NATIONAL TRANSPORTATION SAFETY BOARD
Office of Aviation Safety
Washington, D.C. 20594

October 7, 1999

SYSTEMS GROUP CHAIRMAN FACTUAL REPORT ADDENDUM FOR ELECTRICAL SHORT CIRCUIT/ARCING OF AGED AIRCRAFT WIRING

A. ACCIDENT: DCA96MA070

Location : East Moriches, New York

Date : July 17, 1996

Time : 2031 Eastern Daylight Time

Airplane : Boeing 747-131, N93119
Operated as Trans World Airlines (TWA) Flight 800

B. SYSTEMS GROUP

Chairman : Robert L. Swaim
National Transportation Safety Board
Washington, D.C.

C. SUMMARY

On July 17, 1996, at 2031 EDT, a Boeing 747-131, N93119, crashed into the Atlantic Ocean, about 8 miles south of East Moriches, New York, after taking off from John F. Kennedy International Airport (JFK) All 230 people aboard were killed. The airplane was being operated as a Code of Federal Regulations (CFR) Part 121 flight to Charles De Gaulle International Airport (CDG) at Paris, France, as Trans World Airlines (TWA) Flight 800. Wreckage from the airplane was recovered from more than nine square miles of ocean. Reconstruction of portions of the wreckage found evidence of an explosion in the center wing fuel tank (CWT)

The Systems Group examined wiring in 16 transport category airplanes from February 21 through 25, 1998. (See the Group Chairman Factual Report Addendum for Wire Inspections, dated July 28, 1999). The group found damage to wire insulation, fluid stains on wires, and metal shavings resting on and between wires in wire bundles. As a result of these findings, the Safety Board contracted Lectromechanical Design Company (Lectromec) to conduct laboratory research of short circuit properties with BMS13-42 and BMS13-42A wires from a retired Boeing 747 and with MIL-W-81381 wire (as a baseline). The conductive materials used in tests were metal shavings, water, and lavatory fluids. Lectromec found three categories of electrical activity that were characterized as scintillations, flashing, and strong arcing. Lectromec also performed abrasion tests to examine how metal shavings damaged wire insulation. Lectromec Report No. N191-RPT4AU99 is attached.

[Original signed]

Robert L. Swaim
TWA 800 Systems Group Chairman

Electrical Arcing of Aged Aircraft Wire

for the

National Transportation Safety Board

490 L'Enfant Plaza East, S.W.
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Robert Swaim,
Chairman, TWA800 Systems Group

performed under
Order No. NTSB18-99-SP0127

Report No. N191-RPT4AU99

by

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Report Date: August 4, 1999
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EXECUTIVE SUMMARY

This report describes the results of several different tests relating to the short circuit properties of aged wires. The two types of wire insulations were crosslinked aliphatic polyimide-insulated (BMS13-42 and BMS13-42A) wire and a tape-wrapped aromatic polyimide (MIL-W-81381). The BMS wire had been removed from a Boeing 747 airplane (N93117) that had been in service for more than 25 years. The MIL-W-81381 was used for comparison and a baseline to existing data.

The following four types of tests were conducted:

Wet short-circuit between conductors with a 1% saline-water electrolyte solution, conducted to SAE test standard AS4373 4.5.9 Method 509 (with deviations) for up to 25 minutes.
Wet short-circuit between conductors with lavatory fluid taken from an airplane.
Abrasion tests that placed metal shavings between oscillating wires.
Short circuit tests using metal shavings as the conductor.

There were three different categories of electrical activity observed during the arcing experiments. Each of these activities had unique visual and oscillograph signatures.

Scintillations: high frequency, micro-discharges which causes formation of char on the wire over time.
Flashing: an arcing discharge which can continue over several cycles but not 100s of cycles. Typically 2 to 4 joules of electrical energy are transfer between source and target wire but in some cases up to 90 joules were transferred. Flashing will not cause circuit breakers to open (trip) but will erode the conductors over time.
Strong arcing: an arcing discharge that continues over 100s of cycle and often ends withinterruption of power due to the circuit breaker tripping. Typically 5 kilojoules of electrical energy were dissipated in strong arcing events

Strong arcing was not associated with W42A/8/1-20 wire, but was found in 1 of 3 tests that used W42/1/1-20 wire, which has a thinner layer of insulation. Strong arcing always resulted during wet testing of MIL-W-81381.

Half-sections of aluminum tube were placed behind the wet tests to provide a backdrop for video-recording and to capture material ejected by the short circuit event. Flashing and arcing were normally directional, not a ball-shaped discharge. The direction of the discharge was normally away from the side of the wire bundle that the wires were on and the discharge of some tests did not hit the aluminum tube sections.

More than one type of abrasion test was performed to examine how metal shavings damaged BMS13-42 and BMS13-42A (no MIL-W-81381) wire insulation. The metal shavings

were placed between wires in small bundles, as found during Safety Board tests of February 21-25, 1998, and the bundles were moved with an oscillating bar. The results depended on differences in how the bundles were moved and the size of the shavings. In one configuration two of four (50%) tests resulted in the metal shaving exposing the conductor. In a second configuration, neither of two (0%) tests resulted in the shavings exposing the conductor. However during these tests three separate wires had cracks appear in the insulation due to the ½ inch oscillatory flexing after about 19 hours

Tests were conducted to document the short-circuit capability of the metal shavings on wires that already had the conductor exposed. In five of eight (62.5%) of the tests, the metal shaving acted as a fusible link, interrupting the short-circuit without causing additional damage to the insulation. In the other three tests (37.5%) damage was done to the adjacent wires during the flash event, but in no case did strong arcing occur.

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Background

Arc tracking of aircraft wire is an issue that has received attention in the past[1, 2] because of the potential for equipment malfunction and because it can be a safety risk. There now are common standards for testing different aspects of arcing in qualification tests for new wire.

One of these aspects is the wet arc tracking of the wire. On aircraft, liquids do get onto wires for a variety of reasons: spilled beverages, leaking lavatory water, condensation, or moisture absorbed into salt or other surface contaminates. This can lead to carbon tracking which is a process where a conducting carbon path is slowly built up over time due to low level electrical discharges on the surface of the wire. Figure 1 shows an example of carbon build up on 81381 type wires. This carbon build up can lead to arcing.

Another potential issue is metal drill shaving on and in wire bundles and the potential for mechanical damage to the insulation. The Safety Board investigation documented numerous cases of metal shavings on wire bundles and between the wires of bundles. Figure 2 shows an example of this.

1. F. C. Campbell, Flashover Failures from Wet-Wire Arcing and Tracking, NRL Memorandum Report 5508, pg. 1, Naval Research Laboratory, Washington, DC, (1984)

2. P. L Cahill and J. H. Dailey, Aircraft Electrical Wet-Wire Arc Tracking, Report No. DOT/FAA/CT-88/4, FAA Technical Center, Atlantic City, NJ, (1988)

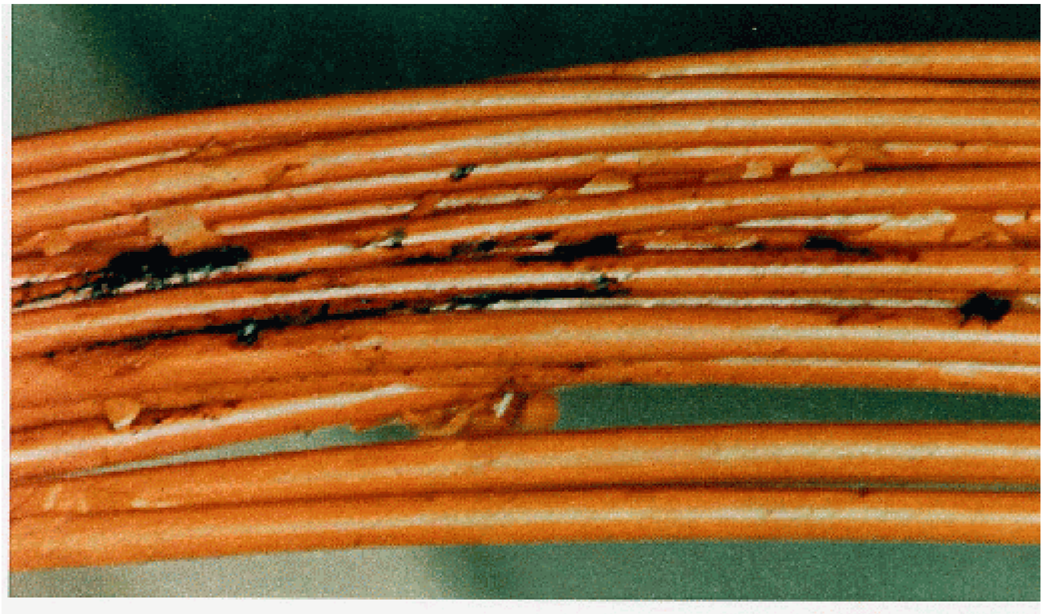


Figure 1. A bundle of Mil-W-81381 wire with visible carbon tracking .

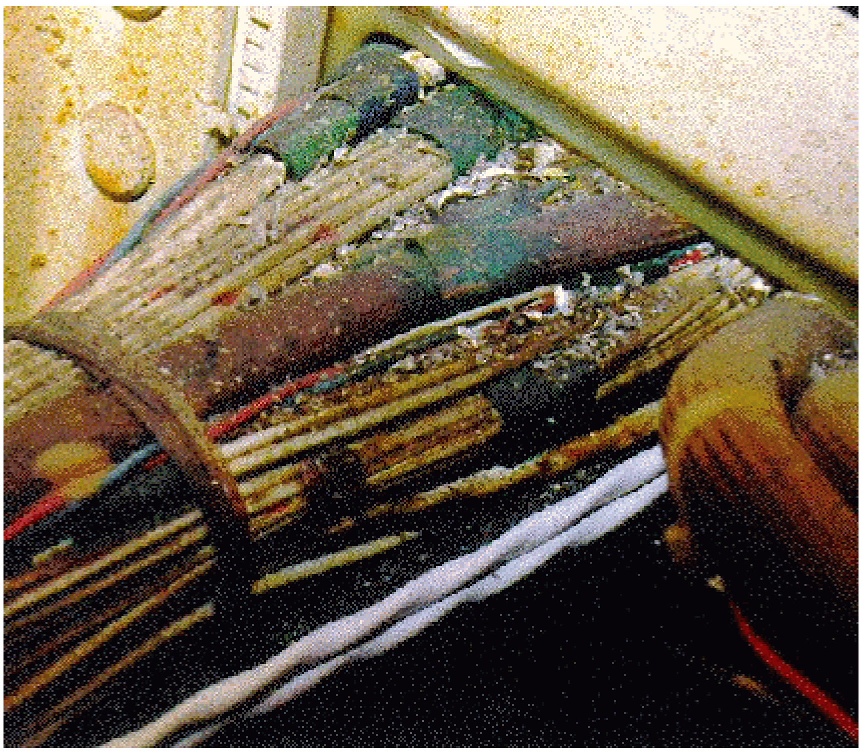


Figure 2. Metal drill shaving on a wire bundle of a commercial aircraft.

EXPERIMENTAL PROCEDURES

Wet Arc Tracking:

The Wet Arc Tracking Test followed the SAE standard AS4373 4.5.9 method 509 test procedures with certain deviations. In this test, a bundle of 7 wires (six around one) is suspended horizontally in a test chamber (Figure 3). The insulation on the top two wires (A1, B1) in this bundle have been pre-damaged with circumferential cuts such that the conductor is clearly visible. The cuts are aligned so that they are separated by 6 mm.

The bundle is connected to a 10 kVA, 3 phase, 400 Hz, 120 Vac line to neutral generator using the circuit shown in Figure 4. In this circuit, a 7.5 Amp circuit breaker and a 1 ohm resistor (simulating a long run of wire) are placed in series with each of the top 5 wires (A1, B1, C, A2, B2) which are called the active wires. The bottom two wires (D1, D2) are not connected to the generator (they are floating) and are called the passive wires.

An Electrolytic solution is dripped on the wire such that the drop lands between the cuts in the insulation. In these tests two different electrolytes were used; A 1% by weight NaCl solution or lavatory waste water. The electrolyte was dripped at a rate of six drops per minute (100 mg/min) except in Test 1 when the rate was 10 drops/min.

The experiment was allowed to run for 10 to 25 minutes or until a circuit breaker tripped. The circuit breakers were sometimes reset once or twice. After the test, the bundle was removed and a wet dielectric test was run on the 5 wires that were not pre-damaged (C, A2, B2, D1, D2).

Shaving Short Circuit

In this test a 7 wire bundle is used with two of the wires having circumferential cuts (~ 1 mm wide) placed in the insulation so that the conductor is visible. These pre-damaged wires are placed on opposite sides of the bundle and a metal shaving is woven through the bundle so that in touches both of the exposed conductors. The bundle is suspended horizontally and the wires are connected to the generator (see Figure 5). The experiment is started when the contactor is closed and ends when a circuit breaker is tripped or the circuit opens due to evaporation of the shaving.

Metal Shavings Abrasion Test

Many different experimental setups were tried for the metal shavings abrasion tests with varying results. Some created damage to the wire insulation and flashing events and others did not. Two setups used are described here while others are described in Appendix B.

90° (Right Angle) Test

In this test, one bundle of seven wires was used with a metal shaving, at least 0.5" long, woven into the bundle. One end of the wire was secured to a stationary platform with a P-clamp while the other end was secured several inches away at 90 degrees from the direction of the first P-clamp, on an oscillating bar. The bundle had the form of a circular arc of about a 2" radius

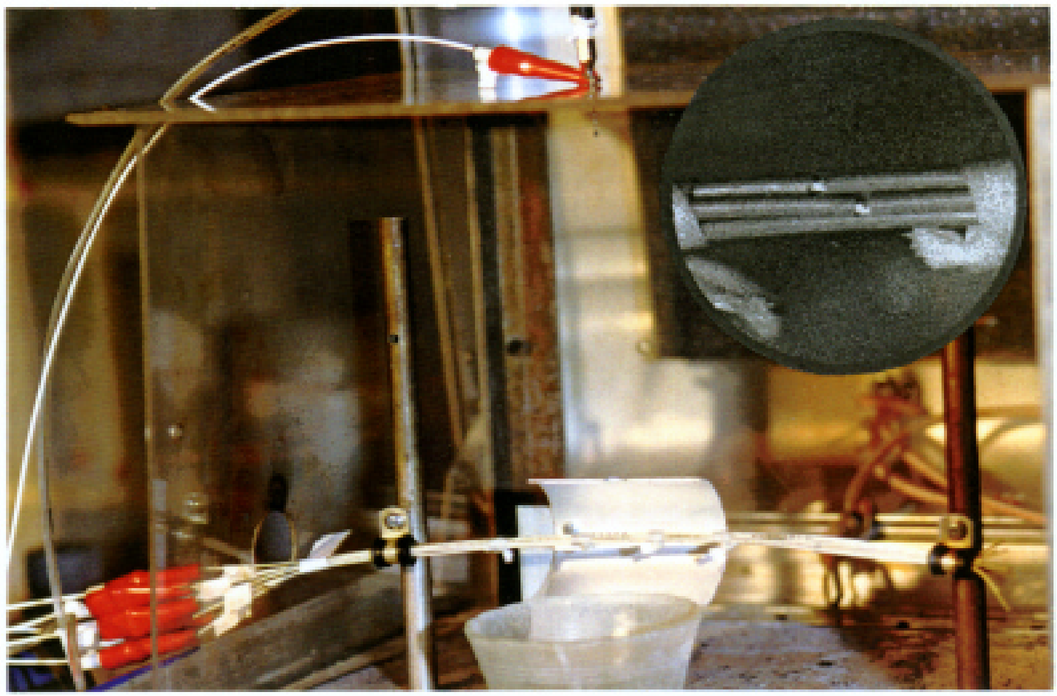


Figure 3. A wire bundle suspended in the wet arc track testing apparatus.(Insert is of the pre-damage cuts in the top wires.)

