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Aircraft Electrical Wet-Wire Arc Tracking

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16. Abstract

Electrical wet-wire arc tracking is a phenomenon that has been known for many years. This can occur when leakage currents on a wet insulation surface are great enough to vaporize the moisture, resulting in the formation of dry spots. These dry spots offer a high amount of resistance to current flow. In turn, an induced voltage will develop across these spots and result in the occurrence of small surface discharges. Initially, these discharges will appear as scintillations at the insulation surface. These discharges produce highly localized temperatures on the order of 1000° Centigrade (C). Temperatures of this magnitude will cause thermal degradation of the insulation material, the nature of which depends on the insulation material used.

The Federal Aviation Administration (FAA) conducted a series of bench scale tests which demonstrated that the ability of an aircraft wire to resist wet arc tracking and possible flashover is highly dependent on the composition of the wire insulation. In addition, the conductivity level of the electrolyte may influence the time and the type of failure (arc track or open circuit) that can occur.

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EXECUTIVE SUMMARY

This report contains the results of an investigation of aircraft electrical wet-wire arc tracking. Electrical wet-wire arc tracking is a phenomenon that has been known for many years. This can occur when leakage currents on a wet insulation surface are great enough to vaporize the moisture, resulting in the formation of dry spots. These dry spots offer a high amount of resistance to current flow. In turn, an induced voltage will develop accross these spots and result in the occurrence of small surface discharges. Initially, these discharges will appear as scintillations at the insulation surface. These discharges produce highly localized temperatures on the order of 1000^{o} Centigrade (C). Temperatures of this magnitude will cause thermal degradation of the insulation material, the nature of which depends on the insulation material used.

Various wire insulation constructions were evaluated. Among those samples tested were current aircraft wire constructions conforming to Federal Aviation Regulations and Military Specifications and experimental samples composed of two or more polymers. It was found that certain polyimide (Kapton®) wire insulation constructions can be modified to resist wet-wire arc tracking by applying thin fluoropolymer coatings. Also, the conductivity of the electrolytic solution may influence the type of failure event (tracking or open circuit) and the time at which this occurs.

Thermogravimetric analysis (TGA) (mass loss versus temperature) was used to evaluate the tendency of a polymer to form a carbonaceous residue which could form a conductive path. TGA data consistently proved to be a valuable tool.

INTRODUCTION

PURPOSE

The purpose of this project was to study the occurrence of aircraft electrical wet-wire arc tracking.

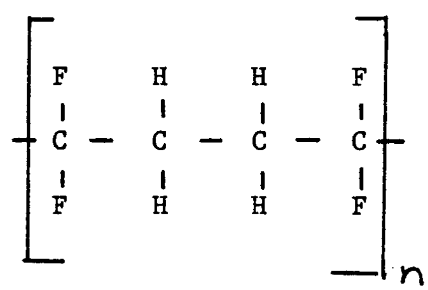
BACKGROUND

Electrical wet-wire arc tracking is a phenomenon that has been known for many years. This can occur when leakage currents on a wet insulation surface are great enough to vaporize the moisture, resulting in the formation of dry spots. These dry spots offer a high amount of resistance to current flow. In turn, an induced voltage will develop across these spots and result in the occurrence of small surface discharges. Initially, these discharges will appear as scintillations at the insulation surface. These discharges produce highly localized temperatures on the order of 1000° Centigrade (C) (reference 1). Temperatures of this magnitude will cause thermal degradation of the insulation material, the nature of which depends on the insulation material used.

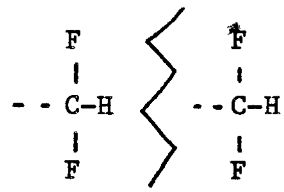
The two most currently used wires in commercial aircraft are MIL-W-81381 wires, insulated with Kapton® aromatic polyimide, and MIL-W-22759 wires, insulated with a fluoropolymer, such as polytetrafluoroethylene (TFE), fluorinated ethylene propylene (FEP), ethylene-tetrafluoroethylene copolymer (ETFE), or other fluoropolymer resin.

The thermal degradation process of Kapton due to the high temperature discharges results in the carbonization of the aromatic polyimide. At first, the carbonization process will occur at small, localized spots. However, as the reaction continues, a carbon path or track will form between conductors. The heat generated by high current flow through the low resistance carbon path rapidly causes severe arcing or flashover.

The aliphatic fluoropolymers specified in MIL-W-22759, with the exception of modified crosslinked ETFE, do not form carbon deposits upon thermal degradation. As these fluoropolymers degrade, low molecular weight gaseous products are formed and the conductor erodes. While modified ETFE also forms gaseous products, its molecular structure allows formation of water and elemental carbon:



The weak bond between carbons, once broken and with incomplete combustion (non-oxidative environment), can yield a carbonized char residue capable of forming a conductive path:



DISCUSSION

EXPERIMENTAL TEST SETUP.

A bench scale test device (figure 1), similar to the device proposed by the British Standards Institution (BSI G230 Test 42), was assembled. The test specimen consisted of seven American Wire Gauge (AWG) 20 interconnect wires, each about 14 inches in length. Approximately 1/2 inch of insulation was stripped from one end of each wire to allow connection to the power supply. Two of the wires had circumferential cuts made approximately midway in their length exposing about 1.2 millimeters (mm) of conductor. The seven wires were tied together in a six-around-one configuration using waxed linen lacing twine per MIL-T-713. The two damaged wires were adjacent to each other but the cuts were separated longitudinally by approximately 10 mm. The bundle was supported in air, 30 degrees from the horizontal by laboratory stands and clamps.

A 220/110 400-cycle three-phase generator, rated at 18.75 kVA, was used as the power source. Figure 2 shows the electrical connections. The electrolyte was ocean water, chemically analyzed at 4.0 percent salts content and having a conductivity of 39.6 millimhos. Ocean water was selected as the electrolyte due to its high conductivity and the fact that the United States Navy has experienced wet arc tracking problems on some of its carrier-based aircraft due to ocean water salt spray. Because blue flush fluid is used in commercial aircraft lavatories, tests were run on a number of wire samples using blue fluid as the electrolyte. For the first set of tests, urea was added to the fluid to simulate human waste. For the second set of tests metallic salts were added to the urea treated fluid to increase conductivity. At this time, the majority of wire samples were not available for testing with the flush fluid, therefore, the data for the test samples tested with this fluid are not complete. The drip rate was set at 6 drops per minute by means of a needle control valve. The drip rate was steady due to a constantly maintained pressure head on the distribution flask. The needle valve was positioned directly above the uppermost cut wire at a height of 10 mm.

