Spark Discharge (PASD) has been demonstrated to be an effective insulation diagnostic for coaxial cables, twisted shielded pair, and more complex single wire bundles commonly found in wiring systems in aircraft and control and monitoring devices. PASD employs a patented, low-energy, arrested-arc concept and time domain reflectometry techniques to produce a well-defined reflection from an insulation defect site. The PASD diagnostic can detect and locate a range of electrical insulation damage in cable/wire bundles with non-uniform impedance profiles.

PASD was first demonstrated on electrical wiring systems in 1996 under a Department of Energy (DOE) sponsored nuclear energy program. Success during the initial development of PASD for the DOE led to a contract with the U.S. Navy to explore the use of this concept for wiring in control and power systems. This work, completed in August 2001, demonstrated the ability of this technique to identify and locate gross defects, as well as difficult to find small-volume dielectric defects in a laboratory environment [1]. This foundational work with PASD led to a three-year Federal Aviation Administration (FAA) sponsored program, beginning in October 2002, that focused on commercial aircraft wiring systems. This FAA program culminated in the practical utilization of the PASD technique. PASD has demonstrated great potential to locate aircraft wiring flaws‡, which are due to aging processes, manufacturing defects, maintenance, and installation damage, as well as a variety of other defects in more conventional wire/cable systems [2].

Figure 1. Inspection of Aircraft Wiring Systems.

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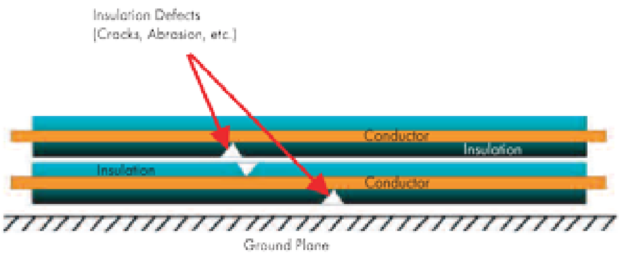

Figure 2. The PASD Breakdown Can Occur Between Two Adjacent Conductors With Insulation Damage, or from a Conductor to a Ground Plane, Such as Braided Shielding.

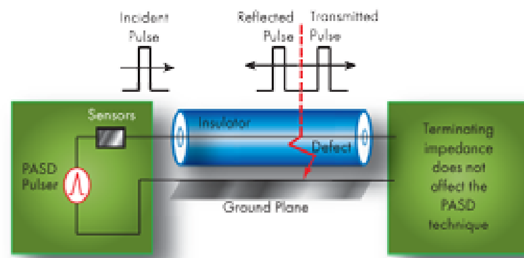

Figure 3. PASD Diagnostic Concept for Locating Defects in Electrical Wiring Systems. (A Single Conductor is Shown Under Test.)

HOW PASD WORKS

The PASD technique uses a high-voltage (approximately 10 kilovolts), low-energy (a few millijoules), short pulse to induce an electrical spark discharge (breakdown) at the site of an insulation defect (Figure 2). The PASD pulse can be generated by a compact, battery driven pulser (Figure 3) and combined with diagnostics that includes software processing in a package the size of a small suitcase. The pulse energy is similar in magnitude to the static discharge generated when walking across synthetic carpets and is insufficient to damage typical insulation or the conductors within wiring systems. The discharge occurs from the conductor in the wire under test to an adjacent return path which typically is another wire or ground plane (e.g., aircraft skin). The development of an arc occurs within a few nanoseconds and produces a momentary short circuit that reflects energy back to the sensors at the injection point. Conventional TDR techniques can then be used to accurately locate the defect site. This technique is a direct test of the dielectric strength of the insulation system. Since the PASD voltage is insufficient to breakdown any significant amount of bulk insulation, only defects which expose the center conductor are identified.

The technique begins with characterizing the impedance of the wire under evaluation, much like a conventional TDR technique, using the PASD pulse at a low voltage setting (hundreds of volts). This establishes an impedance baseline which is critical to PASD's ability to evaluate non-uniform impedance wiring systems. The injected pulse voltage is then raised in gradual steps to explore for defects. If a sufficient defect is present, the sensor waveform will deviate from the low voltage baseline characterization.

Figure 4 shows example waveforms derived from PASD tests on a coaxial cable with a 0.7 mm hole punched through the dielectric. The inner conductor and outer shield remain fully conductive. The two waveforms deviate at the location of the defect, 78 nanoseconds (ns) down the line. In this example, the peak PASD pulse was 9.8 kV at a pulse width of 5 ns. The amplitude scale is the voltage measured at the sensor. The location of the anomaly between the two waveforms describes the physical location of the defect site.

Figure 5 shows PASD waveforms from a test of a damaged twisted shielded-pair cable. Although the insulation and electrical shielding is damaged, the inner conductors and shields remain electrically conductive. The impedance of this cable is highly nonuniform, as evidenced by the multiple reflections in the PASD baseline (solid line). The dashed line is the normalized PASD pulse (4.5 kV) which creates a breakdown at the defect site. The two waveforms separate at approximately 45 ns, accurately indicating the location of the defect. A simple differencing algorithm can easily locate the point where the two waveforms deviate, as illustrated in Figure 4 and Figure 5.

