DOT/FAA/AR-05/49

Office of Aviation Research
Washington, D.C. 20591

Development and Validation of a Microenergy High-Voltage Technology for Aircraft Wiring

October 2005

Final Report

This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161.

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AR-05/49		

4. Title and Subtitle	5. Report Date
DEVELOPMENT AND VALIDATION OF A MICROENERGY HIGH-VOLTAGE TECHNOLOGY FOR AIRCRAFT WIRING	October 2005
	6. Performing Organization Code
7. Author(s) Michael Ballas, Steve Eisenhart, and Annette Garrison	8. Performing Organization Report No.
9. Performing Organization Name and Address General Dynamics 9845 Willows Rd. Redmond, WA 98052-2540	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Office of Aviation Research Washington, DC 20591	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code ANM-114

15. Supplementary Notes

The Federal Aviation Administration Airport and Aircraft Safety R&D Division COTR was Michael Walz.

16. Abstract

This report will introduce the reader to a suite of proactive diagnostic tools for commercial use, employing microenergy high-voltage (MEHV) technology for assessing the integrity of wire insulation. The MEHV specifically identifies those insulation breaches that are likely to or have already degraded to the point of failure, resulting in potential arcing between conductors or between a conductor and the aircraft frame or other low impedance paths to ground. The system has the unique ability to provide distance-to-fault determination, when arcing has not occurred under normal aircraft operating loads. The target application is in testing new and aged vehicle aircraft wire bundles for insulation breaches. MEHV is used to identify and locate compromised or damaged insulation. The MEHV technology was evaluated as a diagnostic concept for detection of defects by conducting validation tests, including safety and performance evaluation.

17. Key Words	18. Distribution Statement
Microenergy technology, Wire tester	This document is available to the public through the National Technical Information Service (NTIS) Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	71	

Form DOT F1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

Page

EXECUTIVE SUMMARY xi

1. INTRODUCTION 1-1

2. ArcSafe PRODUCT DESCRIPTIONS AND OPERATION 2-1

2.1 Micro-Energy Tool Description 2-1
2.2 Micro-Energy Tool Operation 2-2
2.3 Insulation Fault Probe Description 2-3
2.4 Insulation Fault Probe Operation 2-4

3. ENGINEERING DESIGN MODEL HARDWARE AND SOFTWARE COMPLETION 3-1

4. TECHNICAL DISCUSSION OF THE MET DISTANCE-TO-FAULT CALCULATION 4-1

4.1 Scope 4-1
4.2 Conceptual Description 4-1
4.3 Accuracy of the MET to Determine the Distance-to-Fault 4-3

4.3.1 Electromagnetic Field Coupling 4-3
4.3.2 Harness Loss and Dispersion 4-3
4.3.3 Characteristic Impedance Variations 4-4
4.3.4 Propagation Velocity 4-4
4.3.5 Arc Voltage 4-4

4.4 Empirical Data of the Accuracy of the MET in Determining the Distance-to-Fault 4-5

5. VALIDATION AND SAFETY EVALUATION 5-1

5.1 Micro-Energy Tool Nondestructive Nature Validation 5-1

5.1.1 Objective 5-1
5.1.2 Procedure 5-1
5.1.3 Summary 5-2
5.1.4 Observations 5-14

5.2 Insulation Fault Probe Nondestructive Nature Validation 5-16

5.2.1 Objective 5-16
5.2.2 Procedure 5-16

5.2.3 Summary 5-18
5.2.4 Observations 5-18

5.3 Detection and Identification Validation 5-21

5.3.1 Objective 5-21
5.3.2 Procedure 5-21
5.3.3 Summary 5-22
5.3.4 Observations 5-23

5.4 Compatibility and Field Testing Validation on an Aircraft Environment 5-28

5.4.1 Objective 5-28
5.4.2 Procedure 5-28
5.4.3 Summary 5-30
5.4.4 Results 5-30

5.5 Test Voltage and Safety 5-35

5.5.1 Micro-Energy Tool Test Voltage and Safety 5-35
5.5.2 Insulation Fault Probe Test Voltage and Safety 5-38

6. CONCLUSIONS AND RECOMMENDATIONS 6-1

6.1 Conclusions 6-1
6.2 Recommendations 6-1

LIST OF FIGURES

Figure		Page
2-1	Micro-Energy Tool	2-1
2-2	Block Diagram of the MET	2-2
2-3	Insulation Fault Probe	2-3
2-4	The IFP in Operation	2-4
2-5	Block Diagram of the IFP	2-5
3-1	The MET and IFP Prototype Configurations Prior to This Research	3-1
4-1	Idealized Breakdown Waveform	4-2
4-2	The MET-Reported Distance vs Actual Distance Data Displayed for Arcs Below 4000 V, Above 30 Feet in Distance	4-9
4-3	Percent Error of Distance vs Arc-Over Voltage All Long the Pulse Circuit Data Displayed Above 30 Feet in Distance	4-9
4-4	Fifty Feet to Fault, Coiled ETFE, Arc-Over at 5000 V	4-10
4-5	Fifty Feet to Fault, Coiled ETFE, Arc-Over at 600 V	4-10
4-6	Two Hundred Feet to Fault, Coiled ETFE, Arc-Over at 5000 V	4-11
4-7	Two Hundred Feet to Fault, Coiled ETFE, Arc-Over at 1000 V	4-11
4-8	Harness Wire 1, 75 Feet to Fault	4-12
4-9	Harness Wire 9, 21 Feet to Fault	4-12
4-10	Harness Wire 19, 99.7 Feet to Fault	4-13
5-1	Micro-Energy Tool Nondestructive Nature Test Setup	5-2
5-2	Polyimide (M81381/11)—200-ft Length—Initial Condition	5-3
5-3	Polyimide (M81381/11)—200-ft Length—After 126 Qualifying Arcs	5-3
5-4	Polyimide (M81381/11)—200-ft Length—After 627 Qualifying Arcs	5-4
5-5	Polyimide (M81381/11)—200-ft Length—Typical Arc	5-4
5-6	Polyimide (M81381/11)—100-ft Length—Initial Condition (MET Testing)	5-5

5-7	Polyimide (M81381/11)—100-ft Length—After 179 Qualifying Arcs	5-5
5-8	Polyimide (M81381/11)—100-ft Length—After 642 Qualifying Arcs	5-6
5-9	Polyimide (M81381/11)—100-ft Length—Typical Arc	5-6
5-10	Polyimide (M81381/11)—10-ft Length—Initial Condition	5-7
5-11	Polyimide (M81381/11)—10-ft Length—After 128 Qualifying Arcs	5-7
5-12	Polyimide (M81381/11)—10-ft Length—After 617 Qualifying Arcs	5-8
5-13	Polyimide (M81381/11)—10-ft Length—Typical Arc	5-8
5-14	ETFE (M22759/34)—200-ft Length—Initial Condition	5-9
5-15	ETFE (M22759/34)—200-ft Length—After 131 Qualifying Arcs	5-9
5-16	ETFE (M22759/34)—200-ft Length—After 652 Qualifying Arcs	5-10
5-17	ETFE (M22759/34)—200-ft Length—Typical Arc—After 500 Events	5-10
5-18	ETFE (M22759/34)—100-ft Length—Initial Condition	5-11
5-19	ETFE (M22759/34)—100-ft Length—After 136 Qualifying Arcs	5-11
5-20	ETFE (M22759/34)—100-ft Length—After 856 Qualifying Arcs	5-12
5-21	ETFE (M22759/34)—100-ft Length—Typical Arc	5-12
5-22	ETFE (M22759/34)—10-ft Length—Initial Condition	5-13
5-23	ETFE (M22759/34)—10-ft Length—After 101 Qualifying Arcs	5-13
5-24	ETFE (M22759/34)—200-ft Length—Typical Arc	5-14
5-25	Arc Voltage Distribution for MET Nondestructive Test	5-16
5-26	Insulation Fault Probe Nondestructive Nature Test Setup	5-17
5-27	Polyimide (M81381/11)—100-ft Length—Initial Condition (IFP Testing)	5-18
5-28	Polyimide (M81381/11)—100-ft Length—After 120 Repetitions	5-19
5-29	Polyimide (M81381/11)—100-ft Length—After 370 Repetitions	5-19
5-30	ETFE (M22759/34)—75-ft Length—Initial Condition	5-20
5-31	ETFE (M22759/34)—75-ft Length—After 120 Repetitions	5-20

5-32	ETFE (M22759/34)—75-ft Length—After 370 Repetitions	5-21
5-33	Micro-Energy Tool Detection and Identification Test Setup	5-22
5-34	Harness 553, Wire 9, Total Length of Harness is 200 Feet, Arc-Over at 3500 V	5-27
5-35	Harness 552, Wire 24, Total Length of Harness is 100 Feet, Arc-Over at 3700 V	5-27
5-36	The 100-ft Harness, Distance-to-Fault is 100 Feet, Arc-Over at 3500 V	5-28
5-37	Using the MET to Scan the Test Harnesses	5-29
5-38	Using the IFP to Scan the Test Harnesses	5-30
5-39	Harness 570, Wire 13, Arc-Over at 2000 V	5-34
5-40	Harness 570, Wire 19, Arc-Over at 2000 V	5-35

LIST OF TABLES

Table		Page
4-1	Observed Echo Voltage Pulse Width and Second Edge Fall Time Rows Sorted by Wire Length	4-7
4-2	Distance Calculated From Echo Pulse Width Based on Propagation Velocity of 71% Speed of Light Rows Sorted by Wire Length	4-7
4-3	Comparison of Accuracy Using an Oscilloscope to Detect Distance-to-Fault With Accuracy Using a MET to Detect Distance-to-Fault	4-8
5-1	Harnesses Prepared for MET Nondestructive Nature Validation	5-1
5-2	Arc Events for MET Nondestructive Test	5-15
5-3	Harnesses Prepared for IFP Nondestructive Nature Validation	5-16
5-4	Harnesses Prepared for the Detection and Identification Test	5-22
5-5	Harness 551, Polyimide (M81381/11), 12 Conductors, 10-ft Length	5-24
5-6	Harness 552, Polyimide (M81381/11), 12 Conductors, 100-ft Length	5-24
5-7	Harness 553, Polyimide (M81381/11), 12 Conductors, 200-ft Length	5-25
5-8	Harness 561, ETFE (M22759/34), 12 Conductors, 10-ft Length	5-25
5-9	Harness 562, ETFE (M22759/34), 12 Conductors, 100-ft Length	5-26
5-10	Harness 563, ETFE (M22759/34), 12 Conductors, 200-ft Length	5-26
5-11	Harness Prepared for Compatibility and Field Testing	5-29
5-12	Harness 570	5-31
5-13	Harness 580	5-33

LIST OF ACRONYMS

ac	Alternating current
EDM	Engineering development model
ESD	Electrostatic discharge
ETFE	Ethylene-tetrafluoroethylene
FAA	Federal Aviation Administration
GD	General Dynamics
Hi-pot	High potential testing
IFP	Insulation Fault Probe
LRU	Line replaceable unit
MEHV	Microenergy high voltage
MET	Micro-Energy Tool
TDR	Time-domain reflectometry

EXECUTIVE SUMMARY

This report provides validation and test results of the MEHV tool suite (ArcSafe), developed by General Dynamics. The tool consists of two major system components, the Micro-Energy Tool (MET) and the Insulation Fault Probe (IFP). The technology uses high-voltage (0-5000 Vdc), low-current (microamp) energy to locate cracks in wires. The MET, in particular, has the ability to energize a wire under test. If a crack in the insulation (exposed conductor) is present and a nearby ground path (either the frame or an adjacent exposed wire) exists, a low-energy spark is generated, which the MET uses as the driver for a time-domain reflectometry calculation, providing a distance-to-fault calculation. The IFP works as a fine tune (sniffer) fault locator. It also uses a high-voltage source in conjunction with a helium flow to induce electron streaming across an air gap into an insulation crack. With the cable under test grounded, the IFP induces current flow through the wire and a return path back to the IFP, giving both audible and visual feedback to the user. These tools may be used in tandem or as stand-alone fault diagnostic tools.

Tests conducted involved nondestructive validation, fault detection and identification validation, wire compatibility testing, and safety analysis.

Laboratory and on-aircraft tests were conducted at Sandia National Laboratories for all validation exercises. Nondestructive nature validation involved cyclic testing of wire harnesses (condition, wire length, and voltage levels) to determine if recurring spark events would further degrade the integrity of the wire insulator. In most cases, even after hundreds of spark events, microscope investigation revealed little if any damage to the wire insulator.

Fault detection, identification, and wire compatibility testing were performed on both the wire test bed and on-aircraft evaluation, given both polyimide (M81381/11) and ethylene-tetrafluoroethylene (M22759/34 wire types of varying lengths and defect types (i.e., cuts, abrasions, etc.). The objective was to determine the MET's and IFP's ability to identify the existence of faults and assess the accuracy and repeatability of the measured results. Tests were conducted over a range of voltages and faults and were characterized accordingly. Generally, it was determined that the ArcSafe tools (MET and IFP) were able to find and locate some faults successfully; however, it became apparent that the geometry of the wire harness (i.e., how loosely wires are packed in the harness) and the number of breakouts (terminations) on a given harness are contributing factors influencing the MET's reporting accuracy.

The discussion on user safety was based on published human factors data. Given the very low operating currents (microamps) that the MET and IFP operate at, it can be stated that these tools are intrinsically safe. However, preventing damage to equipment requires reasonable precautionary measures. The MET requires that the wire harness under test have all loads disconnected (i.e., floating). Care must be taken to ensure that this is the case prior to testing to avoid damage to sensitive circuitry and dangerous components such as fuel tanks. The IFP requires a low impedance path to ground, which can be through a connected line replaceable unit. However, it is recommended that an alternative path to ground (i.e., shorting plug) be used instead to avoid potential damage to sensitive electronics.

1. INTRODUCTION.

The purpose of this research was to develop and validate microenergy high-voltage (MEHV) technology for aircraft testing. ArcSafe is a suite of MEHV tools developed by General Dynamics (GD) under FAA sponsorship to aid an operator in identifying and locating breaches in wiring insulation. The ArcSafe suite of tools currently consists of the Micro-Energy Tool (MET) and the Insulation Fault Probe (IFP).

The continued safe operation of aircraft well into their expected service life depends on the safe and effective transfer of power and electrical signals between aircraft electrical components. This, in turn, requires the verification of a wire's physical and functional integrity. Since wire is treated as an indefinite life system, formal periodic inspections are necessary to ensure its continued safe operation.

The Federal Aviation Administration (FAA) is conducting a number of research projects addressing aging aircraft concerns. The particular purpose of this research project was the development and validation of MEHV technology and the fabrication of a fully functional engineering design model (EDM). The system was designed to be suitable for infrequent, comprehensive examinations or frequent focused inspections in an airline maintenance environment.

The MEHV method is a qualitative way of testing the integrity of wire insulation. MEHV specifically identifies those insulation breaches that are likely to or have already degraded to the point of failure, resulting in arcing between conductors or between a conductor and the aircraft frame or other low impedance paths to ground.

The target application is the test of new and aged aircraft wire bundles for insulation breaches. MEHV tests dielectric performance of insulation on wire conductors and is intended to be used in

- aircraft manufacturing, modification, and repair operations to ensure installed wiring insulation has not been damaged to the point that safety would be compromised.
- aircraft maintenance operations (C or D checks) to verify that wiring insulation has not degraded or been damaged to the point that safety is compromised or would be compromised in the near future.
- line repair operations in which an arc fault circuit interrupter has tripped and the cause must be identified and located.

2. ArcSafe PRODUCT DESCRIPTIONS AND OPERATION.

2.1 MICRO-ENERGY TOOL DESCRIPTION.

The MET (figure 2-1) uses a new approach to identify and locate breaches in wiring insulation. It identifies insulation breaches that are nearing or have already degraded to the point of arcing from conductor to conductor or to another low impedance path such as the aircraft frame. It identifies these breaches in a manner similar to high potential (Hi-pot) testing; however, the energy available to dissipate at a breach is limited to a value much lower than what occurs using traditional Hi-pot methods. When the breach arcs over, the voltage at the breach collapses and initiates a traveling wave that echoes back and forth between the ends of the cable and the breach location. The MET analyzes the resulting waveform and estimates the length of wire between the MET and the breach in a way that is similar to that used by time-domain reflectometry (TDR).

FIGURE 2-1. MICRO-ENERGY TOOL

Although the MET is similar to Hi-pot and TDR, it has some major differences. The MET addresses the problem of insulation breach detection and location, as discussed below.

Hi-pot testing identifies breaches, but it does not attempt to locate the fault. Hi-pot testers are used to screen for insulation breaches, but typically only source up to 2000 V at greater than 5 mA. When a breach arcs over, the high current can cause damage to the wiring insulation and neighboring equipment. The MET can source up to 5000 V, but the current sourced will be less than 100 μA. The MET was designed to provide an operator with a settable limit to the resulting energy dissipated at the breach. The MET senses how much energy is stored on the wire under test and will not charge the wire higher than the energy limit set by the operator. This provides a means of ensuring that the MET will not degrade the breach further than what existed prior to testing.

Traditional TDR techniques determine the location of shorts and opens on wiring. The traditional TDR approach will not locate breaches in insulation that do not result in a short, as they do not present a distinct characteristic impedance discontinuity for the TDR pulse to reflect against. The MET approach causes an arc to occur at the breach using an elevated potential, with the subsequent collapsing voltage at the breach initiating a rapid falling-edge wave front. The breach will then appear as a significantly reduced impedance until the energy stored in the wiring field has been dissipated. By monitoring the reflection characteristics at the end of the wire, the MET is able to calculate the length of the wire between the end of the wire and the breach.

2.2 MICRO-ENERGY TOOL OPERATION.

The MET is operated through a Windows-based software interface running on a laptop computer that serves to configure the tool and record the results of test sequences. To be tested, the harness has to be first disconnected or otherwise made open circuit at both ends. One end of the harness is then connected to the MET using a short adapter cable or, in some cases, individual pigtail pins. The MET grounds all wires except the single wire under test. A current source (< 100 μA) charges the wire under test to a selected voltage level (5000 V maximum). If an insulation breach is located, an attempt is made to determine the distance to the fault. When testing is complete for that wire, the MET sequences to the next wire, if directed by the software interface. Figure 2-2 shows a block diagram of the MET.

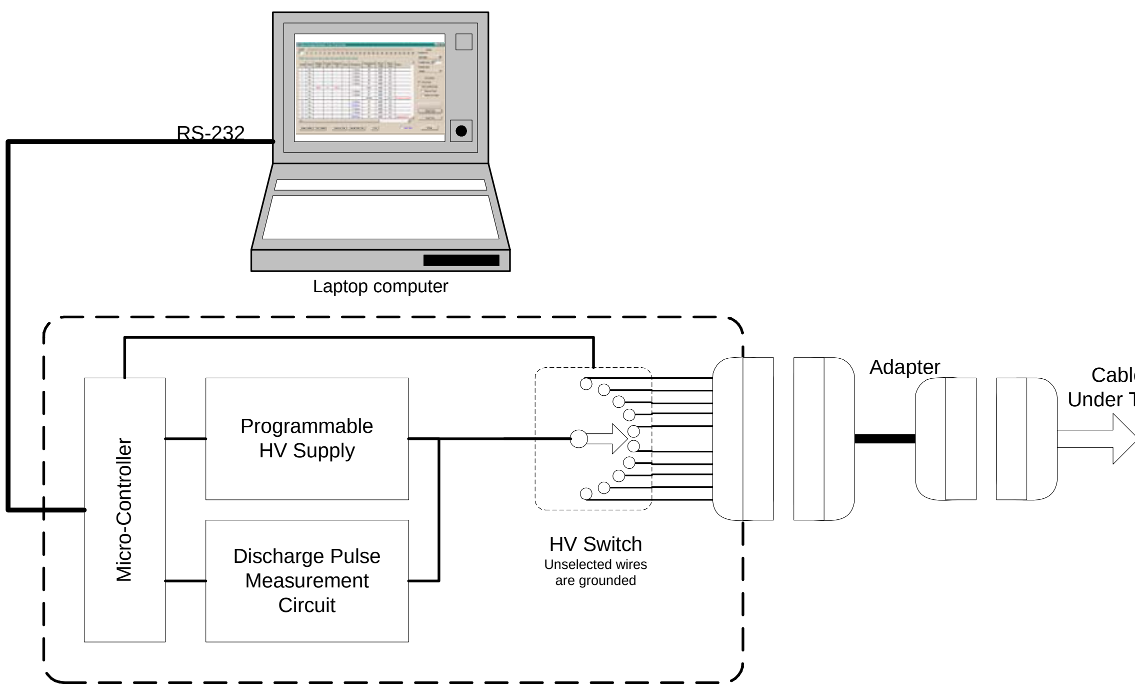

FIGURE 2-2. BLOCK DIAGRAM OF THE MET

2.3 INSULATION FAULT PROBE DESCRIPTION.

The IFP's principle of operation is similar to that of an ohmmeter. However, the use of high voltage (with current limited to less than 5 μA) and helium gas allows the tool to find breaches in insulation without direct galvanic contact. The IFP functions as a fine-tune (sniffer) fault locator. It also uses a high-voltage source in conjunction with helium flow to induce electron streaming across an air gap into an insulation crack. With the cable under test grounded, the IFP induces current flow through the wire and a return path back to the IFP, giving both audible and visual feedback to the user.