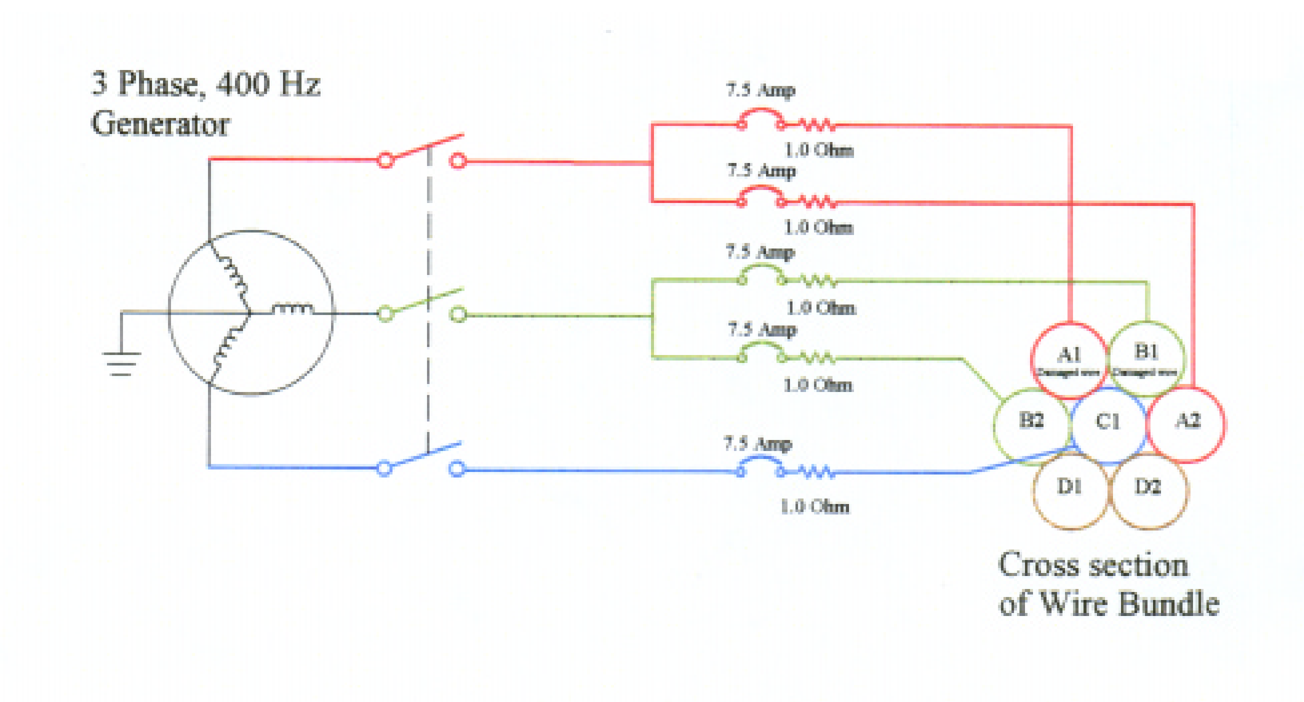


Figure 4. Circuit used in the wet arc tracking tests.

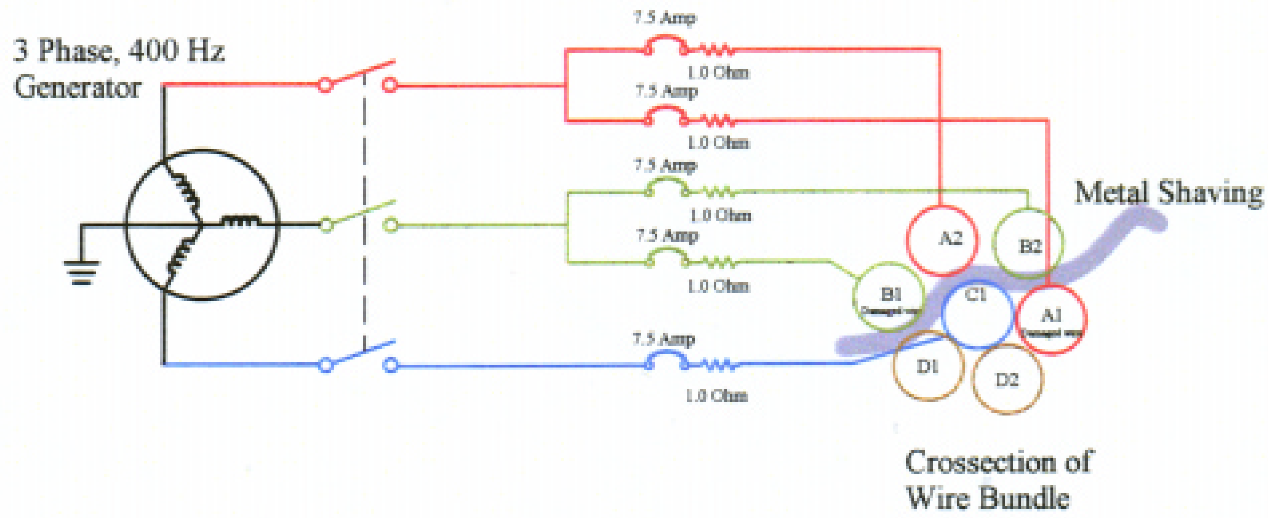


Figure 5. Circuit used in the metal shavings short circuit tests.

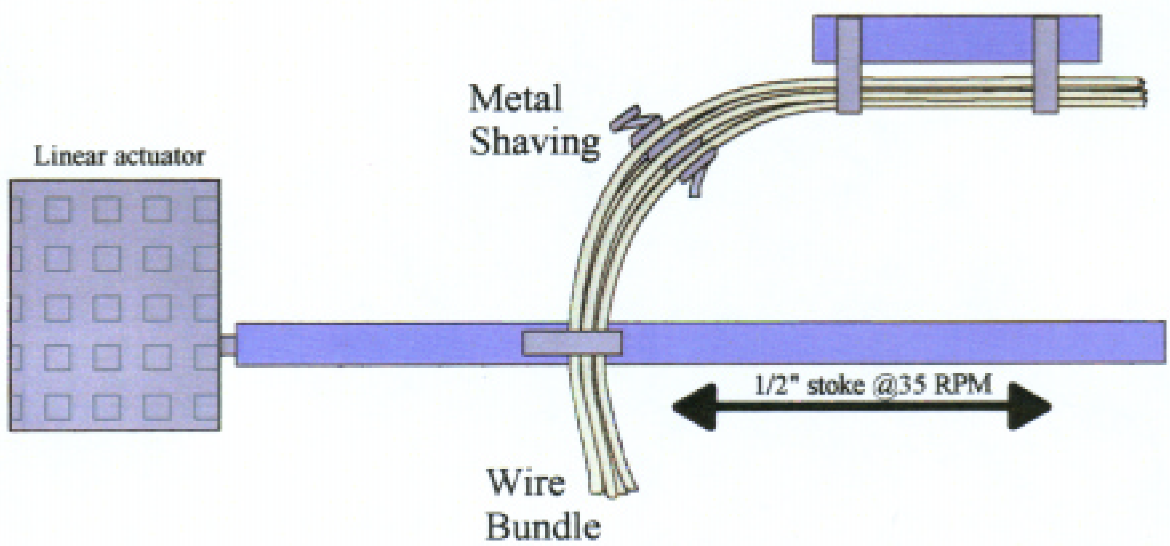


Figure 6. Apparatus used for metal shaving abrader test 90° (right angle).

as shown in Figure 6.The linear motion of the rod causes the wires in the bundle to squeeze together on the shaving and then relax repeatedly..

The wires are connected to the generator and the linear motion is started. The test continues until an electrical event occurs or all of the metal shavings have worked their way out of the bundle

Longitudinal Test

In this test set-up two identical wire bundles are made from three 20 gauge wires and one 18 gauge wire as shown in Figure 7. Each bundle was held together with lacing tape. One of the bundles is secured to a stationary platform with P-clamps and tape. The other bundle is secure to an oscillating bar. The two bundles are parallel at this point and are kept together with nylon ties with several metal shavings placed between the two bundles (Figure 8).

The three 20 gauge wires in both bundles are each connected to one of three phases of the generator as shown in Figure 8. The 18 gauge wire is also connected to one of the phases.

The oscillator is then turned on. The test continues until an electrical event occurs or all of the metal shavings have work their way out of the bundle.

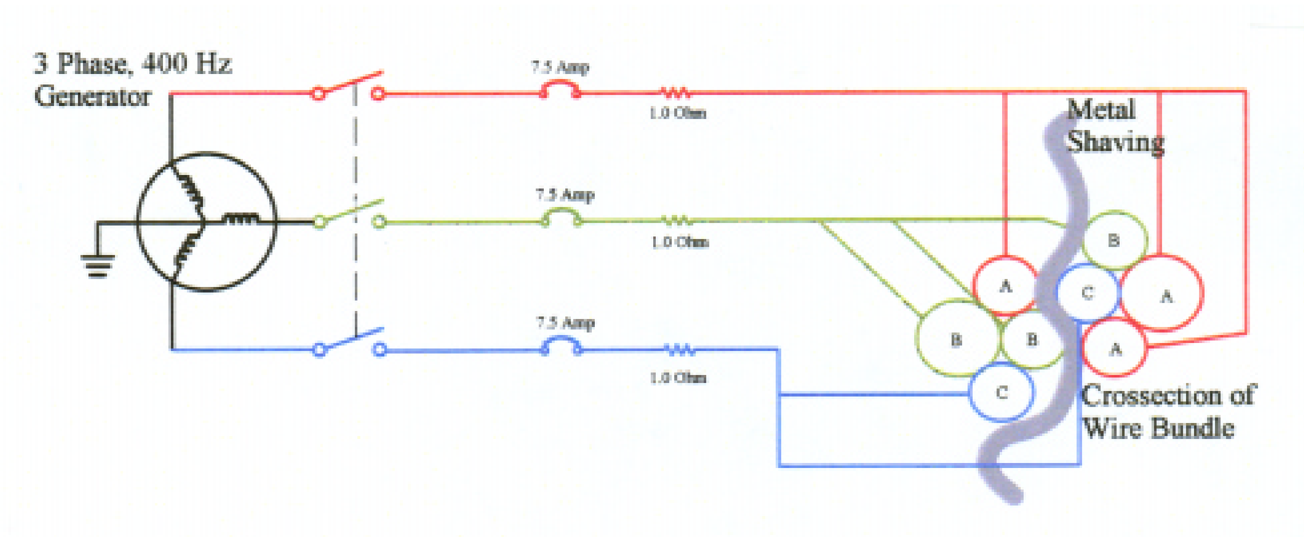


Figure 7. Circuit used for metal shaving abrasion tests (longitudinal).

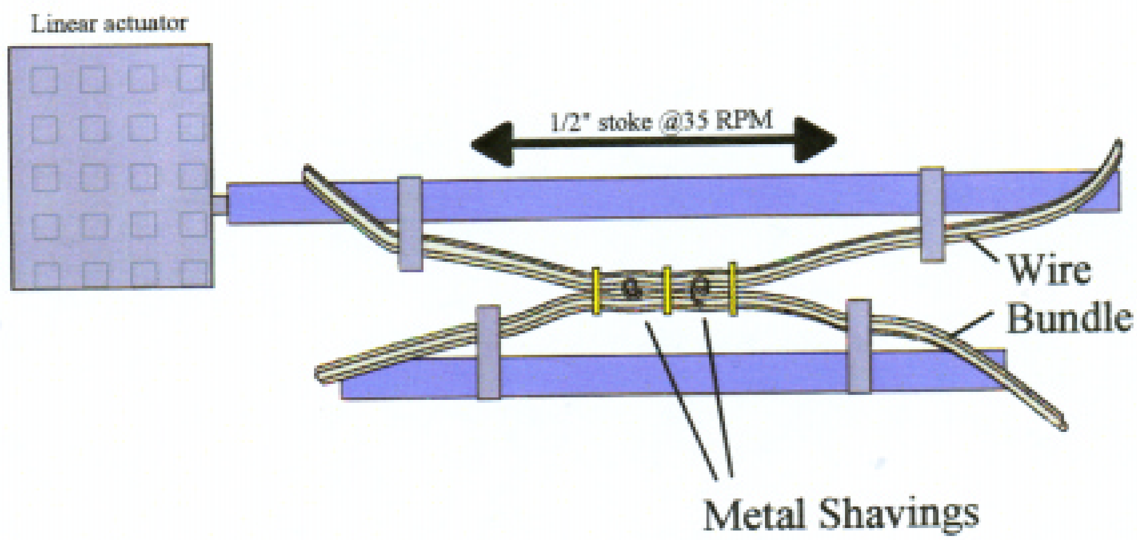


Figure 8. Apparatus used for metal shaving abrasion tests (longitudinal).

Wet Dielectric Test:

This test was run according to AS 4373 4.5.10 with some deviations. In the test the individual wires were placed in a water bath with both ends out of the water (Figure 9). 1000 VDC was applied to the wire conductor and the water bath was grounded. If a current was measured in the circuit it meant that the wire shorted through the insulation to the water bath.

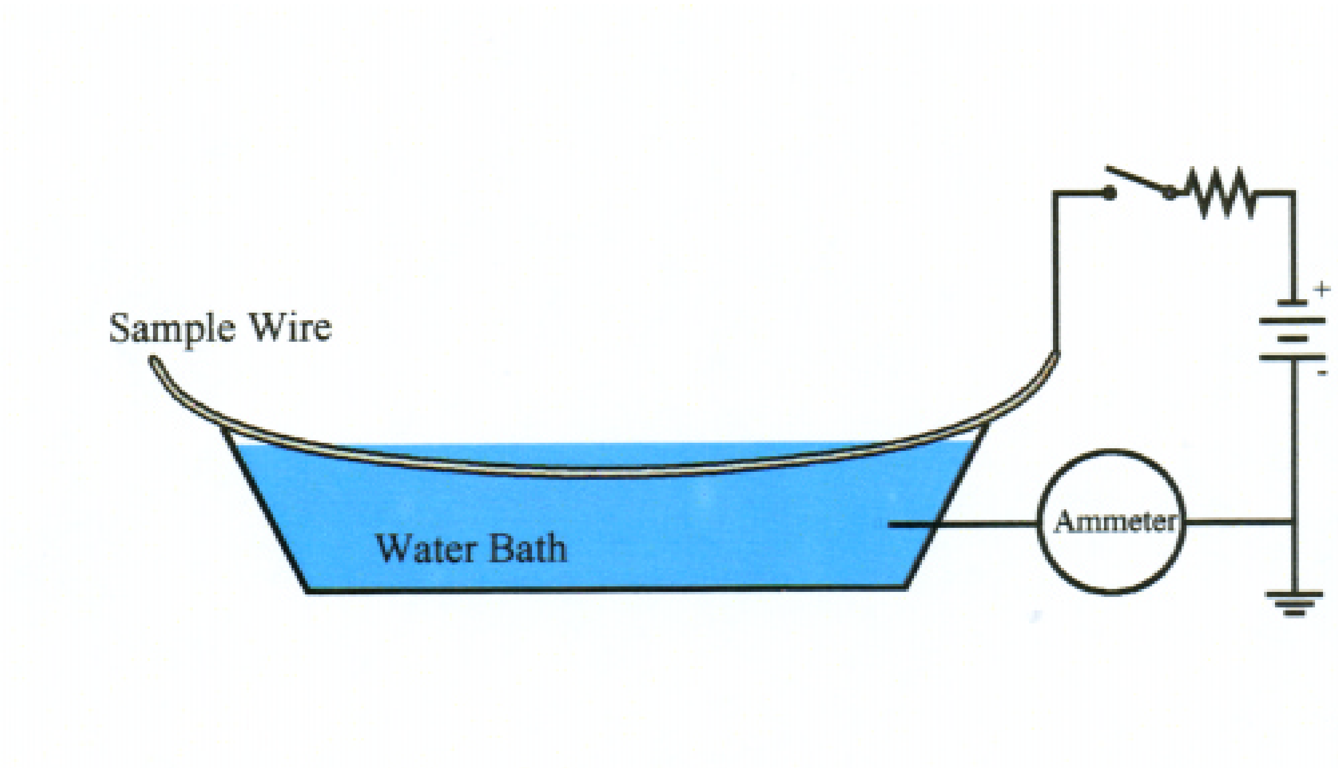


Figure 9. Circuit used for the wet dielectric tests.

DESCRIPTION OF ELECTRICAL ACTIVITY

Three different categories of electrical activity were recorded during the arcing experiments. They were scintillations, flashing and strong arcing. Each of these activities developed a unique visual and oscillograph signature.

Scintillation

Scintillations were the first electrical activity that was observed during the experiments. Visually, they began as pinpoints of light that flickered at the edge of the pre-damaged cracks in the insulation (Figure 10). As time went on and a char track built up on the insulation, the flickers of light appeared at various places along the path between the pre-damaged cracks. During the more lively scintillations an electrical buzzing or crackling sounds could be heard. No scintillations caused a circuit breaker to disrupt power.

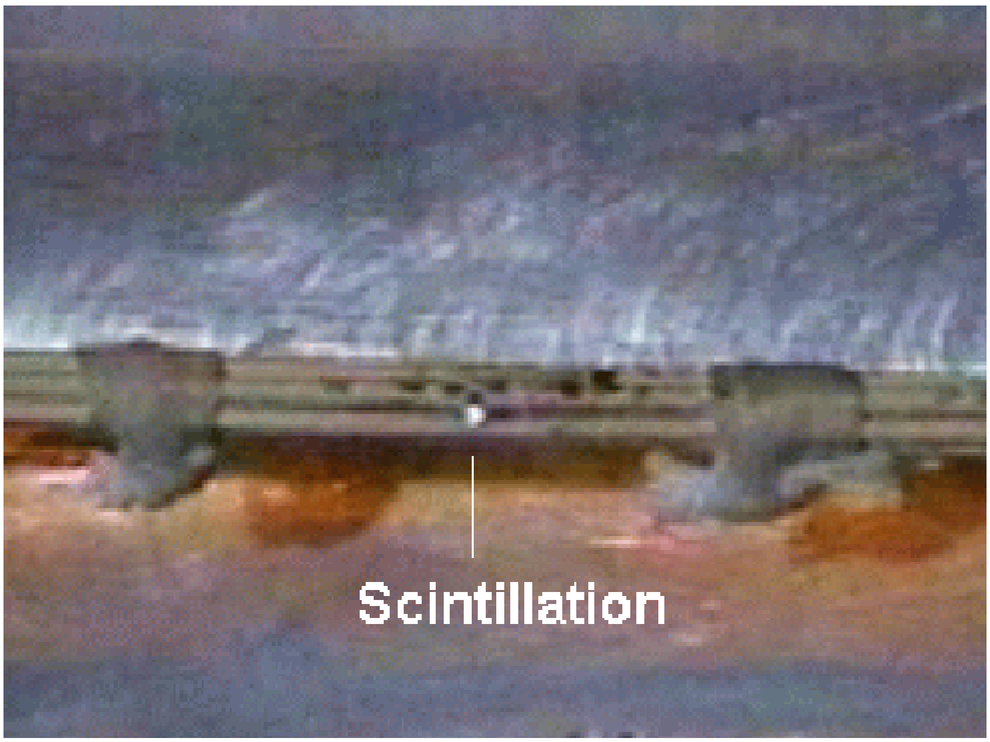


Figure 10. Scintillation at the edge of a pre-damaged crack.