PASD can be applied using several different techniques, including multiple pulse injection which improves PASD's response in long lines. PASD has been effectively demonstrated in wire harnesses up to 200 feet in length

NONDESTRUCTIVE NATURE OF PASD

While PASD is an effective test method, it would not be a viable diagnostic if it were a destructive technique and degraded the properties of the wiring or connectors under evaluation. Therefore, a series of experiments were conducted to carefully quantify PASD's impact on typical wiring insulation materials including Teflon®, polypropylene, celluloid, and Mylar® [3].[9**] Several types of experiments were conducted to evaluate the impact of a PASD breakdown on insulator surfaces. They included: (1) exposing the sample to a series of PASD pulse breakdowns to evaluate whether the breakdown

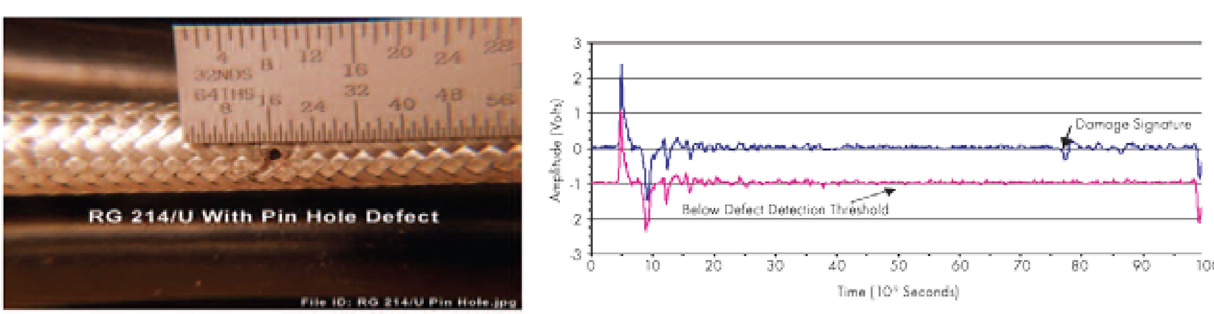

Figure 4. PASD Waveforms from a Test of a Coaxial Cable with a Pin-Hole Defect in the Insulation that Extends to the Inner Conductor.

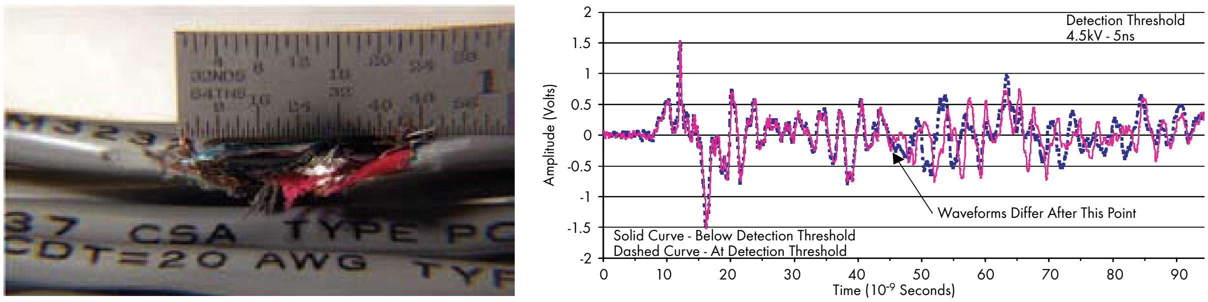

Figure 5. **PASD Waveforms from a Test of a Twisted Shielded Pair Cable.**

voltage decreased with subsequent pulsing; (2) performing a slowly rising DC breakdown test, applying a PASD pulse, and then repeating the DC breakdown test; and (3) determining the effect of high energy discharges on low energy voltage breakdown strength. PASD did not reduce the surface flashover strength of any of the materials tested. The PASD arc breakdown process occurs very rapidly, with the arc channel falling to 10% of its initial resistance value in approximately three nanoseconds. This is an important characteristic as it improves PASD's ability to locate defects. When exposed to slowly rising DC after the application of the PASD pulse, the average breakdown voltages remained the same or actually increased. This is a common high voltage conditioning phenomenon.

ABILITY OF PASD TO LOCATE AIRCRAFT WIRING DEFECTS

The PASD diagnostic has demonstrated that it can detect and locate chaffing, cracking, pin-holes and other breached insulation defects under laboratory conditions and during testing at the FAA's Airworthiness Assurance Nondestructive Inspection (NDI) Validation Center (AANC) in Albuquerque, New Mexico [4]. These types of defects are documented in the Aging Transport Systems Rulemaking Advisory Committee (ATSRAC) publications: *Intrusive Inspection Final Report*[5] and *Aging Transport Systems Task 1 and 2 Final Report*[6], which were comprehensive joint government-manufacturer-operator (industry) studies sponsored by the FAA.

Several types of defects were tested at the AANC test bed facility. A mockup of an aircraft fuselage panel is shown in Figure 6 with a variety of 10 foot wiring harnesses installed. Figure 7 shows the results of an insulation chafe on a 10 foot wiring harness in the

Figure 6. **Mockup of an Aircraft Fuselage Panel with a Variety of 10 foot Wiring Harnesses and Connector Types. Each Harness has Multiple Documented Insulation and Conductor Defects.**

testbed. A 15 ft cable was used to isolate the 10 ft cable under evaluation. The PASD waveforms separate at 84.4 ns indicating the presence of an insulation defect. The velocity of propagation in the cable under test can be easily measured or estimated and is typically 3 ns/foot for loosely bound wires. The fault location can be