The IFP (figure 2-3) uses the principle of electron streaming through pure helium gas to detect and locate exposed conductors in a cable harness. When the trigger on the probe is actuated, a current-limited (<5 μA), high-voltage (1-6 kV adjustable) source is applied to the pointed needle in the probe tip and pure helium gas flows past the tip into the intervening space between the needle and the harness. Electron streamers are emitted from the probe tip through the helium. If these streamers find any exposed conductors, a minute current will flow across the physical gap. The amount of current that flows is approximately proportional to the distance traversed. The operating range is from several inches of separation between the probe tip and exposed conductor all the way to direct contact with the exposed conductor.

FIGURE 2-3. INSULATION FAULT PROBE

2.4 INSULATION FAULT PROBE OPERATION.

Just as using an ohmmeter, the IFP has two test leads. One lead is the ground lead, and the other lead is the high-voltage needle in the probe tip that scans along the harness under test. Figure 2-4 shows the IFP in operation.

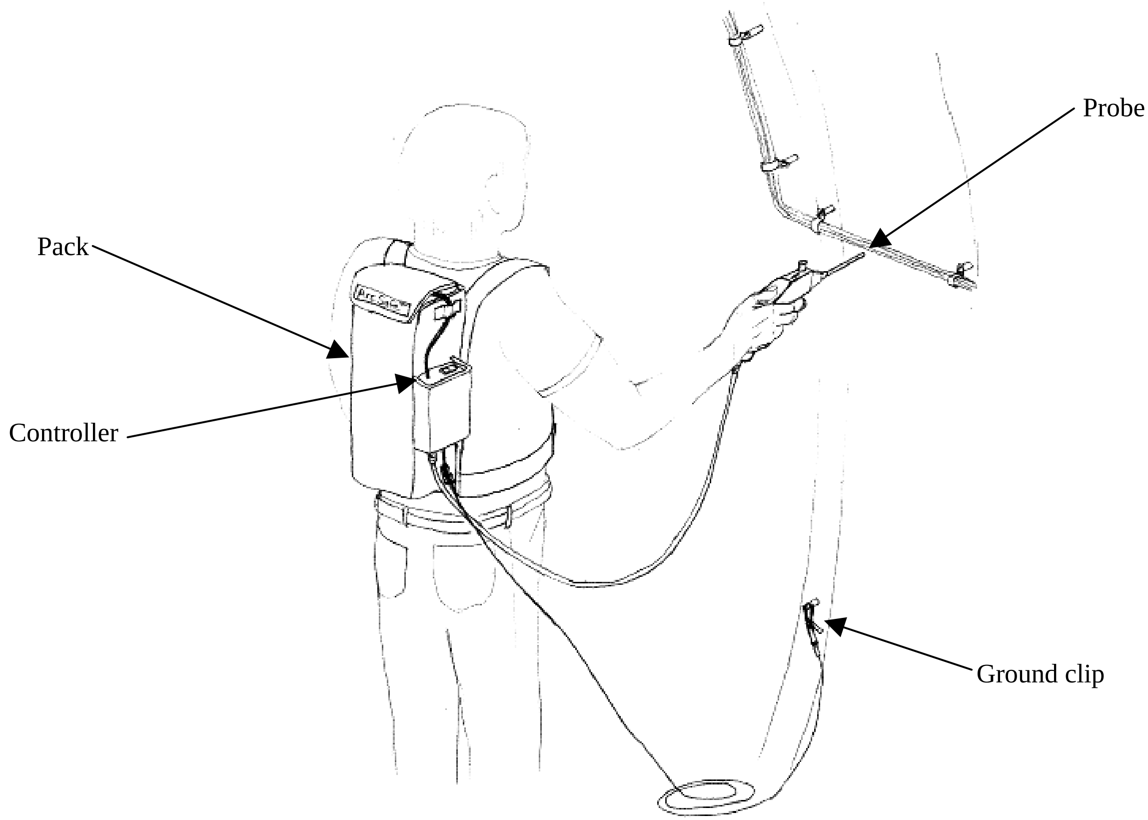

FIGURE 2-4. THE IFP IN OPERATION

The ground lead is attached to the return path for the harness under test. If the harness is attached through typical loads to the aircraft chassis, attaching the ground lead to any ground stud on the aircraft frame will work well. As a rule of thumb, each wire in the harness under test should have a path to the ground lead that is less than 1 megohm. Note that with the current-limited output of the IFP, no more than 6 V can be developed across a 1-megohm load, even if direct galvanic contact is made between the probe tip and the conductor under test.

If an adequate ground from the harness to the aircraft frame is not already available, one can be made using the MET. The MET input connector (which has 40 possible inputs) has a low enough impedance path to the MET ground jack to act as a ground adapter for the IFP. In this setup, the harness under test is attached to the MET input connector, and the MET ground jack is attached to the aircraft frame. The IFP ground lead is attached to the aircraft frame as well.

(The MET and IFP aircraft frame connection points do not have to be at the same location, i.e., the MET ground can be made at one end of the aircraft, and the IFP connection made at the opposite end. These tools may be used in tandem or a stand-alone fault diagnostic tools.)

With the ground lead connection made, the IFP is pointed at the harness about 1 to 3 inches away and moved along its length while listening or watching for an indication of a fault. A speaker emits a sound, with a repetitive audio pattern, to indicate the presence of a fault. There is also an indicator light on the probe that flashes in concert with the audible indicator. The repetition rate of the indicators increases as the probe approaches the fault. The probe can be moved back and forth to find the maximum signal strength.

Figure 2-5 shows a block diagram of the IFP.

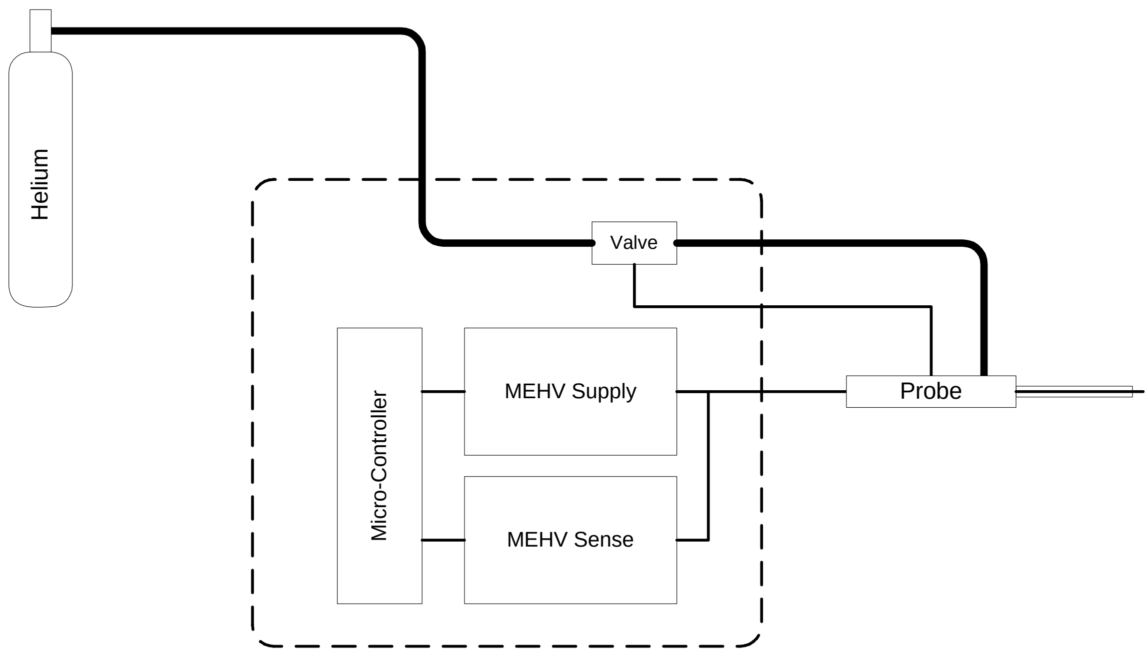

FIGURE 2-5. BLOCK DIAGRAM OF THE IFP

3. ENGINEERING DESIGN MODEL HARDWARE AND SOFTWARE COMPLETION.

Prior to this research, GD was engaged in independently investigating MEHV and arc fault detection technology. MEHV technology development was under development for several years by RB Labs (under a license agreement with General Dynamics-Airborne Electronic Systems). Several prototype configurations for the MET and IFP tools were manufactured. Early laboratory tests, using the MEHV breadboards, showed promise in detecting and locating breaches in harness insulation.

FIGURE 3-1. THE MET AND IFP PROTOTYPE CONFIGURATIONS PRIOR TO THIS RESEARCH

One major goal of this research was to complete the prototype design, focusing on the ease of use, reliability, and maintainability. The MET and IFP designs were completed, with a design review held at the FAA William H. Hughes Technical Center.

The EDM design efforts completed as part of this research were

- Circuits design finalized.
- Optimized the MET pulse detect circuit. Investigated several approaches.
- Designed a 40-position, high-voltage sequencer for the MET. Evaluated several mechanical and solid-state approaches.
- Completed firmware and associated documentation.
- Created a complete production drawing package.
- Produced three EDM units.

4. TECHNICAL DISCUSSION OF THE MET DISTANCE-TO-FAULT CALCULATION.

4.1 SCOPE.

A simplified conceptual description of the MET distance-to-fault calculation technique is presented. Empirical data are presented that addresses the accuracy of the MET to determine the distance to a fault.

4.2 CONCEPTUAL DESCRIPTION.

The goal of the MET was to aid in the detection and location of wiring insulation breaches. The success of this tool was measured in terms of whether the breach was detected, and whether it was located. The MET will detect a breach if it results in a condition where an application of up to 5000 V causes a dielectric breakdown to occur between two conductors or conductive surfaces. When a dielectric breakdown is detected, the next step in the process is to locate where that breakdown is occurring. The MET distance-to-fault calculation technique exploits the characteristic of electromagnetic waves traveling along imperfect transmission lines.

When the breakdown occurs, the voltage at the fault collapses and initiates a traveling wave that echoes back and forth between the ends of the cable and the fault location. These waves initiate at the arc and travel down the harness, reflecting at impedance boundaries. Under ideal test conditions, the traveling waves will produce an echo voltage at the end of the harness that is square in nature, with a period proportional to the distance to the fault. The MET determines the distance-to-fault by detecting the time between the first and second edge of the breakdown waveform voltage at the end of the harness and using this value to determine the distance to the fault.

Figure 4-1 shows the breakdown waveform. Assume the harness wire is charged to some voltage. At time (A), an arc breakdown occurs somewhere down the length of the wire. A summary of the wave events that occur is as follows:

- Time (A)—Arc occurs. Not sensed at MET until time (B)
- Time (B)—Wave arrives at MET and sensed voltage reverses. Wave travels back towards fault.
- Time (C)—Wave arrives back at fault.
- Time (D)—Wave arrives back at MET.
- Time (E)—Wave arrives back at fault.
- Repeats until the energy in the cable dissipates.

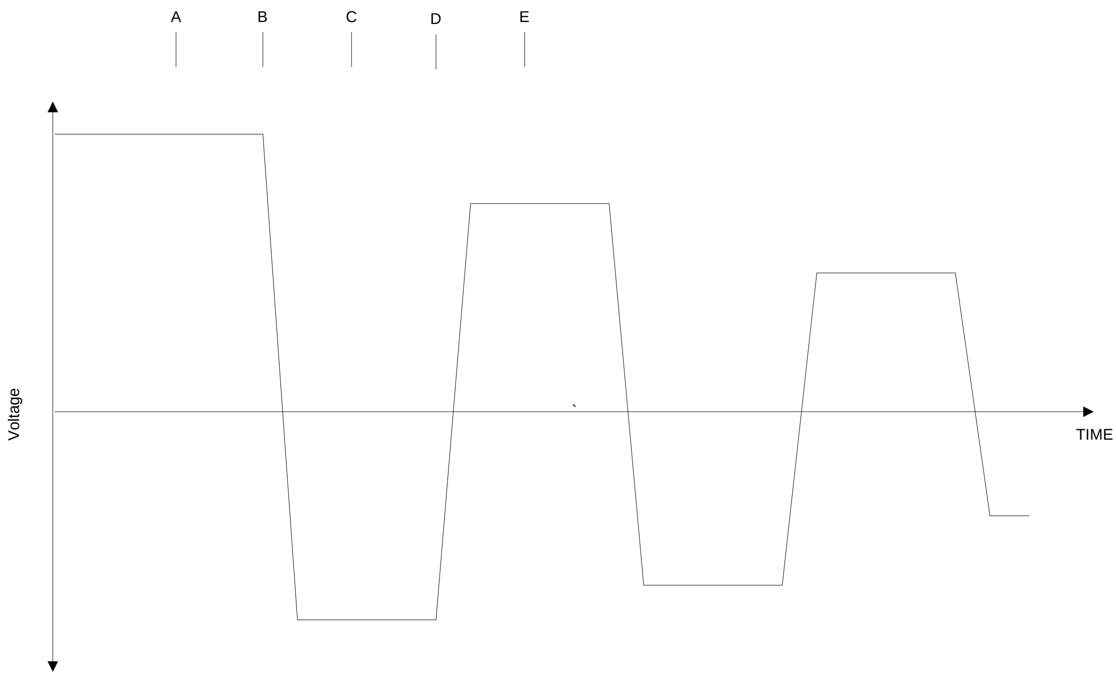

FIGURE 4-1. IDEALIZED BREAKDOWN WAVEFORM
(See list above for description.)

Note that the waveform in figure 4-1 is only valid at the open ends of the harness.

- At the fault, the voltage will be much closer to 0 V after the initial arc, with the voltage developed being a function of the arc impedance and fault current.
- At points midway between the fault and the MET, the wave will step from +V, to ~0, to -V, to ~0, to +V, to ~0, etc.

If the propagation velocity of the cable is known, the distance to the fault can be determined by measuring the time between the edges at time (B) and at time (D). This is the time it takes for the wave to travel from the MET back to the fault, and then back to the MET. The total distance traveled is given by

$$d_{total} = \upsilon_{propogation} * t_{D-B}$$

The distance from the MET to the fault is half the total distance traveled, thus

$$d_{fault} = \frac{d_{total}}{2} = \frac{\upsilon_{propogation} * t_{D-B}}{2}$$

4.3 ACCURACY OF THE MET TO DETERMINE THE DISTANCE-TO-FAULT.

The conceptual model presented so far occurs for controlled impedance transmission lines such as coaxial cable or twisted pair. Not all aircraft wiring harnesses are controlled impedance transmission lines. Tests showed that usable results can often be obtained for the uncontrolled impedance transmission lines that occur for many aircraft wiring bundles.

The MET is able to calculate a distance-to-fault when the resulting echo voltage contains distinguishable edges that physically originate due to wave reflections at the end of the harness and the fault. The physical properties of a wire harness that determine, and ultimately limit, the ability of the MET to accurately determine the distance-to-fault are:

- Electromagnetic field coupling to other conductive structures
- Harness loss and dispersion
- Characteristic impedance variations of the harness between the fault and the MET
- Propagation velocity of the traveling wave
- Arc voltage

4.3.1 Electromagnetic Field Coupling.

The dominant traveling wave is between the two conductive structures that arc together, whether it be wire-to-wire or wire-to-ground plane. However, field energy will also couple between other adjacent conductive structures, such as other wires in the harness or a nearby conductive plane. This coupled field essentially removes energy from the primary traveling wave, resulting in a faster decay of the echo voltage, and provides less discernable edges than would otherwise occur.

The MET has the ability to short all wires in the harness under test except the specific wire under test. This facilitates determining if the specific wire under test has a short to any other wires. However, a direct short termination at the MET would result in a greater energy loss in the primary traveling wave, as the coupled wave would reflect off a short termination, where the primary wave would reflect off an open termination. The coupled reflections would be opposite in amplitude to the primary reflection and would result in field cancellation and a reduction in the primary wave's voltage amplitude. For this reason, each harness wire is terminated in 100 ohms prior to connecting to the grounding ring. This resistance is close to the approximate characteristic impedance of a typical harness and results in a lower-coupled wave reflection, resulting in less primary wave loss.

4.3.2 Harness Loss and Dispersion.

Harness loss plays a role in determining how fast the traveling waves amplitude decays, resulting in less discernable edges.

Dispersion causes different frequencies to travel at different velocities, ultimately causing the edges of the echo voltage to have longer rise and fall times for successive edges. Longer rise and fall times create an accuracy error since the pulse width depends on where on the edge the transition is detected, and it also makes it more difficult to discern the true edge from other edges caused by impedance variations between the arc fault and the MET.

4.3.3 Characteristic Impedance Variations.

Slight characteristic impedance variations occur as a result of physical features such as the wire changing separation distance or running through a bulkhead connector.

In the extreme, characteristic impedance variations between the arc fault and the MET can cause echo voltage waveform edges that are not distinguishable from the desired edges that occur at the end of the wire and the fault. Analyzing the entire echo voltage waveform after the fault occurs can aid in discerning the desired edges from the minor edges that occur during slight characteristic impedance variations along the wire.

A significant difficulty occurs when the faulted wires branch off in separate paths. Part of the wave continues toward the MET and the other part along the new path. The split off wave will continue along a separate path, reflecting off impedance boundaries, creating a new set of waves in addition to the primary wave traveling towards the MET. This situation compounds itself rather quickly. This creates edges in the echo voltage that often make it impossible to decipher which edge corresponds to an echo off which physical feature.

4.3.4 Propagation Velocity.

The propagation velocity of the voltage wave is a function of the permittivity of the material between the conductive wires. For air, the propagation velocity is the speed of light. If the space is filled with an insulation material such as Teflon, the propagation velocity is more like 7/10 the speed of light. If the space is filled with both wire insulation and air, the propagation velocity will lie between these two values, strongly influenced by which material most of the electromagnetic field is propagating in.

An uncertainty in the propagation velocity will carryover to the MET distance-to-fault calculation. For special circumstances, the propagation velocity will be accurately known, such as for coaxial cable. For uncontrolled impedance wiring, the propagation velocity will not be accurately known, and just as likely will not be constant over the entire run of the harness. Acceptable results can be obtained for the majority of harness cases by assuming the propagation velocity is 7/10 the speed of light. This will yield a calculation that often has an error of less than 10%.

4.3.5 Arc Voltage.

The magnitude of the arc breakdown voltage has some influence on the shape of the voltage wave edges. Some explanations for this include the following:

- The higher the arc-over voltage, the more energy that is stored on the wire harness. The energy stored on the wire has to be high enough to maintain a low impedance arc at the fault for at least as long as it takes for the voltage wave to travel from the arc to the MET and back to the arc. This ensures the arc will still look like a short when the wave returns.

- Too high a voltage, and the resulting wave radiation causes longer edge rise times. Part of the energy travels on the transmission line at a reduced speed, and part of it travels through the air at the speed of light. This energy couples back into the harness and test equipment, modifying the detected wave shape.