An oscillogram of scintillations (Figure 11) showed them to be high frequency events which distorted the current and voltage waveforms. The frequency components appear to be greater than 1 megahertz. Quantitative measurements at these frequencies require the inductances and capacitances of each of the components of the circuit (i.e. generator, circuit resistors, oscilloscope etc.) to be measured and analyzed which was not in the scope of this work. Energy transfer between wires cause voltage distortions (noise) and this process caused changes to the insulation as a char path was built.

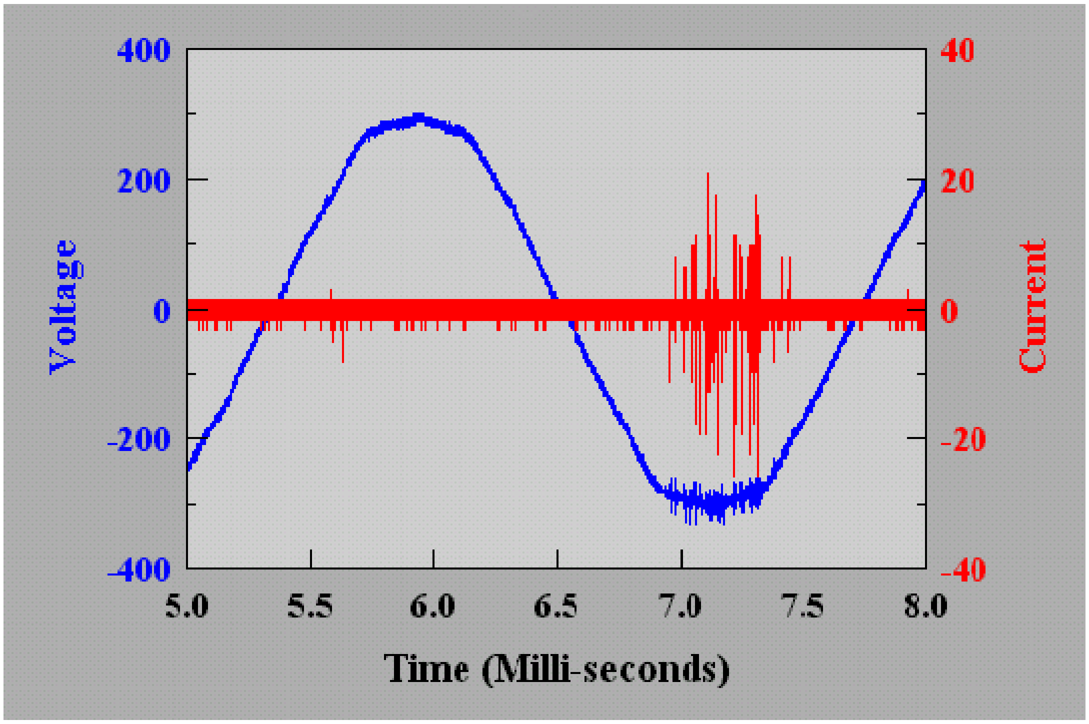


Figure 11. Oscillogram of voltage from phase A to B (blue) and current in phase A (red) during scintillations.

<u>Flashing</u>

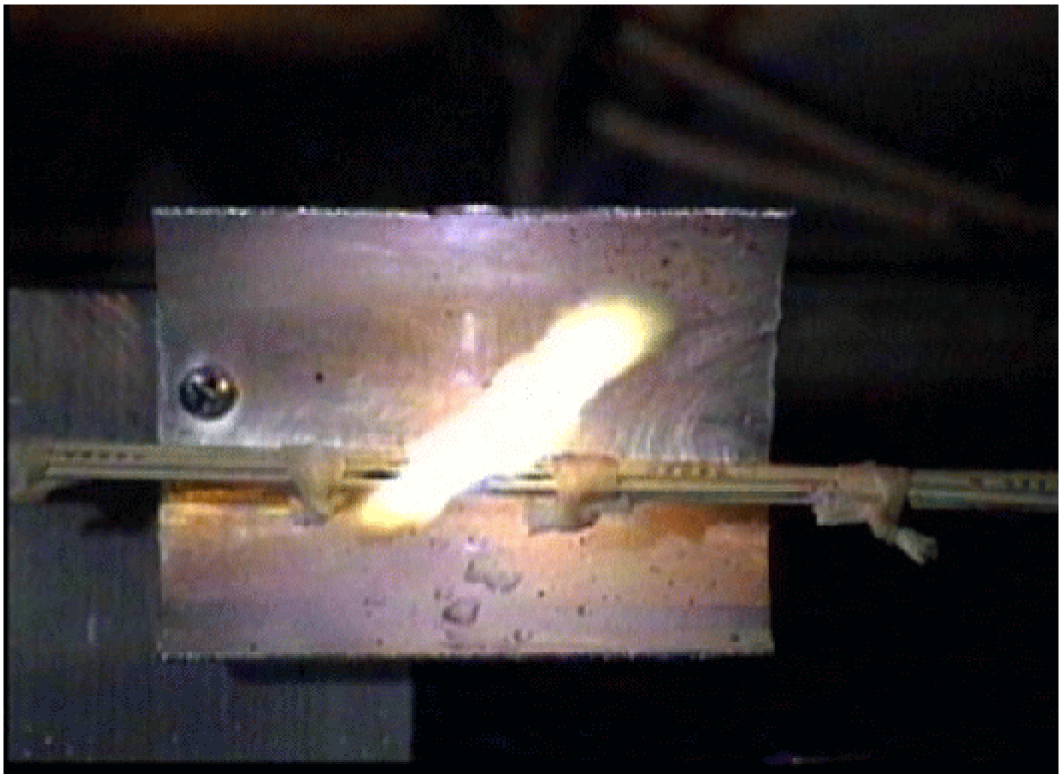
The flashing events usually occurred after the sample has been scintillating for some time. As the name suggests what is seen is a single flash of light with an accompanying popping sound. When flashing begins to occur on a sample there are usually many seconds or even minutes between events. However, as time continues the frequency of these events increases to the point where there may be several events per second. Most samples would go through a period of tens of seconds of rapid flashing followed by several minutes of dormancy. Figure 12 shows an example of a flashing event captured by video recording. The flash often showed up in only one frame with the framing rate being 50 frames per second (1 every 20 milliseconds). None of the flashing events caused a circuit breaker to open. The longest wet test conducted was 25 minutes.

The oscillogram (Figure 13) shows that the waveform during a flashing event is that of a classical arcing event [3]. The blue line represents the voltage between the two pre-damaged wires and begins with a normal 400 Hz sine waveform. However in the next cycle the voltage collapses into a classic arc waveform with a relatively constant arc voltage of ~ 100 volts. The voltage then returns to the normal sine waveform. Looking at the red line representing the current in the wire, there is little to no current to the left. During the arcing event the current rises to a peak of 65 amperes and then returns to zero current as the voltage waveform returns to normal.

3. Cobine J. D. <u>Gaseous Conductors</u>, Dover Publication, New York, 1958, pgs. 348 and 353.

The voltage and current waveforms were used to calculate the electrical energy dissipated in the arc. Figure 14 shows the electrical power during a flashing event, it reaching a peak of 8 kilowatts (kW). The total electrical energy dissipated was about 4 joules [4]. Over time the flashing can cause damage to the insulation and the conductor.

Figure12. An example of a flashing event.



4. This is the energy needed to melt about 6 milligrams of aluminum, the equivalent of a fraction of a paper clip

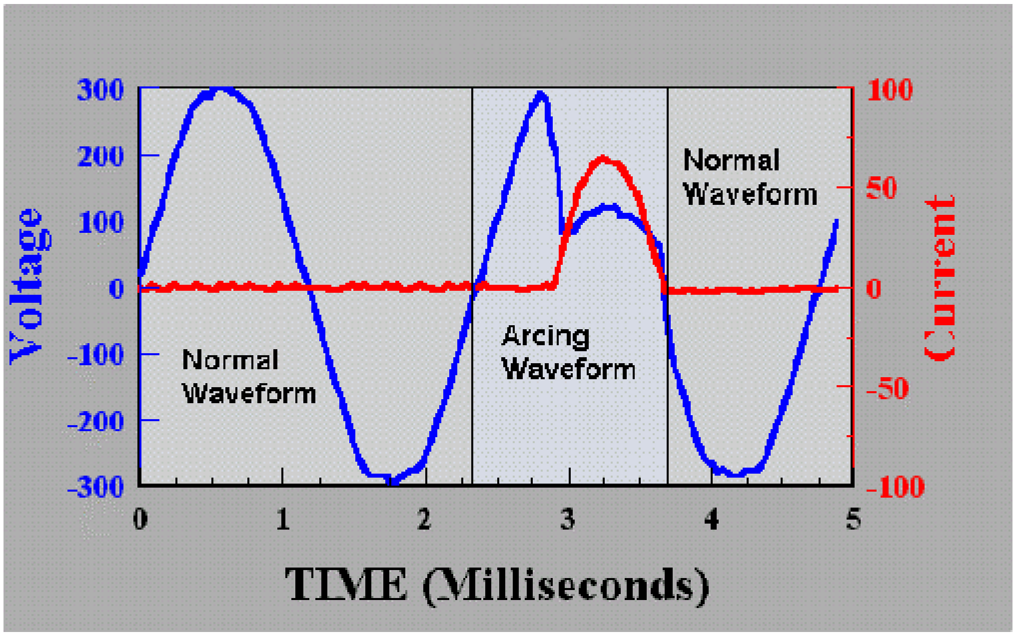


Figure 13. Oscillogram of voltage and current during a flashing event.

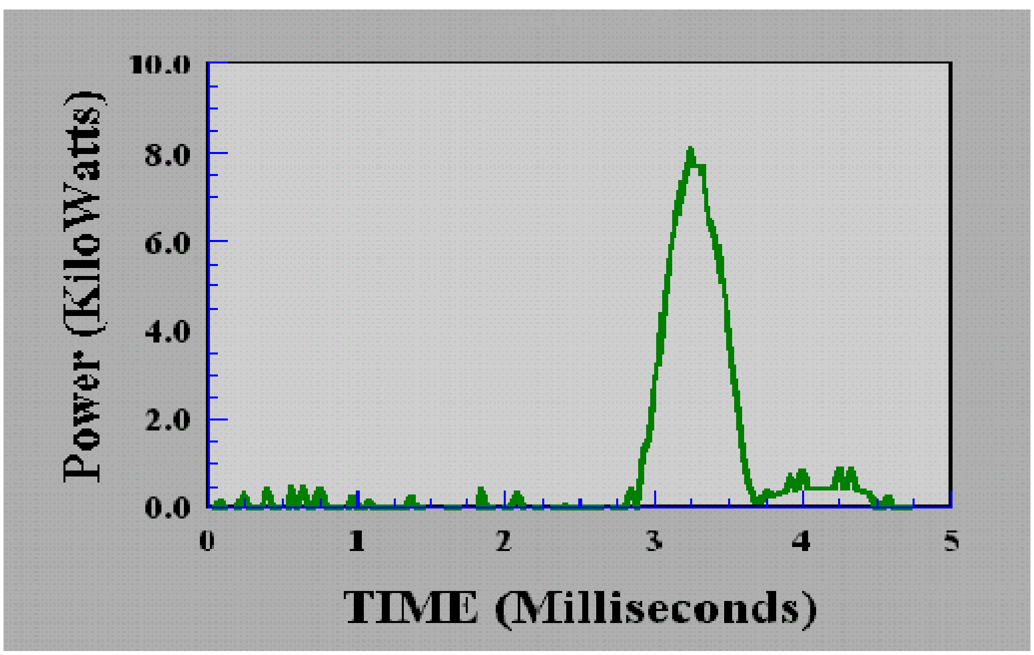


Figure 14. The electrical power dissipated during a flash event.

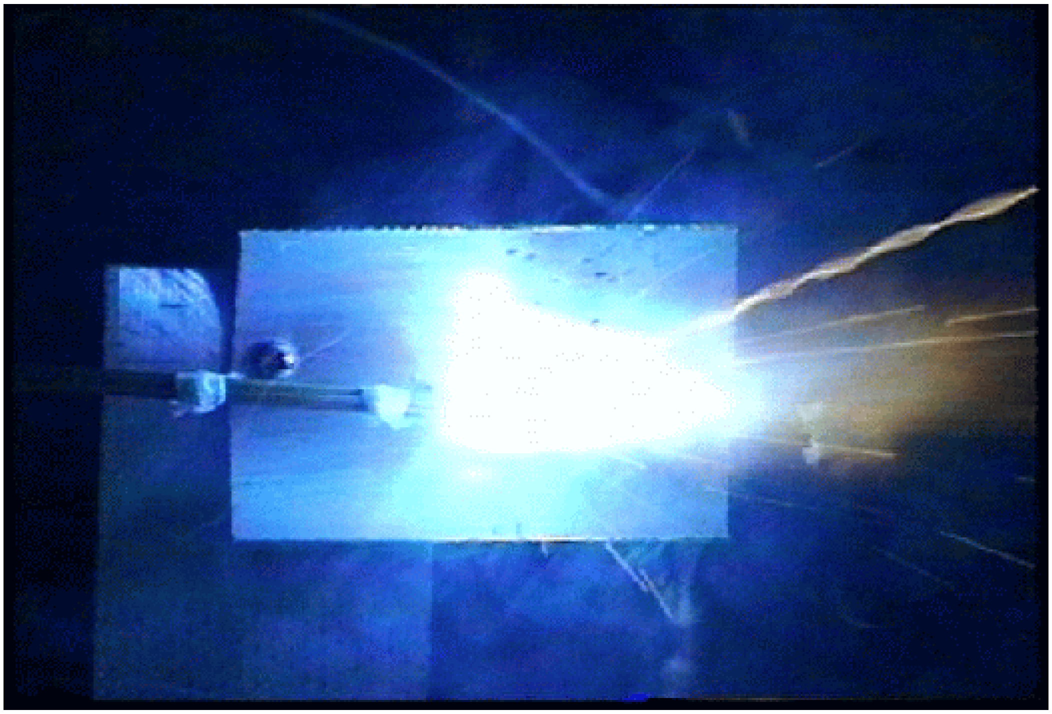


Figure 15. Example of a strong arcing event.

Strong Arcing

Strong Arcing events were characterized by an active bright flash or glow that continued for a up to a second or more (Figure 15) with an intense electrical hum or crackling. The arc can cause much collateral damage to the insulation of adjacent wires, some of which became involved in the event. Strong arcing was often terminated with tripping of the circuit breaker.

The difference between the oscillogram of a flash and a strong arcing event is that the same voltage arc waveform is repeated continuously in the arc at each half cycle for the duration of the short circuit. The phase to phase voltage at the beginning of an arc is shown in Figure 16 . The current in this arc started out in the range of 65 amperes (peak). After the other wires (including the phase C wire) became involved in the arc the current increased to peaks of 120 amperes. Power peaks were found of up to 15 kW (Figure 17) and a total electrical energy dissipated of about 5 kilojoules (kJ) .

The magnitudes of the power peaks in the strong arcing event shown in Figure 17 are about a factor of 2 higher than those found in the flashing event previously discussed because more wires were involved. Also different is the arc waveform is repeating continuously for hundreds of cycles in a strong arcing event, as compared to one to ten or twenty cycles for a flashing event. This increases the time in which energy is dissipated in a strong arcing event.