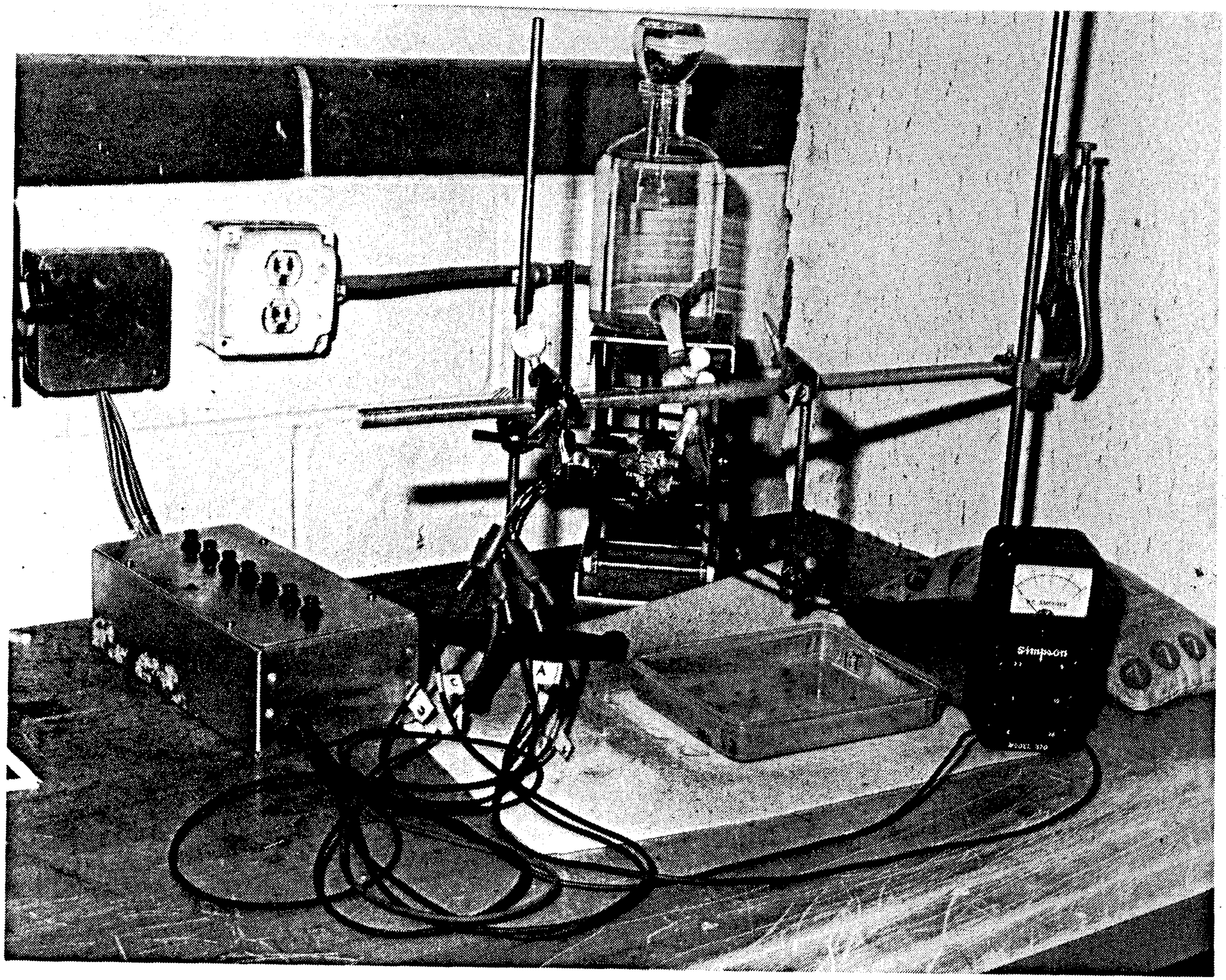
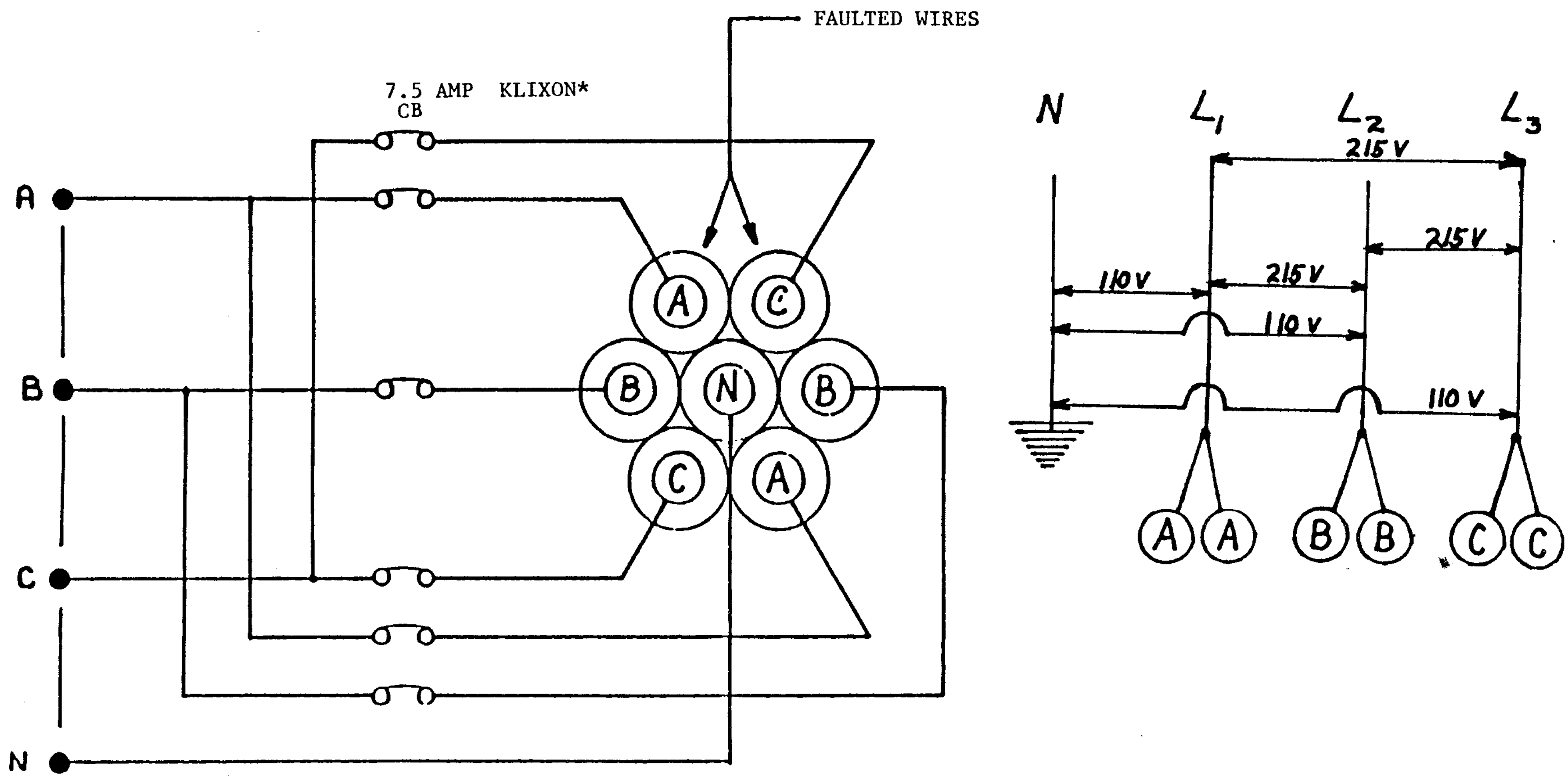


FIGURE 1. TEST DEVICE



*REGISTERED TRADEMARK OF TEXAS INSTRUMENTS, INC.

FIGURE 2. ELECTRICAL CONNECTIONS

TEST SAMPLES.

Wet-wire arc tracking tests are currently being conducted in laboratories throughout the United States and Europe. While polyimide materials will track, they do show excellent resistance to abrasion, they have the ability to withstand extremes of temperature, and they emit very little smoke (reference 2). The fluoropolymers have outstanding weatherability, inertness to solvents and generally will not track (reference 3). In order to derive the benefits from both insulator materials, wire constructions incorporating both polyimide and fluoropolymer materials are now being developed and tested. Table 1 is a listing of wire constructions that were evaluated for wet tracking resistance.

TEST RESULTS.

Table 1 describes samples tested. The wet arc tracking test results with ocean water are summarized in table 2. All samples with the exceptions of Nos. 2, 8, and 10 are constructions of polyimide and fluoropolymer materials.

Tables 3 and 4 summarize the results of the arc tracking tests performed wire constructions using lavatory blue flush fluid at two levels of solution conductivity.

REACTION TIME. Referring to the 12 test samples in table 2, it can be seen that very large variations in time-to-event exist for the different types of wire. Of the nine test samples made up of polyimide-fluoropolymer materials, five of these constructions tracked and four samples opened. Of the remaining three samples, two of these constructions tracked and one construction opened. Test sample No. 2, which is Kapton polyimide with Liquid H-30I® topcoat tracked in 44 seconds while sample No. 11, which incorporates a Teflon® inner wrap with a Kapton topcoat ran for over 37 hours and finally opened. No comparability with respect to time can be seen for the polyimide-fluoropolymers that tracked. Moreover, those that resulted in open circuits ranged in run times of 4 hours up to 37 hours.

DAMAGE TO WIRE BUNDLES. From table 2, it can be seen that one of the polyimide-fluoropolymer wire bundles (No. 6) severed upon resetting of the first circuit breaker (figure 3). This sample incorporated a cross-linked extruded ETFE topcoat over a Kapton polyimide inner wrap. Note that initially five circuit breakers tripped as a result of severe arcing. Bundle No. 2, Kapton (Liquid H topcoat), also severed upon resetting the first circuit breaker (figure 4). In both cases, resetting of circuit breakers resulted in increasingly severe failure of the wire bundles due to arcing. In this case, a total of six circuit breakers had initially tripped.

For those polyimide-fluoropolymer constructions that opened (Nos. 1, 3, 11, and 12), no evidence of damage to any of the other wires in the bundles other than the open wires themselves was detected (figures 5, 6, 7, and 8). Sectioning of the open wires occurred as a result of an electroerosion process. This was apparent by the formation of a copper-containing green salt during the test on the wire bundles.