- Test results at suggest that the best formed waves for detecting occur at arc-over voltages of about 3000 V, with accuracy decreasing somewhat at higher and lower arc-over voltages.

4.4 EMPIRICAL DATA OF THE ACCURACY OF THE MET IN DETERMINING THE DISTANCE-TO-FAULT.

Several wire harness configurations were created to determine the accuracy of the MET in determining the distance to a fault.

It should be noted that for reasons as described in section 4.3, a harness can be configured so that the accuracy of fault detection is quite high (within 5%), or configured so that a distance cannot be determined at all. A distance cannot be determined under two conditions:

- The voltage wave decays so quickly, there is not a second edge to detect.

- Reflection edges occur at impedance discontinuities that are as high in amplitude as those due to reflection off the MET and the fault.

The data presented was collected by using the MET to scan the test harness and by observing the voltage waveform at the MET. For the oscilloscope captures shown, the waveform was alternating current (ac) coupled, and the arc-over voltage was a negative value. This creates a waveform that is inverted from the ideal waveform depicted in figure 4-1, and has the direct current component removed.

The data presented in this section were gathered from tests performed on test harnesses created:

- One harness with 24 conductors. Wires 1, 6, 10, 13, 15, 16, 17, 18, 19, and 20 had faults. The distance-to-fault ranged from 21 to 126 feet. The harness was routed back and forth on two sides of a 4′ by 8′ aluminum plane. The harness is mounted approximately 1″ from the aluminum plane.

- 200-ft coiled ETFE wire pair.

- 102-ft coiled polyimide wire pair.

- 102-ft uncoiled polyimide wire pair.

- 50-ft coiled ETFE wire pair.

- 15-ft coiled ETFE wire pair.

The wire pairs were terminated to a custom spark device that allowed the spark-over voltage to be adjusted. The harness on the aluminum ground plane did not have faults that could have their arc-over voltage adjusted. These harness configurations provide a sampling of the MET distance-to-fault calculation performance when testing harnesses that are adjacent to a ground plane and harnesses not adjacent to a ground plane.

The collected data reveals several general properties:

- The leading edge of the echo waveform is always fast. Measured values indicate a rise time of greater the 10 nanoseconds.
- Due to dispersion and other losses, the second and subsequent edges can be slowed substantially or nonexistent. Sometimes the echo voltage is sinusoidal in appearance, without distinct edges. Under these circumstances, there is considerable error in the calculated distance to the fault.
- The test harness configurations resulted in fall times that range from 6% to 32% of the echo voltage pulse width. Note that the fall time may be subject to interpretation due to some waveforms having a sinusoidal shape resulting in an unclear or pessimistic fall time interpretation.
- For a lossless transmission line, the leading edge and second edge will have equal amplitudes. For an actual wiring harnessed laid on a conductive structure, the second edge can be quite a bit lower in amplitude than the leading edge and almost nonexistent.
- As actual pulses may not be square in nature, it was determined the most accurate method of determining the pulse width of echo voltages was measuring the time from when the leading edge was first detected to the point when the echo voltage first starts falling on the edge that was determined to represent the reflection off the fault. This is in contrast to the MET implementation, which, for practical reasons, typically detects the pulse width close to the bottom portion of the second edge.

Table 4-1 presents the observed waveform pulse width along with the fall time of the second edge. This table gives an indication of how much error is introduced, depending on where on the second edge a pulse-width detect circuit triggers. As just noted, the MET pulse-width detect circuit typically triggers low on the second edge to avoid false tripping on minor reflection edges. The subsequent error is compensated for by the time-to-distance conversion algorithm.

For practical testing, the propagation velocity is not known. An assumed fixed propagation velocity of 71% of the speed of light produced the least error over the entire set of test harnesses. These data are presented in table 4-2. The percent error ranges from 2% to 12%.

Tables 4-1 and 4-2 present data collected using measurements obtained using an oscilloscope. The MET contains a pulse-width detect circuit, and the distance-to-fault is automatically calculated and displayed on the laptop interface.

TABLE 4-1. OBSERVED ECHO VOLTAGE PULSE WIDTH AND SECOND EDGE FALL TIME ROWS SORTED BY WIRE LENGTH

Harness/Wire Pair	Actual Distance (ft)	Pulse Width Low (ns)	Pulse Width High (ns)	Fall Time to Pulse Width (%)
200-ft coiled ETFE	207	530	700	32
Harness wire 15	126	354	383	8
Harness wire 16	126	356	379	6
102-ft coiled polyimide	102	287	312	9
102-ft straight polyimide	102	270	302	12
Harness wire 19	100	282	300	6
Harness wire 20	100	282	302	7
Harness wire 1	75	220	259	18
Harness wire 6	75	237	256	8
50-ft coiled ETFE	50	140	176	26
Harness wire 13	46	134	143	7
Harness wire 17	32	96	108	13
Harness wire 18	32	96	110	15
Harness wire 10	21	64	71	11
15-ft coiled ETFE	15	48	61	27

TABLE 4-2. DISTANCE CALCULATED FROM ECHO PULSE WIDTH BASED ON PROPAGATION VELOCITY OF 71% SPEED OF LIGHT ROWS SORTED BY WIRE LENGTH

Harness/Wire Pair	Calculated Distance Based on Pulse Width Low (ft)	Error of Calculated Distance (%)	Error in feet
200-ft coiled ETFE	185.0	-11%	-22
Harness wire 15	123.6	-2%	-2
Harness wire 16	124.3	-1%	-2
102-ft coiled polyimide	100.2	-2%	-2
102-ft straight polyimide	94.3	-8%	-8
Harness wire 19	98.4	-2%	-2
Harness wire 20	98.4	-2%	-2
Harness wire 1	76.8	2%	2
Harness wire 6	82.7	10%	8
50-ft coiled ETFE	48.9	-2%	-1
Harness wire 13	46.8	2%	1
Harness wire 17	33.5	5%	2
Harness wire 18	33.5	5%	2
Harness wire 10	22.3	6%	1
15-ft coiled ETFE	16.8	12%	2

Table 4-3 compares the accuracy obtained when using an oscilloscope versus the distance reported by the MET. This table provides the accuracies obtainable over a sampling of different wire configurations and lengths. It should be noted that the MET was calibrated using this set of test harnesses, and as such, the MET-reported distance-to-fault is set so that it gives reasonable accuracy over a variety of harness configurations versus concentrating on the accuracy for one particular harness configuration.

TABLE 4-3. COMPARISON OF ACCURACY USING AN OSCILLOSCOPE TO DETECT DISTANCE-TO-FAULT WITH ACCURACY USING A MET TO DETECT DISTANCE-TO-FAULT

Harness/Wire Pair	Length	Average % Error Using Scope	Average % Error Using MET
200-ft coiled ETFE	207.0	-11	-6
Harness wire 15	126.1	-2	1
Harness wire 16	126.1	-1	0
102-ft coiled polyimide	104.0	-2	-5
102-ft straight polyimide	102.0	-8	-2
Harness wire 19	99.7	-2	2
Harness wire 20	99.7	-2	3
Harness wire 1	75.0	2	11
Harness wire 6	75.0	10	11
50-ft coiled ETFE	50.0	-2	6
Harness wire 13	45.7	2	-3
Harness wire 17	31.6	5	3
Harness wire 18	31.6	5	4
Harness wire 10	21.4	6	-5
15-ft coiled ETFE	15.0	12	-39

Two plots are presented to represent the repeatability of the MET-reported distance-to-fault. Figure 4-2 shows a plot of the reported distance versus actual distance for different distances to faults. Arc-over voltages above 4000 V were excluded, as the error appears to increase drastically above this threshold, irrespective of distance-to-fault. Harnesses less than 30 feet were excluded, as the error increases below this threshold, irrespective of arc-over voltage. Figure 4-3 shows a plot of the distribution of error versus arc-over voltage for harnesses longer than 30 feet.

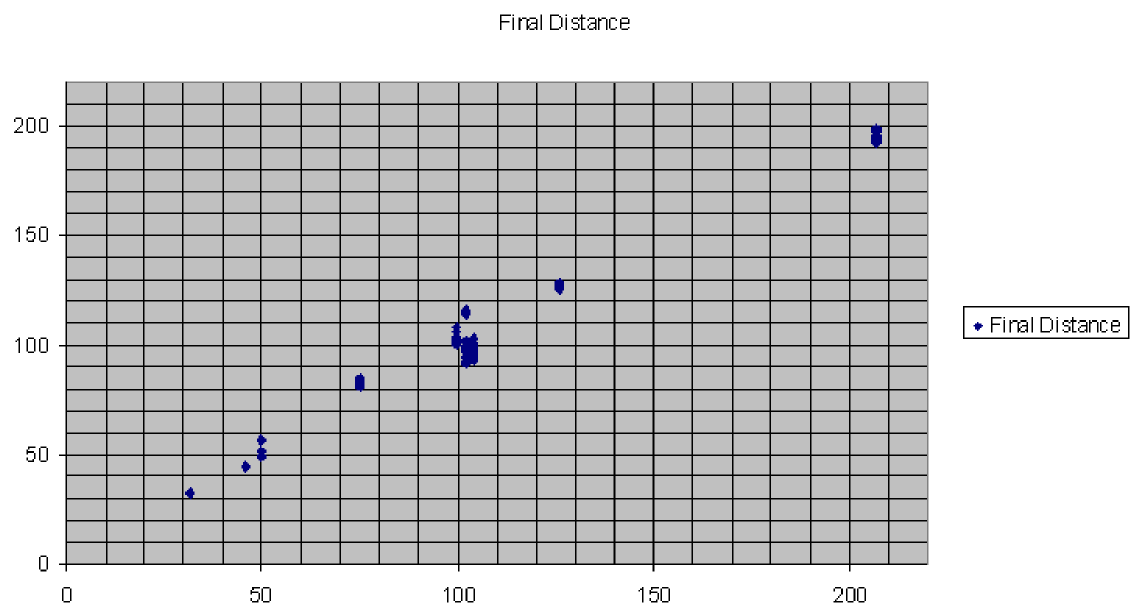

FIGURE 4-2. THE MET-REPORTED DISTANCE VS ACTUAL DISTANCE DATA DISPLAYED FOR ARCS BELOW 4000 V, ABOVE 30 FEET IN DISTANCE

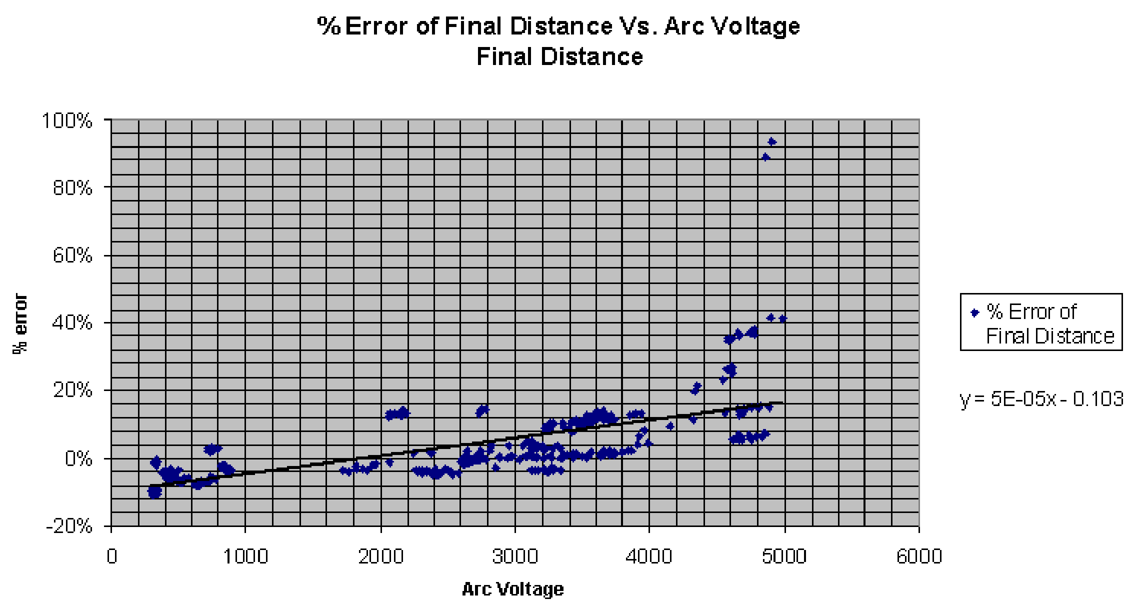

FIGURE 4-3. PERCENT ERROR OF DISTANCE VS ARC-OVER VOLTAGE ALL LONG THE PULSE CIRCUIT DATA DISPLAYED ABOVE 30 FEET IN DISTANCE

This discussion closes with a collection of scope traces depicting actual fault waveforms (figures 4-4 through 4-9) obtained on various harness configurations. Trace 1 is the fault waveform recorded using a oscilloscope, and trace 2 is the width detected by the MET pulse-width detect circuit. The vertical scales are not accurate—the traces are intended only to show the fault waveform shape. Note the fault waveform is ac-coupled.