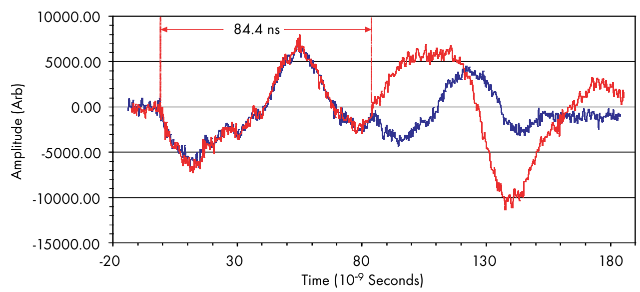

Figure 7. **PASD Probe Waveforms for an Insulation Chafe Defect.**

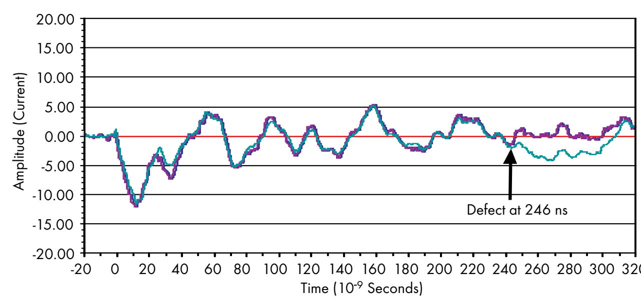

Figure 8. **PASD Waveforms from a Test of a 100 Foot Wire Harness with an Insulation Defect at 80 Feet.**

readily calculated using the propagation velocity and injected pulse width. PASD identified the defect at approximately 8.8 feet from the injection end of the harness. The actual location of the defect was at 8.0 feet.

Figure 8 shows PASD waveforms from tests on a 100 foot pair of wires using a multipulse approach. In this example, an insulation defect was present with a 1.0 mm air gap between two conductors that resulted when a small amount of insulation had been stripped away. The two waveforms deviate at the location of the defect, 246 nanoseconds down the line, which equates to 79.3 feet. The actual location of the defect was at 80 feet. PASD located the defect to within 8 inches in an 80 foot long section of wiring. This accuracy would save significant maintenance time, especially if wiring is hidden behind panels or bulkheads as typically found in aircraft or marine vessels, such as ships or submarines. The variations in the waveforms in Figure 8 are caused by the varying impedance profile down the harness. The nature of modest impedance variations in wiring systems is not important, since PASD uses a differencing technique to locate the defect.

PASD performed well against an array of challenges presented by the AANC wiring test bed. A summary of testing results at the AANC is shown in Table 1. With a 1 mm air gap, PASD found 12 out of 15 defects present, including challenging cracked insulator defects. PASD was 100% effective in locating chafe and breach defects with air gaps up to 1 mm. These results have not been matched by other diagnostic techniques.

Table 1. Test Results at the FAA's AANC Wiring Test Bed.

Gap Spacing††	Quantity	Defects Detected	Defects Undetected
Insulation Chafe Defect			
1 mm Gap	7	7	0
3 mm Gap	5	3	2
Insulation Breach Defect			
1 mm Gap	2	2	0
3 mm Gap	6	3	3
Cracked Insulation Defect			
1 mm Gap	6	3	3
3 mm Gap	1	0	1
TOTAL	27	18	9

SUMMARY

PASD is effective at detecting and locating a variety of insulation defects in complex wiring geometries. It is highly immune to line impedance variations, an important property in aircraft or other complex wiring systems, and has been shown to be nondestructive to electrical insulation materials. Due to the simplicity of the PASD concept, the low energy PASD pulser and diagnostics can be readily implemented into a portable diagnostic system. PASD shows great promise as an effective diagnostic to find difficult to locate insulation defects such as breached insulation, chaffing, and physically small insulation cracks. Although the PASD technique will likely evolve as it enters into field applications (pulse shape, testing strategy, etc.) it is capable of making a near-term impact on the ability of inspection and maintenance organizations to detect and locate potentially hazardous insulation defects.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Federal Aviation Administration's William J. Hughes Technology Center for supporting the development of PASD for application in commercial aircraft wiring systems.

NOTES & REFERENCES

* There are typically many (up to 40) individual wires which form two wire circuits.

† TDR is a method used to detect defects in an electrical transmission system (typically conductive wiring). A voltage is sent through the system and the reflected signal is superimposed on the original to identify any anomalies, which indicate the presence of defects.

‡ PASD can detect flaws of any size as long as the wire insulation is removed down to the inner conductor. The flaw, for example, could be nearly invisible to the unassisted eye.

§ The effect of PASD on Kapton® insulation was not investigated. However, since the PASD pulse energy is very low, it is not expected to damage this type of wire insulation.

** Teflon®, Mylar®, and Kapton® are registered trademarks of E.I. du Pont de Nemours and Company

†† The gap spacing refers to the physical air gap from the exposed wire conductor to the nearest ground plane or adjacent grounded conductor.

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Appendix A

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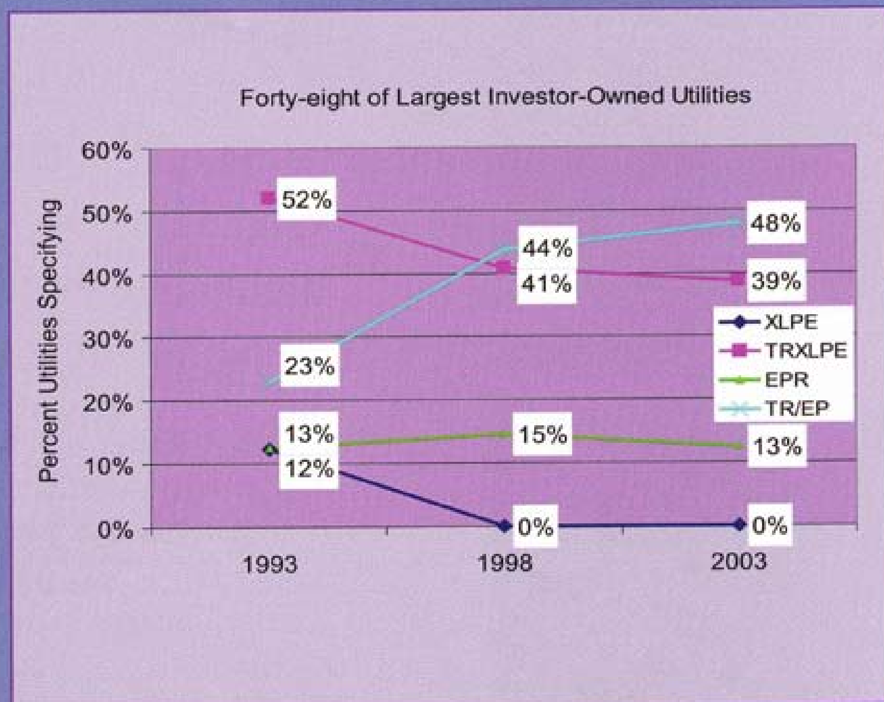