TABLE 1. TEST SAMPLES DESCRIPTIONS

Number	Specification	Materials (see key)	AWG
1	Lab Sample	Kapton® polyimide Mica tape-TFE tape-topcoat	20
2	MIL-W-81381/12	Kapton polyimide-polyimide topcoat (Liquid H-301®)	20
3	Lab Sample	Kapton polyimide-PFA topcoat	20
4	Lab Sample	Kapton polyimide-Tefzel® (ETFE) topcoat	20
5	Lab Sample	Kapton polyimide-PTFE Dispersion topcoat	20
6	Lab Sample	Kapton polyimide-modified cross-linked fluorocarbon topcoat	20
7	Lab Sample	Kapton polyimide-TFE tape topcoat	20
8	MIL-W-22759/16	Extruded Tefzel (ETFE)	20
9	ACT 260-1	Kapton polyimide-PTFE topcoat CAA (ref. no. E 10903)	20
10	MIL-W-22759/41	Extruded radiation cross-linked ETFE	20
11	Lab Sample	Teflon®-inner wrap-Kapton polyimide outer wrap	20
12	Lab Sample	Kapton polyimide-irradiated Tefzel topcoat	20

Material Key

PTFE or TFE - Polytetrafluoroethylene
ETFE - Ethylene-tetrafluoroethylene
PFA - Perfluoroalkoxy-fluorocarbon

TABLE 2. TEST SAMPLE SUMMARY - OCEAN WATER

Sample Bundle	Test Time	Tracking	Open Circuit	Notes (CB's reset 1 time)
1	28 hr.-10 min.		Yes	2 wires open
2	44 sec.	Yes		6 CB's tripped. Upon reset bundle severed.
3	17 hr.-10 min		Yes	2 wires open
4	6 hr.-55 min.	Yes		2 CB's tripped. Upon reset same 2 breakers tripped.
5	2 min.	Yes		1 CB tripped. Upon reset a total of 3 breakers tripped.
6	1 hr.-15 min.	Yes		5 CB's tripped. Upon reset 3 breakers tripped and bundle severed.
7	1 hr.-35 min.	Yes		3 CB's tripped. Upon reset same 3 breakers tripped.
8	14 hr.-5 min.		Yes	2 wires open
9	40 min.	Yes		3 CB's tripped. Upon reset 4 breakers tripped.
10	10 hr.-45 min.	Yes		2 CB's tripped. Upon reset 2 wires severed.
11	37 hr.-15 min.		Yes	3 wires open
12	4 hr.-25 min.		Yes	2 wires open

TABLE 3. TEST SAMPLE SUMMARY - LAVATORY FLUSH FLUID

Sample Bundle	Test Time	Tracking*	Open Circuit	Notes (CB's reset 1 time)
MIL-W-81381/12	2 hr.-10 min	Yes		2 CB's tripped. Upon reset same breakers tripped.
ACT 260-1	5 hr.-5 min.		Yes	2 wires open
MIL-W-22759/11	5 hr.		Yes	1 wire open
MIL-W-22759/41	4 hr.-35 min.		Yes	2 wires open

TABLE 4. TEST SAMPLE SUMMARY - TREATED LAVATORY FLUSH FLUID

Sample Notes Bundle	Test Time	Tracking	Open Circuit	(CB's reset 1 time)
MIL-W-81381/12 Liquid H-301 topcoat	58 sec.	Yes		1 CB tripped. Upon reset same breaker tripped.
ACT 260-1	10 hr.-45 min.		Yes	2 wires open
MIL-W-22759/11	11 hr.		Yes	2 wires open
MIL-W-22759/41	12 hr.-5 min		Yes	2 wires open