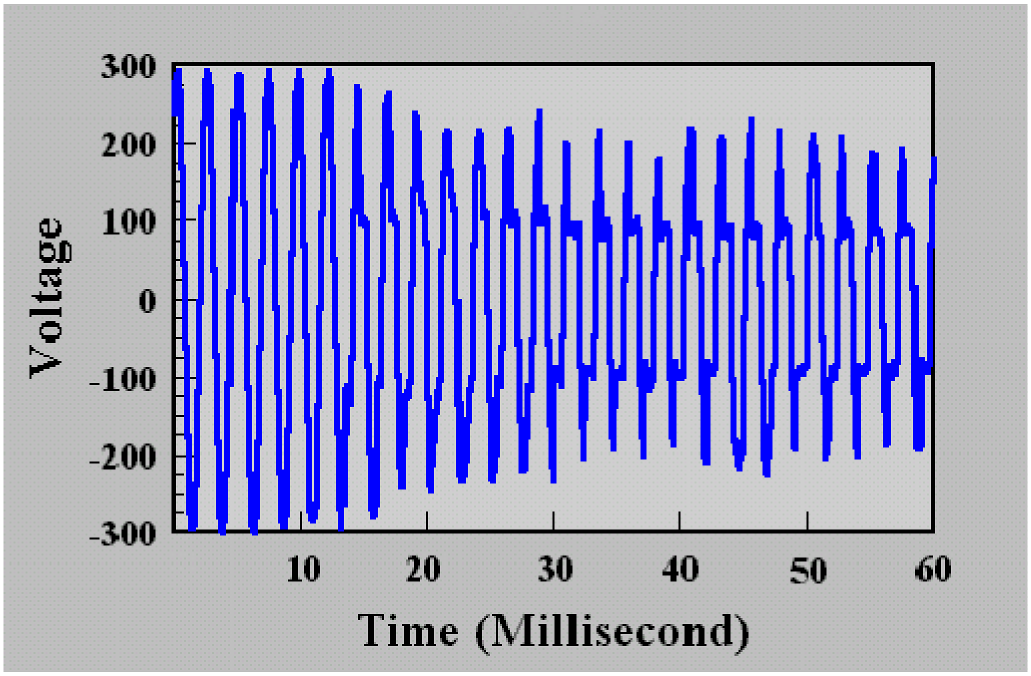


Figure 16. Oscillogram of voltage at the beginning of a strong arcing event.

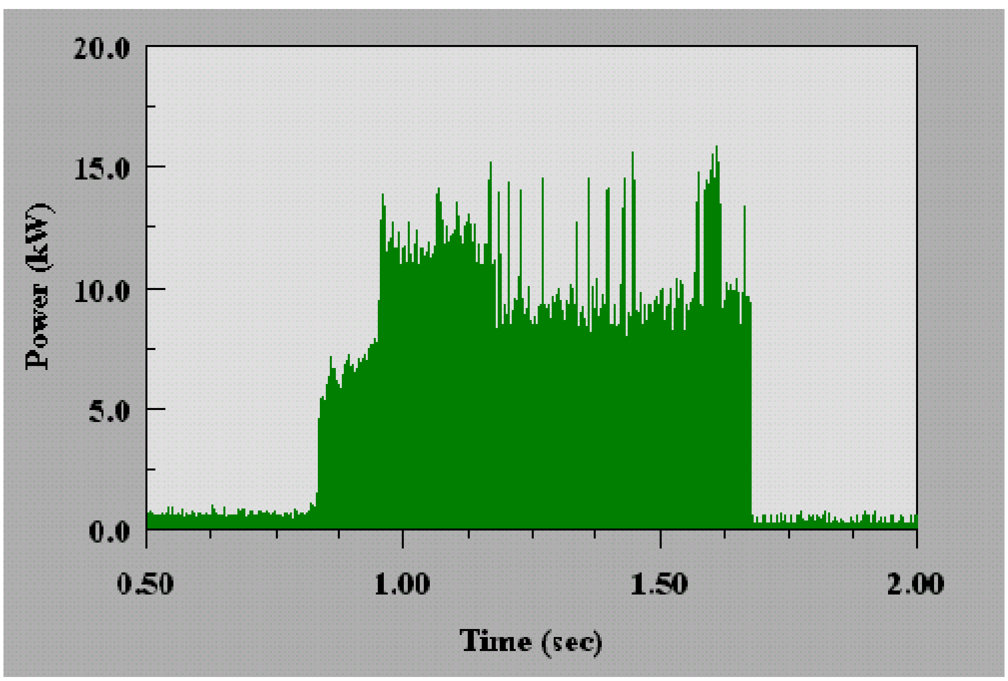


Figure 17. Power in strong arcing event, extrapolated from two phase measurement.

RESULTS

Table 1 lists the Test run giving the type of test and type of wire sample used. Tables 2 to 5 are summaries of the results of each of the test. Appendix A has a detailed description for each of the individual tests.

Table 1. List of Tests and types of wire used.

Test Number	**Test Type**	**Sample Wire Type**
Preliminary Test 1	Wet Arc Tracking	BMS-W42/1/1-20
Preliminary Test 2	Wet Arc Tracking	BMS-W42/1/1-20
Test 1	Wet Arc Tracking	BMS-W42A/8/1-20
Test 2	Wet Arc Tracking	BMS-W42A/8/1-20
Test 3	Wet Arc Tracking	BMS-W42/1/1-20
Test 4	Wet Arc Tracking	Mil-W-81381/12-20
Test 5	Wet Arc Tracking	Mil-W-81381/12-20
Test 6	Wet Arc Tracking	BMS-W42A/8/1-20
Test 7	Wet Arc Tracking	BMS-W42A/8/1-20
Test 8	Metal Shavings Short Circuit	BMS-W42A/8/1-16
Test 9	Metal Shavings Short Circuit	BMS-W42A/8/1-16
Test 10	Metal Shavings Short Circuit	BMS-W42A/8/1-16
Test 11	Metal Shavings Short Circuit	BMS-W42A/8/1-16
Test 12	Metal Shavings Short Circuit	BMS-W42/1/1-20
Test 13	Metal Shavings Short Circuit	BMS-W42/1/1-20
Test 14	Metal Shavings Short Circuit	BMS-W42A/8/1-20
Test 15	Metal Shavings Short Circuit	BMS-W42A/8/1-20
Test 16	Metal Shavings Abrasion (90 °)	BMS-W42A/8/1-20
Test 17	Metal Shavings Abrasion (long.)	BMS-W42/1/1-20
Test 18	Metal Shavings Abrasion (long.)	BMS-W42/1/1-20
Test 19	Metal Shavings Abrasion (long.)	BMS-W42/1/1-20
Test 20	Metal Shavings Abrasion (long.)	BMS-W42/1/1-20

Table 2. Summary of Wet Arc Tracking Results: Grouped according to wire type

Wire Spec	Test #	Electrolyte	Duration	Qualitative Description	# Circuit Breakers Tripped	# of Wires that Failed Wet Dielectric Test	Length of Damage/ Char Build up
W 42A/8/1-20	Test 1	1% NaCl	20 min.	Some intense flashing	0	2 of 5	1/2"
W 42A/8/1-20	Test 2	1% NaCl	25 min.	Some intense flashing	0	2 of 5	5/8"
W 42A/8/1-20	Test 6	Lav. Water	10 min.	Some intense flashing	0	2 of 5	1/4"
W 42A/8/1-20	Test 7	Lav. Water	16 min.	Some intense flashing	0	0 of 5	3/8"
W 42/1/1-20	Pre Test A	1% NaCl	5 min	Some intense flashing	0	NA	1/2"
W 42/1/1-20	Pre Test B	1% NaCl	<1/2 min	Some intense flashing	0	NA	1/4"
W 42/1/1-20	Test 3	1% NaCl	~3 min	Strong Arcing	1 (reset then 3)	5 of 5	1/2"
Mil-W-81381	Test 4	1% NaCl	~1.5 min.	Strong Arcing	3 (reset)	4 of 5	2"
Mil-W-81381	Test 5	1% NaCl	< ½ min.	Strong Arcing	3 (no reset)	3 of 5	7/8"

Note: The insulation thickness for W42A/8/1-20 wire is ~11 mils and for W42/1/1-20 is ~7 mils but in both cases the primary insulation is an aliphatic polyimide (Poly X). The Mil-W-81381/12-20 has an insulation thickness of 8 to 9 mils.

Table 3. Summary of Metal Shavings Short Circuit Test: Grouped according to wire type

Wire Spec	Test #	Shaving Material	Shaving Cross section (Mils)	Circuit Breaker/Circuit Resistor	Qualitative Description	# Circuit Breakers Tripped	# of Wires that Failed Wet Dielectric Test	Length of Damage/ Char Build up
W 42A/8/1-16	Test 8	Steel	110 X 9	7.5 Amp/ 1 Ω	Short Flash	0	0 of 5	0"
W 42A/8/1-16	Test 9	Steel	65 X 28	15 Amp/ 0.5 Ω	Intense Flash	0	5 of 5	1.5"
W 42A/8/1-16	Test 10	Steel	48 X 26	15 Amp/ 0.5 Ω	Short Flash	0	2 of 5	1/8"
W 42A/8/1-16	Test 11	Al 7075	120 X 6	15 Amp/ 0.5 Ω	Short Flash	0	0 of 5	0"
W 42/1/1-20	Test 12	Steel	51 X 10	7.5 Amp/ 1 Ω	Short Flash	0	1 of 5	1/4"
W 42/1/1-20	Test 13	Al 7075	50 X 8	7.5 Amp/ 1 Ω	Short Flash	0	0 of 5	0"
W 42A/8/1-20	Test 14	Steel	52 X 9	7.5 Amp/ 1 Ω	Short Flash	0	0 of 5	0"
W 42A/8/1-20	Test 15	Al 7075	70 X 8	7.5 Amp/ 1 Ω	Short Flash	0	0 of 5	0"

Table 4. Summary of Metal Shavings Abrasion Test: 90° (Right Angle)

Wire Spec	Test #	Shaving Material	Shaving Cross section (Mils)	Duration	Qualitative Description	# Circuit Breakers Tripped	# of Wires that Failed Wet Dielectric Test	Insulation Damage
W 42A/8/1-20	Test 16A	Steel	41 X 26	19.25 hours	No Flash	0	1 of 7	Moderate damage to PolyX Flexing broke 1 wire
W 42A/8/1-20	Test 16B	Al 7075	42 X 30	19.25 hours	No Flash	0	2 of 7	Moderate damage to Topcoat Flexing broke/cracked 2 wires

Table 5. Summary of Metal Shavings Abrasion Test: Longitudinal

Wire Spec	Test #	Shaving Material	Shaving Cross section (Mils)	Duration	Qualitative Description	# Circuit Breakers Tripped	# of Wires that Failed Wet Dielectric Test	Insulation Damage
W 42/1/1-20	Test 17	Steel	~40 X 25	1+ hours	Small Flash	0	2 of 8	Cuts in Poly X to the conductor
W 42/1/1-20	Test 19	Steel	49 X 18	4 hours	No Flash	0	2 of 8	Cuts in Poly X to the conductor
W 42/1/1-20	Test 18	Al 7075	48 X 26	~15 minute	No Flash	0	0 of 8	Abrasion of Topcoat
W 42/1/1-20	Test 20	Al 7075	120 X 6	4 hours	No Flash	0	0 of 8	Abrasion of Topcoat

APPENDIX A: Description of Individual Test Results

Wet Arc Tracking Tests

Preliminary Tests A & B

Wet Arc Tracking
Bundle: Seven wires (6 over 1) of BMS 42/1/1-20 specification, 15 inches in length.
Electrolyte: 1% saline solution @ 100mg/minute
Circuit Resistance: 1 Ohm
Generator: 3 phase, 400Hz, 120 line to neutral (208 line to line), 10 kVA.
Length of tests: 5 minutes (Test A) and ½ minute (Test B)

Observation	Preliminary Test A	Preliminary Test B
Visible scintillation	Yes	Yes
Flash	Yes	Yes
Strong Arcing	No	Approaching
Circuit Breakers Tripped	No	No
Damage Length	1/2"	1/4"
Number of Wires Failing Wet Dielectric Test	–	–

Both tests gave similar results although preliminary test A was run for 5 minutes and preliminary test B was run for only ½ of a minute. Both began scintillations almost immediately and soon developed flashing type events.

In test A the sample was very active for the first minute or so and then had periods of dormancy interrupted by short spurts of activity. Examination of the bundle shows damage and char for about ½ an inch around the pre-damaged cuts. Also, about 3/8 of the conductors of the top two wires had been eroded away (Figure 18).

The bundle in test B experienced a period of intense activity within the first 30 seconds approaching strong arcing with 20+ cycles of continuous arcing (Figure 19). This period included current peaks of 75 Amperes and over 350 joules of electrical energy was dissipated in the event. The sample was then removed and examined. There was about a 1/4 inch of damage and char build up around the cut in the insulation, but both conductors were still intact.

No circuit breaker tripped in either test.

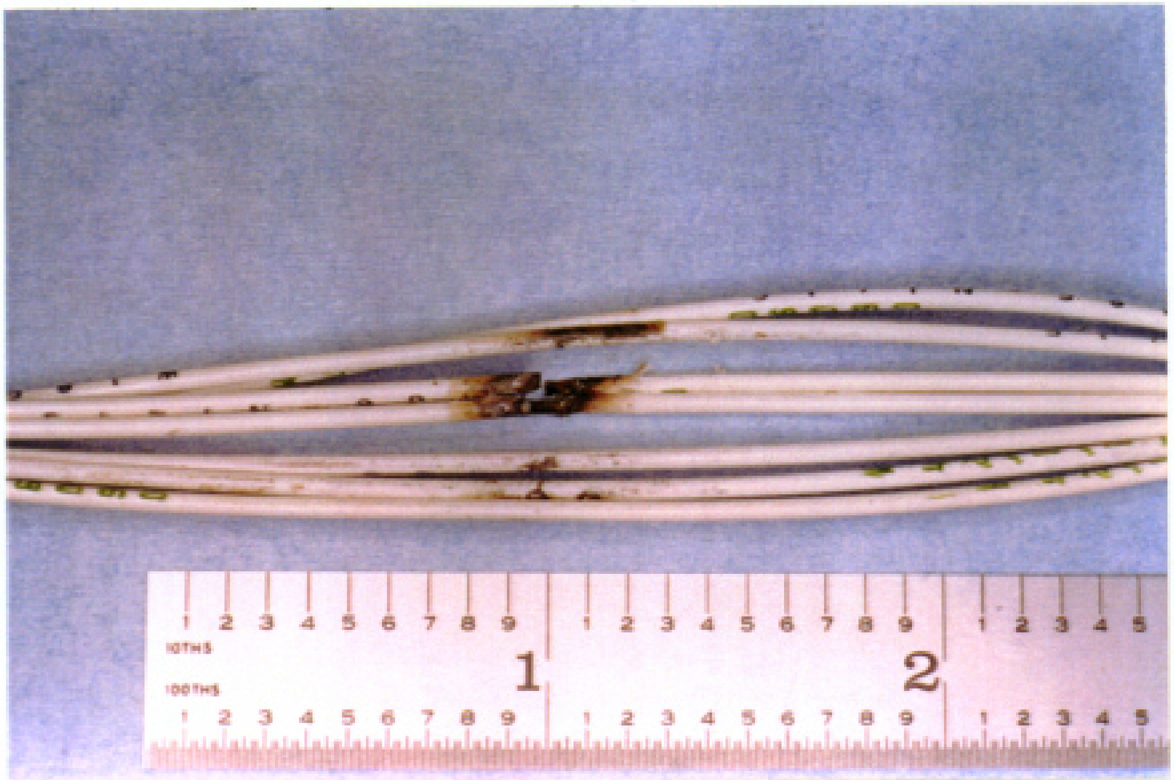


Figure 18. Preliminary Test A: Bundle after wet arc track testing for 5 minutes.

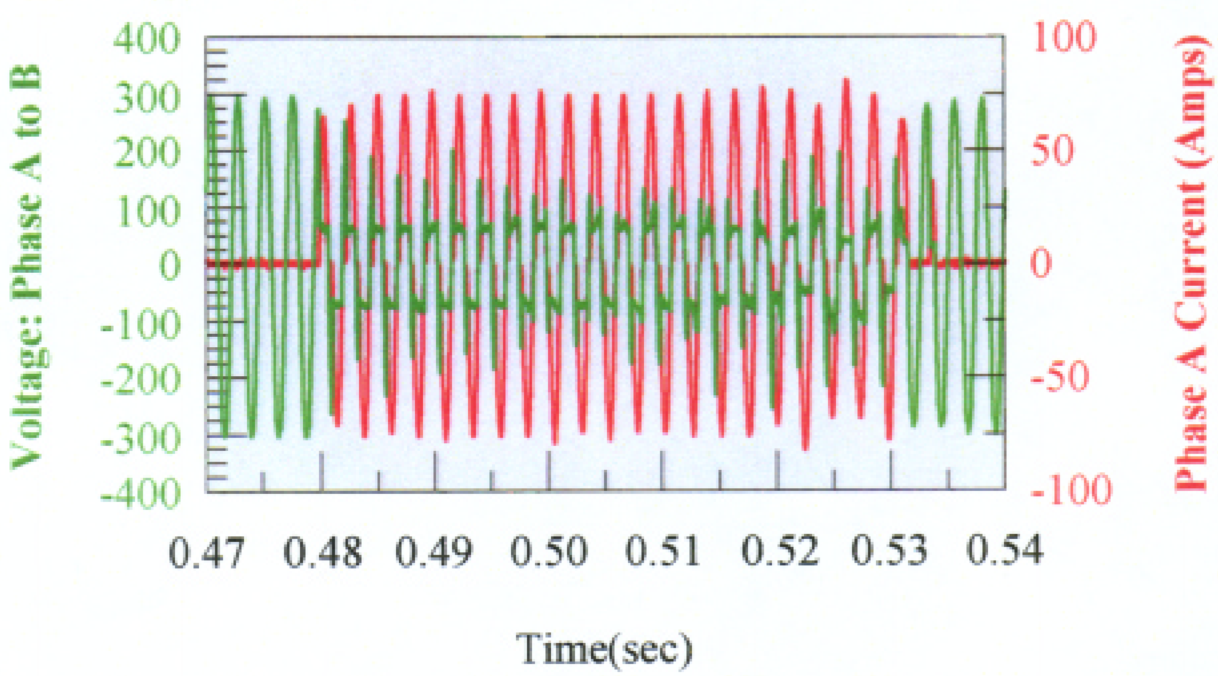


Figure 19.Preliminary Test B: Oscillogram of current during intense flashing event.