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DEIS F E A T U R E A R T I C L E

A New Capability to Detect and Locate Insulation Defects in Complex Wiring Systems

Key Words: Wiring diagnostic, pulse arrested spark discharge (PASD), defect location, time domain reflectometry

Larry Schneider, Kevin Howard, Steve Glover, Tom Lockner, Mike Dinallo, Gary Pena

Sandia National Laboratories, Albuquerque, New Mexico

The PASD diagnostic has demonstrated that it can detect and locate chafing, cracking, pin-holes, and other breached insulation defects.

Introduction

Detecting and locating insulation defects in wiring systems is a non-trivial challenge. Ideally, the diagnostic should be non-destructive, capable of detecting a variety of insulation defects (such as cracking, chafing, and abrasion), and should be able to locate the defect accurately to reduce potential inspection and maintenance costs. The diagnostic should also have a low rate of false detection. Complicating this quest is the nature of some complex wiring systems. For example, commercial aircraft wiring systems are composed of harnesses containing single wire pairs that are sometimes bundled into harnesses periodically bound by ties or lacing, which creates highly non-uniform impedance profiles down the line length. Insulation defects may be physically small, resulting in an immeasurable change in the impedance at the defect site. These characteristics tend to render impedance measuring or conventional time-domain-reflectometry (TDR) concepts ineffective. Other approaches, such as partial discharge or DC breakdown techniques, may detect some types of insulation defects but cannot locate them in complex impedance wiring systems.

Pulse Arrested Spark Discharge (PASD) has been demonstrated for many types of faults, types of constructions, and insulations to be an effective insulation diagnostic. These include coaxial cables, twisted shielded pair, and more complex single-wire bundles commonly found in aircraft wiring systems. PASD employs a patented low-energy, arrested-arc concept and TDR techniques to produce a well-defined reflection from an insulation defect site. The PASD diagnostic has detected and located a range of electrical insulation damage in cable/wire bundles with non-uniform impedance profiles. It was first demonstrated on electrical wiring systems in 1996 under a Department of Energy-sponsored Nuclear Energy (DOE) program. Success during initial development of PASD for the DOE led to a contract with the US Navy to explore the use of this concept for complex wiring in control and power systems. This work, completed in August 2001, demonstrated the ability of this technique to identify and locate gross defects and difficult small-volume dielectric defects in a laboratory environment [1]. This foundational work with PASD led to a 3-yr US Federal Aviation Administration (FAA) program, beginning in October 2002, with a focus on commercial aircraft wiring systems and a reduction to the practice of the PASD technique. PASD has demonstrated the potential to locate difficult aircraft wiring flaws relevant to aging processes, manufacturing

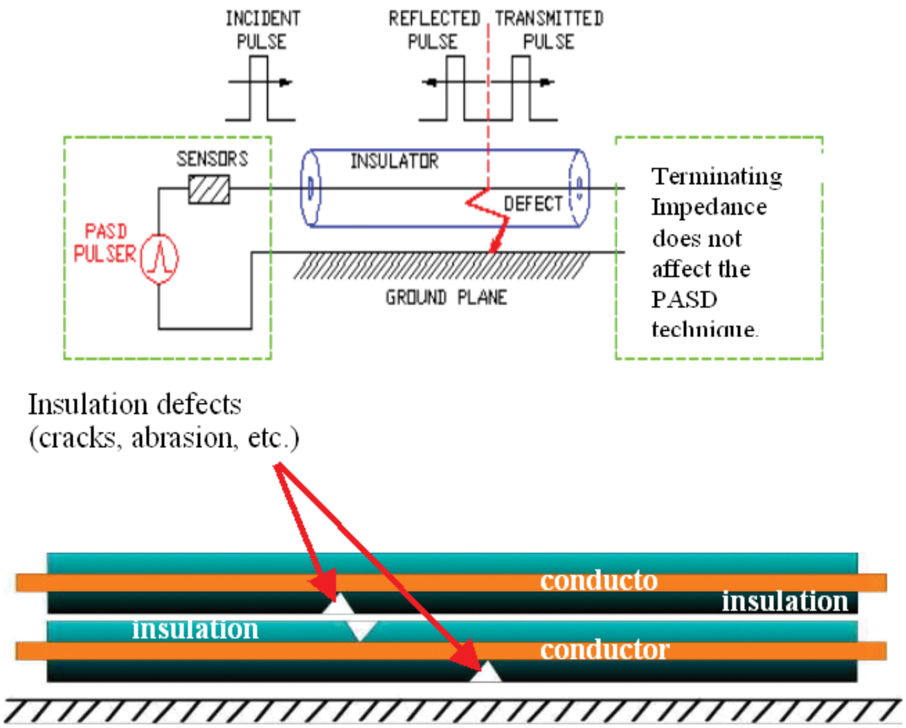

Figure 1. (Top) PASD diagnostic concept for locating defects in electrical wiring systems. A single conductor is shown under test. The ground plane can be an adjacent insulated conductor or metallic plane, such as an aluminum aircraft shell. An electrical break down occurs because of an injected, low-energy, high-voltage pulse. (Bottom) The PASD breakdown can occur between two adjacent conductors with insulation damage or from a conductor to ground plane such as braided shielding or a metal plane.

defects, and installation damage as well as a variety of other defects in more conventional wire/cable systems [2]. Sandia National Laboratories was awarded a US Patent for PASD on February 8, 2005.