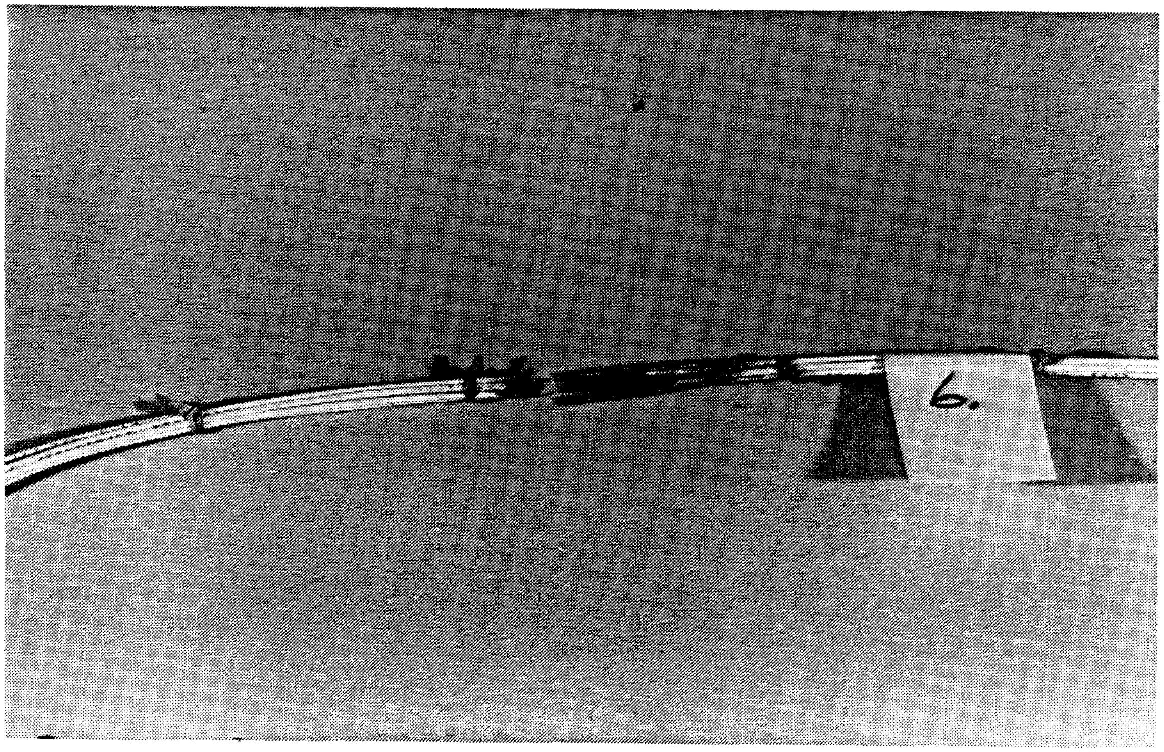


FIGURE 3. LAB SAMPLE PHOTOGRAPH - WIRE BUNDLE 6

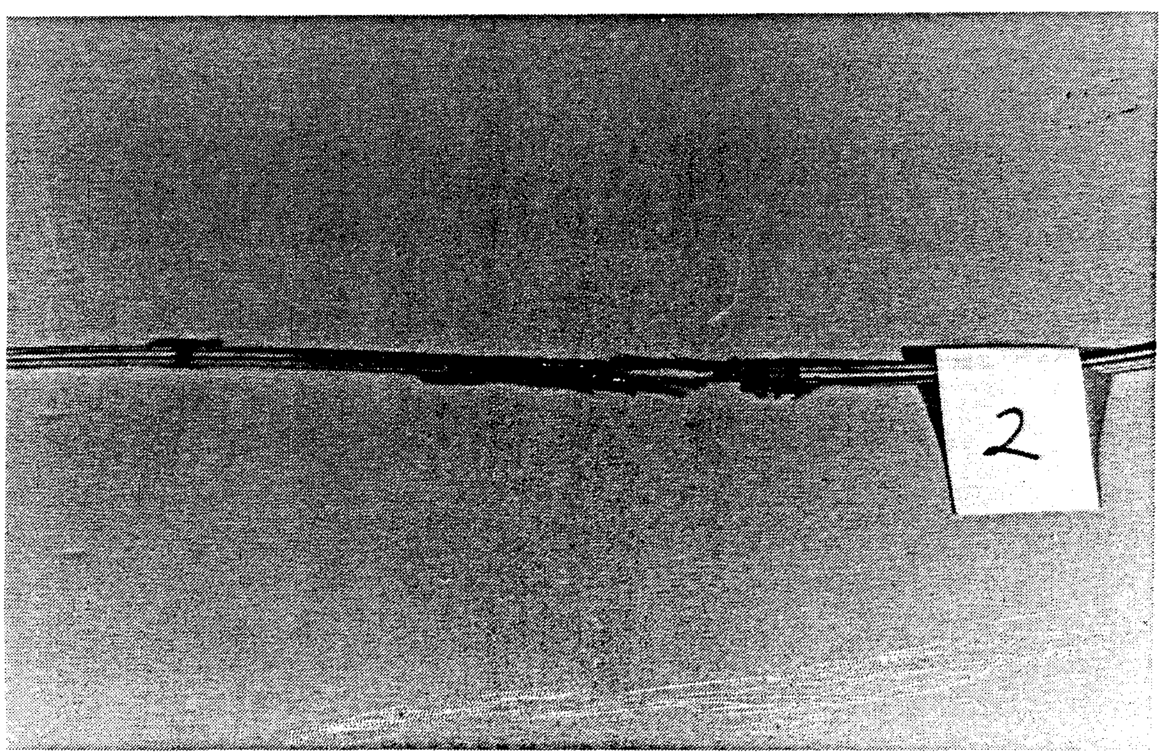


FIGURE 4. MIL-W-81381/12 PHOTOGRAPH - WIRE BUNDLE 2

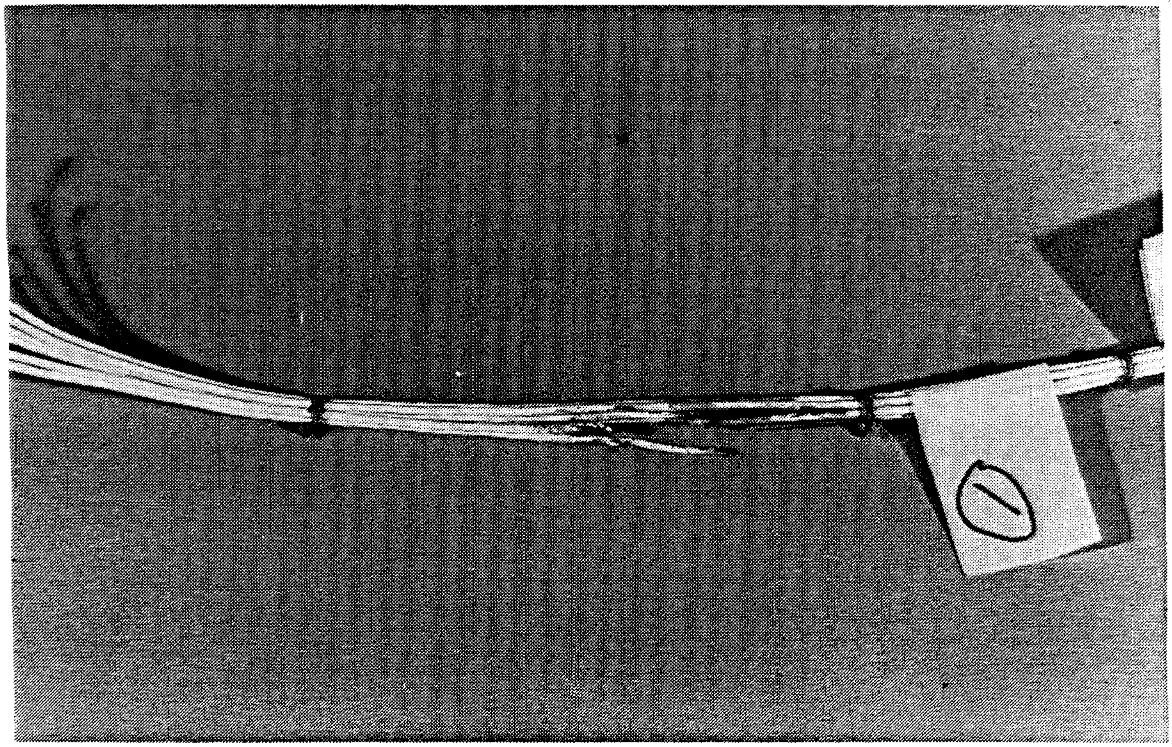


FIGURE 5. LAB SAMPLE PHOTOGRAPH - WIRE BUNDLE 1

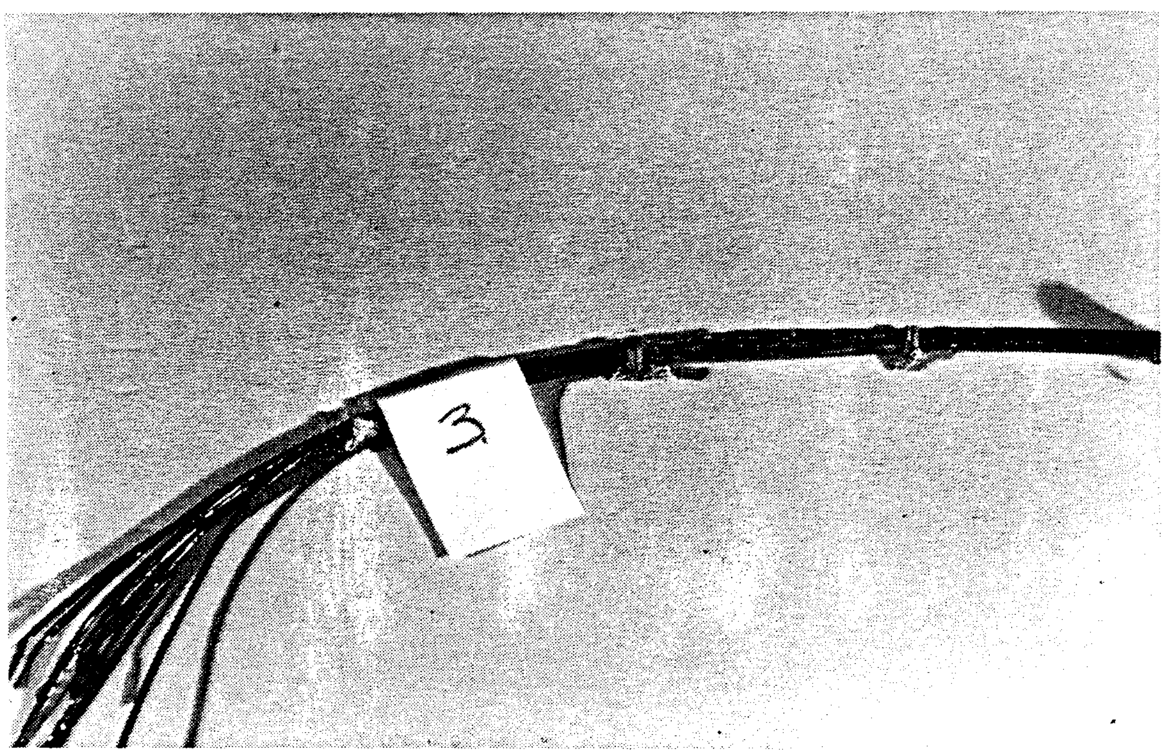


FIGURE 6. LAB SAMPLE PHOTOGRAPH - WIRE BUNDLE 3

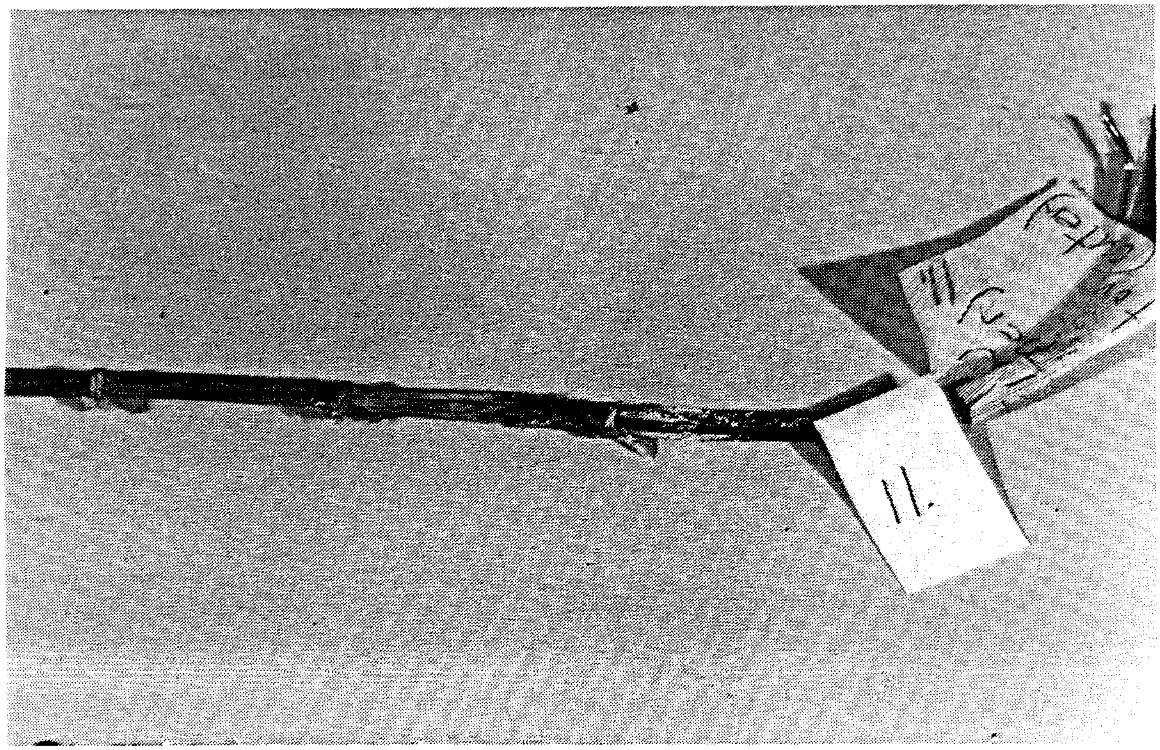


FIGURE 7. LAB SAMPLE PHOTOGRAPH - WIRE BUNDLE 11

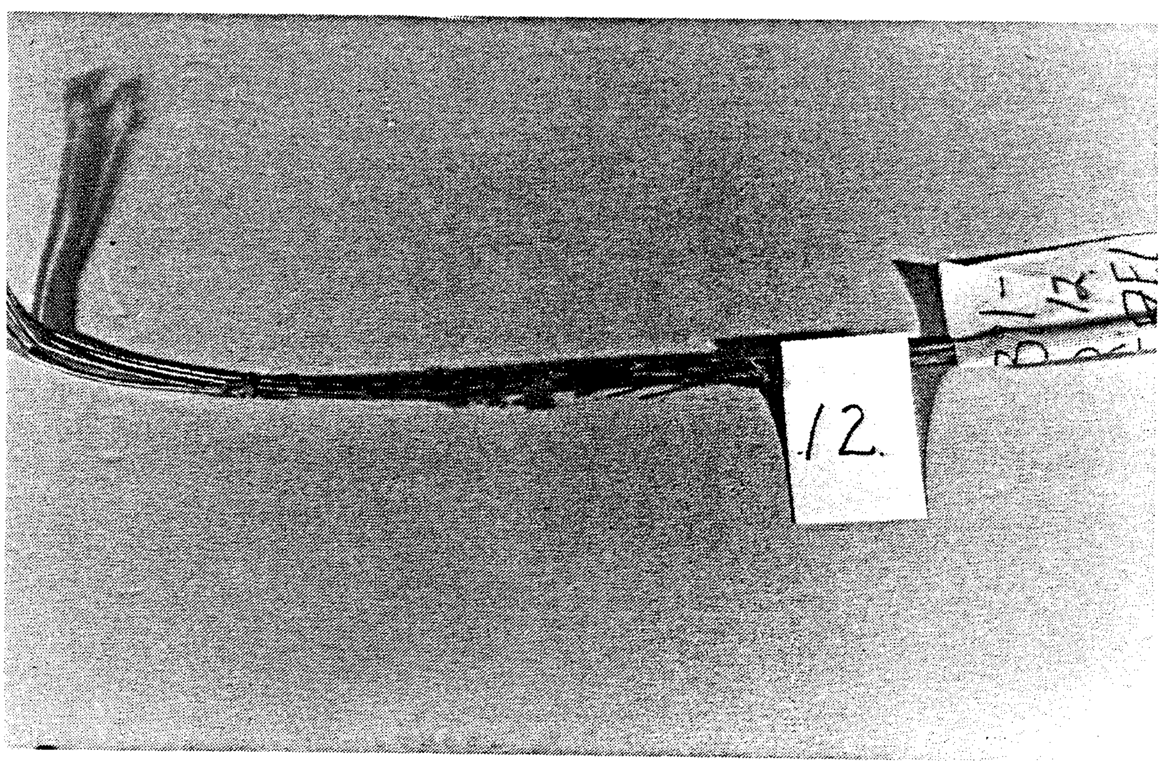


FIGURE 8. LAB SAMPLE PHOTOGRAPH - WIRE BUNDLE 12

Carbonization of the insulation material took place in all cases where the polyimide-fluoropolymers test bundles tracked (figures 9, 10, 11, and 12). While these test bundles did not completely sever, damage to more than the two initially cut wires resulted as a result of arc tracking. Bundle No. 10 (crosslinked-extruded modified ETFE) tracked while bundle No. 8 (extruded ETFE) opened (figures 13 and 14). As stated earlier in this report, modified crosslinked ETFE (ethylene-tetrafluoroethylene copolymer) can form elemental carbon upon thermal degradation in a nonoxidative environment. No determination was made as to why char formation occurred for this sample tested in air.

In the tests with lavatory blue water (tables 3 and 4), it can be seen that all test bundles opened with the exception of MIL-W-81381/12 which tracked. Those samples which opened had the familiar copper-containing green salt present but no damage to any of the other wires in the bundle other than the two precut wires. The MIL-W-81381 wires had the carbon residue present that would be expected with tracking. However, no damage occurred to the wires in the bundles other than those that corresponded to the tripped breakers.