Test 1 & 2

Wet Arc Tracking
Bundle: Seven wires (6 over 1) of BMS 42A/8/1-20 specification, 15 inches in length.
Electrolyte: 1% saline solution @ 200 mg/minute (test 1) , 100 mg/minute (test 2)
Circuit Resistance: 1 Ohm
Generator: 3 phase, 400Hz, 120 line to neutral (208 line to line), 10 kVA.
Length of test: 20 minutes (Test 1), 25 minutes (Test 2)

Observation	Test 1	Test 2
Visible scintillation	00:23	00:15
Flash	16:01	8:44
Strong Arcing	No	No
Circuit Breakers Tripped	No	No
Damage Length	1/2"	5/8"
Number of Wires Failing Wet Dielectric Test	2 of 5 [C] & [B2]	2 of 5 [C] & [A2]

The results of Test 1 and Test 2 were similar to each other though Test 2 did become more active a little sooner than did Test 1. Visible scintillations began within the first minute of the tests. In a couple of minutes, a char path began to develop between the two pre-damaged cracks in the insulation and scintillations were observed along this path. This is shown in Figure 20.

As the tests went on flashing events began to take place. At first the flashing events were at least several seconds apart, sometimes they were up to a minute apart. Soon there were periods where the flash events repeated continuously, sometime several flashes per second. This was followed by periods of dormancy where no electrical activity was observed. The intensity of the flash events varied both in the light and sound produced sometimes lasting several frames of video. After a series of flashes a chemical combustion flame (candle-like flame) was observed burning the insulation for a few seconds (Figure 21). The samples were each tested between 20 and 25 minutes and no circuit breakers tripped.

Looking at the oscillograms taken during the more active times of the test, we see that several of the flashing events lasted for 5 to 10 cycles. An example of this is shown in Figure 22 which shows the current in one of the three phases during Test 1. The sequence begins with 8 cycle consecutive cycles having high current for at least one of the ½ cycles and some times both of the ½ cycles. This is followed by a period intermittent cycles of high current lasting for 50 milliseconds followed by another 5 cycles that had continuous arcing currents. Not shown in Figure 22, but recorded on the oscilloscope, is that there were no high current cycles for the next 4 seconds (corresponding to more than a 1000 cycles).

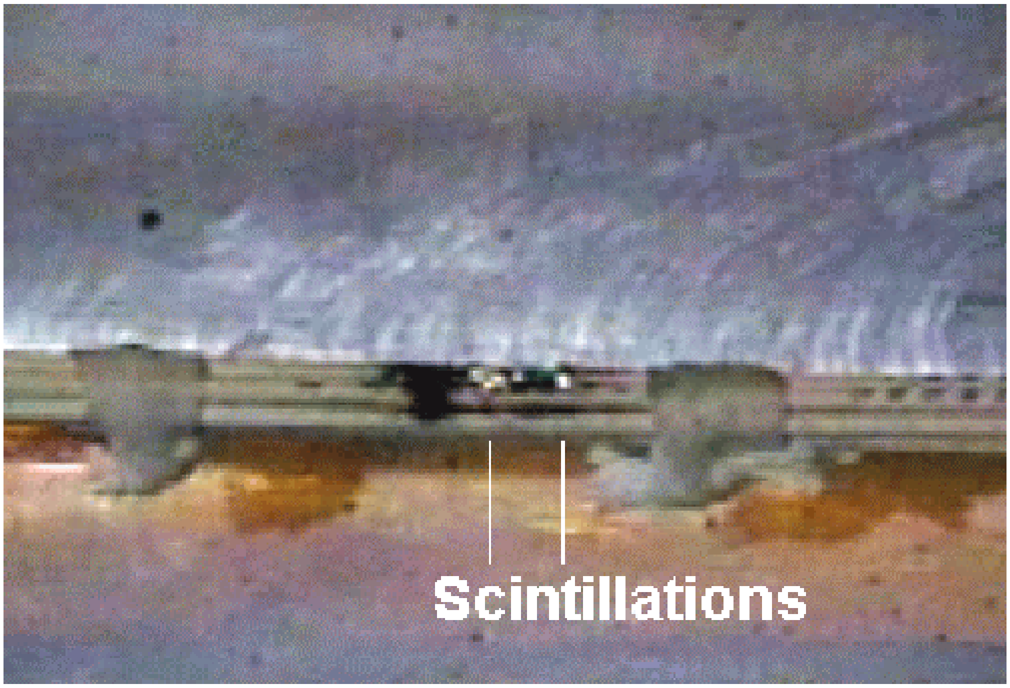


Figure 20. Test 2: Scintillations along the built up char path.

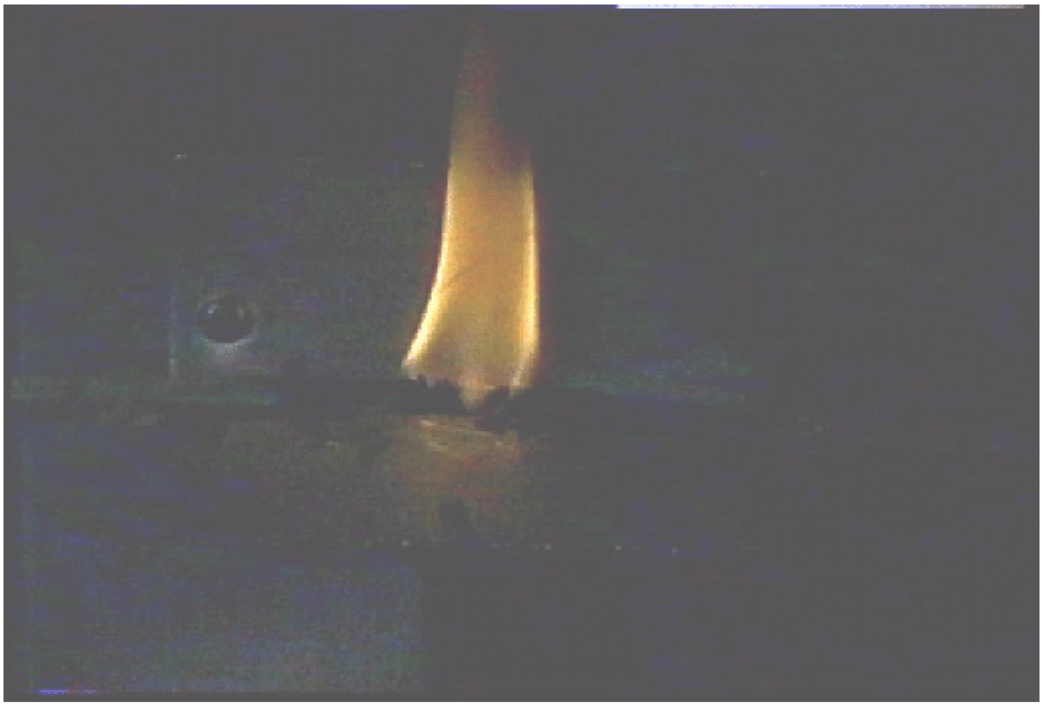


Figure 21. Test 2: A Chemical combustion flame observed after a series of flashing events.

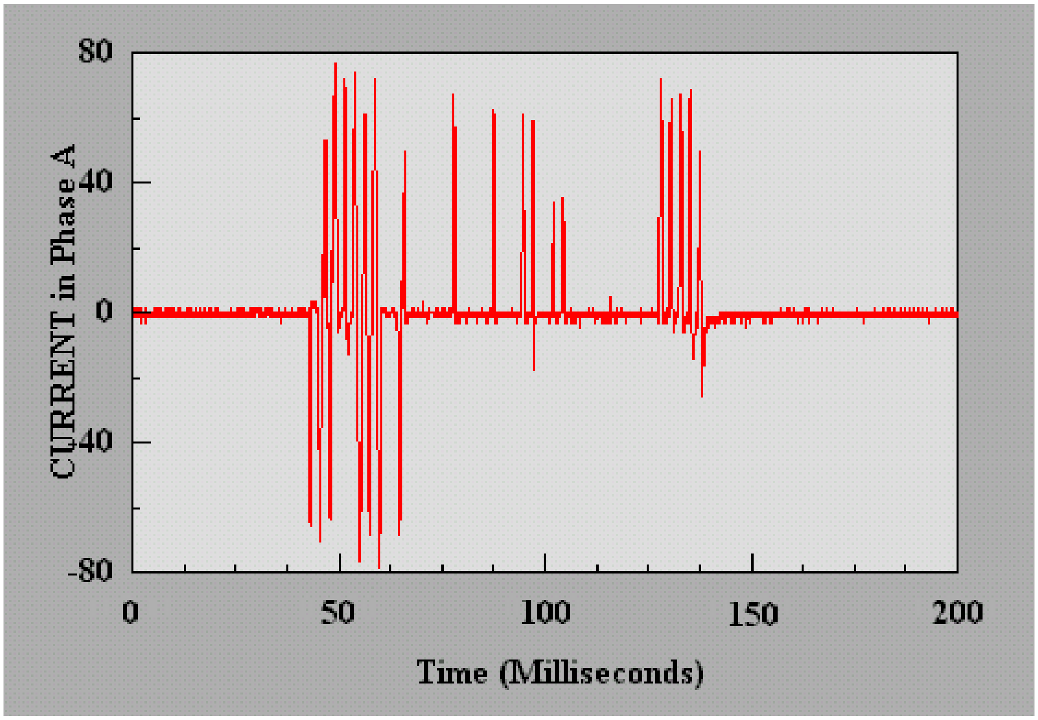


Figure 22. Test 1: Oscillogram showing intermittent current during a flashing event.

Examination of the bundles after the tests shows that the damage and char build up was over a 1/2 to 5/8 inch length of the wire bundle. In each test, the conductor of 2 (test 1) or 3 (test 2) of the wires were eroded away up to ½ of an inch. In test 1 the eroded conductors were from wire [A1] and wire [B2] (wire [B2] was not originally damaged but must have become damaged soon after the start of the test.). In each test, two of the five previously undamaged wires failed a wet dielectric test. Figure 23 shows the sample from Test 2 after being removed from the arc tracking apparatus.

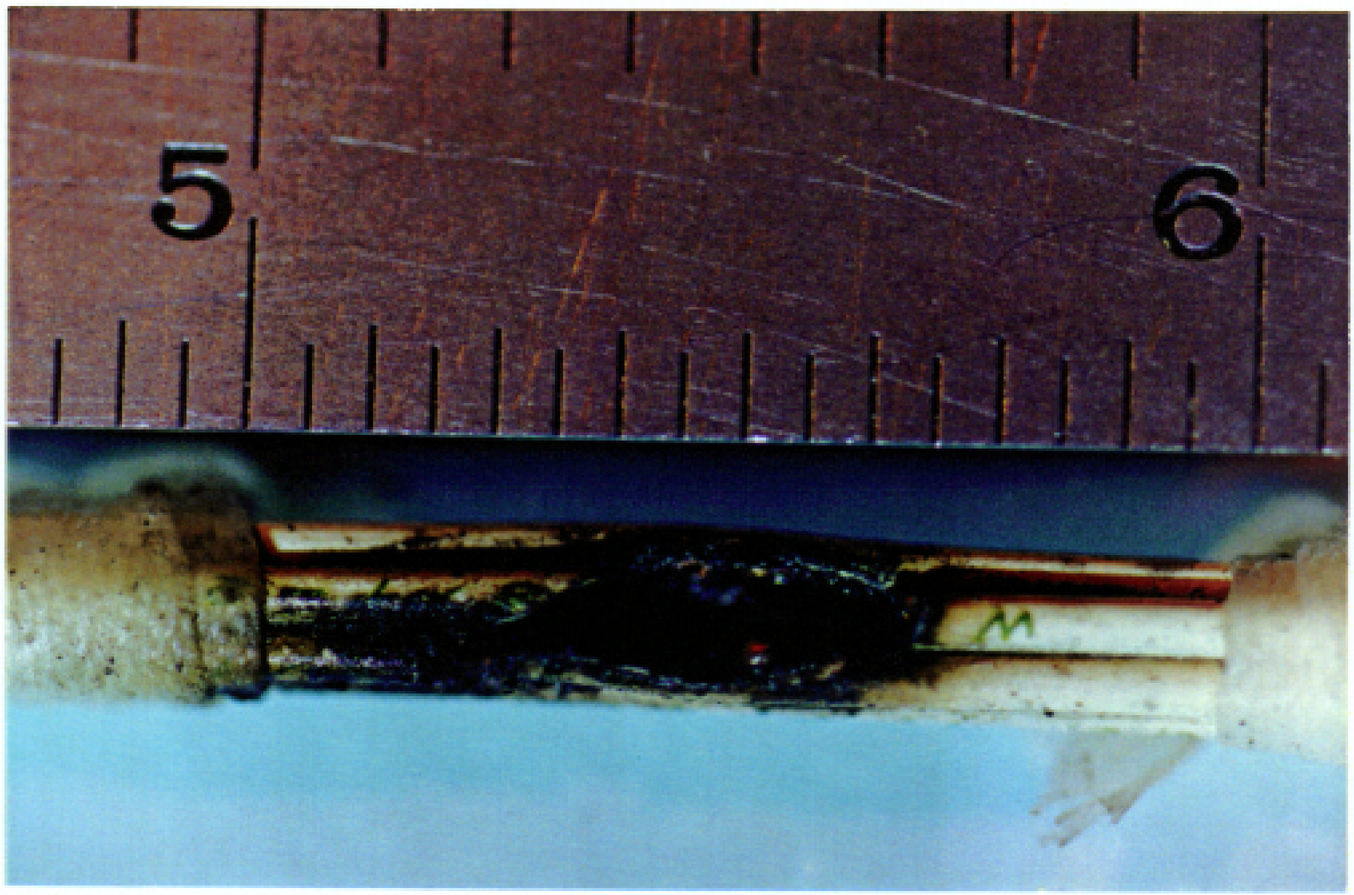


Figure 23. Test 2: Sample bundle after 25 minutes of wet arc track testing.

Test 3

Wet Arc Tracking
Bundle: Seven wires (6 over 1) of BMS 42/1/1-20 specification, 15 inches in length.
Electrolyte: 1% saline solution @100mg/minute
Circuit Resistance: 1 Ohm
Generator: 3 phase, 400Hz, 120 line to neutral (208 line to line), 10 kVA.
Length of test: 5 Minutes

Observation	Test 3
Visible scintillation	00:10
Flash	3:03
Strong Arcing	3:11
Circuit Breakers Tripped	Yes
Damage Length	2"
# Wires Failing Wet Dielectric Test	5 of 5 [C] ,[A2], [B2], [D1] & [D2]

Scintillations were observed on the sample almost immediately after Test 3 was started. Several minutes in to the test, before a visible char track was developed a flash was observed. On the next drop of saline the sample burst into intense arcing that lasted less that a second and damaged all of the active wires in the bundle though no circuit breakers were tripped (Figure 24). The sample became dormant for about 30 seconds before another burst of arcing which did trip the circuit breaker in series with wire [C]. The arcing stopped and the sample was inactive for about 5 minutes. At this point the circuit breaker was reset and the bundle arced again. This time 3 circuit breakers [B1], [B2] and [C] were tripped and the arc stopped. The sample was then removed from the test apparatus.

A look at the oscilloscope recording of the first burst of strong arcing shows that the event lasted for less than 1/4 of a second and that all three phases became involved within 30 milliseconds (Figure 25). There were many current peaks greater than 100 amperes during the arc. Estimates of the electrical energy dissipated in the two events before the circuit breaker tripped is about 2 kilojoules. The second burst of arcing that resulted in the tripping of the circuit breaker was not recorded because the data from the first arcing was in the process of being stored to disk at that time.

Examination of the sample after the test (Figure 26) showed that the damage and charring of the wire took place over a 2 inch span of the bundle and ~1 inch of the 5 active wires were eroded. All wires failed a wet dielectric test.