PASD

The PASD technique uses a high-voltage (several kV), low-energy (few mJ), short pulse to induce an electrical spark discharge at the site of an insulation defect (Figure 1). This pulse is generated by a compact, battery-driven pulser. It is combined with diagnostics including software processing in a package the size of a small suitcase. The pulse energy is similar in magnitude to a static discharge generated when walking across synthetic carpets. This energy level is low enough to not damage typical insulation or the conductors within wiring systems for the types of insulation faults examined to date. The discharge occurs from the conductor in the wire under test to an adjacent return path, which can be another wire or ground plane. The arc impedance collapse, which occurs within a few nanoseconds, produces a momentary short circuit that reflects energy back to the sensors at the injection point. Conventional TDR techniques can then be used to locate the defect site accurately. This technique is a direct test of the dielectric strength of the insulation system. Because the PASD voltage is high enough to break down only insignificant amounts of bulk insulation, only defects that expose the center conductor are affected.

The PASD technique begins with a characterization of the impedance of the wire under test, much like a conventional TDR technique, using the PASD pulse at a low voltage setting (hundreds of volts). This establishes an impedance baseline that is critical to the PASD's ability to perform in non-uniform impedance wiring systems. The injected pulse voltage is then raised in gradual steps to explore for defects. If a threshold size of defect is present, the sensor waveform will deviate from the baseline low voltage characterization. Note the baseline response is measured during the same test period, as the increasing test voltage is applied. There is no need for a databank of baseline circuit characteristics required for the sake of comparison.

Figure 2 shows example waveforms derived from tests on a coaxial cable with a 0.7-mm hole punched through the dielectric. The location of the change in the two sensor voltage-vs.-time waveforms describes the physical location of the defect site. A differencing algorithm locates the change between the two waveforms. PASD can be applied using several different tech-

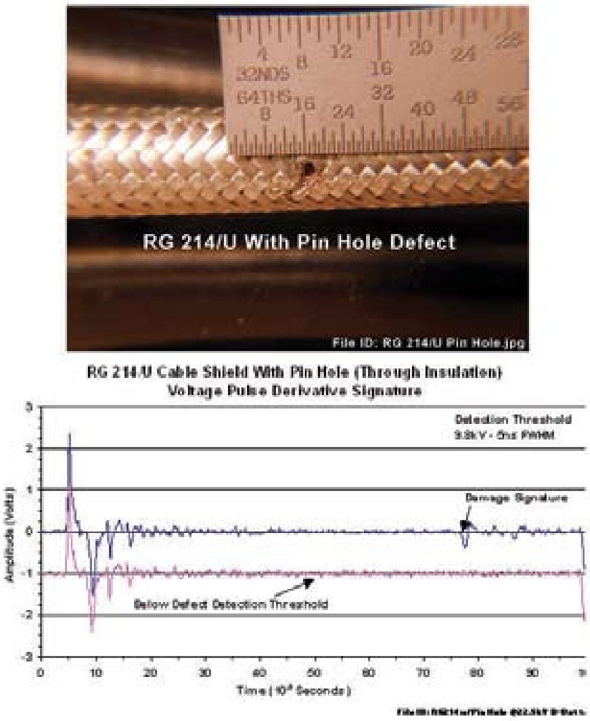

Figure 2. PASD waveforms from a test of a coaxial cable with damage to the outer shield braid and internal insulation. The inner conductor and outer shield remain fully conductive. The two waveforms deviate at the location of the defect, 78 ns down the line. In this example, the peak PASD pulse was 9.8 kV at a pulse width of 5 ns. The amplitude scale is the voltage measured at the sensor.

niques, including the use of multiple-pulse injection to improve PASD's response in long lines. PASD has been effectively demonstrated in wire harnesses up to 60 m (200 ft) in length.

Non-Destructive Nature of PASD

As effective as PASD can be, it would not be a viable diagnostic if it were destructive or degraded the properties of the wiring or connectors under test. A series of experiments were conducted to carefully quantify PASD's impact on typical aircraft wiring insulation including Teflon®, polypropylene, celluloid, and Mylar(r) [3]. Figure 3 shows the test fixture used during these experiments. Several types of experiments were conducted to evaluate the impact of a PASD breakdown on insulator surfaces. They included 1) exposing the sample to a series of PASD pulse breakdowns to evaluate whether the breakdown voltage decreased with subsequent pulsing; 2) performing a slowly rising DC breakdown test, applying a PASD pulse, and then repeating the DC breakdown test; and 3) effect of high-energy discharges on low-energy voltage breakdown strength.

Figure 4 shows data from the repeated application of a PASD pulse sufficient to break down the sample. The variation in breakdown voltages is statistical in nature. Figure 5 shows DC breakdown testing of a set of 21 insulation samples before and after the application of a PASD pulse. PASD did not reduce the surface flashover strength of any of the materials tested. The PASD arc breakdown process occurs very rapidly. The impedance of the arc channel falls to 10% of its initial value in approximately 3 ns. This is an important characteristic, as it improves PASD's ability to locate defects. Figure 6 shows typical breakdown PASD curves for insulation samples.