EFFECT OF ELECTROLYTE CONDUCTIVITY. Of all the samples tested with each electrolyte, only MIL-W-81381/12 with Liquid H-301 topcoat showed a tendency to track more rapidly as the conductivity of the electrolyte increased. From tables 2, 3, and 4:

Test Time (Tracking)	Conductivity
2 hours - 10 minutes	15.0 millimhos
58 seconds	30.0 millimhos
44 seconds	39.6 millimhos

However, many different electrolytes at various conductivities would have to be tested in order to prove conclusively that this is true. Furthermore, since only Kapton with Liquid H-301 topcoat was evaluated, this tendency may not exist for other types of Kapton topcoats (e.g., Pyralin® white topcoat).

Ocean water was selected as the electrolyte for testing those samples described in table 1 because of its high conductivity. The type of event (tracking-open) and the time of the failure were also evaluated as a function of conductivity. Sample No. 9 (ACT-260-1) opened when tested with the blue flush fluids at 15.0 and 30.0 millimhos conductivity but tracked when tested with the ocean water (39.6 millimhos). The same is true of MIL-W-22759/41 wire. As stated earlier in this report, the majority of samples were not available for testing with the flush fluids. Therefore, it is not possible at this time to make any generalized conclusions on the effect of electrolyte conductivity on the type and time of wet arc failure for various wire insulation compositions.