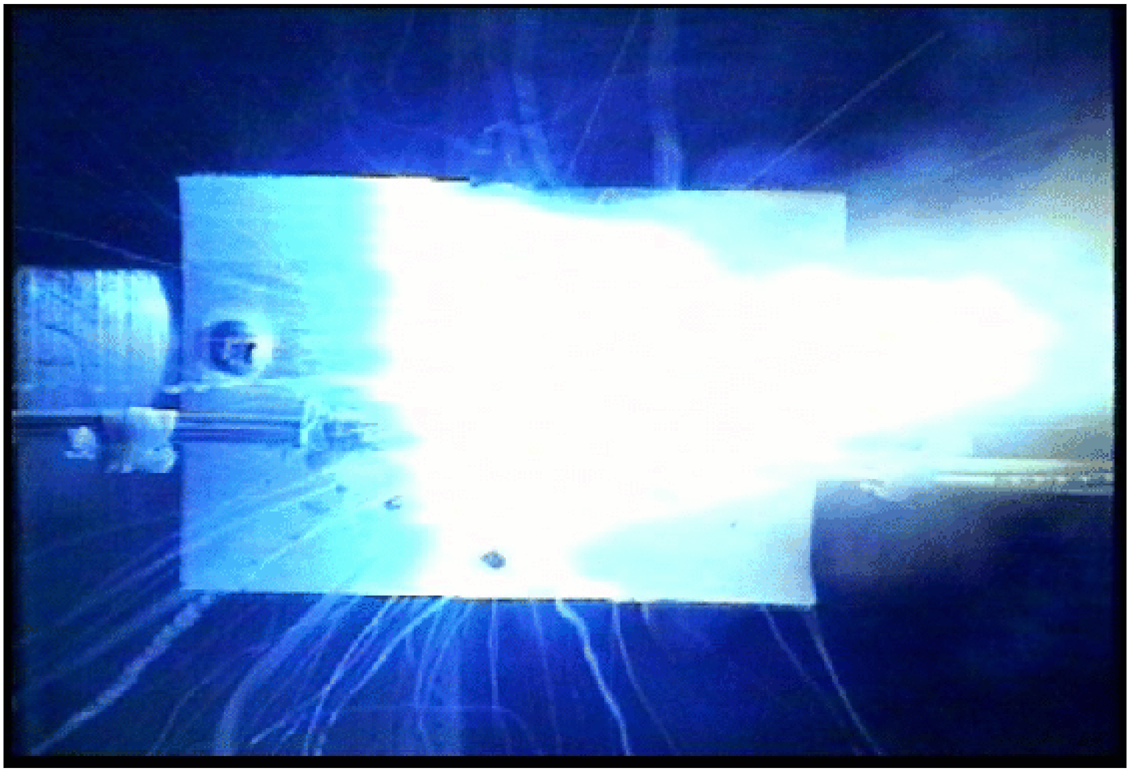


Figure 24. Test 3: Strong arcing on a W42/1/1-20 Sample.

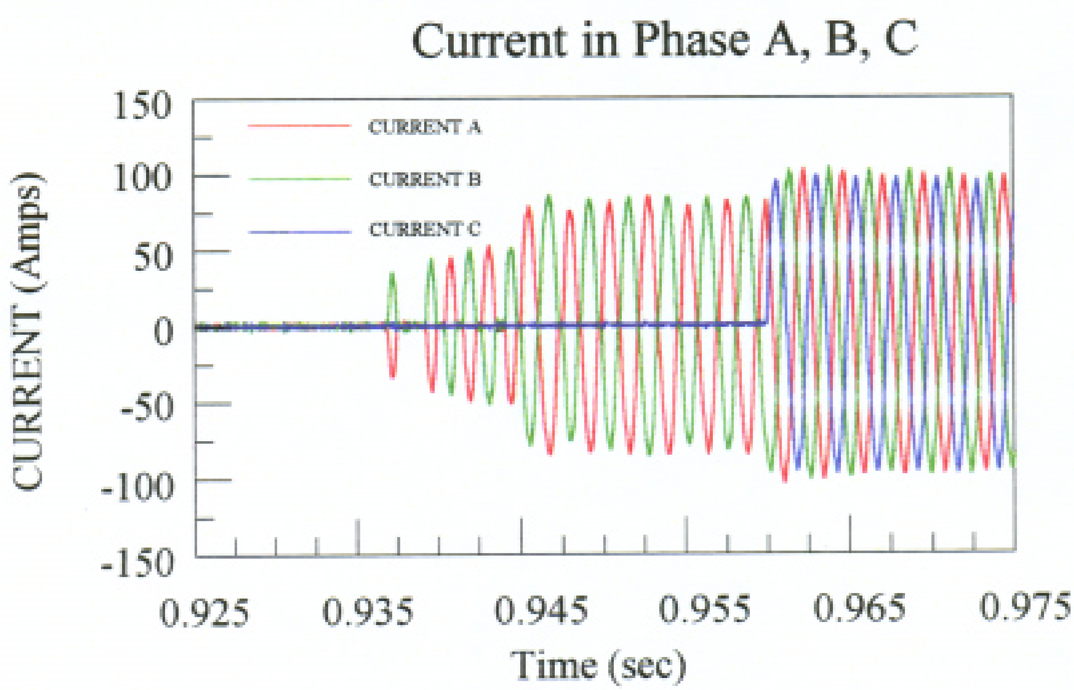


Figure 25. Test 3: Oscillogram of three phase current during arcing event.

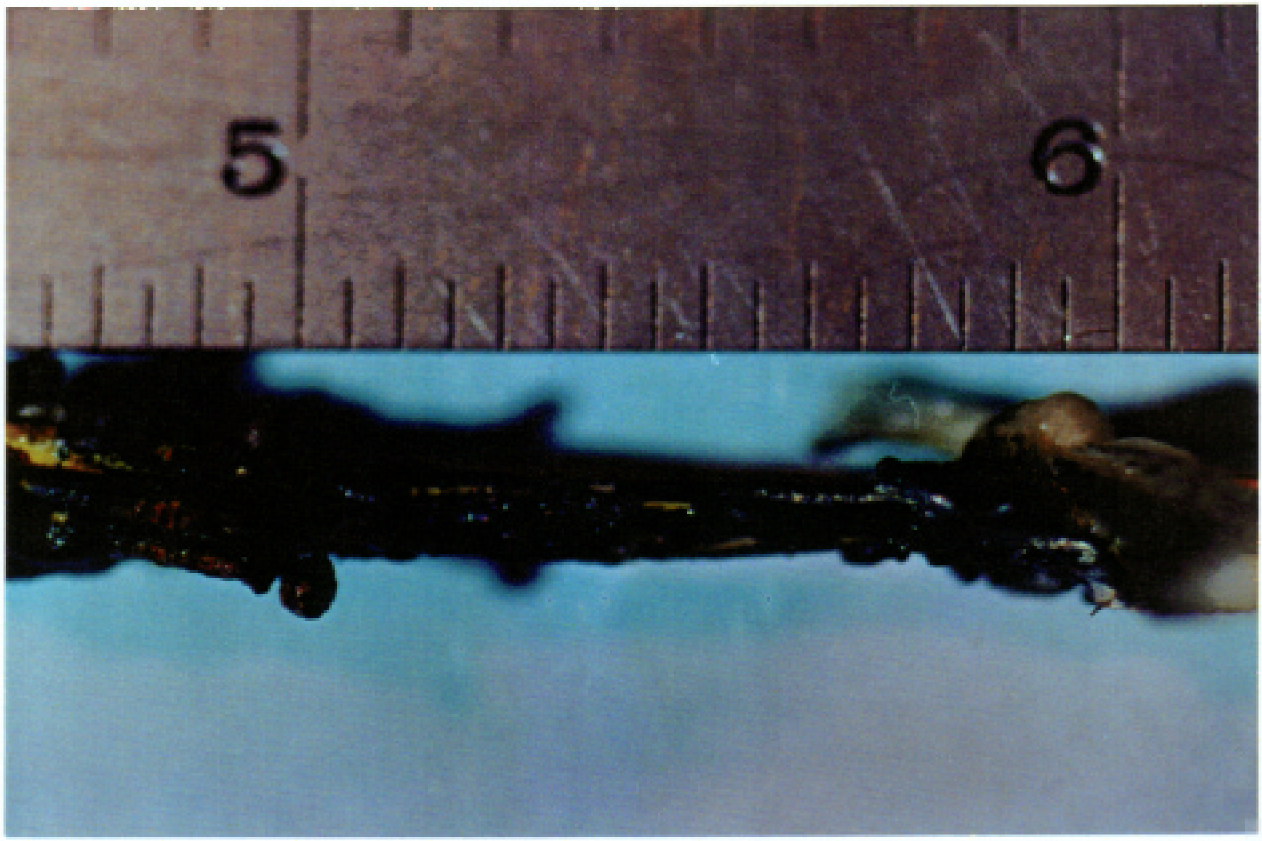


Figure 26. Test 3: Sample bundle after the test which included circuit breaker reset.

Test 4 & 5

Wet Arc Tracking
Bundle: Seven wires (6 over 1) of Mil-W-81381/12-20 specification, 15 inches in length.
Electrolyte: 1% saline solution @ 100mg/minute
Circuit Resistance: 1 Ohm
Generator: 3 phase, 400Hz, 120 line to neutral (208 line to line), 10 kVA.
Length of tests: <1.5 minutes

Observation	Test 4	Test 5
Visible scintillation	00:20	00:15
Flash	No	No
Strong Arcing	80 sec	20 sec
Circuit Breakers Tripped	Yes	Yes
Damage Length	2"	7/8"
Number of Wires Failing Wet Dielectric Test	4 of 5 [C], [A2], [B2] &[D2]	3 of 5 [C], [A2] & [B2]

Both of the samples in Tests 4 and 5 had relativity short periods of scintillation followed by strong arcing (Figure 27) that damaged the other wires in the bundle and tripped several circuit breakers.

In Test 5 the sample had been wetted with the 1% saline solution before the power was applied. The sample was washed with distilled water and dried with a paper towel. However, this may not have remove all of the saline which may have caused the sample in Test 5 to have strong arcing quicker than the sample in Test 4.

In Test 4 a circuit breaker [C] was reset and strong arcing restarted until circuit breakers re-tripped. A second circuit breaker [B1] was reset and again strong arcing restarted causing more damage to the wire until the breakers re-tripped and the arcing stopped. The sample was then removed. In Test 5 no circuit breakers were reset and the sample was removed after the first strong arcing event.

The oscillogram from the initial arcing in Test 4 indicates that the event last about 3/4 of a second and had current peaks of 125 amperes (Figure 28). The power is estimated to have been 8 kilojoules. The arcing in Test 5 lasted a little under 1 second.

Examination of the bundles showed that the damage to the wire in Test 4 extended for about 2" and that 3/4" of the 5 active wires had eroded completely away (Figure 29). 4 of 5 wires failed a wet dielectric test. Because the circuit breaker was not reset, the damage to the wire in Test 5 was less than Test 4 with the damage only extending 3/4". Although each of the five active wires had been cut through by the arcing, the eroded length was only 3/8". Three of the five wires failed the wet dielectric test.

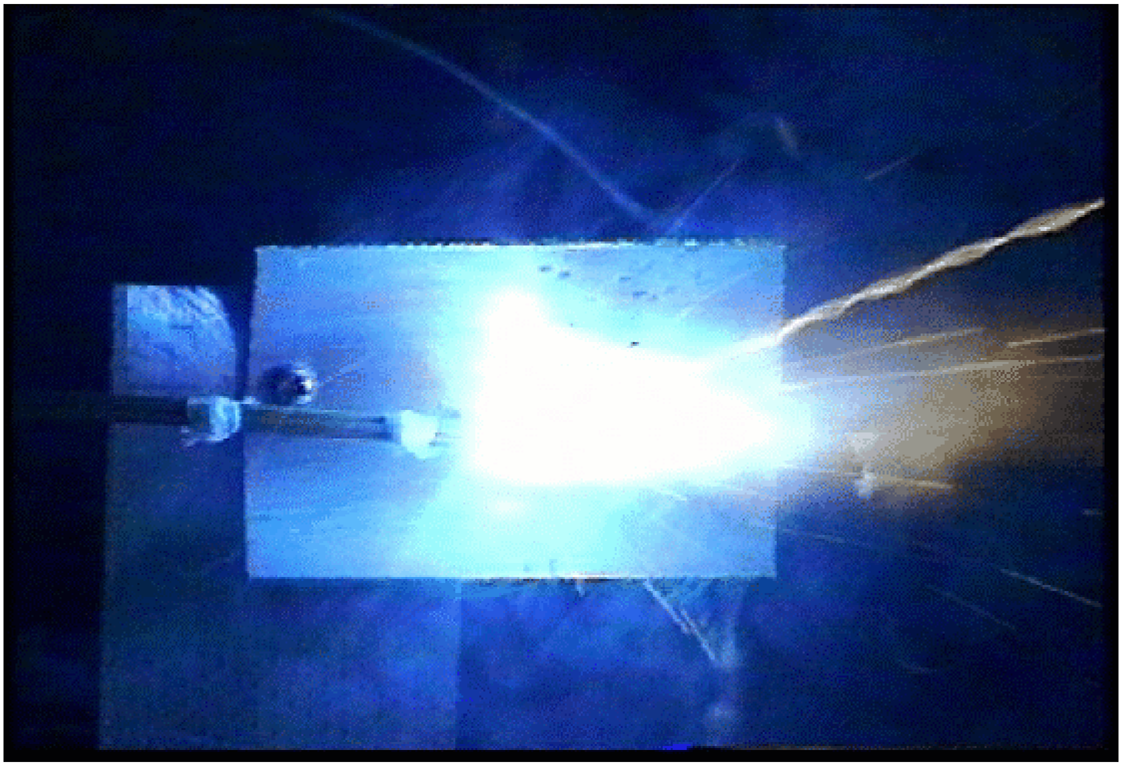


Figure 27. Test 4: Strong arcing on a Mil-W-81381/12-20 wire bundle

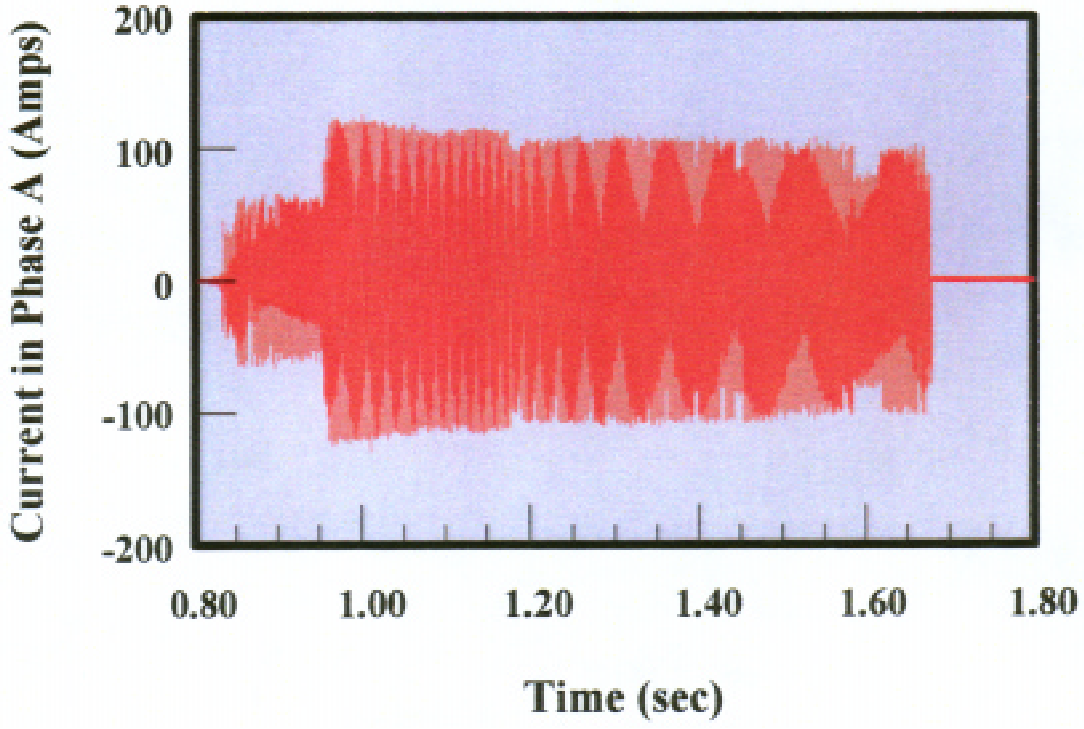


Figure 28. Test 4: Oscillogram of phase A current during a strong arcing event.

30

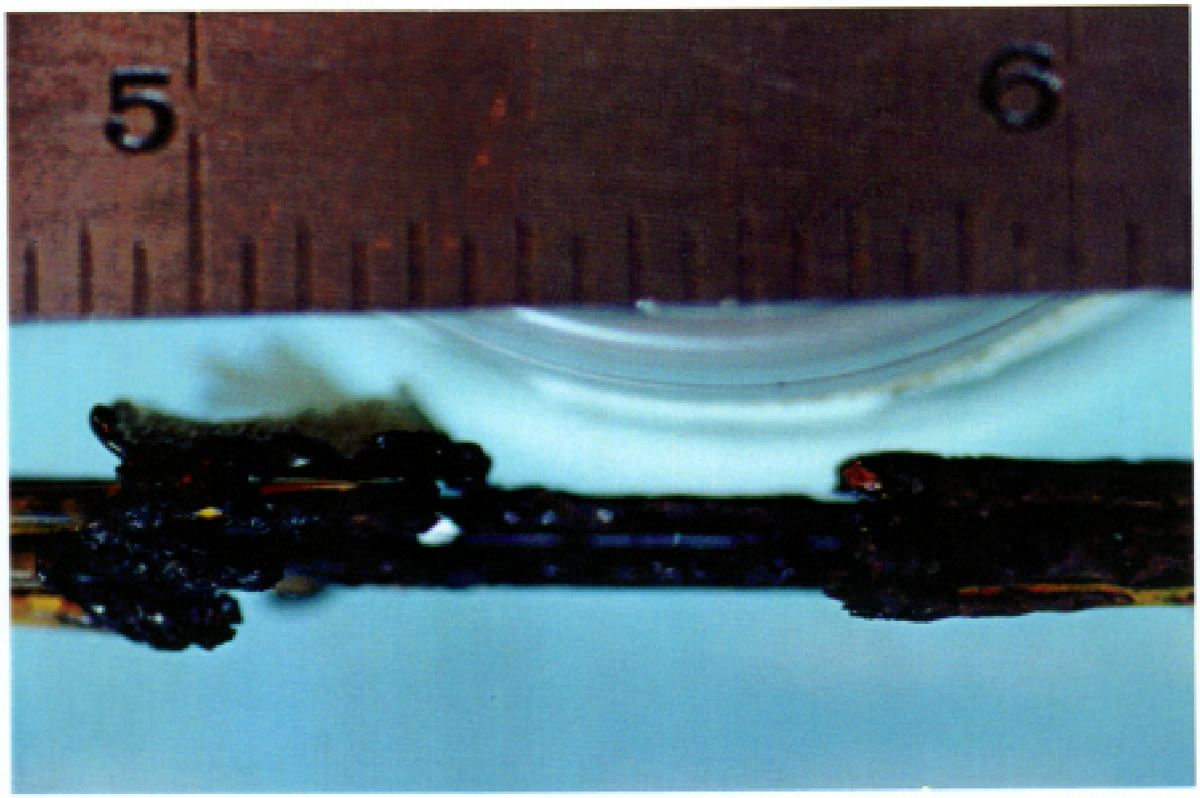


Figure 29. Test 4: Wire bundle after the test including two circuit breaker resets.