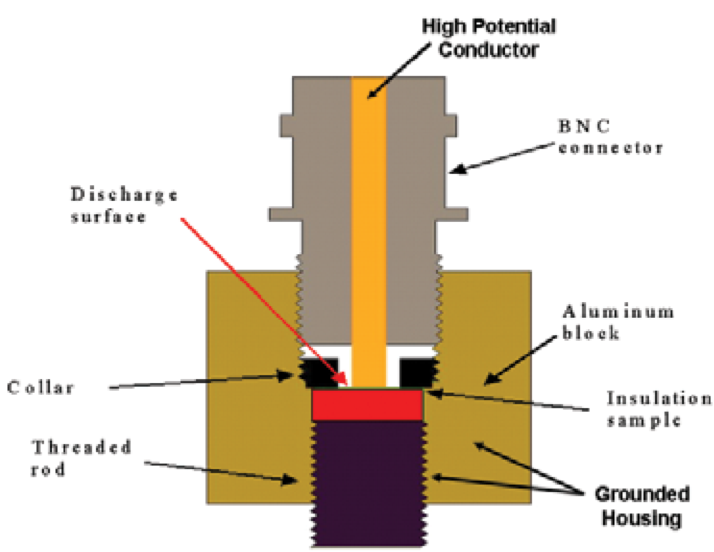

Figure 3. Test fixture used during flashover experiments. Eight-millimeter diameter insulation samples, shown in red, were inserted into the center of the figure. Breakdown occurs on the sample surface between the high potential conductor, which passes down through the BNC connector, and the grounded outer housing at the collar.

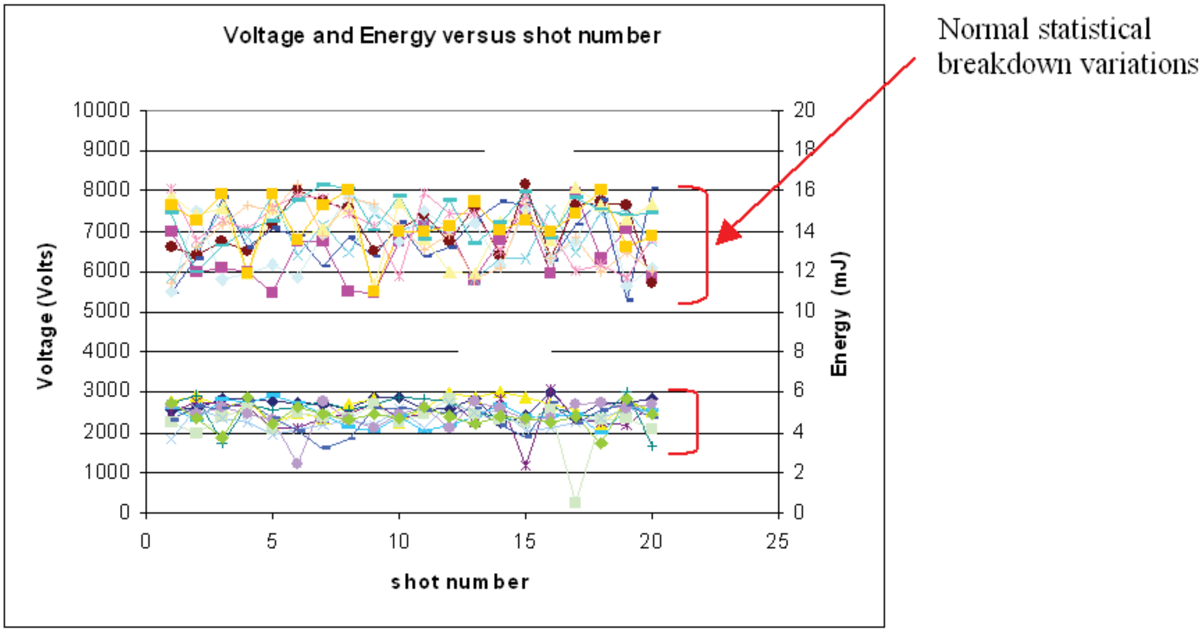

Figure 4. Typical breakdown results for an insulation sample exposed to repeated PASD breakdowns. Eight samples of the same dielectric material were exposed to 20 consecutive PASD breakdowns. The breakdown voltage of the samples did not tend to be lower. The average energy dissipated at the breakdown site was approximately 5 mJ per shot.

Ability of PASD to Locate Aircraft Wiring Defects

The PASD diagnostic has demonstrated that it can detect and locate chafing, cracking, pin-holes, and other breached insulation defects under laboratory conditions and during testing at the FAA's Airworthiness Assurance NDC Validation Center (AANC) in Albuquerque, NM [4]. These types of defects are documented in the ATSRAC publications *Intrusive Inspection Final Report*, December 2000 [5], and *Aging Transport Systems Task 1 and 2 Final Report*, August 2000 [6], which were comprehensive joint government-manufacturer-operator (industry) studies sponsored by the FAA.