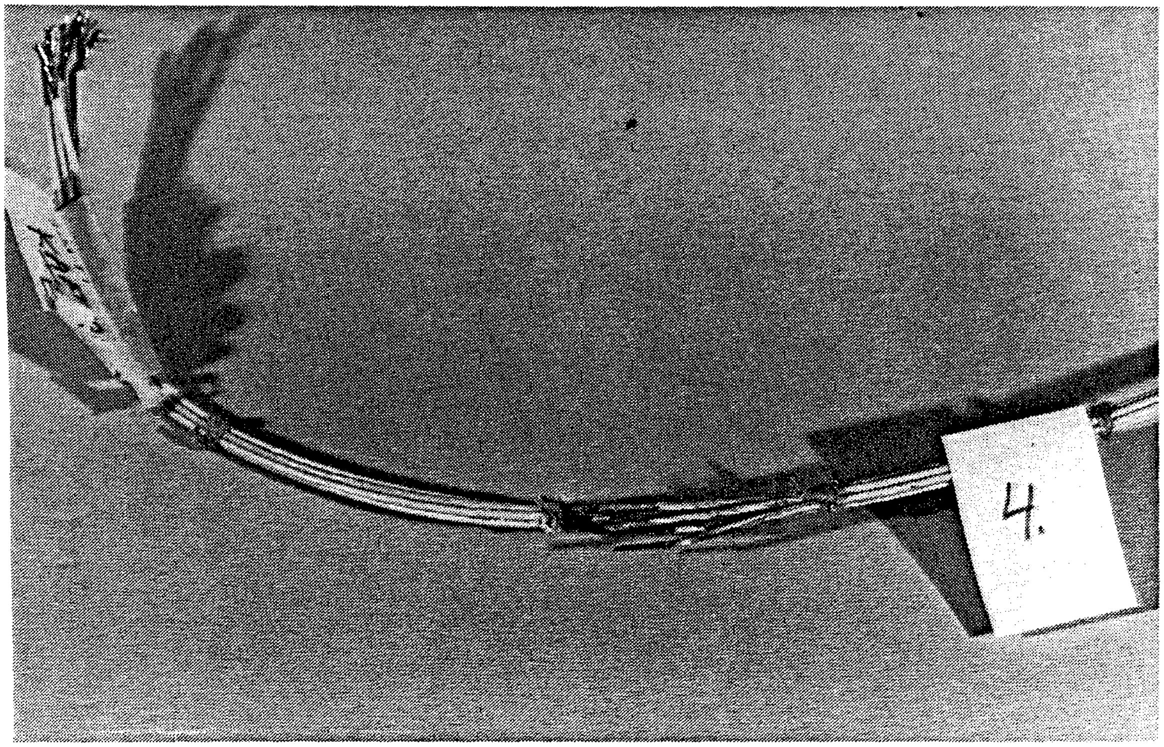


FIGURE 9. LAB SAMPLE PHOTOGRAPH - WIRE BUNDLE 4

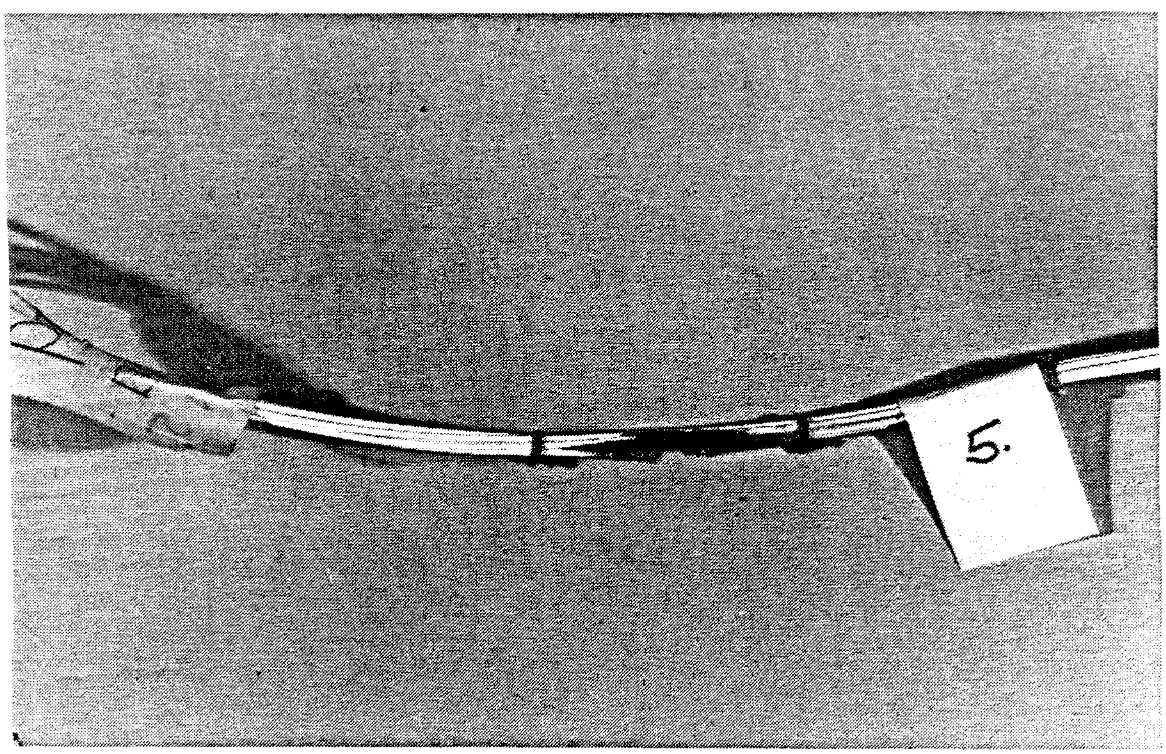


FIGURE 10. LAB SAMPLE PHOTOGRAPH - WIRE BUNDLE 5

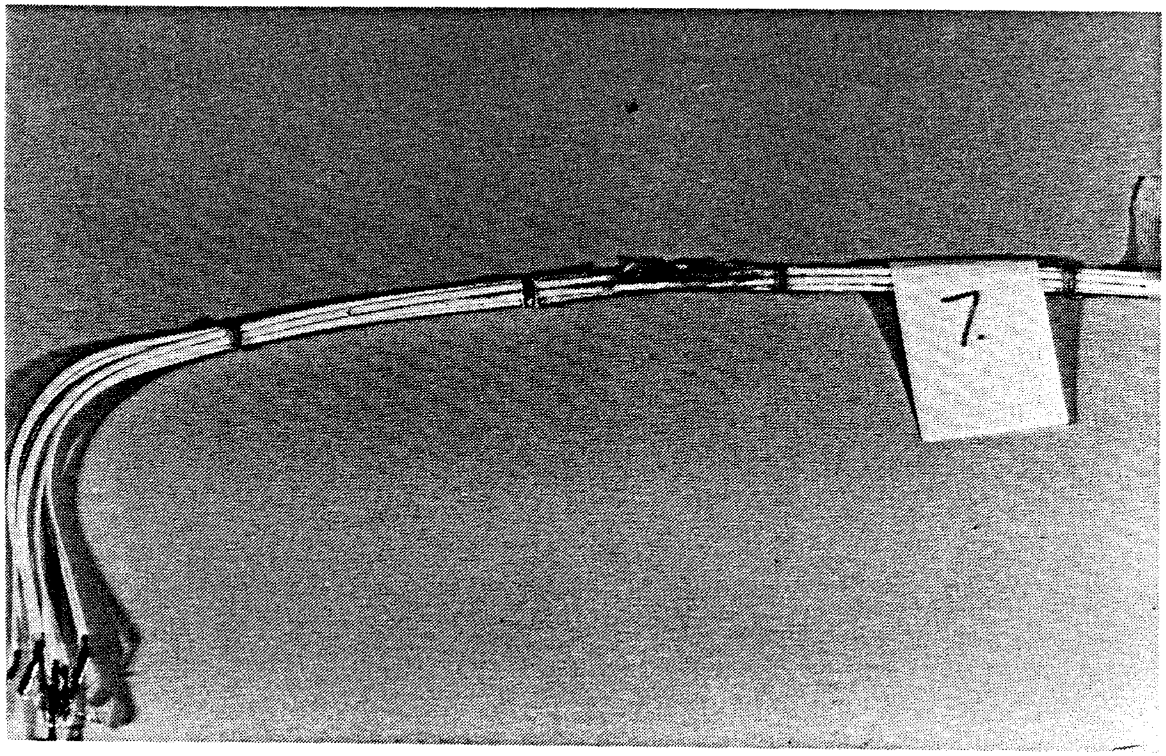


FIGURE 11. LAB SAMPLE PHOTOGRAPH - WIRE BUNDLE 7

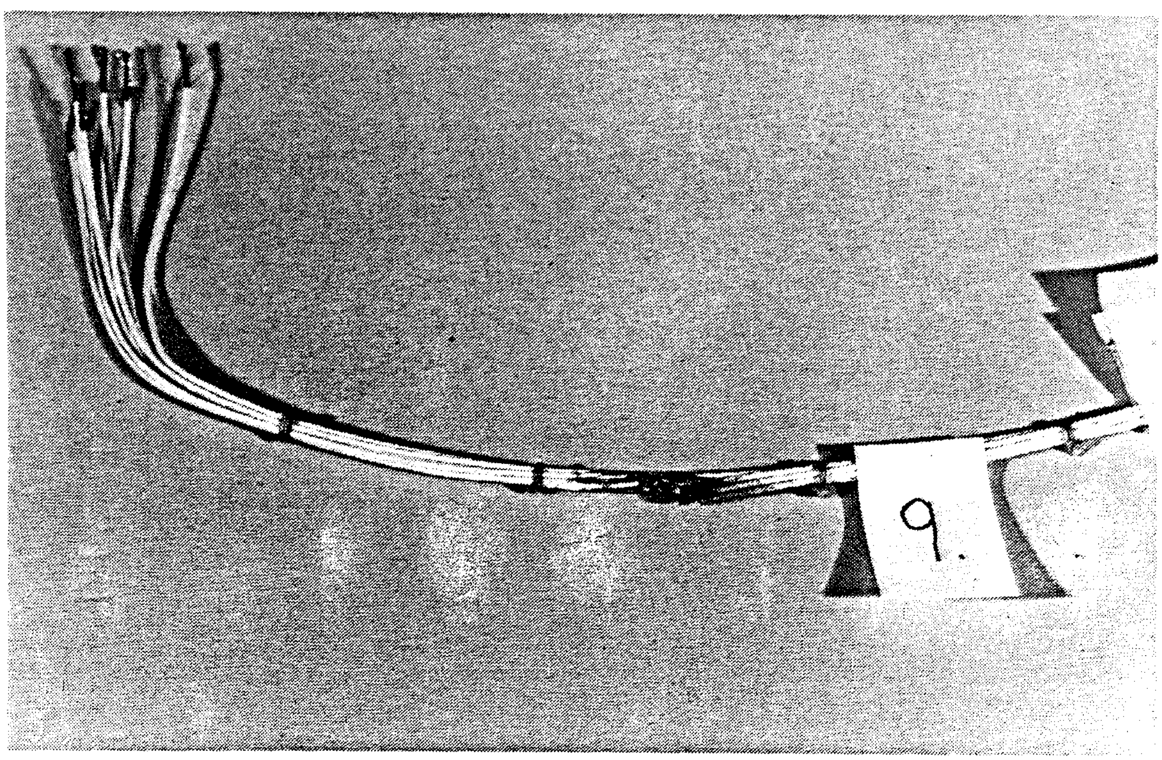


FIGURE 12. ACT 260-1 PHOTOGRAPH - WIRE BUNDLE 9

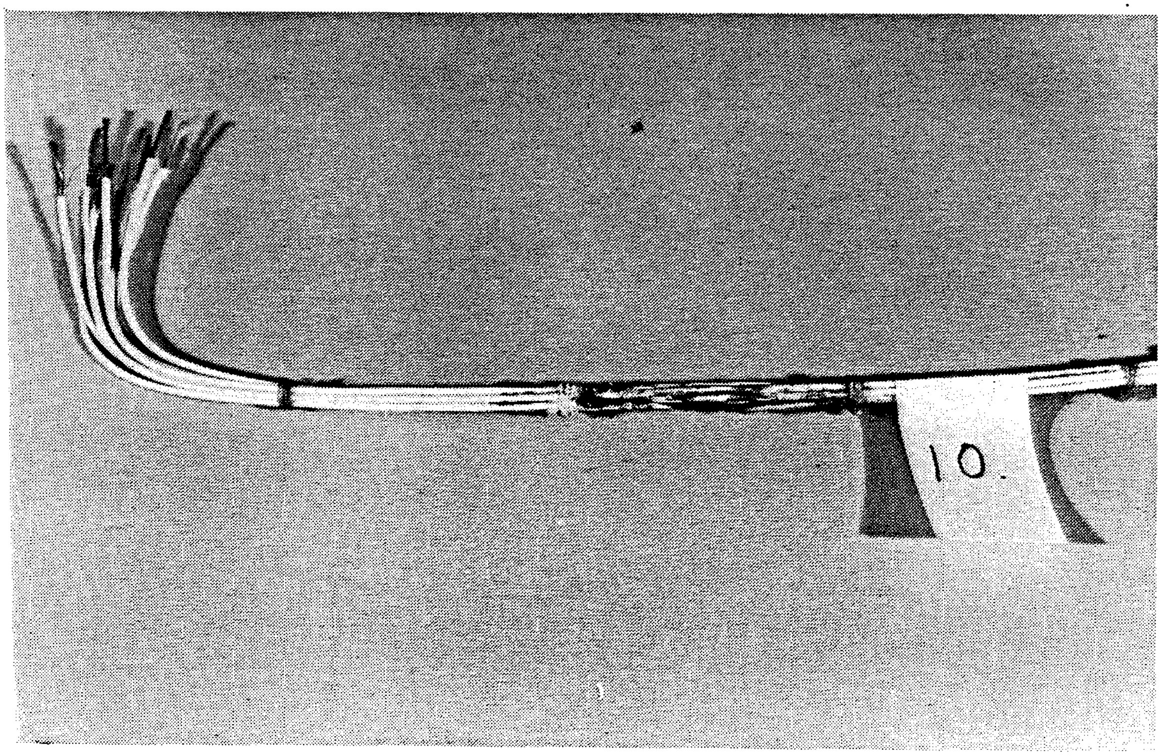


FIGURE 13. MIL-W-22759/41 PHOTOGRAPH - WIRE BUNDLE 10

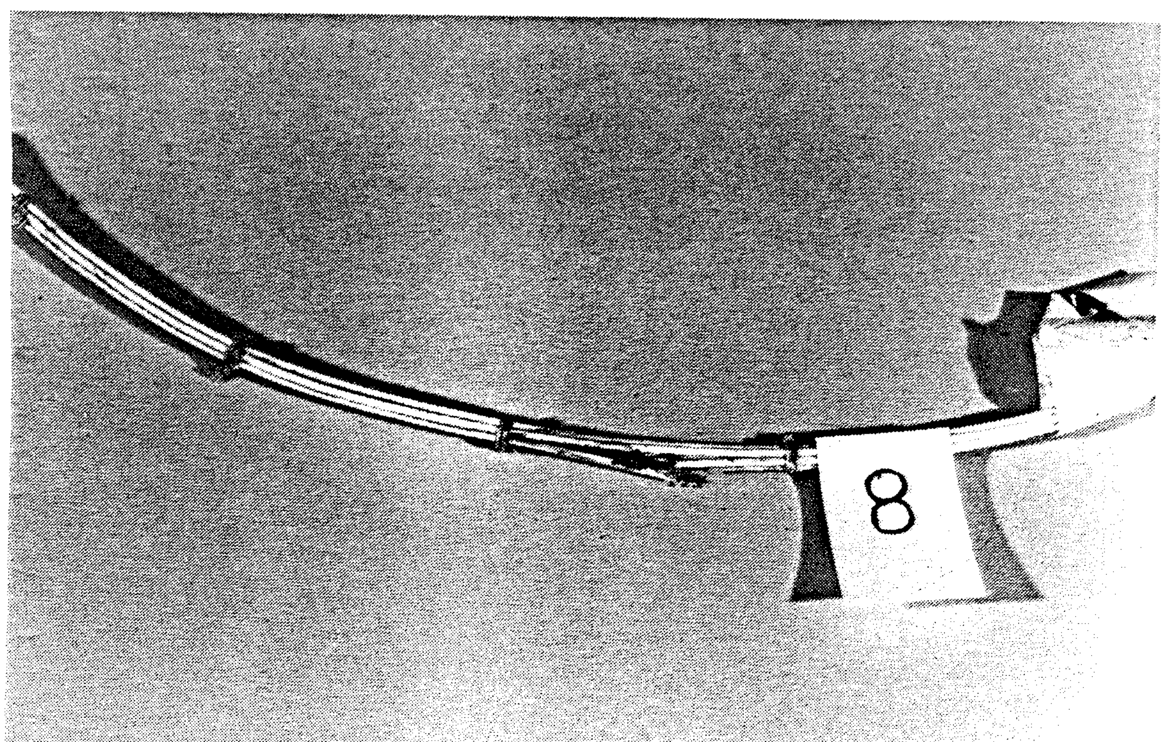


FIGURE 14. MIL-W-22759/16 PHOTOGRAPH - WIRE BUNDLE 8

THERMOGRAVIMETRIC ANALYSIS. Thermogravimetric analysis tests were run on a number of wire insulation materials to further characterize real and potential char formation. The results of these tests were compared with the results of the arcing tests to determine if some predictability of performance could be correlated.

Referring to figure 15, TGA run on Kapton polyimide shows that char formation occurs in both the nonoxidative environment (nitrogen), and in the oxidative environment (air). In nitrogen, the Kapton sample yields a 40 percent by weight carbon residue at 900° C. For the Kapton sample heated in air carbon formation begins at approximately 500° C and continues to form until approximately 800° C where it then reacts with oxygen, forming carbon dioxide.

Figure 16 shows Teflon samples (polytetrafluoroethylene aliphatic fluoropolymer) heated in both air and nitrogen. No char formation is seen. The two curves are superimposable which indicates that gaseous products are formed in both the oxidative and nonoxidative environments.

Figure 17 shows TGA curves of ETFE and modified crosslinked ETFE heated in a nonoxidative nitrogen environment. Note that some char formation occurs upon degradation of the modified crosslinked ETFE but not the ETFE fluoropolymer. The ETFE degrades with formation of gaseous products which would be expected with an unmodified fluoropolymer.