Test 6 & 7

Wet Arc Tracking
Bundle: Seven wires (6 over 1) of BMS 42A/8/1-20 specification, 15 inches in length.
Electrolyte: Lavatory Waste Water @ 100mg/minute
Circuit Resistance: 1 Ohm
Generator: 3 phase, 400Hz, 120 line to neutral (208 line to line), 10 kVA.
Length of test: 10 to 16

Observation	Test 6	Test 7
Visible scintillation	00:10	00:25
Flash	5:17	7:28
Strong Arcing	No	No
Circuit Breakers Tripped	0	0
Damage Length	1/4"	3/8"
Number of Wires Failing Wet Dielectric Test	2 of 5 [C] & [B2]	0 of 5

The results in Tests 6 & 7 were similar to those in Tests 1 & 2 but the accumulated damage was less because the test were not run as long. Visible scintillations began almost immediately after the start of the test. After several minutes a char path began to develop and soon after the first flash event was observed. Like the earlier test the single flash events (Figure 30) soon turned into a rapid series of flash pop events and chemical combustion flames were also observed.

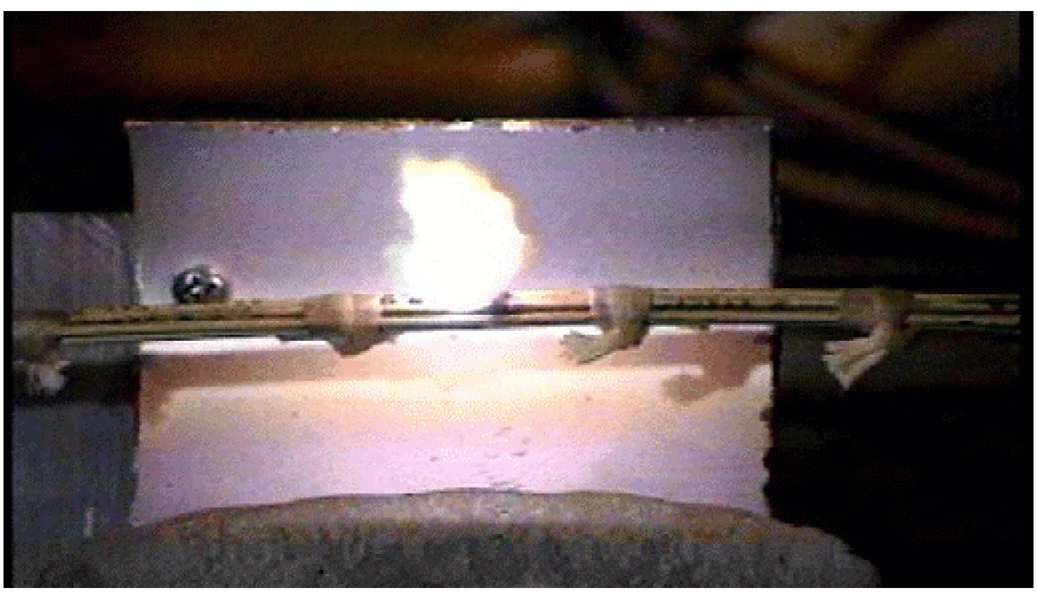


Figure 30. Test 6: Flash event during wet arc track testing with lavatory waste water.

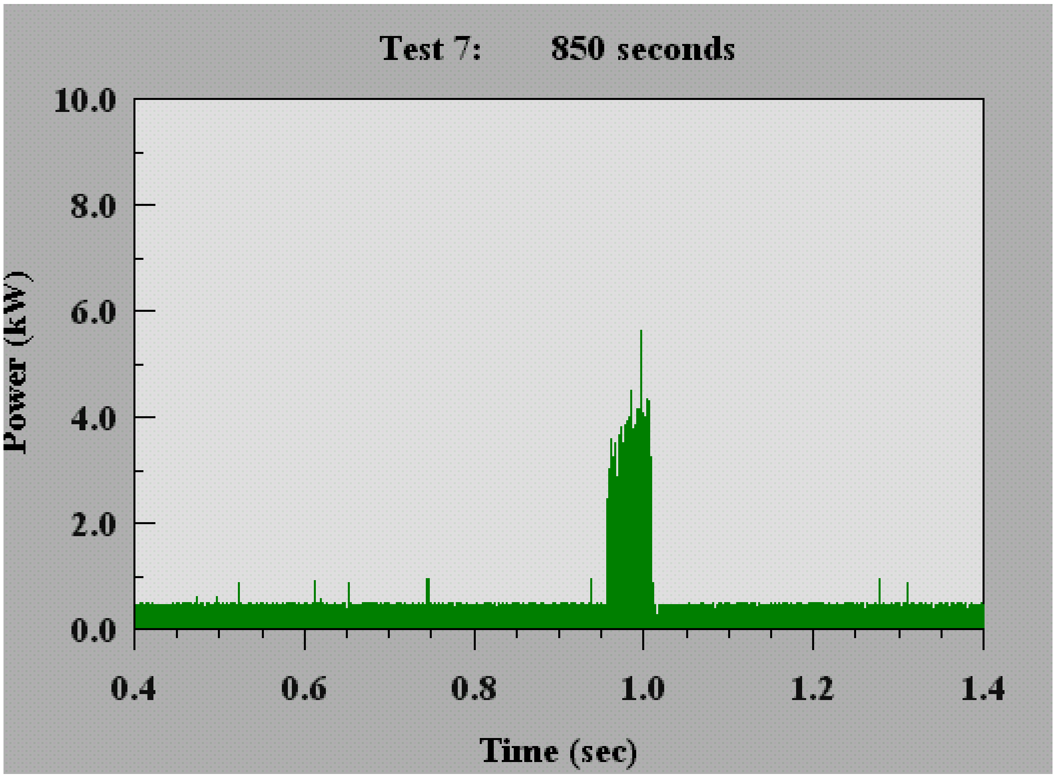


Figure 31. Test 6: Electrical power dissipated during a flash event.

The oscilloscope recording showed that some of the more active flash events had arcing waveforms up to 20 continuous cycle (.05 seconds) with power peaks in the 3 to 6 kW range (Figure 31). The electrical energy dissipated in the event shown in Figure 31 was about 90 joules.

Examination of the bundles after the tests revealed the same type of as that found in Tests 1 and 2 but not to as high an extent, probably because these bundles were not tested as long (Figure 32).

The DC electrical conductivity of the of the lavatory waste water, the 1% saline solution and distilled water were measured for comparison. The results are given in Table 6.

Table 6. DC conductivity of electrolytes and distilled water.

Liquid	Conductivity (mmho/m)
Used lavatory waste water	32
1 % saline solution	40
Distilled water	1.6

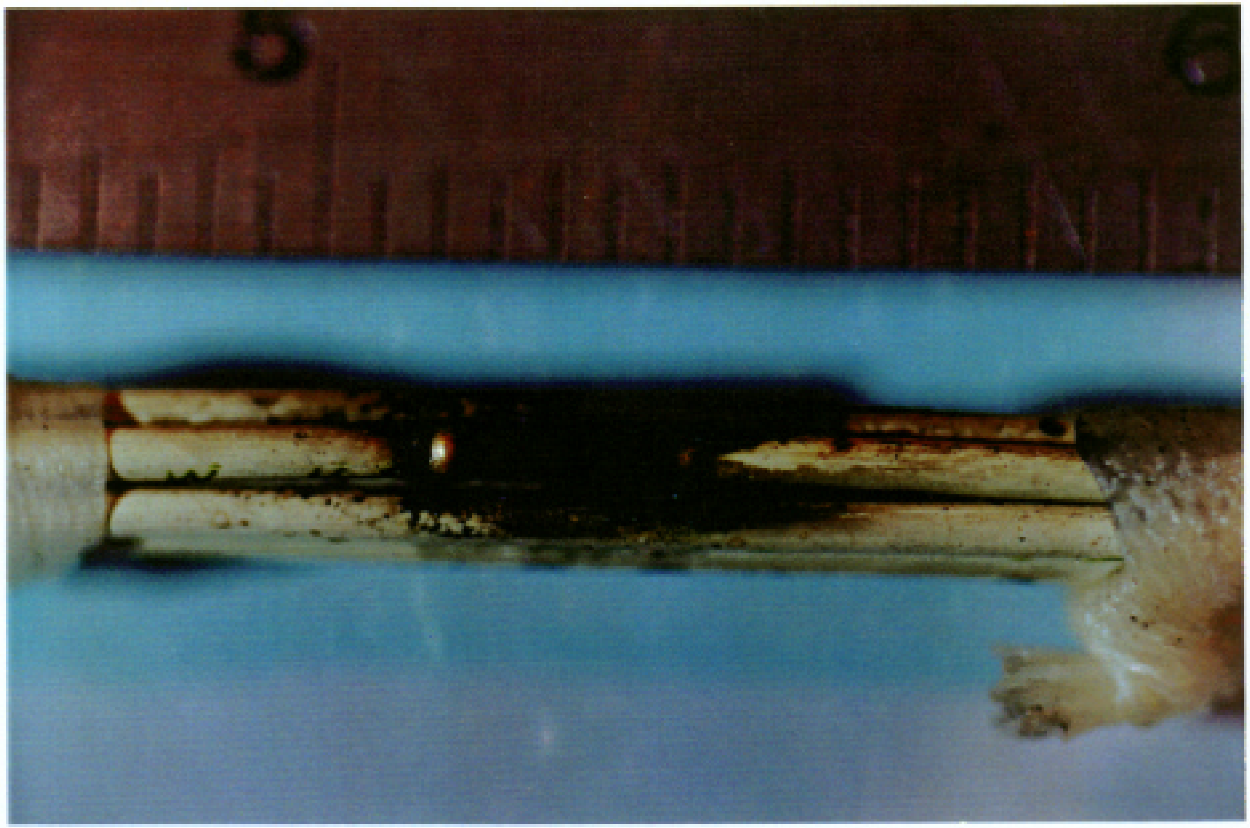


Figure 32. Test 6: Sample bundle after wet arc track testing with lavatory waste water for 10 minutes.

Metal Shavings Short Circuit

Test 8:

Bundle: Seven wires (6 over 1) of BMS 42A/8/1-16 specification, 15 inches in length.
Metal Shaving: Steel; 75 mils by 10 mils
Circuit Resistance: 1 Ohm
Generator: 3 phase, 400Hz, 120 line to neutral (208 line to line), 10 kVA.

Observations	Test 8
Flash	Yes
Strong Arcing	No
Circuit Breakers Tripped	No
Damage Length	0
Number of Wires Failing Wet Dielectric Test	0 of 5

Initially a thin steel shaving was used and when the power was applied to the sample the circuit cleared (opened) immediately. The oscilloscope indicated that there had been a current with a 85 Amp peak for ½ cycle and then zero current. The sample was taken apart and there found to be slight discoloration of some of the insulator but the shaving was intact. Apparently the edges of the shaving evaporated, opening the circuit.

The sample was remade with a thicker shaving (75mils by 10 mils) and the lacing tape holding the sample together was pulled tighter than before. When the power was applied there was a visible flash and then the sample was dormant. None of the circuit breakers tripped. The oscilloscope indicated 2 ½ cycles of current with an 85 Amp peak. There was little damage to the surrounding insulation and all wires passed a wet dielectric test.

Test 9:

Bundle: Seven wires (6 over 1) of BMS 42A/8/1-16 specification, 15 inches in length.
Metal Shaving: Steel; 65 mils by 28 mils
Circuit Resistance: 0.5 Ohm
Circuit Breakers: Effectively 15 amps
Generator: 3 phase, 400Hz, 120 line to neutral (208 line to line), 10 kVA.

Observations	Test 9
Flash	Yes
Strong Arcing	No
Circuit Breakers Tripped	No
Damage Length	1.5
Number of Wires Failing Wet Dielectric Test	5 of 5

In this test a thicker steel shaving (65 mils by 28 mils) was used in an attempt to avoid the quick evaporation found in Test 8. When power was applied to the sample, the B1 circuit breaker tripped after 220 milliseconds of 85 amperes peak current. No flash or damage to the insulation was observed. The circuit breaker was reset and the power was reapplied with the same result.

The circuit was then changed so that the A1 and A2 circuit breakers were put in parallel as was the B1 and B2 circuit breakers. This effectively increased the circuit breakers in series with the pre-damaged wire from 7.5 to 15 amperes. It also decreases the circuit resistance to 0.5 Ω in series with the sample. When the power was applied there was 350 millisecond with a 125 amp peak short circuit current followed by intermittent flash type events for 200 milliseconds (Figure 33). This caused physical damage to the wire insulation and deposited black soot for about 3/4" surrounding the pre-damaged area. The oscillogram indicates that the C phase wire (previously undamaged) became involved in the arc with current peaks of 100 Amperes. None of the circuit breakers tripped. All 5 of the non pre-damaged wires failed the wet dielectric test indicating substantial damage to the insulation.

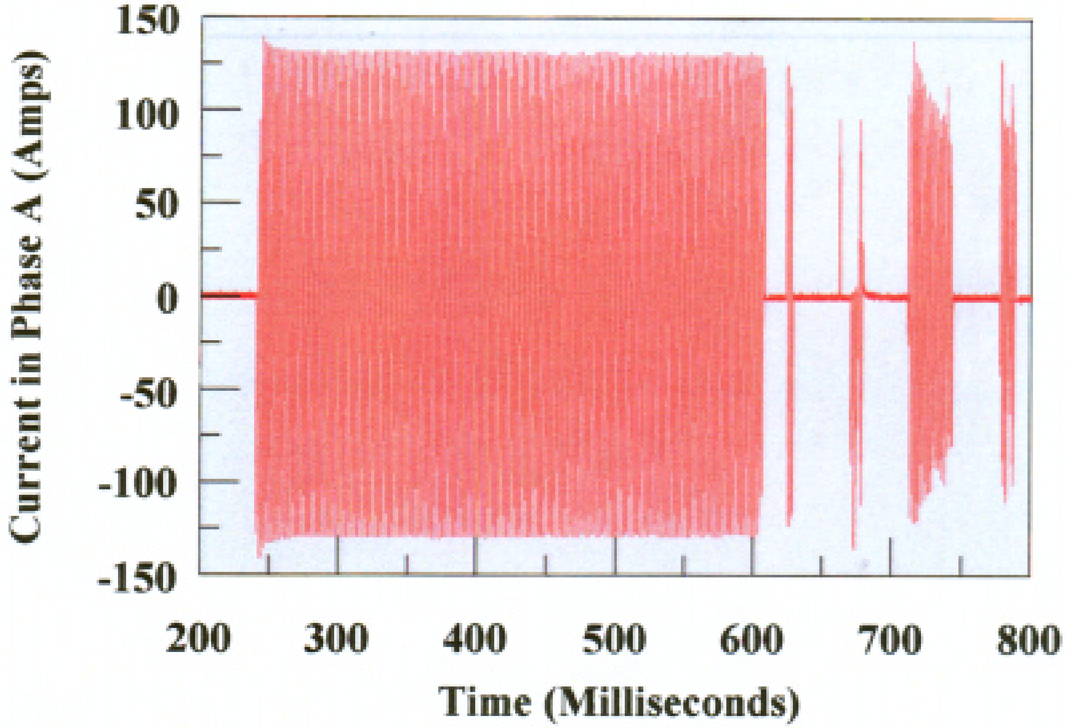


Figure 33. Test 9: Oscillogram of short circuit current that turns into intermittent arcing.

Test 10:

Bundle: Seven wires (6 over 1) of BMS 42A/8/1-16 specification, 15 inches in length.
Metal Shaving: Steel; 48 mils by 26 mils
Circuit Resistance: 0.5 Ohm
Circuit Breakers: Effectively 15 amps
Generator: 3 phase, 400Hz, 120 line to neutral (208 line to line), 10 kVA.