Several types of defects were tested using the AANC test bed enclosure, which is a mock-up of aircraft wiring harnesses attached to aircraft-type aluminum panels. The PASD pulse was applied between different connector pins in a sequential manner to test a given set of conductors in the aircraft harness. The reflected signal was detected and recorded using a standard digi-

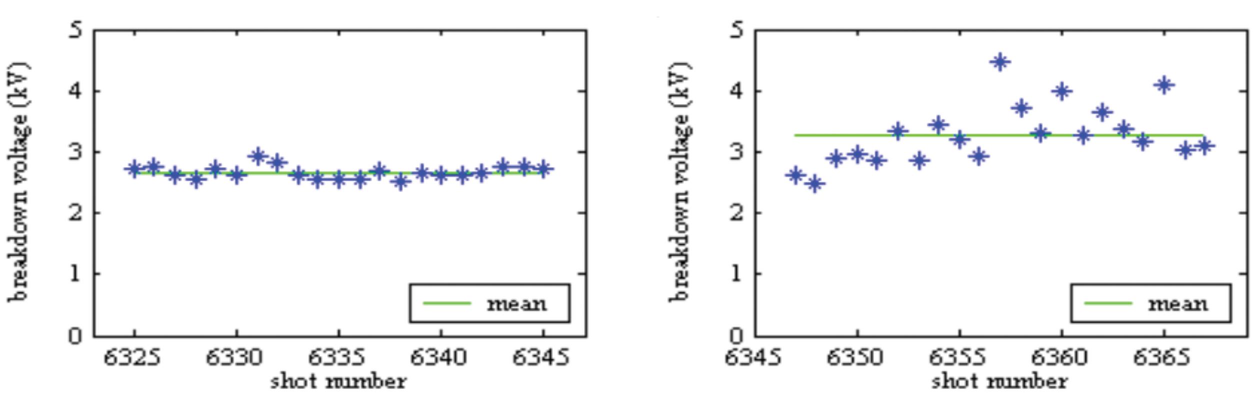

Figure 5. (Left) Example slow-rising, low-energy, DC breakdown voltages for multiple insulation samples. The samples broke down at an average of 2.8 ± 0.2 kV. (Right) When exposed to slowly rising DC after the application of the PASD pulse, the average breakdown voltages remained the same or actually increased. This is a common high-voltage conditioning phenomenon.

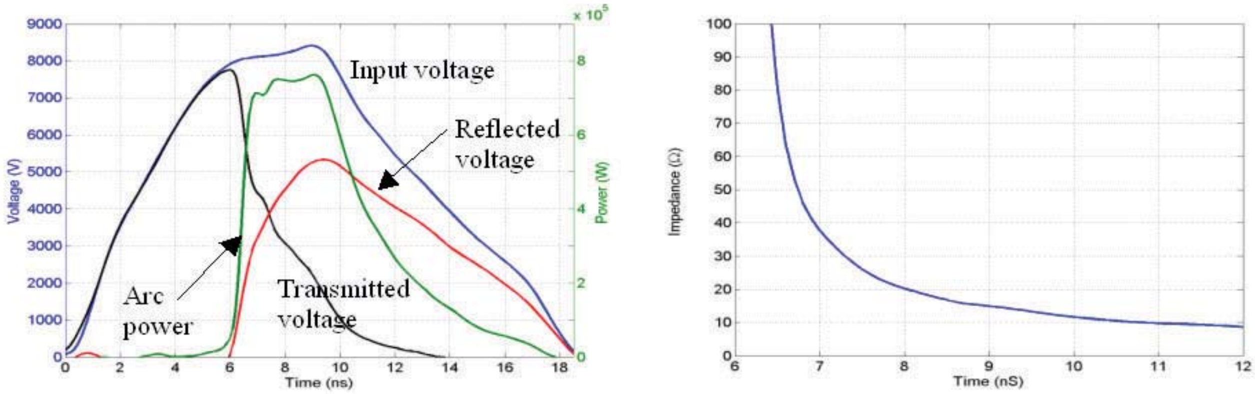

Figure 6. (Left) Arc impedance history. The power in the arc rises very rapidly (<2 ns), creating a fast-rising reflected voltage waveform. It is this waveform that sets the location accuracy of PASD. (Right) Typical arc impedance as a function of time.

tizing oscilloscope. Figure 7 shows the results on a 3-m pair of single wires, where one of the wires contained a insulation chafe (DT-1) defect. PASD is also effective on longer wiring runs. Early in the development of PASD, there was a concern that the high frequency content of the PASD pulse would not propagate efficiently down long lines containing insulation designed for low frequency performance. However, dispersion was not found to be a significant factor. As the PASD pulse propagates down long lines, the majority of the attenuation in the pulse amplitude is caused by the non-uniform impedance profile of the line. This is especially significant in loosely bound single wire pairs. Even with the lossy characteristics of typical aircraft wire insulation and the wide variation in line impedance, PASD performed well in testing at 30 m. For longer line lengths, a 1 to 2-kV DC pre-charge was applied to the line, then the PASD pulse. The pre-charge can be either a simple DC charge, or a pulse of a few microseconds. This "multipulse" approach is more effective that the single pulse approach when dealing with longer line runs. This result can readily be explained. In long lines, the constant impedance variations continuously erode the peak amplitude of the PASD pulse. If enough erosion occurs, there will be insufficient potential to break down a defect site. By applying a slowly rising pre-pulse, the potential along the entire line raised independent of the impedance variations. The fast risetime PASD pulse is then injected and propagates down the line to the defect site. Because the defect site is already charged to a kilovolt or so,

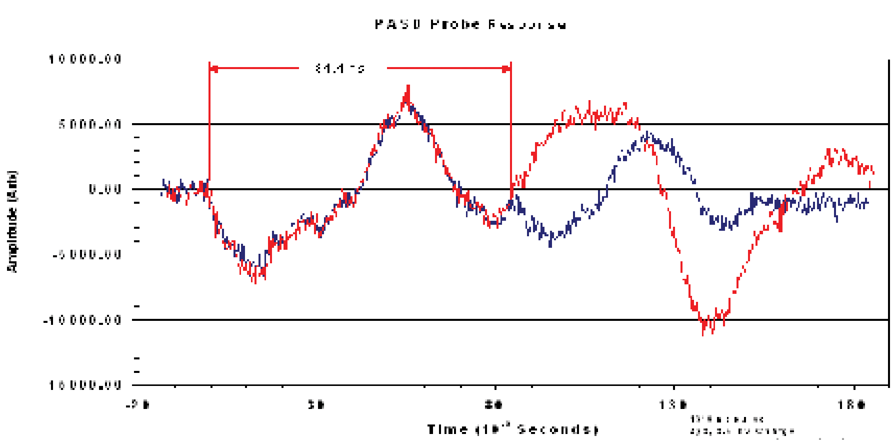

Figure 7. PASD probe waveforms for an insulation chafe defect (DT-1). The PASD waveforms separate at 84.4 ns. This implies that the defect was located at approximately 2.7 m (8.8 ft) from the injection end of the harness. The actual location of the defect was at 2.4 m (8.0 ft).