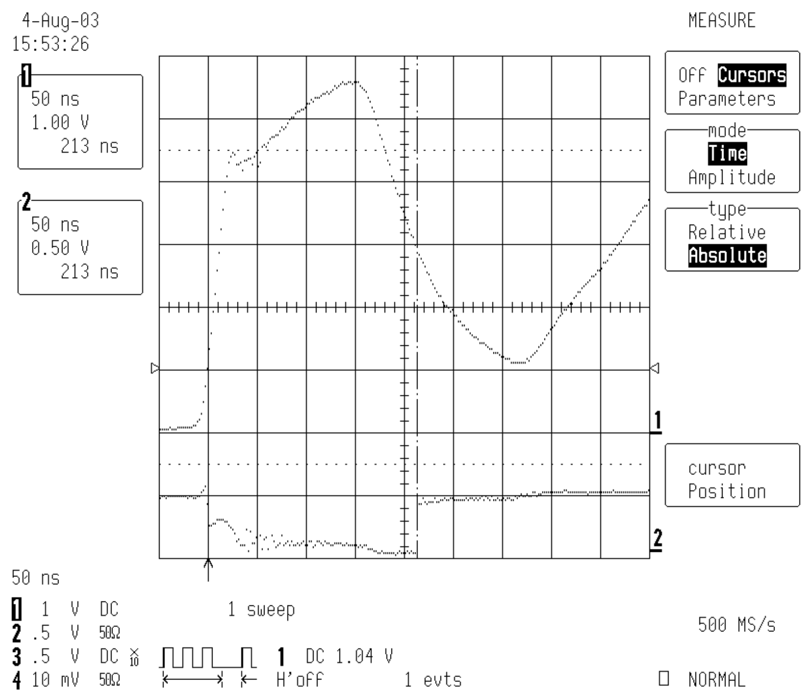

FIGURE 4-4. FIFTY FEET TO FAULT, COILED ETFE, ARC-OVER AT 5000 V

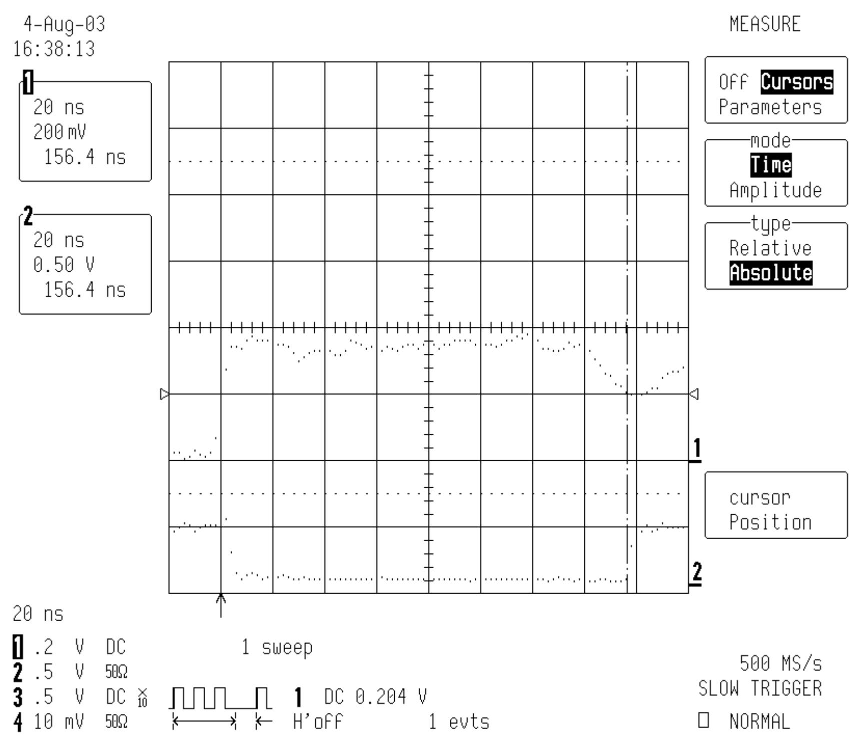

FIGURE 4-5. FIFTY FEET TO FAULT, COILED ETFE, ARC-OVER AT 600 V

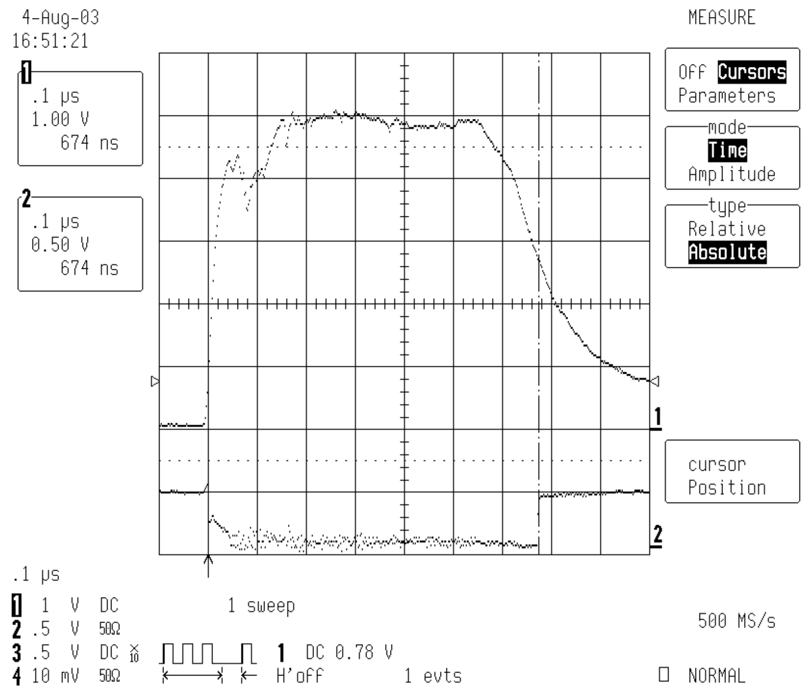

FIGURE 4-6. TWO HUNDRED FEET TO FAULT, COILED ETFE, ARC-OVER AT 5000 V

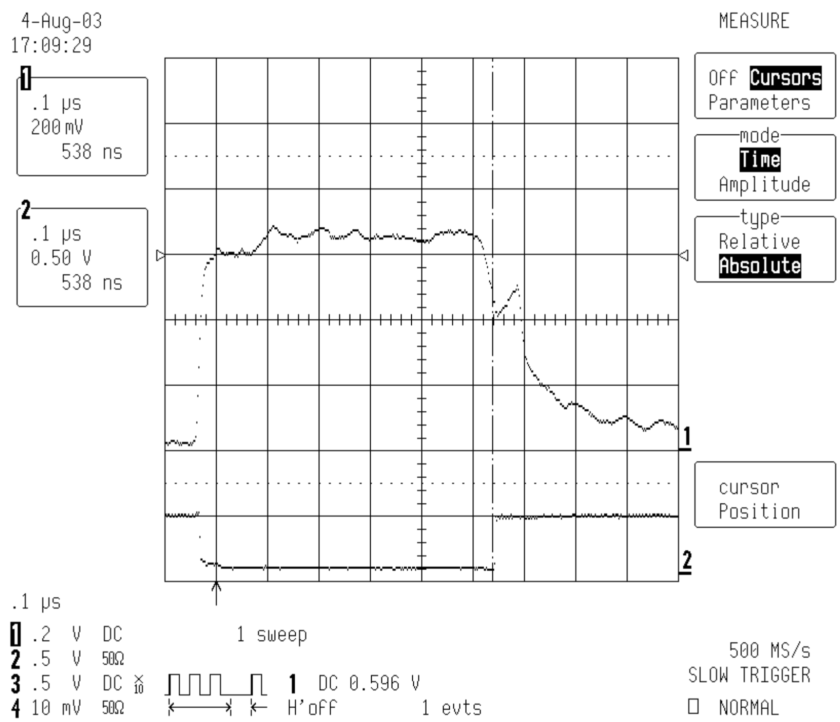

FIGURE 4-7. TWO HUNDRED FEET TO FAULT, COILED ETFE, ARC-OVER AT 1000 V

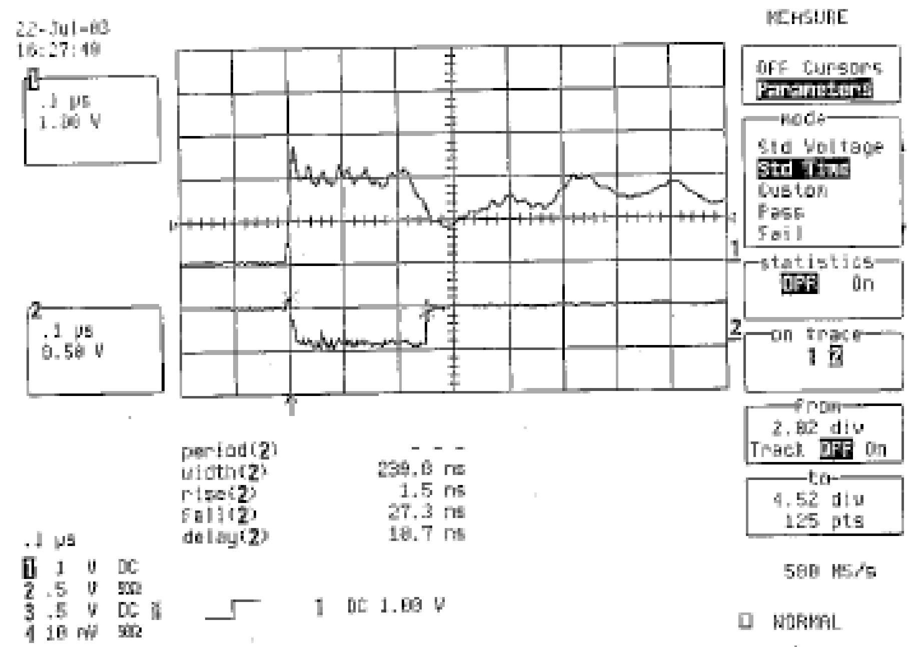

FIGURE 4-8. HARNESS WIRE 1, 75 FEET TO FAULT

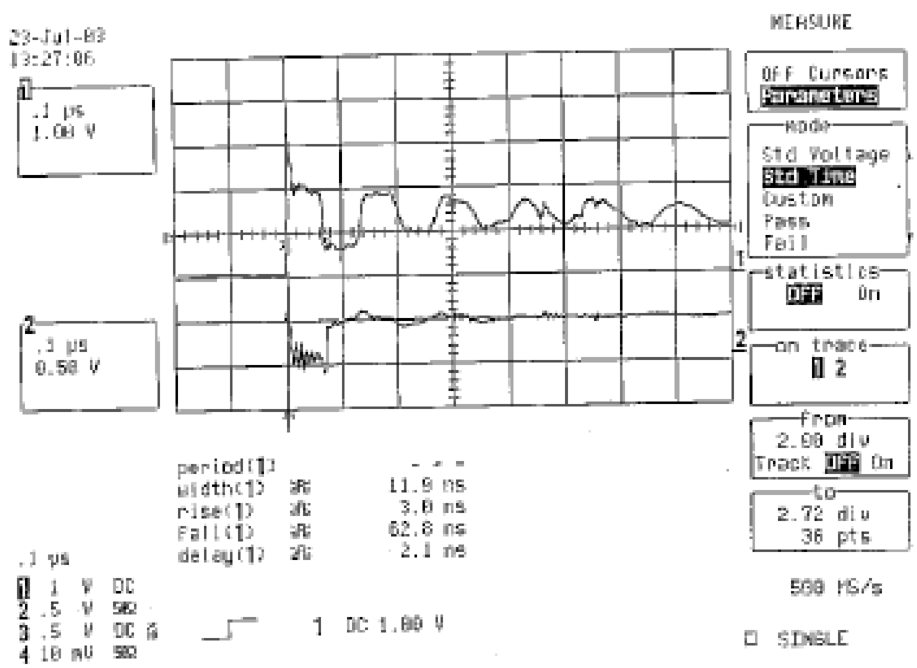

FIGURE 4-9. HARNESS WIRE 9, 21 FEET TO FAULT

This discussion presented a number of parameters that can have an effect on the fault waveform. The ultimate effect can be anywhere from a lessening in the accuracy in the distance-to-fault measurement to the inability in determining a distance-to-fault at all. These waveforms are presented as a demonstration of the general performance of this technology. The reader is cautioned against making sweeping assumptions based on these scope traces. For instance, figure 4-10 shows a very clean waveform accompanied by an accurate distance-to-fault calculation. It would be incorrect to assume that similar configurations would always result in similar accuracies. The same reasoning applies for the figures that show inaccurate distance-to-fault calculations. The characteristic impedance of the cable can be affected by minor variations in the lay of the harness, such as proximity to conductive structures, or a local separation in the wires. Predicting the effect prior to testing is complicated.

The traces presented are typical waveforms that were encountered, with and without the harness adjacent to a ground plane. They are neither the most ideal waveforms encountered, nor the worst waveforms encountered.

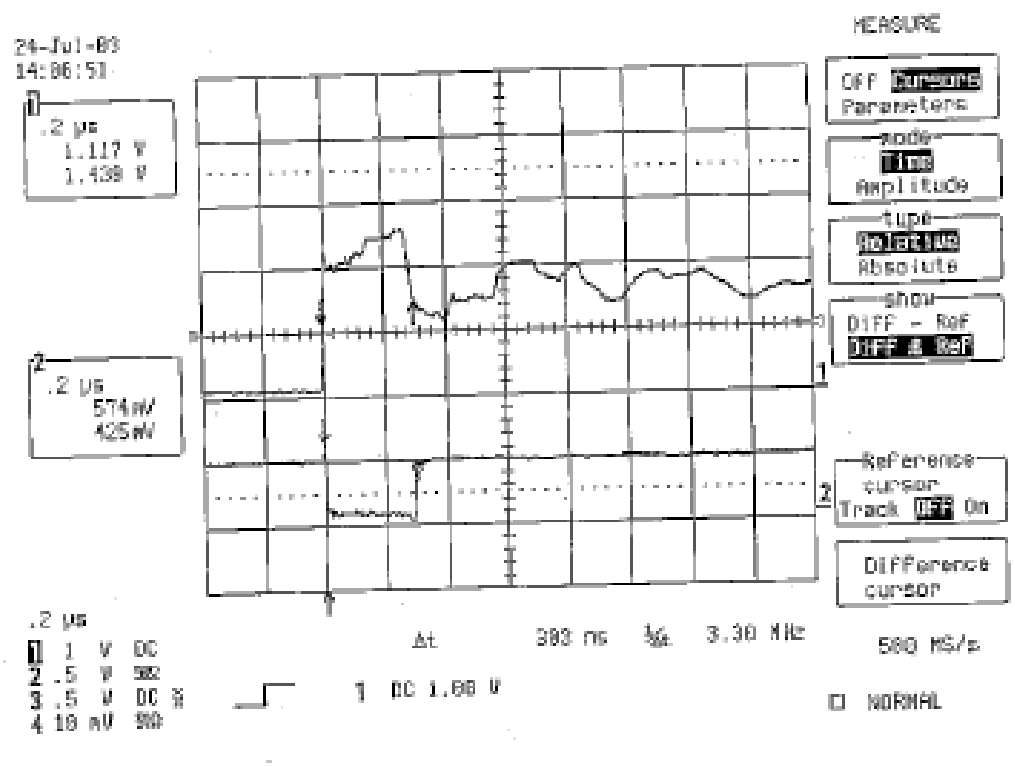

FIGURE 4-10. HARNESS WIRE 19, 99.7 FEET TO FAULT

5. VALIDATION AND SAFETY EVALUATION.

5.1 MICRO-ENERGY TOOL NONDESTRUCTIVE NATURE VALIDATION.

5.1.1 Objective.

This testing was performed to demonstrate the nondestructive nature of using the MET repeatedly on a section of wire with a cut fault. A visual assessment is made to determine if any additional damage would take place to the insulation around the fault.

5.1.2 Procedure.

Six harness specimens were prepared. These harnesses had a fault slit cut into the insulation of both conductors with a razor blade at approximately three-quarters of the length of each harness. This type of fault was chosen to expose the most insulation to a subsequent arc at that location. The longer harnesses were wound on a spool to facilitate testing.

TABLE 5-1. HARNESSES PREPARED FOR MET NONDESTRUCTIVE NATURE VALIDATION

Harness Number	Wire Type	AWG	Length (feet)	Number of Conductors
1	Polyimide (M81381/11)	22	10	2
2			100	2
3			200	2
4	ETFE (M22759/34)	22	10	2
5			100	2
6			200	2

For each harness, the fault was placed under a microscope and the MET connected to the harness on the three-quarter length side. The MET was set to loop test the fault. The fault was adjusted to maintain a 3500 to 5000 V arc breakdown throughout the test. The arc voltage for each applied fault was recorded using the MET laptop graphical user interface.

The fault was inspected using a microscope after approximately 10, 100, and 500 arc events. The microscope was attached to a digital camera, and the image was digitally stored at approximately 30X magnification. Figure 5-1 shows the setup for this test.

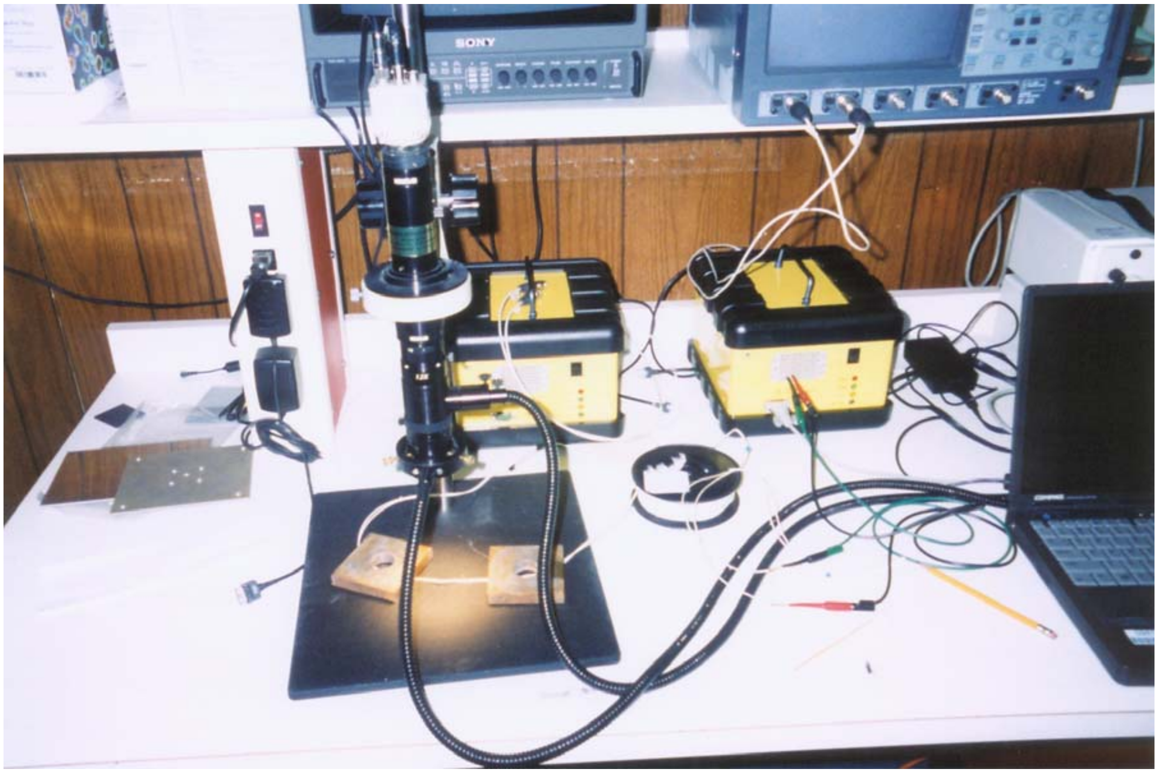

FIGURE 5-1. MICRO-ENERGY TOOL NONDESTRUCTIVE NATURE TEST SETUP

5.1.3 Summary.

The test results are shown of the arc for the wire specimens before and during testing, as well as summarizing the number of tests and arc voltage distribution for those tests. The wire bundles used in this evaluation were made with polyimide (M81381/11) and ETFE (M22759/34) wire types. These wire types were chosen as they represent typical constructions used in transport category airplanes.

During and after repetitive MET testing, the faults on the wire were inspected under a microscope at approximately 30X magnification.

For both wire types tested, no significant degradation of the wire or insulation was observed. After 500 tests, some cosmetic effects were noticeable, but do not degrade the insulative properties of the conductors more than what existed due to the fault itself.

5.1.3.1 Polyimide (M81381/11) Observations.

The results of the polyimide (M81381/11) tests are shown in figures 5-2 through 5-13.

After 10 and 100 events, no carbon film deposits or visible melting of the insulation was observed. Note that this insulation type is dark in color; therefore, carbon film may not be as noticeable as it would be for white ETFE (M22759/34).

FIGURE 5-2. POLYIMIDE (M81381/11)—200-ft LENGTH—INITIAL CONDITION

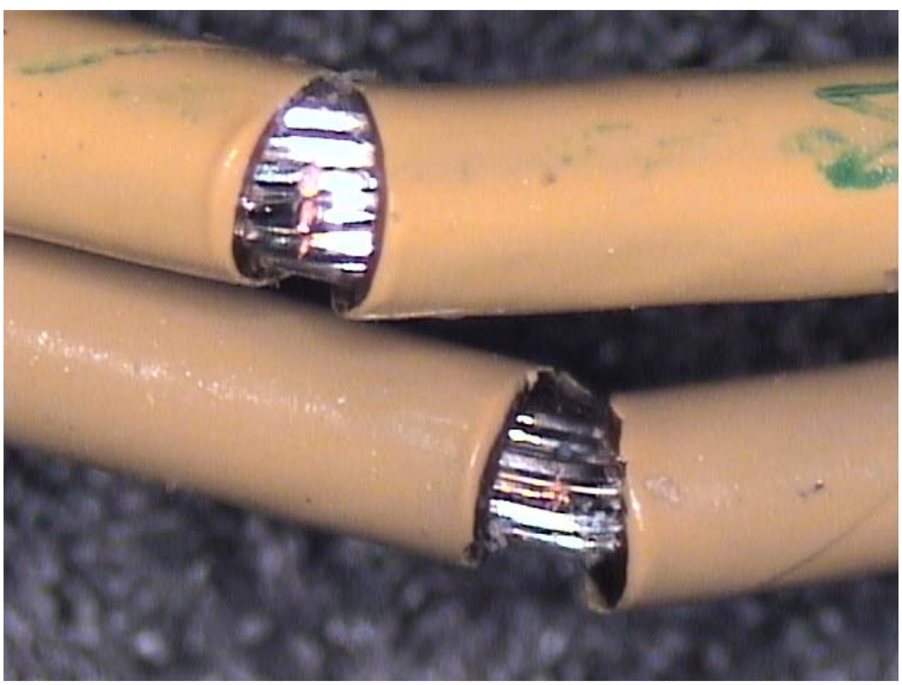

FIGURE 5-3. POLYIMIDE (M81381/11)—200-ft LENGTH—AFTER 126 QUALIFYING ARCS

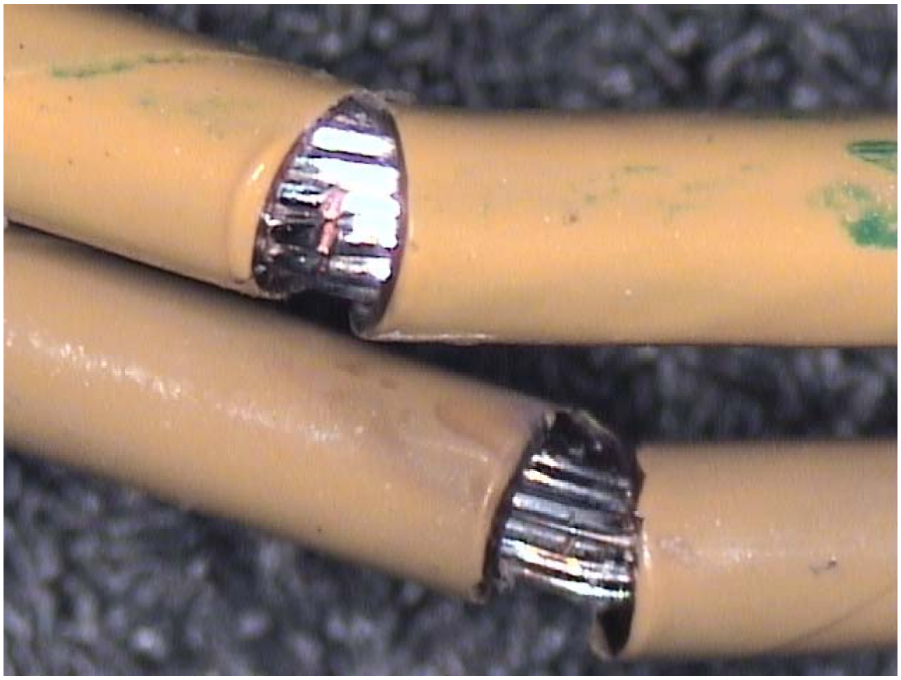

FIGURE 5-4. POLYIMIDE (M81381/11)—200-ft LENGTH—AFTER 627 QUALIFYING ARCS

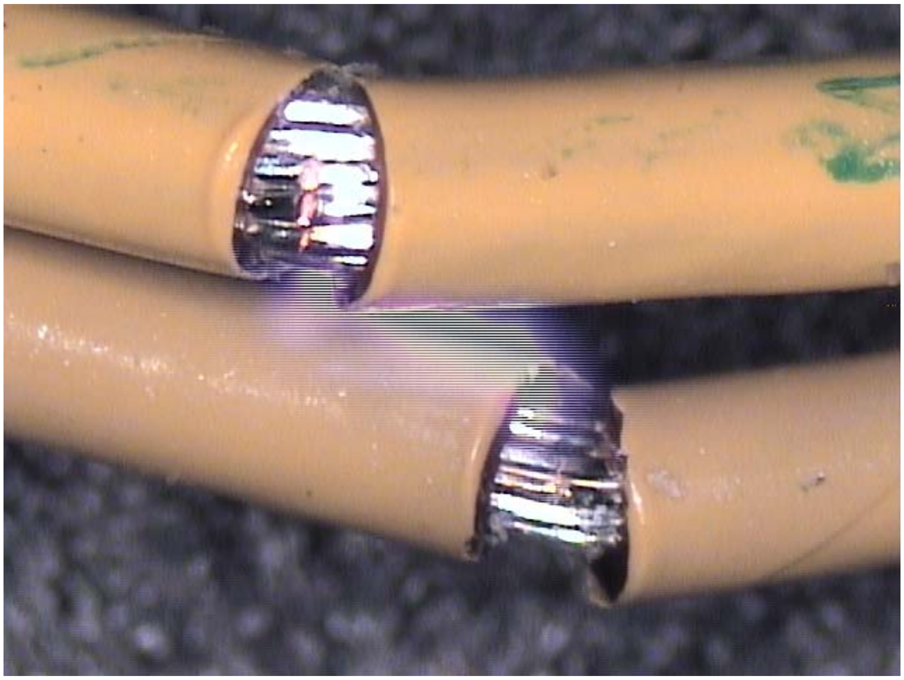

FIGURE 5-5. POLYIMIDE (M81381/11)—200-ft LENGTH—TYPICAL ARC
(Note: At this separation, it took 4000-5000 V to initiate an arc.)