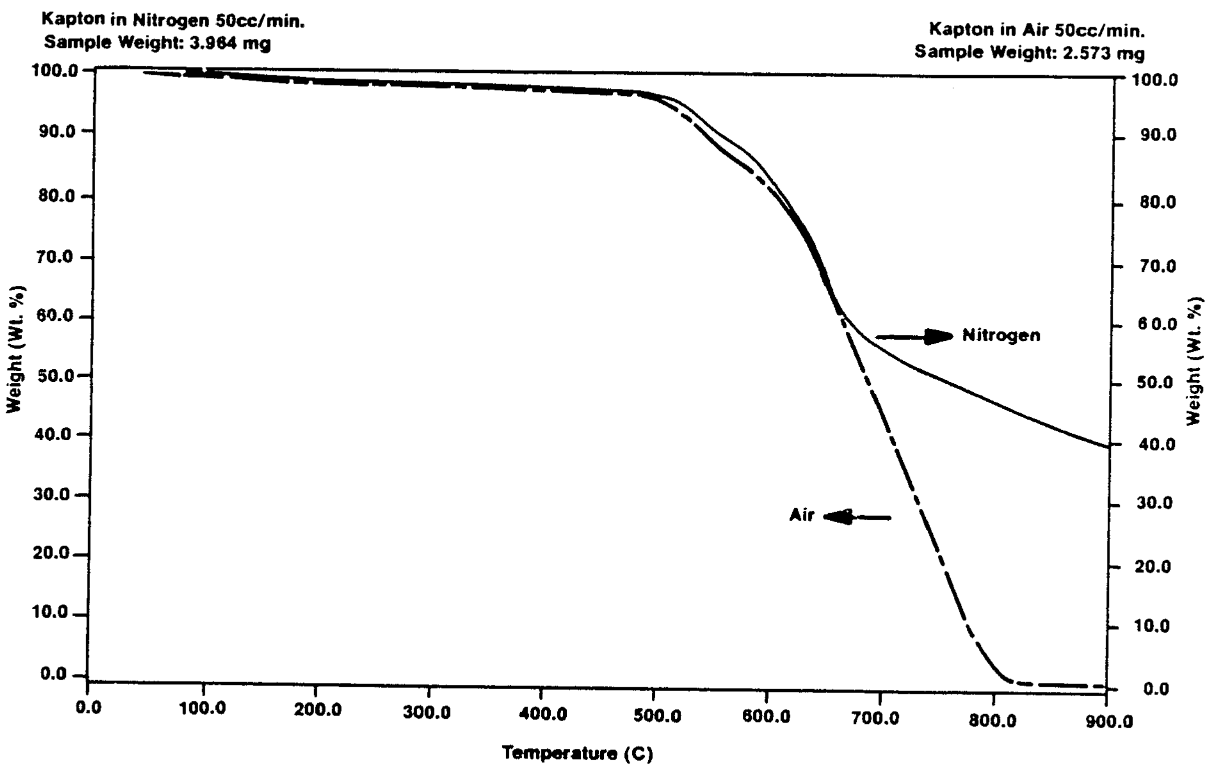


FIGURE 15. THERMOGRAVIMETRIC ANALYSIS--KAPTON

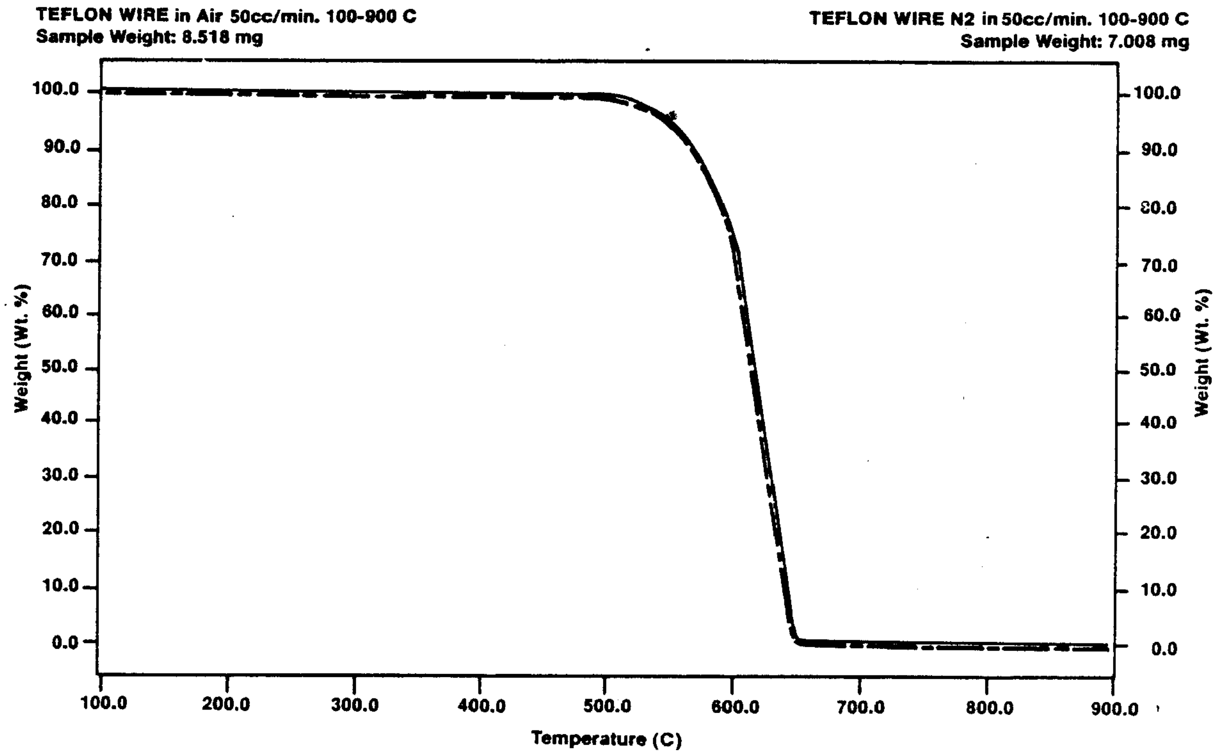


FIGURE 16. THERMOGRAVIMETRIC ANALYSIS--TEFLON

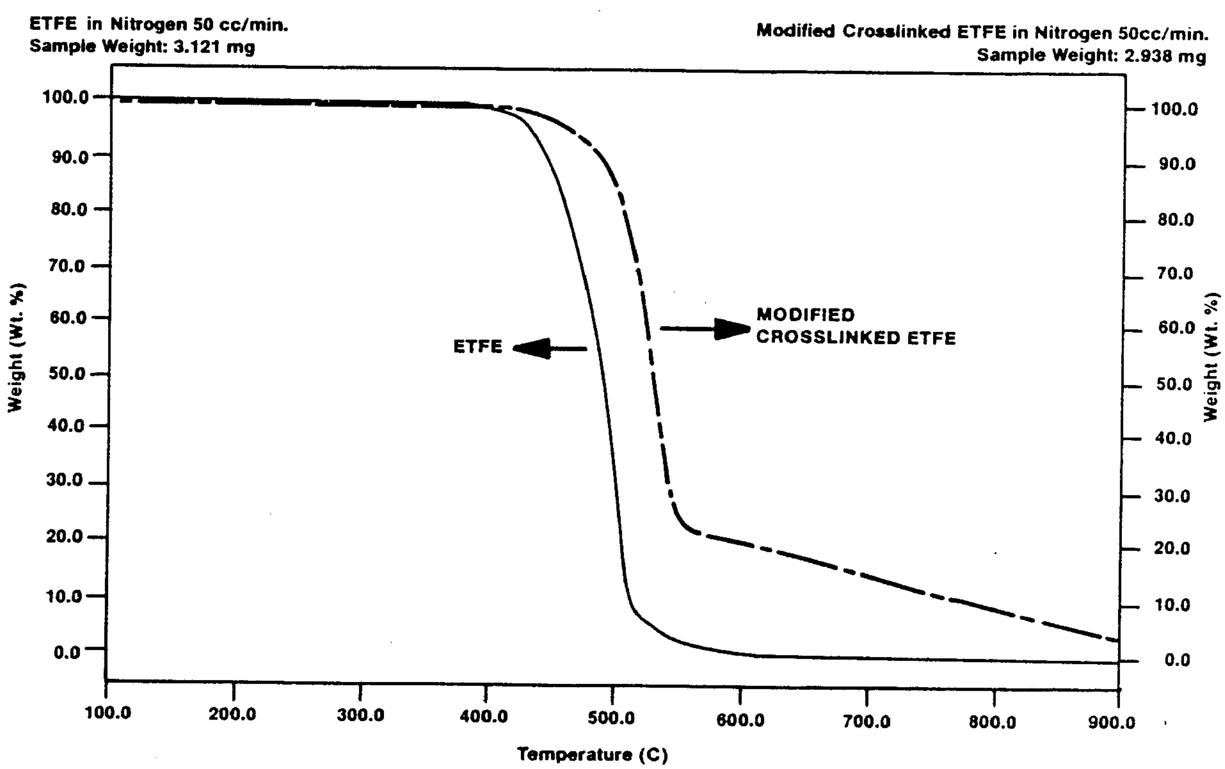


FIGURE 17. THERMOGRAVIMETRIC ANALYSIS--ETFE

CONCLUSIONS

1. Certain polyimide-fluoropolymer constructions can resist wet-wire arc tracking.

2. The conductivity of the electrolyte may influence the type of event (tracking-open) and the time in which this occurs.

3. Thermogravimetric analysis data can provide valuable information on the tendency of a polymer to form a char residue in an oxidative or nonoxidative environment.

4. Resetting circuit breakers can result in increasingly severe failures of the wire bundle due to additional arcing.

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