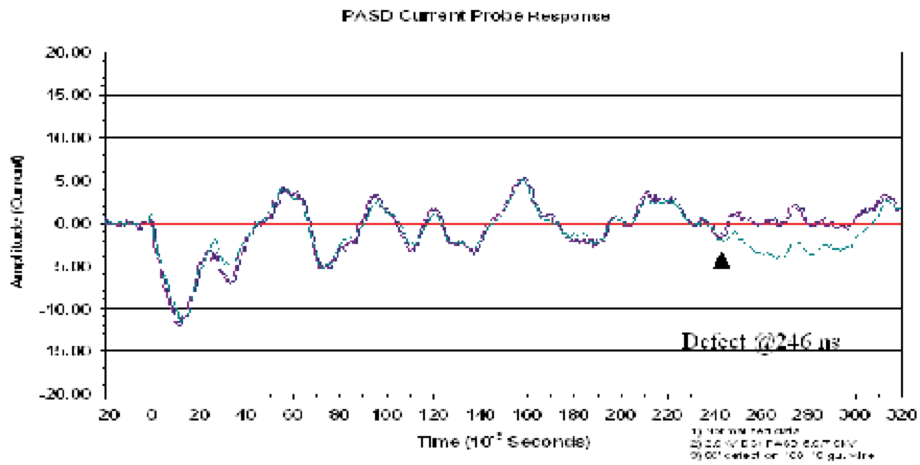

Figure 8. PASD waveforms from a test of a 3-m (100-ft) wire harness with an insulation defect at 24 m (80 ft). The two waveforms deviate at the location of the defect, 246 ns down the line. The variations in the waveforms are caused by a varying impedance profile down the harness. The nature of impedance variations is not important, as PASD uses a differencing technique to locate the defect.

it is much easier for the PASD pulse to breakdown the defect site. Figure 8 shows PASD waveforms from tests on a 30-m (100-ft) pair of wires using a multipulse approach. In this example, an insulation defect was present with a 1.0-mm air gap between two conductors with a small amount of insulation stripped away, exposing the center conductor

Table 1. Test results at the FAA's AANC wiring test bed. The gap spacing refers to the physical air gap from the exposed wire conductor to the nearest ground plane or adjacent grounded conductor. With a 1-mm air gap, PASD found 12 of 15 defects present, including challenging cracked insulator defects. PASD was 100% effective in locating chafe surfaces and breach defects with air gaps up to 1 mm.

Gap spacing	QTY	Defects detected	Defects undetected
DT-1 Insulation chafe defect			
1 mm gap	7	7	0
3 mm gap	5	3	2
DT-2 Insulation breach defect			
1 mm gap	2	2	0
3 mm gap	6	3	3
DT-3 Cracked insulation defect			
1 mm gap	6	3	3
3 mm gap	1	0	1
TOTAL	29	17	12

PASD performed well against an array of challenges presented by the AANC wiring test bed, including various defect types including chafes, breaches, and cracks in the insulation. Each of these ATSRAC defect types involves some degree of insulation removal down to the center conductor. A summary of the test results at the AANC is shown in Table 1.

Summary

PASD is effective at detecting and locating a variety of insulation defects in complex wiring geometries such as breached insulation, chaffing, and physically small insulation cracks. It is highly immune to line impedance variations, an important property in aircraft wiring systems, and has been shown to be nondestructive to electrical insulation materials. Because of the simplicity of the PASD concept, the low-energy PASD pulser and diagnostics can be readily implemented into a portable, briefcase-sized diagnostic system. Although this patented technique will likely evolve as it enters into field applications (pulse shape, testing strategy, etc.), it is capable of making a near-term impact on the ability of inspection and maintenance organizations to detect and locate potentially hazardous insulation defects. For further information on PASD, contact Larry Schneider, Deputy-Director, Pulsed Power Sciences Center, Sandia National Laboratories, Albuquerque, NM 87185-1152.

Acknowledgments

The authors acknowledge the FAA's William J. Hughes Technology Center for supporting the development of PASD for application in commercial aircraft wiring systems. We also acknowledge contributions by other contributors including John Barnum, Larry Warne, Roy Jorgenson, Gary Pena, and Parris Holmes at Sandia National Laboratories.

Appendix A

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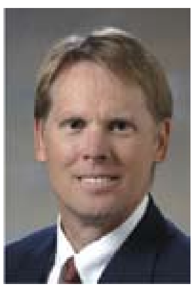

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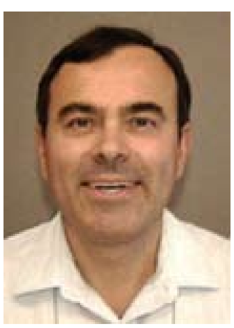

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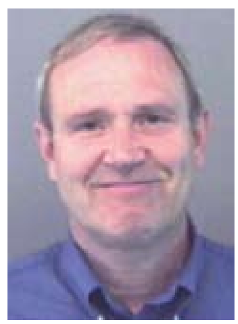

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