FIGURE 5-6. POLYIMIDE (M81381/11)—100-ft LENGTH—INITIAL CONDITION (MET TESTING)

FIGURE 5-7. POLYIMIDE (M81381/11)—100-ft LENGTH—AFTER 179 QUALIFYING ARCS

FIGURE 5-8. POLYIMIDE (M81381/11)—100-ft LENGTH—AFTER 642 QUALIFYING ARCS

FIGURE 5-9. POLYIMIDE (M81381/11)—100-ft LENGTH—TYPICAL ARC
(Note: At this separation, it took 4000-5000 V to initiate an arc.)

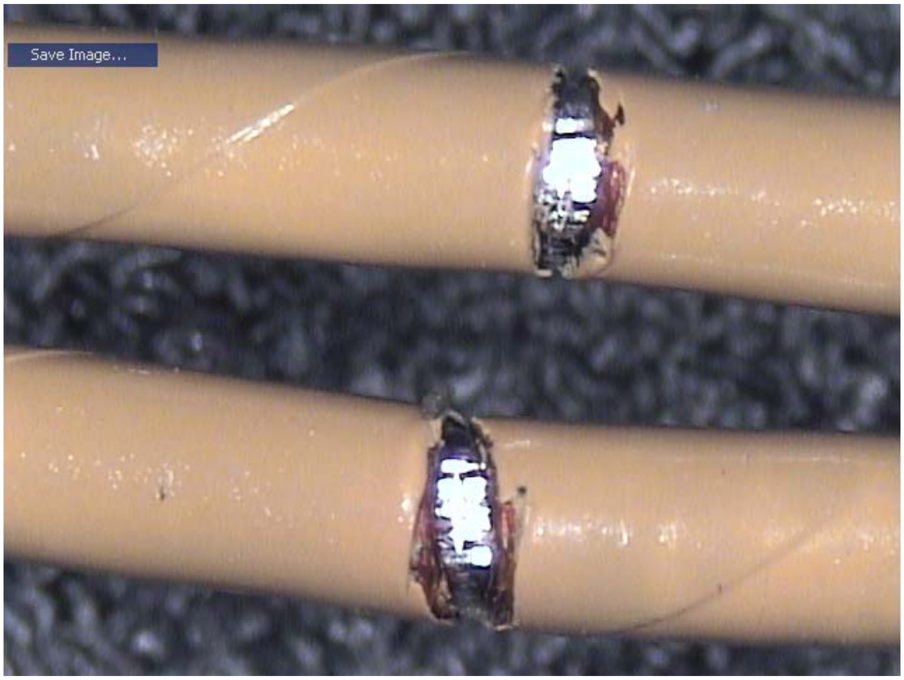

FIGURE 5-10. POLYIMIDE (M81381/11)—10-ft LENGTH—INITIAL CONDITION

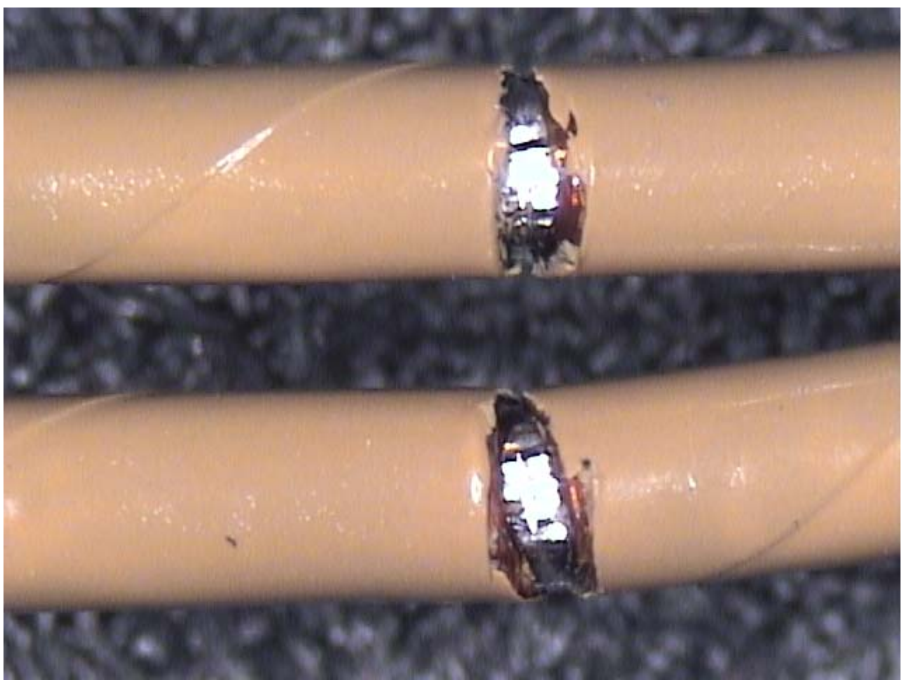

FIGURE 5-11. POLYIMIDE (M81381/11)—10-ft LENGTH—AFTER 128 QUALIFYING ARCS

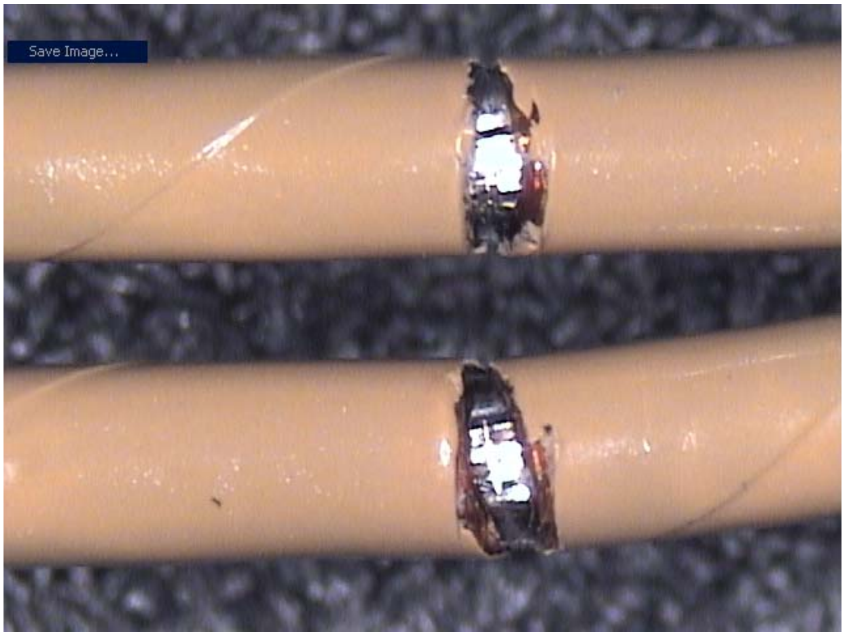

FIGURE 5-12. POLYIMIDE (M81381/11)—10-ft LENGTH—AFTER 617 QUALIFYING ARCS

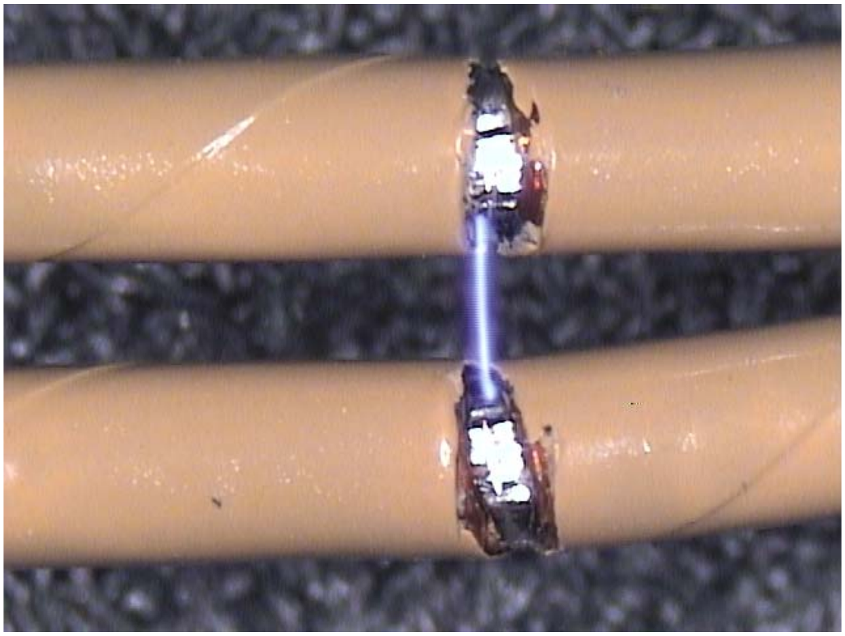

FIGURE 5-13. POLYIMIDE (M81381/11)—10-ft LENGTH—TYPICAL ARC
(Note: At this separation, it took 4000-5000 V to initiate an arc.)

After 500 events, some minor melting of the polyimide film on the very outside jacket was noticed on the 200-ft specimen, as in figure 5-4. This specimen was situated so that the arc had to travel along the surface of the conductor insulation. No visible effects were noted on the 100- and 10-ft specimens. This was, primarily, a cosmetic effect and does not create a condition that would cause the breach to arc-over at a lower voltage.

5.1.3.2 ETFE (M22759/34) Observations.

The results of the ETFE (M22759/34) tests are shown in figures 5-14 through 5-24.

FIGURE 5-14. ETFE (M22759/34)—200-ft LENGTH—INITIAL CONDITION

FIGURE 5-15. ETFE (M22759/34)—200-ft LENGTH—AFTER 131 QUALIFYING ARCS

FIGURE 5-16. ETFE (M22759/34)—200-ft LENGTH—AFTER 652 QUALIFYING ARCS

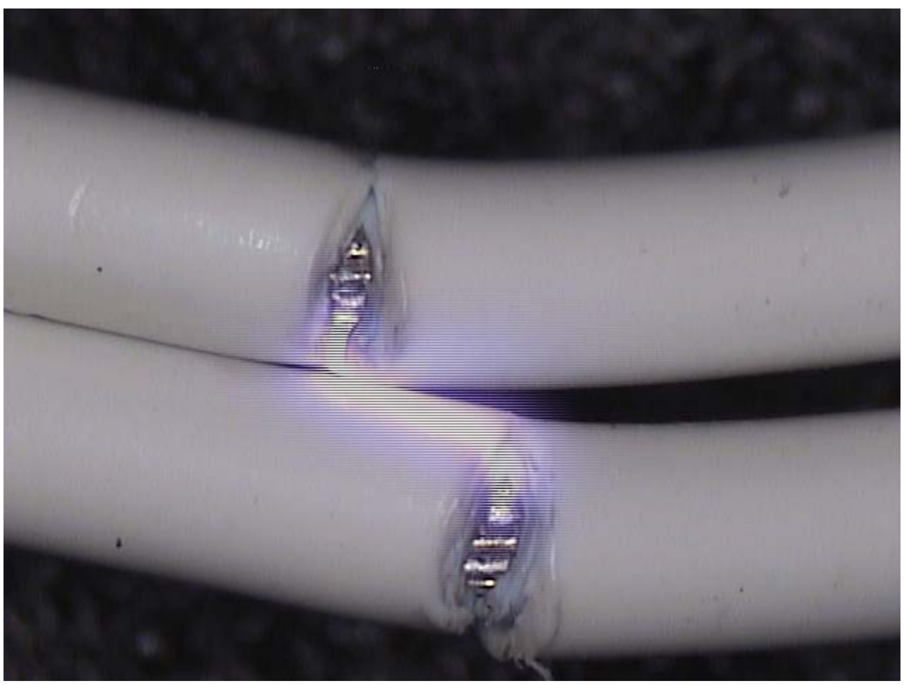

FIGURE 5-17. ETFE (M22759/34)—200-ft LENGTH—TYPICAL ARC—AFTER 500 EVENTS
(Note. At this separation, it took 4000-5000 V to initiate an arc.)

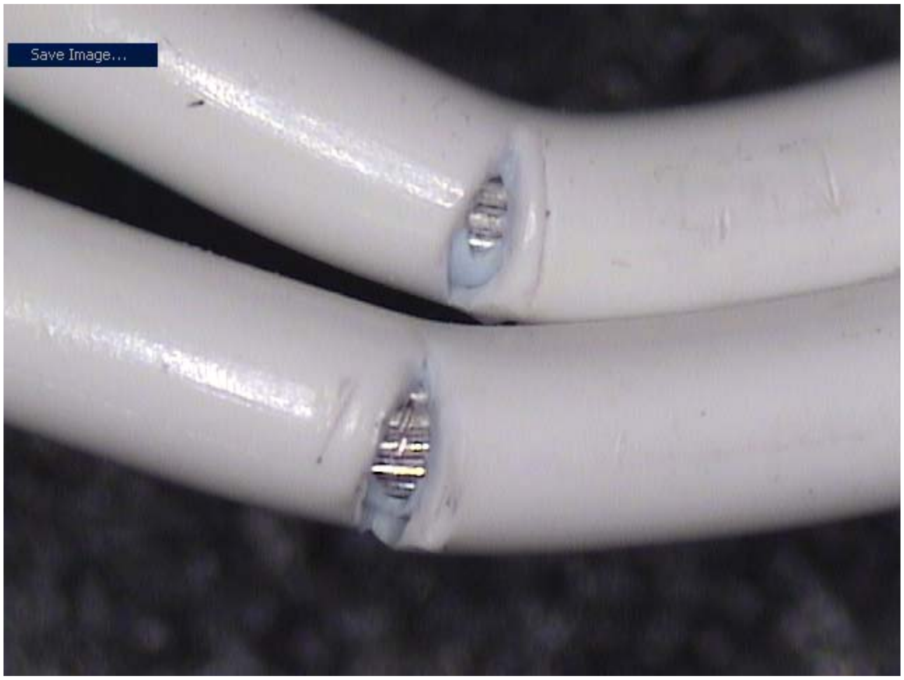

FIGURE 5-18. ETFE (M22759/34)—100-ft LENGTH—INITIAL CONDITION

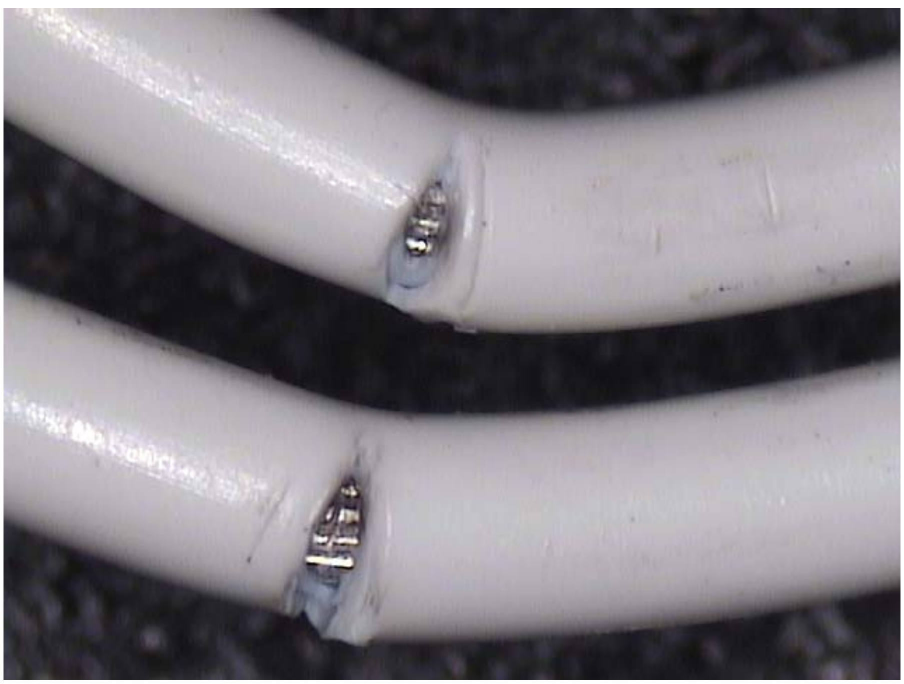

FIGURE 5-19. ETFE (M22759/34)—100-ft LENGTH—AFTER 136 QUALIFYING ARCS

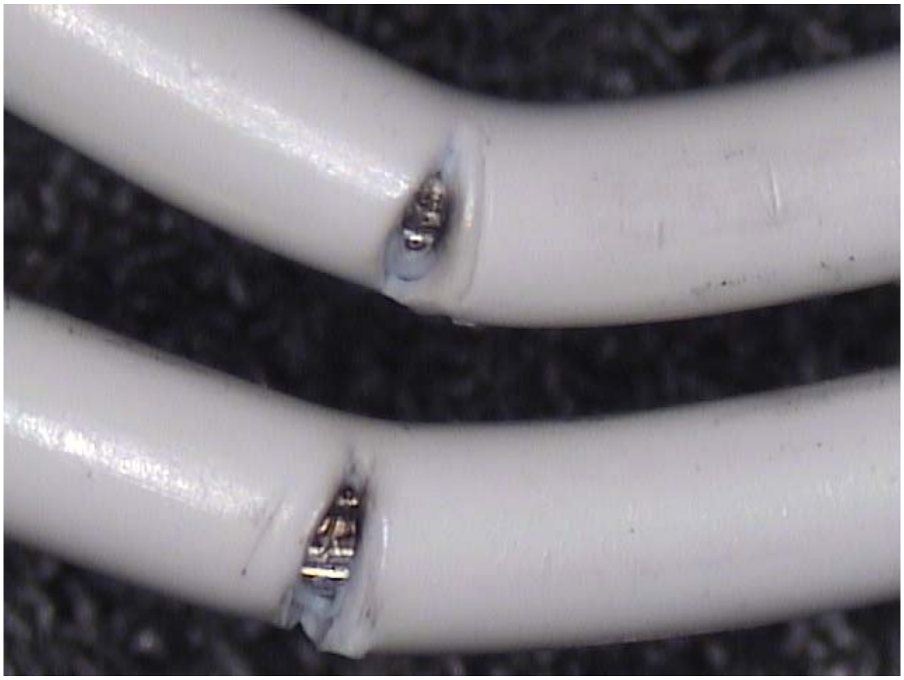

FIGURE 5-20. ETFE (M22759/34)—100-ft LENGTH—AFTER 856 QUALIFYING ARCS

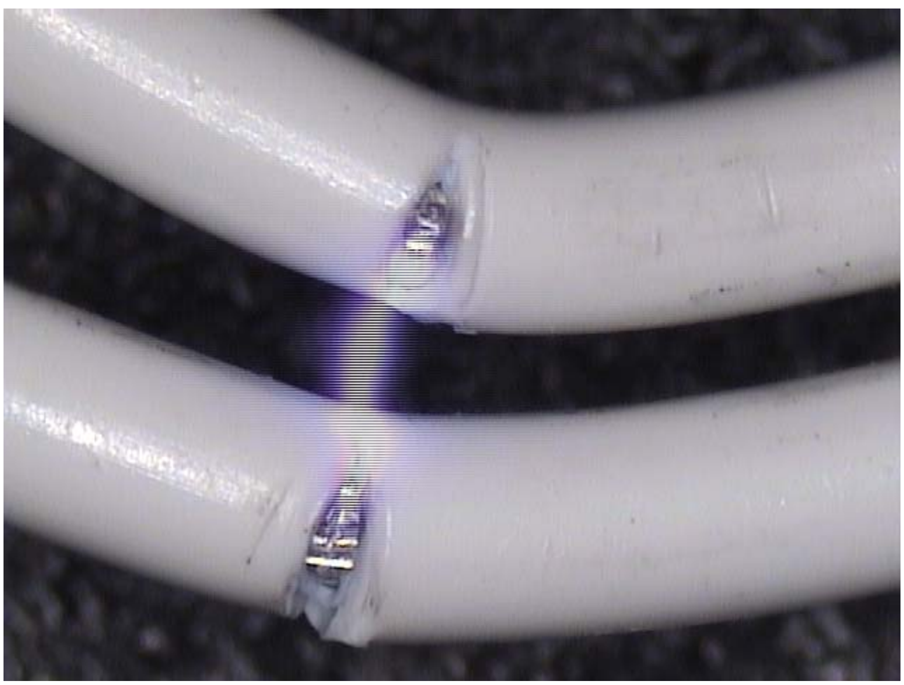

FIGURE 5-21. ETFE (M22759/34)—100-ft LENGTH—TYPICAL ARC
(Note: At this separation, it took 4000-5000 V to initiate an arc.)

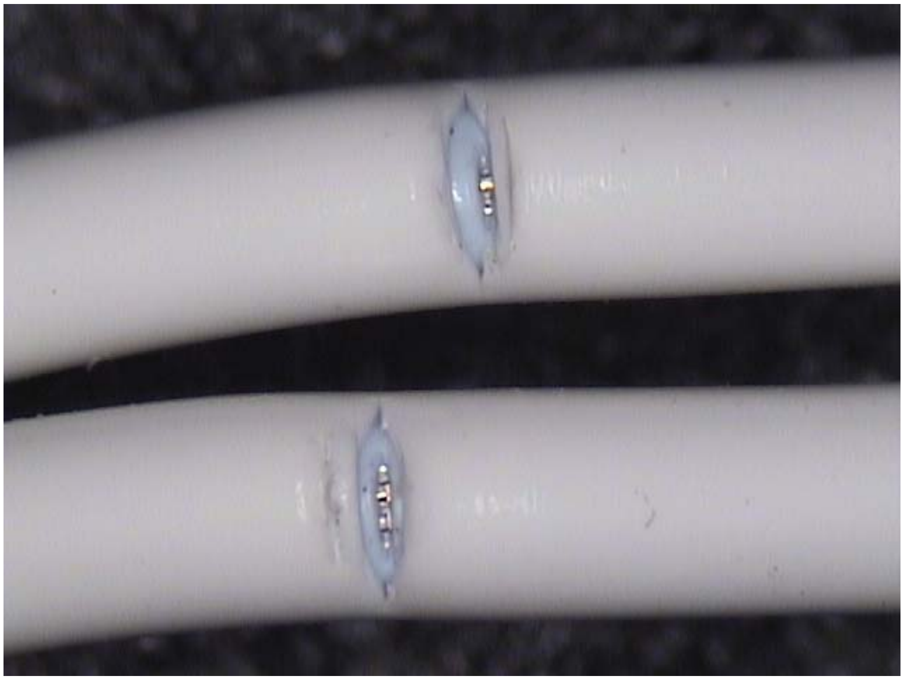

FIGURE 5-22. ETFE (M22759/34)—10-ft LENGTH—INITIAL CONDITION

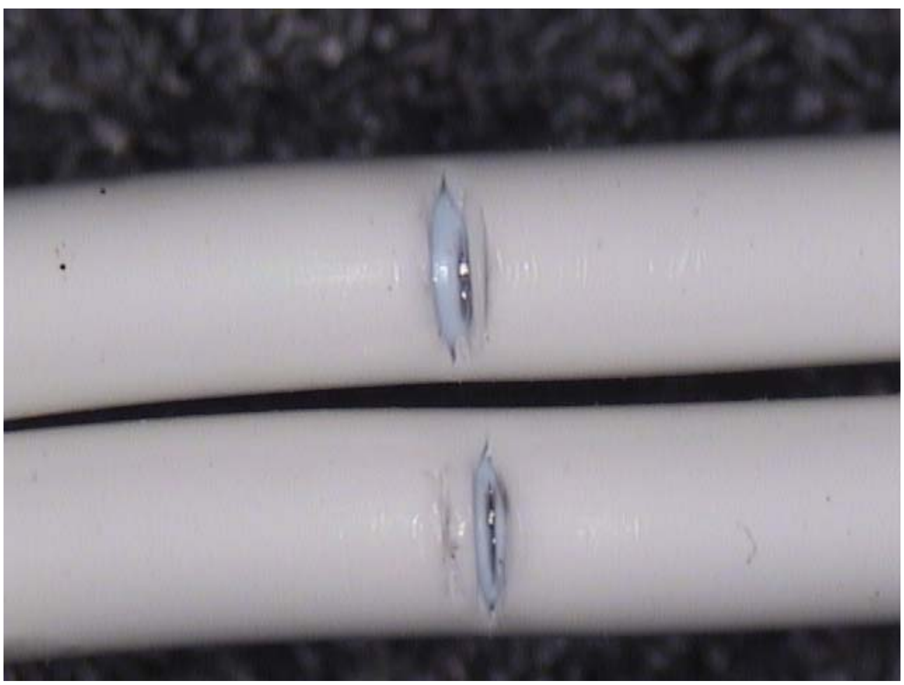

FIGURE 5-23. ETFE (M22759/34)—10-ft LENGTH—AFTER 101 QUALIFYING ARCS

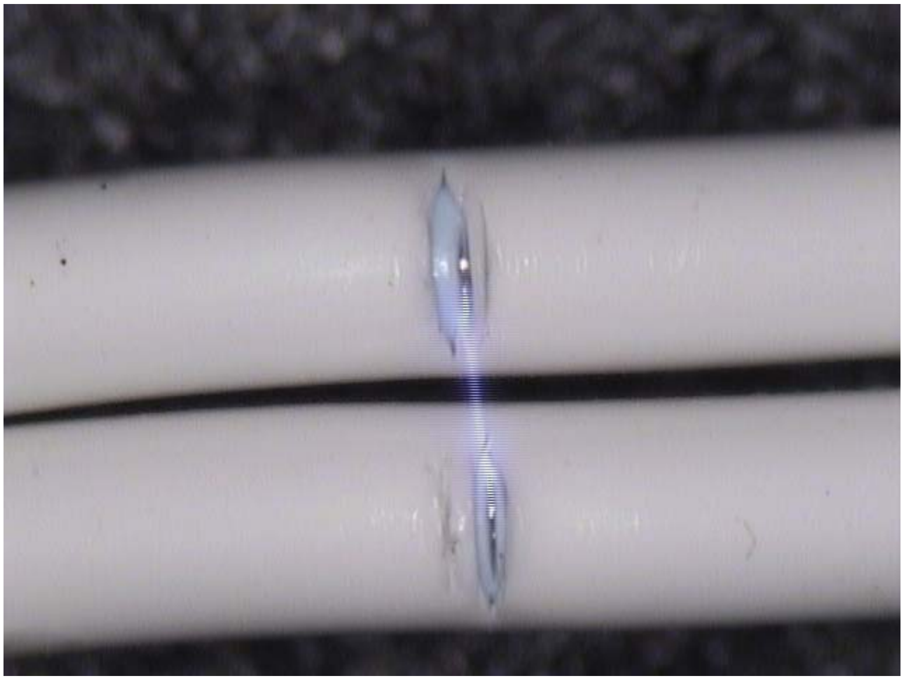

FIGURE 5-24. ETFE (M22759/34)—200-ft LENGTH—TYPICAL ARC
(Note: At this separation, it took 4000-5000 V to initiate an arc.)

After 10 to 100 events, it was possible to see an extremely faint carbon film deposited at some locations on the inside edges of the fault cut into the insulation. This effect was more prevalent on the 200-ft specimen than on the 100- and 10-ft specimens and was only visible under a microscope. This effect can be seen by comparing figures 5-14 (200-ft length, initial condition) and 5-15 (200-ft length after 131 qualifying arcs).

After 500 events, a heavier carbon film deposit was noticeable. This can be seen in figures 5-16 and 5-17. It is important to note that the film did not cause a decrease in the arc-over voltage, indicating no further breakdown in conductor insulation.

No visible melting of the insulation or effect, other than a thin carbon film, was observed for any of the ETFE (M22759/34) specimens.

5.1.4 Observations.

If damage is to occur to the wire or its insulation, it is anticipated that the worst-case would occur when maximum energy is dissipated at the arc event. The arc dissipation profile over time was not characterized, but it is reasonable to assume that the maximum energy available to dissipate at the arc is bounded by the total energy stored on the test harness. The energy stored on the test harness resides in the parasitic capacitance of the harness and can be calculated as a function of the voltage the harness is charged to using the following equation.

$$E = \tfrac{1}{2} * C * V^2$$

The nondestructive nature testing applied the maximum test voltage of the MET to each wire specimen at least 500 times.

Testing proceeded by adjusting the fault gap to maintain an arc breakdown voltage between 3500 and 5000 V. Since 5000 V is the maximum voltage the MET can apply, 5000 V was chosen. Testing showed that it was difficult to maintain a more precise arc breakdown range at 5000 V, thus, 3500 V was used.

The gap distance between wires for this testing was approximately 0.040″. The gap distance at each fault required frequent adjustments to maintain the desired arc breakdown voltage. The wires were not clamped in place, and it only took a few thousands of an inch disturbance to the gap distance to vary the arc-over voltage outside the desired test range. Too much distance caused the fault not to occur, and not enough distance caused an arc breakdown voltage at too low of a voltage for this evaluation.

Arc events occurred that were lower than the 3500 to 5000 V range, and these instances were not counted towards the 500 times repetition for the purposes of nondestructive testing. Table 5-2 lists the number of arc events that occurred for each wire specimen. Figure 5-25 shows the number of arcs that actually occurred at each voltage for each wire specimen.

TABLE 5-2. ARC EVENTS FOR MET NONDESTRUCTIVE TEST

Wire Specimen	Total Arc Events	Qualifying Arc Events (arcs > 3500 V)
Polyimide, M81381/11 10 ft	626	617
Polyimide, M81381/11 100 ft	643	642
Polyimide, M81381/11 200 ft	627	627
ETFE, M22759/34 10 ft	680	595
ETFE, M22759/34 100 ft	926	856
ETFE M22759/34 200 ft	686	652

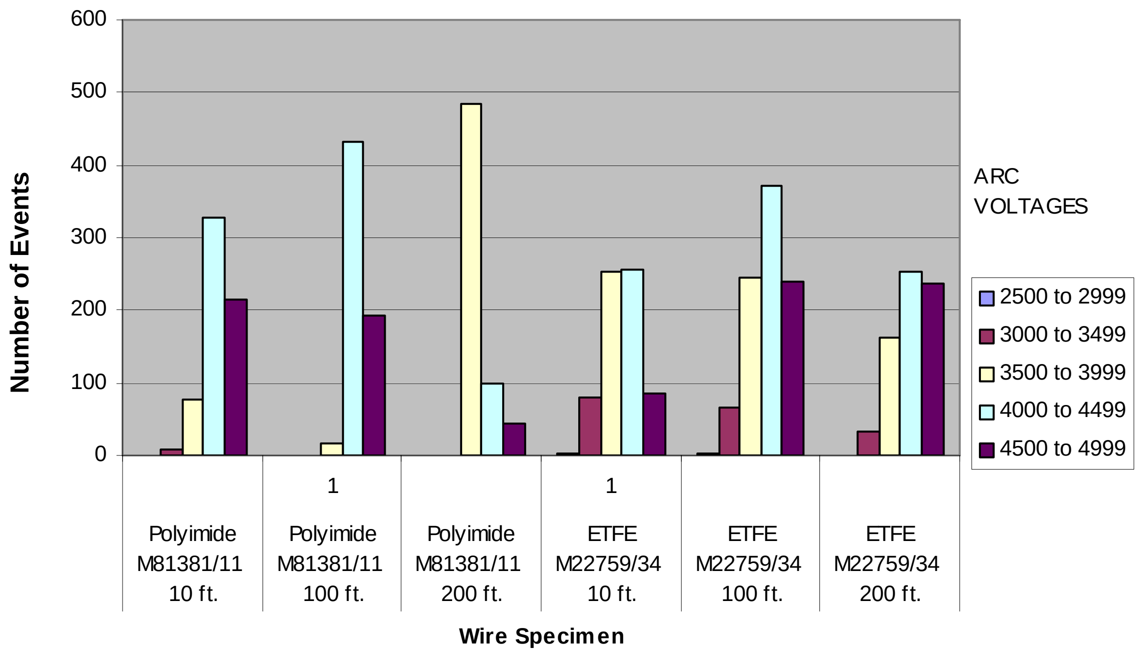

FIGURE 5-25. ARC VOLTAGE DISTRIBUTION FOR MET NONDESTRUCTIVE TEST

5.2 INSULATION FAULT PROBE NONDESTRUCTIVE NATURE VALIDATION.

5.2.1 Objective.

This testing was performed to demonstrate the nondestructive nature of using the IFP repeatedly on a section of wire with a cut fault. The purpose of the test was to show little or no damage had taken place to the insulation around the fault.

5.2.2 Procedure.

Two harness specimens were tested. These harnesses had a fault slit cut into the insulation on one of the conductors with a razor blade at approximately three-quarters of the length of each harness. This type of fault was chosen since it would expose the most insulation to a subsequent arc at that location. The harnesses were placed on a spool to facilitate testing.

TABLE 5-3. HARNESSES PREPARED FOR IFP NONDESTRUCTIVE NATURE VALIDATION

Harness Number	Wire Type	AWG	Length (feet)	Number of Conductors
1	Polyimide (M81381/11)	22	100	2
2	ETFE (M22759/34)	22	75	2

For each harness, the fault was placed under a microscope and the two wires of the harness were grounded to the IFP on the three-quarter length side. The IFP voltage was turned as high as it would go (5400 V) and helium was attached. With the IFP trigger depressed, the probe was moved to the fault until an audible signal was heard, indicating the fault had been detected, and then moved away from the fault until the audible signal stopped, indicating a fault was present. The probe was moved toward and away from the fault 370 times for each harness.

The fault was inspected using a microscope after approximately 10, 120, and 370 test cycles. The microscope was attached to a digital camera, and the image was digitally stored at approximately 30X magnification. Figure 5-26 shows the setup for this test.

FIGURE 5-26. INSULATION FAULT PROBE NONDESTRUCTIVE NATURE TEST SETUP

5.2.3 Summary.

The test results are shown in photographs of the arc for the wire specimens before and during testing. The results of the polyimide (M81381/11) tests are shown in figures 5-2 through 5-13. The results of the ETFE (M22759/34) tests are shown in figures 5-14 through 5-24. The wire bundles used in this evaluation test were made with polyimide (M81381/11) and ETFE (M22759/34) wire types.

During and after repetitive IFP testing, the faults on the wire were inspected under a microscope at approximately 30X magnification. For both wire types, no effects were visible.

5.2.4 Observations.

If damage is to occur to the wire or its insulation, it is anticipated that the worst-case would occur when maximum energy is available at the IFP probe tip. This occurs at when the IFP voltage is turned as high as it will go. The probe emits a stream of current limited to 6 μA.

The voltage at which the probe stream initiates and the magnitude of the resulting current stream are independent of the length of the wire under test. Figures 5-27 through 5-32 show the results of the tests.

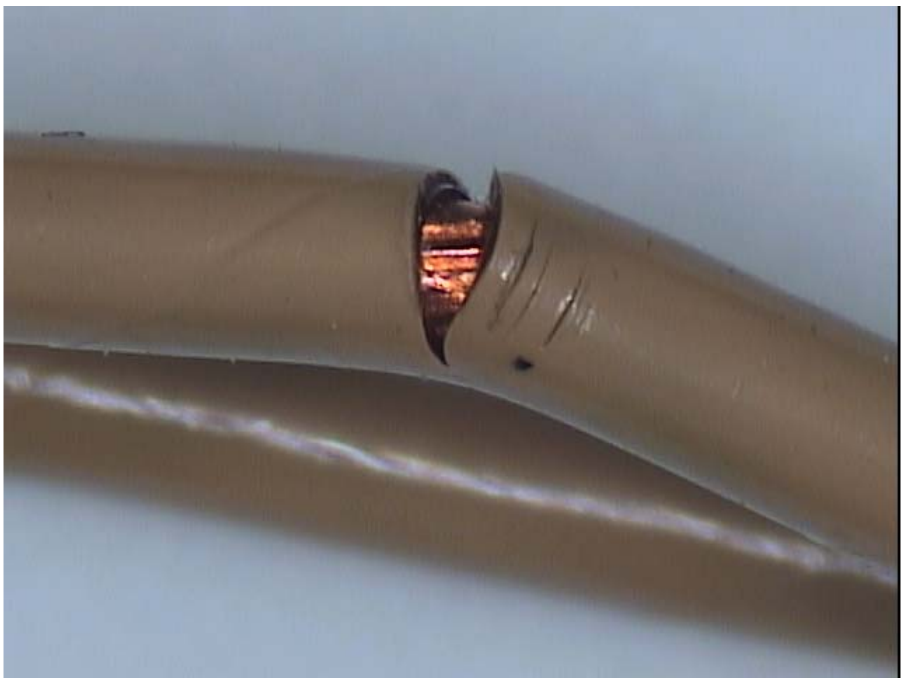

FIGURE 5-27. POLYIMIDE (M81381/11)—100-ft LENGTH—INITIAL CONDITION (IFP TESTING)

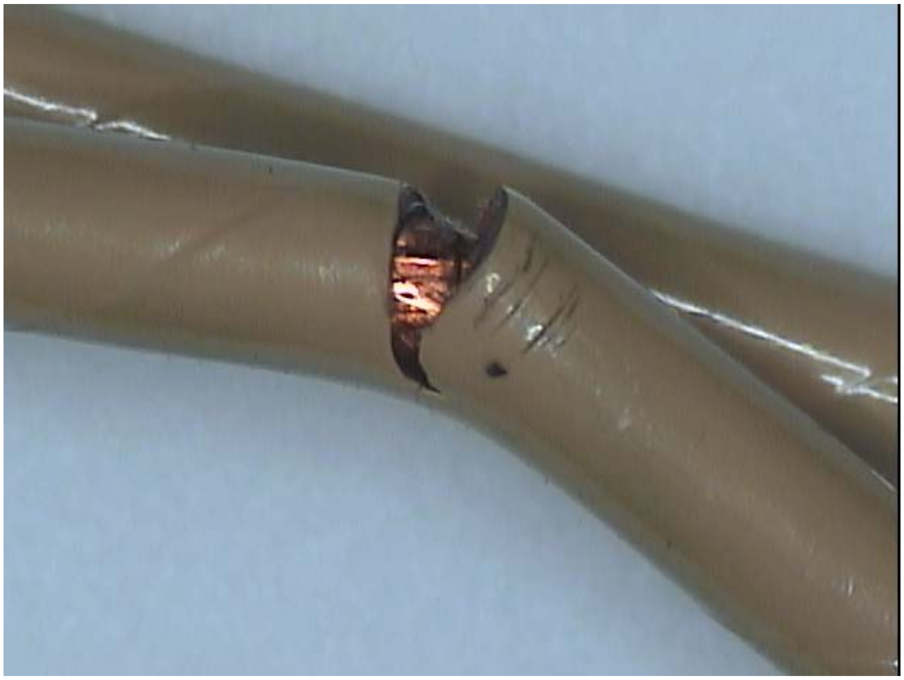

FIGURE 5-28. POLYIMIDE (M81381/11)—100-ft LENGTH—AFTER 120 REPETITIONS

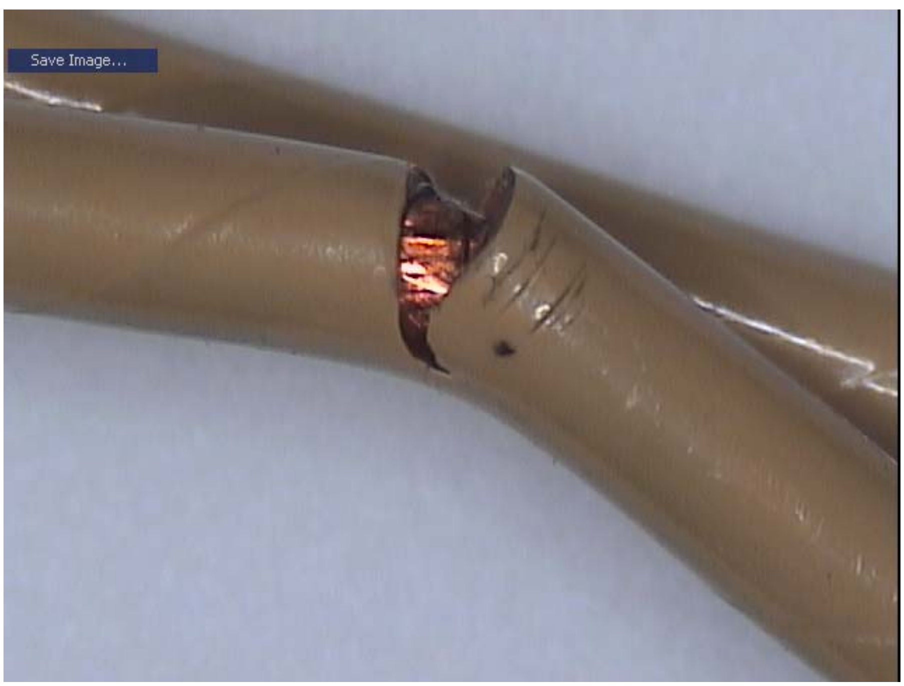

FIGURE 5-29. POLYIMIDE (M81381/11)—100-ft LENGTH—AFTER 370 REPETITIONS

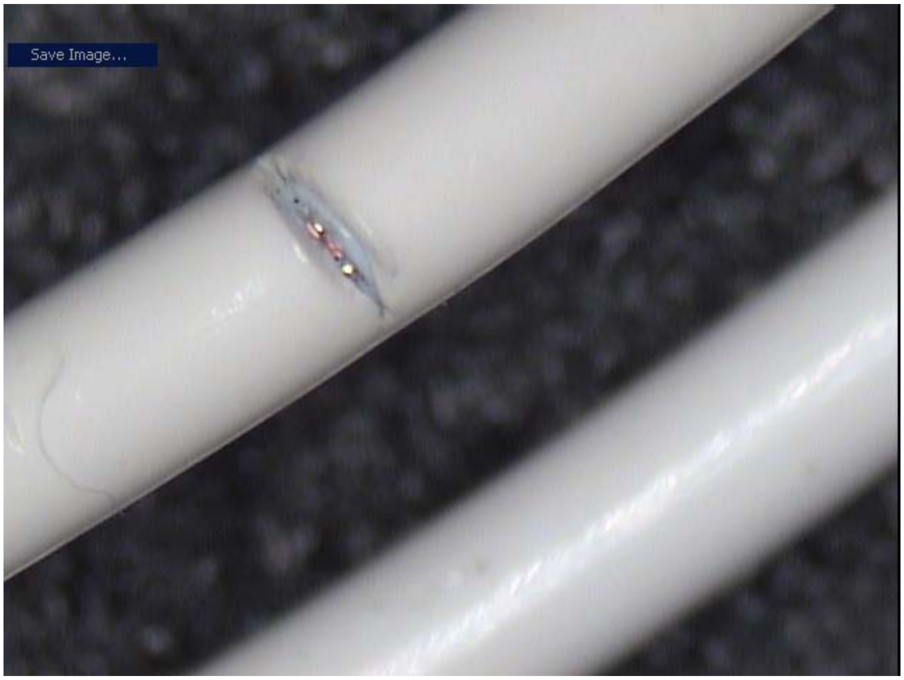

FIGURE 5-30. ETFE (M22759/34)—75-ft LENGTH—INITIAL CONDITION

FIGURE 5-31. ETFE (M22759/34)—75-ft LENGTH—AFTER 120 REPETITIONS

FIGURE 5-32. ETFE (M22759/34)—75-ft LENGTH—AFTER 370 REPETITIONS

5.3 DETECTION AND IDENTIFICATION VALIDATION.

This testing was not performed using the IFP. The wires were installed in a cable tray at the FAA Airworthiness Assurance Nondestructive Inspection Validation Center (FAA-AANC) facility. This setup was arranged in a manner that did not allow the length of the harnesses to be scanned with the IFP.

5.3.1 Objective.

This testing determined the ability of the MET to detect and identify the location of various insulation breaches.

5.3.2 Procedure.

FAA/AANC personnel fabricated six harnesses, as shown in table 5-4.

For each harness, instances of the following faults were applied to the cables: cuts, abrasions, cracks, chaffing, and arcing to ground at various locations.

The locations of the faults were not provided to the personnel at the time of the test. The personnel scanned the prepared harnesses and attempted to detect and locate as many faults as possible using the MET. Figure 5-33 shows the setup for this testing.

TABLE 5-4. HARNESSES PREPARED FOR THE DETECTION AND IDENTIFICATION TEST

FAA/AANC Harness Designation	Wire Type	AWG	Length (feet)	Number of Conductors
551	Polyimide (M81381/11)	22	10	12
552	Polyimide (M81381/11)	22	100	12
553	Polyimide (M81381/11)	22	200	12
561	ETFE (M22759/34)	22	10	12
562	ETFE (M22759/34)	22	100	12
563	ETFE (M22759/34)	22	200	12

FIGURE 5-33. MICRO-ENERGY TOOL DETECTION AND IDENTIFICATION TEST SETUP
(All the harnesses are installed in a rectangular cable tray at ceiling level.)

5.3.3 Summary.

The MET will successfully identify a breach that results in a dielectric breakdown of less than 5000 V with respect to the wire under test. The distance to breach reporting accuracy is subjective to the configuration of the harness under test. For a given harness, the results are repeatable in that the tool consistently finds that a breach has occurred. However, the accuracy in determining the distance to fault will vary depending on the harness configuration. The MET is able to calculate a distance to fault when the resulting echo voltage contains distinguishable edges that physically originate due to wave reflections at the end of the harness and the fault. The physical properties of a wire harness that determine, and ultimately limit, the ability of the MET to accurately determine the distance to fault are:

- Electromagnetic field coupling to other conductive structures
- Harness loss and dispersion
- Characteristic impedance variations of the harness between the fault and the MET
- Propagation velocity of the traveling wave
- Arc voltage

Using the MET, the contractor was able to detect approximately 35% of the breaches. Since the testing was in blind format, actual defect locations and severities were not known. Not all the inserted breaches were placed close enough to arc-over at less than 5000 V. The MET only detects conductor-to-conductor faults that will arc-over at less than 5000 V. Fault conductor-to-conductor separation distances of greater than approximately 0.1″ will not result in an arc-over condition at less than 5000 V. Actual operating voltages of typical aircraft systems will not approach 5000 V, even during transient events. (After testing was completed, it was noticed that some of the faults were not near another conductor or frame.)

When an arc was induced at a breach, it typically emitted an audible snap when the discharge occurred. This sound allowed the fault to be located by using one’s ear to home in on the source of the snap. The snap was ignored during the test, since the point of the test was to determine the MET’s ability to locate the breach.

5.3.4 Observations.

The results for each harness test are shown in tables 5-5 through 5-10. The column labeled Fault Inserted lists only faults that were actually present. Faults not detected were not revealed to the personnel. There are occasions where no defect was present and the MET produced a result. This phenomena will be investigated later. The column labeled MET Scan Results lists those faults diagnosed by the MET.

The MET laptop interface reports a distance-to-fault, if one can be calculated. The distance-to-fault was also captured using an oscilloscope to monitor the arc fault return echo. Both distances are reported for any arc breakdowns detected.

The MET was unable to estimate the distance-to-fault for some of the detected breaches. A detailed investigation of the cause has shown that the geometry of the wire harness, specifically the relative spacing between conductors, had a profound effect on the accuracy of the measurement. When the distance is reported as undetermined, it is because the arc fault return echo was too faint to observe.

TABLE 5-5. HARNESS 551, POLYIMIDE (M81381/11), 12 CONDUCTORS, 10-ft LENGTH

Wire	Fault Inserted	MET Scan Results
1		
2		
3		
4		
5	Hard Short to 8 at 7.7 ft	Short, probably to wire 8
6	Insulation breach 180° 100% at 7.2 ft	Arc breakdown, ranged from 2900 to 4500 V Distance: MET 4.7 ft/Scope 7.9 ft, probably to wire 9
7		
8	Hard Short to 5 at 7.7 ft	Short, probably to wire 5
9	Faulted splice at 7 ft	Arc breakdown, ranged from 3100 to 4100 V Distance: MET undetermined/Scope undetermined, probably to wire 6
10		
11		
12		

TABLE 5-6. HARNESS 552, POLYIMIDE (M81381/11), 12 CONDUCTORS, 100-ft LENGTH

Wire	Fault Inserted	MET Scan Results
1		
2		
3		
4	Hard short to 5 at 10 ft	Short, probably to wire 5
5	Hard short to 4 at 10 ft	Short, probably to wire 4
6		
7		
8		
9		
10	Open wire defect at 84 ft	Arc breakdown, ranged from 1700 to 2300 V Distance: MET undetermined/Scope undetermined, probably to wire 12
11		
12	Insulation breach 180° 100% at 3.5 ft	Arc breakdown, ranged from 3600 to 3800 V Distance: MET undetermined/Scope undetermined, probably to wire 10

TABLE 5-7. HARNESS 553, POLYIMIDE (M81381/11), 12 CONDUCTORS, 200-ft LENGTH

Wire	Fault Inserted	MET Scan Results
1		
2	Insulation breach at 120 ft	Short, probably to wire 3
3	No defect	Short, probably to wire 2
4		
5		
6		
7		
8		
9	No defect	Arc breakdown, ranged from 3500 to 3600 V Distance: MET undetermined/Scope 65 ft, probably to wire 11
10		
11	No defect	Arc breakdown, 3900 V, occurred only once Distance: MET undetermined/(did not capture using scope), probably to wire 9
12		

TABLE 5-8. HARNESS 561, ETFE (M22759/34), 12 CONDUCTORS, 10-ft LENGTH

Wire	Fault Inserted	MET Scan Results
1	Hard short to 8 at 8 ft	Short, probably to wire 8
2	Open wire defect at 4.7 ft	Arc breakdown, ranged from 1500 to 3900 V Distance: MET undetermined/Scope 4 ft, probably to wire 4
3		
4	Insulation breach 180° 100% at 7.9 ft	Arc breakdown, ranged from 1600 to 3400 V Distance: MET 5.6 ft/Scope 4 ft, probably to wire 2
5		
6	Insulation breach 180° 100% at 7.9 ft	Arc breakdown, ranged from 3300 to 3500 V Distance: MET undetermined/Scope 10 ft Probably to wire?
7		
8	Hard short to 1 at 8 ft	Short, probably to wire 1
9		
10		
11		
12		

TABLE 5-9. HARNESS 562, ETFE (M22759/34), 12 CONDUCTORS, 100-ft LENGTH

Wire	Fault Inserted	MET Scan Results
1		
2		
3		
4		
5	Insulation breach 180° 100% at 3 ft	Arc breakdown, ranged from 3400 to 3800 V Distance: MET 1.1 ft/Scope 1.9 ft, probably to wire 6
6	Insulation breach 180° 100% at 3 ft	Arc breakdown, ranged from 2500 to 3400 V Distance: MET 1.1 ft/Scope 1.9 ft, probably to wire 5
7		
8		
9		
10		
11		
12		

TABLE 5-10. HARNESS 563, ETFE (M22759/34), 12 CONDUCTORS, 200-ft LENGTH

Wire	Fault Inserted	MET Scan Results
1	Insulation breach 180° 100% at 70 ft	Arc breakdown, ranged from 2800 to 3100 V Distance: MET undetermined/Scope 83 ft, probably to wire 7
2		
3		
4		
5		
6	Insulation breach 180° 100% at 198 ft	Arc breakdown, ranged from 1800 to 2200 V Distance: MET 112 ft/Scope 98 ft, probably to wire 10
7	No defect	Arc Breakdown, Ranged from 2500 to 3300 V Distance: MET undetermined/Scope 83 ft, probably to wire 1
8		
9		
10	No defect	Arc breakdown, ranged from 3000 to 3400 V Distance: MET undetermined/Scope 105 ft, probably to wire 6
11		
12		

Figure 5-34 presents an example of the difficulty encountered by the MET on calculating a distance to fault. The cursor location shows a spike that corresponds to the actual distance-to-fault. Figure 5-35 shows an example of a test on a separate harness that also produced an unusable fault waveform. This trace is a little deceiving; there is a perceivable edge, however, it occurs more than 70 ns past the time that would correspond to the total length of the harness under test (283 ns would correspond to 100 feet, assuming a propagation velocity of 0.71 the speed of light). Trace 1 is the fault waveform recorded using an oscilloscope, and trace 2 is the width detected by the MET pulse-width detect circuit. The vertical scales are not accurate—the traces are intended only to show the fault waveform shape. Note the fault waveform is ac-coupled.

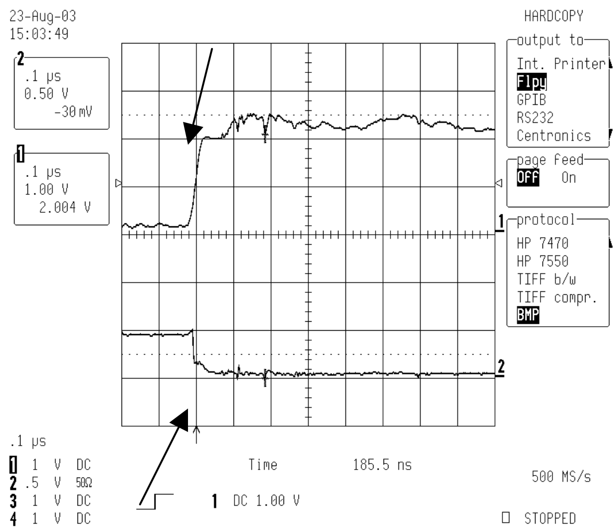

FIGURE 5-34. HARNESS 553, WIRE 9, TOTAL LENGTH OF HARNESS IS 200 FEET, ARC-OVER AT 3500 V

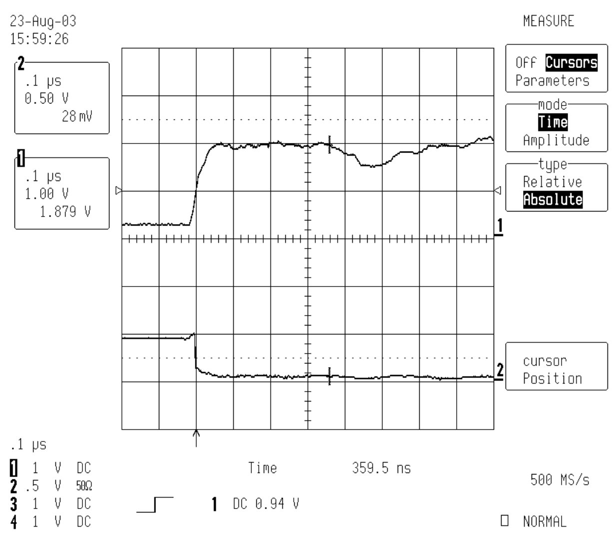

FIGURE 5-35. HARNESS 552, WIRE 24, TOTAL LENGTH OF HARNESS IS 100 FEET, ARC-OVER AT 3700 V

The MET experienced considerable difficulty in calculating the distance-to-fault, which the official test data suggests. Of particular interest, is the manner in which wires are bound together (i.e., packing density). It was shown that if wires are loosely bundled, a widely and continuously varying characteristic impedance is produced along the cable run. This is the result of the ratio of the distance between wires and the distance from the wires to ground plane, varying significantly along the run.

As an interesting comparison, testing personnel installed a separate 100-foot wire pair harness in the same tray as the test harness. As shown in figure 5-36, the fault wave has a drastically improved shape (relative to the test harness waveform shown in figures 5-34 and 5-35), and the distance-to-fault was accurately predicted. The predominant difference between these harnesses was that the harness built had the wires tightly bundled.

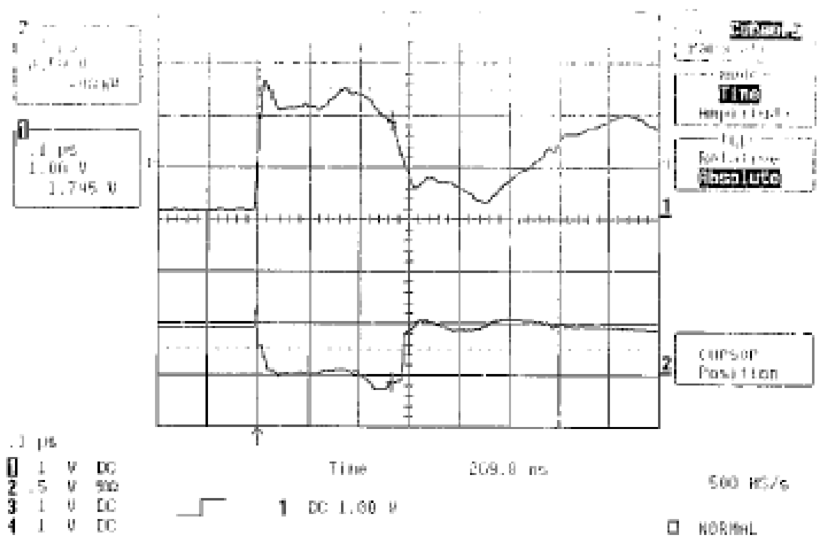

FIGURE 5-36. THE 100-ft HARNESS, DISTANCE-TO-FAULT IS 100 FEET, ARC-OVER AT 3500 V

5.4 COMPATIBILITY AND FIELD TESTING VALIDATION ON AN AIRCRAFT ENVIRONMENT.

5.4.1 Objective.

This testing demonstrated the effectiveness of the MET and IFP to find common types of faults on different types of harnesses and wiring configurations. This testing was performed in an actual aircraft environment.

5.4.2 Procedure.

FAA/AANC personnel fabricated two harnesses, as shown in table 5-11.

TABLE 5-11. HARNESS PREPARED FOR COMPATIBILITY AND FIELD TESTING

FAA/AANC Harness Designation	Wire Type	AWG	Length (feet)	Number of Conductors
570	Polyimide (M81381/11)	22	200	12
	ETFE (M22759/34)	22	200	12
580	Polyimide (M81381/11)	22	200	12
	ETFE (M22759/34)	22	200	12

For each harness, instances of the following faults were applied to the cables: cuts, abrasions, cracks, chaffing, and arcing to ground at various locations. The harnesses were installed in the passenger cabin area of a retired, gutted Boeing 737 fuselage at the FAA/AANC facility. The harnesses are about three times the length of the fuselage, so they each made about three trips up and down the length of the plane when they were routed. The routing of the wire followed major cable runs at the top, sides, and floor of the cabin area.

The locations of the faults were not provided to the personnel at the time of the test. The personnel scanned the prepared harnesses and attempted to detect and locate as many faults as possible using the MET.

Figures 5-37 and 5-38 show the MET and IFP being used during this test.

FIGURE 5-37. USING THE MET TO SCAN THE TEST HARNESSES

FIGURE 5-38. USING THE IFP TO SCAN THE TEST HARNESSES

5.4.3 Summary.

The MET will successfully identify a breach that results in a dielectric breakdown of less than 5000 V with respect to the wire under test. The distance-to-breach reporting accuracy is subjective to the configuration of the harness under test such as electromagnetic field coupling to other conductive structures, harness loss and dispersion, characteristic impedance variations of the harness between the fault and the MET, propagation velocity of the traveling wave, and arc voltage. For a given harness, the results are repeatable. However, the accuracy will range from within a few percent to undetermined, depending on the harness configuration.

The personnel used the MET and IFP to scan the wires for breaches and detected approximately 64% of the breaches. When an arc was induced at a breach, it typically emitted an audible snap when the discharge occurred. This sound allowed the fault to be located by using one's ear to home in on source of the snap. The audible snap often provided a quick method of locating a breach. The IFP was then used to scan the wires independently. If a breach existed behind a panel or an area difficult to penetrate with the IFP, it may not have been detected.

5.4.4 Results.

The results for each harness test are tabulated in tables 5-12 and 5-13. The column labeled Fault Inserted lists any faults that were actually present.

If a fault could be located using the IFP, or an audible snap indicated the location of the fault, this is indicated in its respective column. The MET laptop interface reports a distance-to-fault, if one can be calculated. Both distances are reported for any arc breakdowns detected. When the distance is reported as undetermined, it is because the arc fault return echo was too faint to observe.

TABLE 5-12. HARNESS 570

Wire	Fault Inserted	Located Using IFP	Located Using Audible Snap	MET Scan Results/Other Comments
1				
2	Hard short to 3 at 6.5 ft	No	No	Short, probably to wire 3
3	Hard short to 2 at 6.5 ft	No	No	Short, probably to wire 2
4				
5				
6				
7				
8				
9	Insulation breach 180° 100% at 190 ft	Yes	Yes	Arc breakdown, ranged from 3500 to 4500 V Distance: MET 229.8 ft/Scope 216 ft, probably to wire 11
10				
11	Insulation breach 180° 100% at 190 ft	Yes	Yes	Arc breakdown, ranged from 3600 to 3800 V Distance: MET 229.9 ft/Scope 216 ft, probably to wire 9
12				Low resistance measurement 1 to 2 mega ohm
13	Insulation breach 360° 100% at 80 ft	Yes	Yes	Arc breakdown, ranged from 1700 to 2500 V Distance: MET 88.1ft/Scope 94 ft, probably to wire 14
14	Insulation breach 360° 100% at 80 ft	Yes	Yes	Arc breakdown, ranged from 1200 to 2000 V Distance: MET 88.1 ft/Scope 94 ft, probably to wire 13
15				
16				
17	Insulation breach 360° 100% at 80 ft **	No	No	Arc breakdown, ranged from 2200 to 2800 V Distance: MET 7.1 ft/Scope 5 ft, probably to wire 19 (see notes)

TABLE 5-12. HARNESS 570 (Continued)

Wire	Fault Inserted	Located Using IFP	Located Using Audible Snap	MET Scan Results/Other Comments
18	No Defect **	No	No	Arc breakdown, ranged from 2200 to 2800 V Distance: MET 7.1 ft/Scope 5 ft, probably to wire 19 (see notes)
19	Insulation breach 360° 100% at 130 ft	No	No	Arc breakdown, ranged from 1500 to 2200 V Distance: MET undetermined/Scope 5 ft, probably to wire 18
20				
21				
22				
23				
24				

Note: Two types of insulation breeches were located using the IFP. These were 2, 5, and 9. These were not detected with the MET, as they were not in contact with another conductor or structure. Independent IFP scanning of this cable was done when the MET portion of the test was completed.

**This fault was actually found to be between wires 17 and 19, due to a wiring mismatch in the adapter cable. (This was realized posttest.)

This cable had four other insulation defects that were not found. These may not have been conducive to MET and IFP detection capabilities or in areas hard to get to.

TABLE 5-13. HARNESS 580

Wire	Fault Inserted	Located Using IFP	Located Using Audible Snap	MET Scan Results/Other Comments
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12	Insulation breach 360° 100% at 50 ft	Yes	Yes	Arc breakdown, ranged from 3400 to 4000 V Distance: MET 68.9 ft/Scope 73 ft, probably to wire 13
13	Insulation breach 360° 100% at 50 ft	Yes	Yes	Arc breakdown, ranged from 3600 to 3900 V Distance: MET 67.9 ft/Scope 73 ft, probably to wire 12
14				
15				
16				
17				
18				
19				
20				
21	Insulation breach 360° 100% at 9.5 ft	Yes	Yes	Arc breakdown, ranged from 3400 to 3800 V Distance: MET 8.8 ft/Scope 14.5 ft, probably to wire 22
22	Insulation breach 360° 100% at 9.5 ft	Yes	Yes	Arc breakdown, ranged from 3300 to 4400 V Distance: MET 10.1 ft/Scope 14.5 ft, probably to wire 21
23				
24				

Note: Two types of insulation breeches were located using the IFP. These were 1 and 8. These were not detected with the MET, as they were not in contact with another conductor or structure. Independent IFP scanning of this cable was done when the MET portion of the test was completed.

This cable had four other insulation defects that were not found. These may not have been conducive to MET and IFP detection capabilities or in areas hard to get to.

Two examples of the waveforms obtained during this testing are provided. These examples can be compared with the waveforms in section 5.3 and the examples shown in section 4. A good example and a not so good example are shown. The good example (figure 5-39) indicates the type of waveform that produced a fairly accurate distance-to-fault calculation. The not so good example (figure 5-40) shows the type of waveform produced when a distance-to-fault could not be determined. Trace 1 is the fault waveform recorded using an oscilloscope, and trace 2 is the width detected by the MET pulse-width detect circuit. The vertical scales are not accurate—the traces are intended only to show the fault waveform shape. Note the fault waveform is ac-coupled.

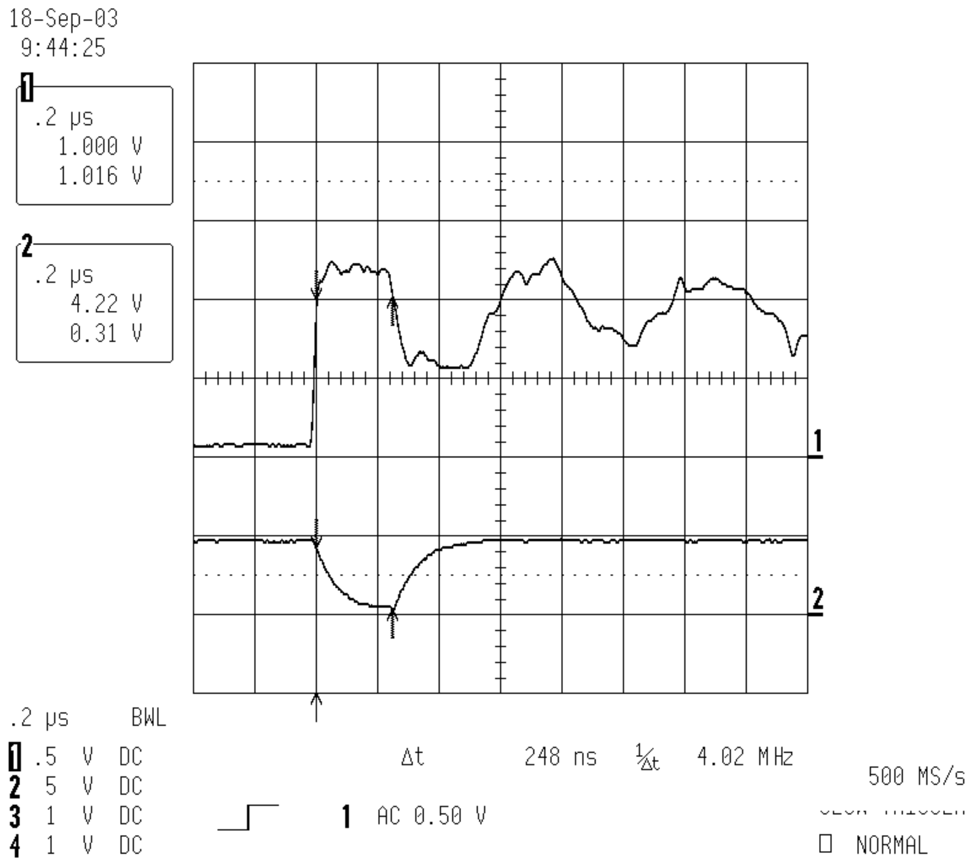

FIGURE 5-39. HARNESS 570, WIRE 13, ARC-OVER AT 2000 V

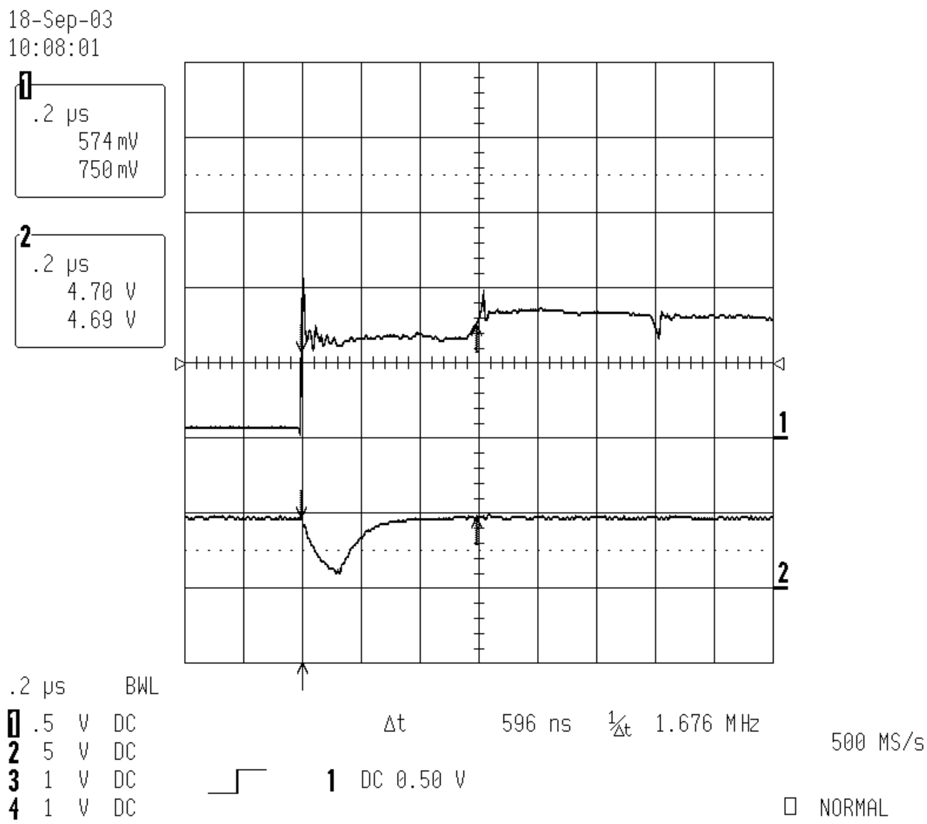

FIGURE 5-40. HARNESS 570, WIRE 19, ARC-OVER AT 2000 V

5.5 TEST VOLTAGE AND SAFETY.

5.5.1 Micro-Energy Tool Test Voltage and Safety.

The MET applies up to 5000 V to a wire to test for breakdown. The maximum test voltage is programmable from 0 to 5000 V, therefore, it can be tailored on a case-by-case basis.

When applying the maximum voltage for a particular situation, one should consider the safety constraints described below.

5.5.1.1 Safety to Personnel.

Detailed information regarding the effects of electric shock on humans is generally available. The information presented is based largely on the paper “Deleterious Effects of Electric Shock” by Professor C.F. Dalziel, 1961. This paper presents quantitative experimental data performed on humans and animals.

This safety assessment assumes the test operators have no ailments that would cause them to be more sensitive to electric shock than an average healthy worker.

It is the current that flows through the body that determines shock severity. Based on 60 Hz currents, which experimentally have the most severe effects for the lowest amplitudes, the following statements can be made.

- Currents less than 1 mA cannot be felt.
- Currents in the 1 to 8 mA range result in a shock, but generally are not painful.
- Currents in the 8 to 20 mA range result in a painful shock.
- Currents above 50 mA affect the heart.
- Currents above 200 mA cause severe burns and severe muscle contraction.

The MET produces a high voltage, but the current is limited to a safe level. There is a 50 megohm resistor in series with the high-voltage supply inside the MET. This limits the maximum output current to 5000 V/50 megohm = 100 μA. This level is intrinsically safe to humans, as it is an order of magnitude below the experimentally established level where current cannot be felt.

Consideration must be made to the fact that when the MET is connected to a test harness, the low output current can charge up the parasitic harness capacitances up to the maximum test voltage. Dalziel's paper presents data pertaining to impulse shock data, as would result from discharging a capacitor. Assuming the human body presents roughly 500 ohms of impedance, coming into contact with a wire charged to 5000 V would result in an initial discharge current of 5000 V/ 500 ohms = 10 amps. (Keep in mind this is not that high of an initial current, common electrostatic discharge (ESD) events generated by walking across a carpet have a higher initial current than this, the concern is the energy that is discharged during the event.) Dalziel's data suggests that a "reasonably safe surge" at this initial current would be if the decay time constant of the resulting current was less than 1 ms. Reasonably safe can be taken to mean injury could occur, but not fatal.

The decay time constant is a function of the capacitance and load that discharges the capacitance. Still assuming the human body represents 500 ohms, a 1-ms time constant would occur if the parasitic harness capacitance summed to 2 μF (time constant = R * C). A 2 μF capacitor, charged to 5000 V stores 25 Joules of energy. Arbitrarily derating Dalziel's safe surge limit two orders of magnitude results in an adjusted safe limit of 20,000 pF, or 250 mJ at 5000 V.

As previously described, the MET has a settable limit to how much energy is stored on a wire under test. Two hundred fifty mJ is more energy than would be stored for a typical test. For example, assuming there is 1 pF per inch of parasitic cable capacitance, a 200-ft harness would result in 2400 pF of parasitic capacitance, or 30 mJ if charged to 5000 V. Experience using the MET shows that a shock under this condition results in a shock that is uncomfortable, but does not cause injury.

<u>5.5.1.2 Safety to Equipment</u>.

When using the MET, the cable harness to be tested needs to be disconnected from all line replaceable units (LRU). If there is a potential that a breach may arc to an adjacent harness that is connected to an ESD-sensitive LRU, that LRU should be disconnected as well.

When the MET induces an arc at a breach, it results in a high dV/dt pulse traveling down the wire. This pulse can damage components sensitive to ESD. The worst-case voltage pulse an LRU would sustain is one that can be modeled with a voltage peak equal to the arc-over voltage driven by a capacitor equal to the test harness parasitic capacitance in series with the characteristic impedance of the line.

The MET cannot develop a voltage across most loads due to its limited current output (maximum 100 μA). For example, the MET can only develop 10 V across a 100k ohm resistor, even when set to output its maximum test voltage of 5000 V. This limits the possibility that the MET will damage an LRU if it has not been disconnected from the cable harness under test. The MET will indicated that a load is present if it cannot develop a voltage on the wire under test.

Some types of loads can be damaged if left connected to the cable harness under test. These include sensitive electronics that maintain a very high impedance until their dielectric barrier breaks down, potentially resulting in device damage. For example, a circuit isolated by an optocoupler or a wire loaded only by a capacitor.

Testing reported in section 5 showed that the insulation at the breach was not further degraded with application of over 100 arc events. A light carbon film was observed, using microscopic inspection, but no further reduction in insulative properties was noted. Testing of over 500 arc events showed a darkening of the carbon film, but still no observable degradation of the insulative properties at the breach.

Using the MET has not caused any wire insulation breakdown. Six hundred Vac-rated aircraft wire is typically tested at the time of manufacture by running it through energized beads at 8000 Vdc and by applying 2500 Vac at 60 Hz. Wire is typically designed so that it can withstand at least 2.5 times its rated voltage indefinitely. Six hundred Vac-rated wire should be able to readily withstand a momentary peak voltage of Vpeak = 2500 Vac * 1.4 = 3500 Vdc with little risk of damage. It should also be noted that if the MET applies 5000 V, and a breakdown does not occur, it is unlikely the wire will breakdown at normal operating voltage levels.

For a typical wire harness, the connectors represent the weakest dielectric point. Typical aerospace connectors have a rated dielectric withstand capability measured in 100's of volts. Testing showed that many connectors can withstand the momentary application of the maximum 5000 V capability of the MET, even though they are rated for much lower voltage levels. None of the testing performed by GD has revealed a degradation in the dielectric withstand capabilities of the connectors after testing, even after they breakdown during testing. The low current that flows has minimal damage or carbon track-producing capability.

It is difficult to make a definitive statement regarding the fire or explosion safety of the spark produced by the MET. There is no risk when testing harnesses in regions that do not contain explosive vapors or where the harnesses are not contaminated with flammable deposits. Industry touted levels of spark energy required to ignite Jet A fuel vapors in aircraft gas tanks range from 35 mJ actual ignition levels down to intrinsically safe levels of 20 μJ. For reference, the maximum energy level available to a spark when using the MET at a test level of 5000 V is typically less than 30 mJ for a majority of encountered harnesses. The exact energy available depends on the parasitic capacitance of the harness under test, which can be calculated using the following equation:

$$E = \tfrac{1}{2} * C * V^2$$

Where E is the energy available, C is the parasitic capacitance of the cable, and V is the voltage applied to the harness under test.

5.5.2 Insulation Fault Probe Test Voltage and Safety.

The IFP applies up to 6000 V to a wire to test for breakdown. When applying the maximum voltage for a particular situation, one should consider the safety constraints described below.

5.5.2.1 Safety to Personnel.

This safety assessment assumes that the test operators have no ailments that would cause them to be more sensitive to electric shock than an average healthy worker.

The IFP produces a high voltage, but the current is limited to a safe level. There is a 100-megohm resistor in series with the high-voltage supply inside the MET. This limits the maximum output current to 6000 V/1 gigohm = 6 μA. This level is intrinsically safe to humans, as it is two orders of magnitude below the experimentally established level where current cannot be felt.

Caution must be used since the IFP can potentially charge any conductive object that comes within a few inches of its energized tip. This will only happen when the conductive object is well insulated from the return path to the IFP. This concern only applies if the insulation resistance to the IFP return is greater than about 10 megohms.

The IFP is very safe when testing a harness where all conductors have a path of less than 10 megohms to an aircraft frame and the IFP return is attached to the aircraft frame. The operator should be careful not to bring the energized tip within several inches of any floating, high-capacitance conductive harnesses or structures. Inadvertently charging and touching a floating 200-foot harness with 2400 pF of stray capacitance would create a discharge with 43 mJ of energy. This would be an uncomfortable shock, but should not cause injury.

The IFP does not have a means to determine if it is charging up an isolated conductor. If a charge is inadvertently placed on a floating harness, it should bleed off within a few minutes.

5.5.2.2 Safety to Equipment.

When using the IFP, all wires in the cable harness should have a path of less than 1 megohms to the IFP return.

The IFP does not have a means to determine if it is charging up an isolated conductor. If a charge is inadvertently placed on a floating harness, it should bleed off within a few minutes.

Inadvertently charging up a floating wire could cause an arc to occur at an unintended location. This is typically a benign event, but should be considered when performing tests around ESD sensitive LRU's and in areas where combustion is a concern.

Some types of loads can be damaged if left connected to the cable harness under test. These include sensitive electronics that maintain a very high impedance until their dielectric barrier breaks down, potentially resulting in device damage. For example, a circuit isolated by an optocoupler or a wire loaded only by a capacitor.

6. CONCLUSIONS AND RECOMMENDATIONS.

6.1 CONCLUSIONS.

The goal of the MET and the IFP is to aid the field personnel in the detection and location of wiring insulation breaches. Both of these technologies can be used to complement each other in the detection of fault on wire harnesses. Testing done on this research show that the MET and the IFP are non destructive.

The MET will successfully identify a breach that result in a dielectric breakdown of less than 5000V with respect to the wire under test. Distance to breach reporting accuracy is subjective to the configuration of the harness under test. For a given harness, the results are repeatable. However, the distance to fault accuracy will range from within a few percent to undetermined, depending on the harness configuration. The MET only detects conductor-conductor faults that will arc over at less than 5000V. Fault conductor-to-conductor separation distances of greater that approximately 0.1″ will not result in an arc over condition at less than 5000V. The MET's high voltage did not degrade the dielectric properties of the wire.

The IFP functions as a fine tune fault locator. The IFP aids field personnel on the detection of breaches on the wire, where the IFP can be used independently to scan wires, and when an arc was induced at a breach a sound would allow the user to home in on the source of the sound. The IFP uses a high voltage source in conjunction with helium gas to induce electron streaming across an air gap into an insulation breach giving both audible and visual feedback to the user. If breach exist behind a panel or an area difficult to penetrate with the IFP the breach may not be detected.

6.2 RECOMMENDATIONS.

Tested revealed wiring configuration or scenarios where the MET was not able to calculate distance to fault. It is recommended to further study possibilities of improving the MET's ability to accurately determine the distance to fault in m ore challenging wiring scenarios, including harness with complex breakouts, terminations, and geometry. There could be an issue with the energy used and dissipated during testing of the MET. A detailed study of the effect of low energy high voltage signal on aircraft fuel systems and Line Replacement Units should be performed. Further improvement on the design and manufacture of a more robust, more accurate and smaller system.