Observations	Test 10
Flash	Yes
Strong Arcing	No
Circuit Breakers Tripped	No
Damage Length	1/8"
Number of Wires Failing Wet Dielectric Test	2 of 5

This test used the same arrangement as Test 9 with effective 15 amperes circuit breakers. The first application of power resulted in a 140 amp peak short circuit current for 15 milliseconds which resulted in some melting.

The sample was then rearranged and power was reapplied. This resulted in a small flash and then the sample become dormant. There was some melting and char build up in the immediate vicinity of the shaving. Two of the five non-predamaged wires failed a wet dielectric test. None of the circuit breakers tripped during this test.

Test 11:

Bundle: Seven wires (6 over 1) of BMS 42A/8/1-16 specification, 15 inches in length.
Metal Shaving: Aluminum 7075; 120 mils by 6 mils
Circuit Resistance: 0.5 Ohm
Circuit Breakers: Effectively 15 amps
Generator: 3 phase, 400Hz, 120 line to neutral (208 line to line), 10 kVA.

Observations	Test 11
Flash	Yes
Strong Arcing	No
Circuit Breakers Tripped	No
Damage Length	0
Number of Wires Failing Wet Dielectric Test	0 of 5

This test used the same arrangement as Test 9 with effective 15 amperes circuit breakers and a relatively thin aluminum 7075 shaving. Application of power resulted in a small flash and 140 amp peak short circuit current for 8 milliseconds. There was no visible damage to the insulation except for a spot of char build up. None of the circuit breakers tripped.

Test 12:

Bundle: Seven wires (6 over 1) of BMS 42/1/1-20 specification, 15 inches in length.
Metal Shaving: Steel; 51 mils by 10 mils
Circuit Resistance: 1 Ohm
Generator: 3 phase, 400Hz, 120 line to neutral (208 line to line), 10 kVA.

Observations	Test 12
Flash	Yes
Strong Arcing	No
Circuit Breakers Tripped	No
Damage Length	1/4"
Number of Wires Failing Wet Dielectric Test	1 of 5

This test used the original arrangement with a single 7.5 amperes circuit breaker in series with each active wire. Application of power resulted in a flash (Figure 34)and the sample then became dormant. Soot was deposited near the pre-damaged cuts in the wire (Figure 35). No circuit breakers were tripped and one of five wires failed the wet dielectric test.

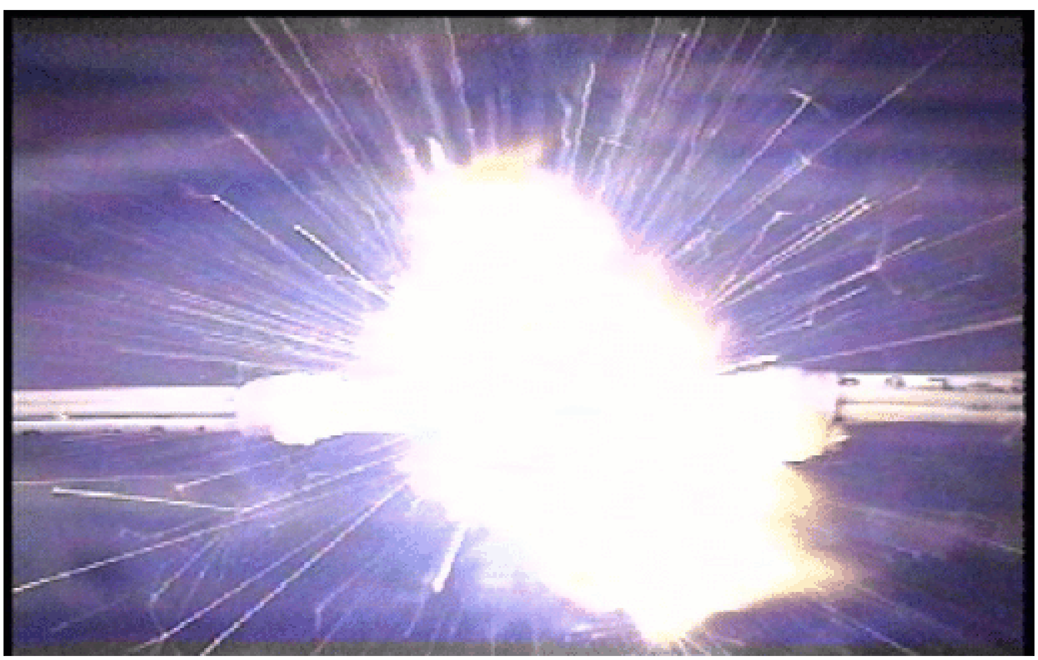


Figure 34. Test 12: Flash event during a metal shavings short circuit test.

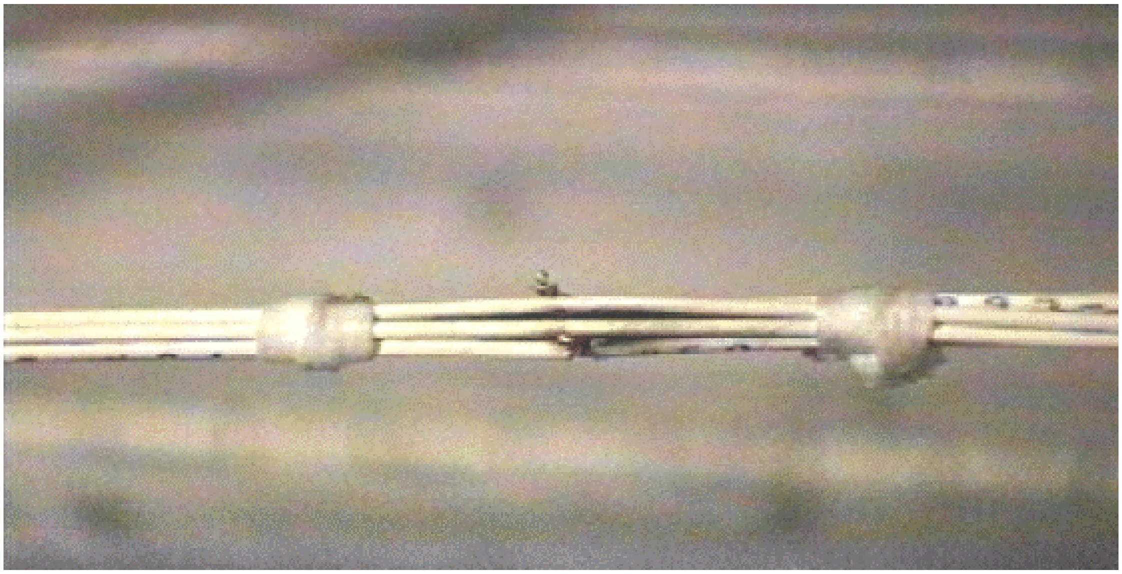


Figure 35. Test 12: Sample bundle after the flash shown in Figure 34.

The oscillograph showed the there was sporadic arcing waveform with current peaks reaching 80 amperes for 150 milliseconds (Figure 36). Near the end of this period the C phase wire became involved in the arcing.

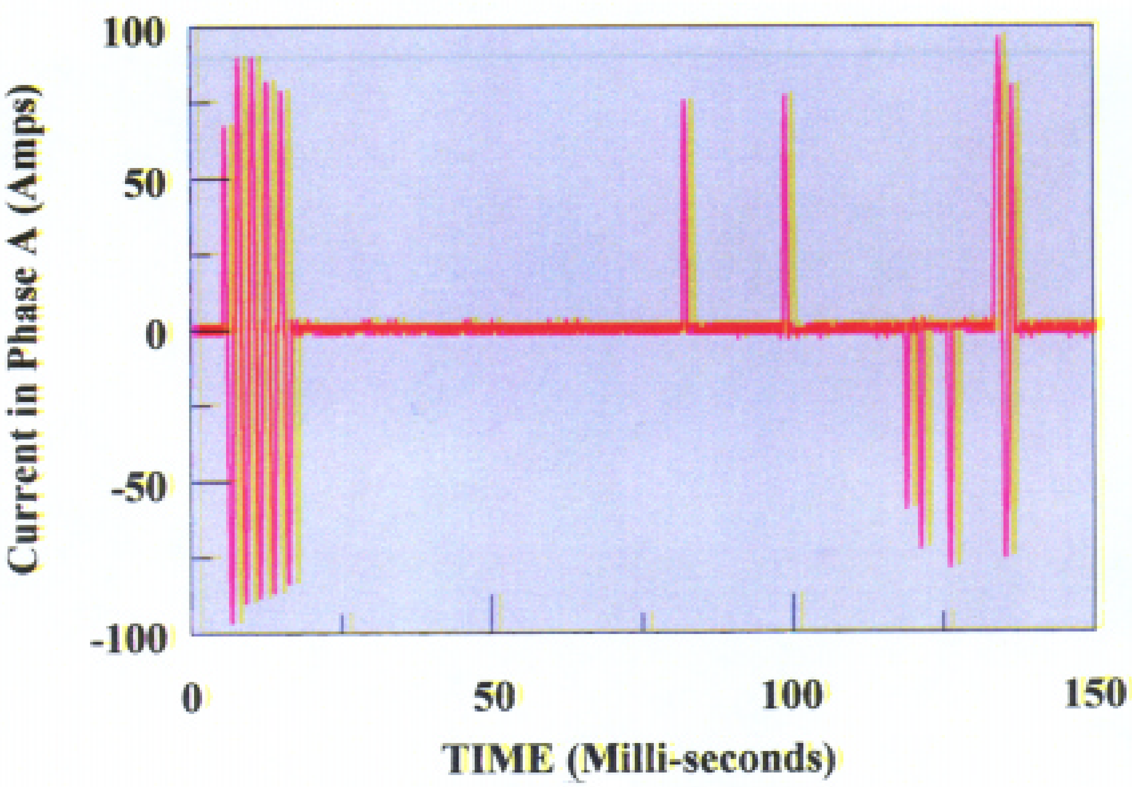


Figure 36. Test 12:Oscillogram of intermittent current during a flash event.

Test 13:

Bundle: Seven wires (6 over 1) of BMS 42/1/1-20 specification.
Metal Shaving: Aluminum 7075; 50 mils by 8 mils
Circuit Resistance: 1 Ohm
Generator: 3 phase, 400Hz, 120 line to neutral (208 line to line), 10 kVA.

Observations	Test 13
Flash	Yes
Strong Arcing	No
Circuit Breakers Tripped	No
Damage Length	0
# Wires Failing Wet Dielectric Test	0 of 5

In this test an Aluminum 7075 (50 mils by 8 mils) was used. Upon application of the voltage there was a high buzzing sound followed by a small flash. The sample then became dormant. There was no soot built up or visible damage to the insulation and none of the circuit breakers tripped. The oscilloscope showed a 100 amp peak short circuit current for 125 milliseconds that transitioned into an arc waveform for less than ½ a cycle before clearing (no current). None of the five wires failed the wet dielectric test.

Test 14:

Bundle: Seven wires (6 over 1) of BMS 42A/8/1-20 specification.
Metal Shaving: Steel; 52 mils by 9 mils
Circuit Resistance: 1 Ohm
Generator: 3 phase, 400Hz, 120 line to neutral (208 line to line), 10 kVA.

Observations	Test 14
Flash	Yes
Strong Arcing	No
Circuit Breakers Tripped	No
Damage Length	0
# Wires Failing Wet Dielectric Test	0 of 5

This sample flashed immediately after power was applied to the sample. A small amount of soot was deposited on the wire. The insulation appeared to be slightly damaged but none of the five wire tested failed the wet dielectric test.

The oscillogram shows that there was intermittent arcing for less than 20 milliseconds and that the phase C wire did not become involved. There were peak current of 100 amperes and the total energy dissipated was about 18 joules. Figure 37 shows the power and energy dissipated during the flash.

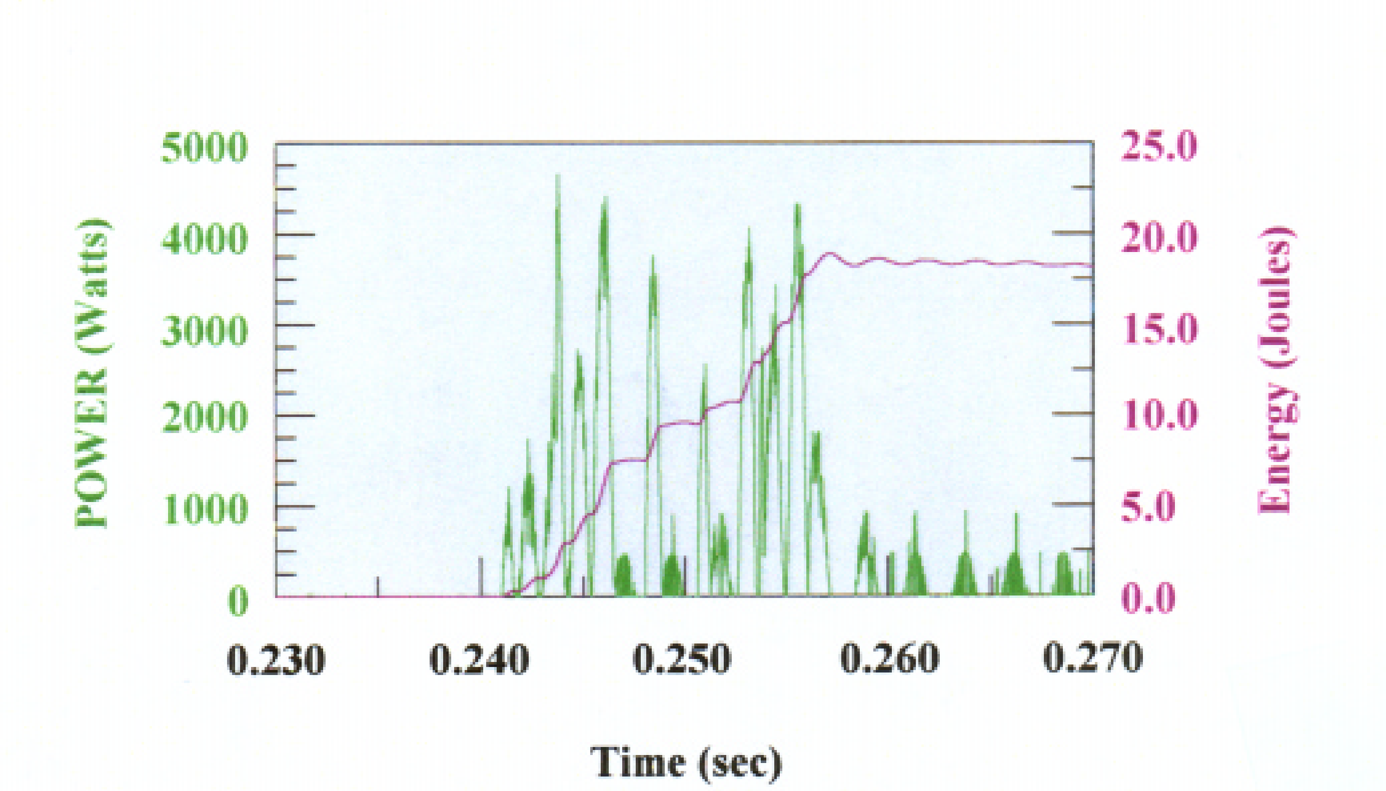


Figure 37. Test 14: Electrical power and energy dissipated during a flash event.

Test 15:

Bundle: Seven wires (6 over 1) of BMS 42A/8/1-20 specification.
Metal Shaving: Aluminum 7075; 70 mils by 8 mils
Circuit Resistance: 1 Ohm
Generator: 3 phase, 400Hz, 120 line to neutral (208 line to line), 10 kVA.

Observations	Test 15
Flash	Yes
Strong Arcing	No
Circuit Breakers Tripped	No
Damage Length	0
# Wires Failing Wet Dielectric Test	0 of 5

This sample flashed immediately and then became dormant. There was no soot deposited and no visible damage to the insulation. None of the circuit breakers tripped and none of the five wires tested failed the wet dielectric test.

The oscilloscope showed was only a ½ cycle of an arcing waveform with a peak current of 100 amperes. The total electrical energy dissipated in the flash was 2 joules.

Metal Shavings Abrasion

Test 16 A & B:

Metal shaving abrader test 90° (right angle).
2 Bundles: Seven wires each of BMS 42A/8/1-20 specification.
Metal Shaving: Bundle A: Steel; 41 mils by 26 mils
Bundle B Aluminum 7075; 42 mils by 30 mils
Circuit Resistance: 1 Ohm
Generator: 3 phase, 400Hz, 120 line to neutral (208 line to line), 10 kVA.

Observations	Test 16A	Test 16B
Flash	No	No
Strong Arcing	No	No
Circuit Breakers Tripped	No	No
Damage Length	0	0
# Wires Failing Wet Dielectric Test	1 of 7	2 of 7

In this test two samples were run concurrently. Bundles were identical to each other except that bundle A had a steel shaving woven between its wires and bundle B had an aluminum 7075 shaving. The test was run for 19 1/4 hours with no arcing events (Figure 38). While the wire sustained some damage in the area of the shaving, the damage was primarily to the topcoat with the steel shaving doing moderate damage to the Poly X layer (Figure 39).

The flexing of the bundles did cause more severe damage in areas away from the shaving. In test A, one of the wire was broken completely in half. In test B, one wire was broken in half and the insulation on other wire cracked so that the conductor was exposed. These three wires failed the wet dielectric test while all of the other wires passed.

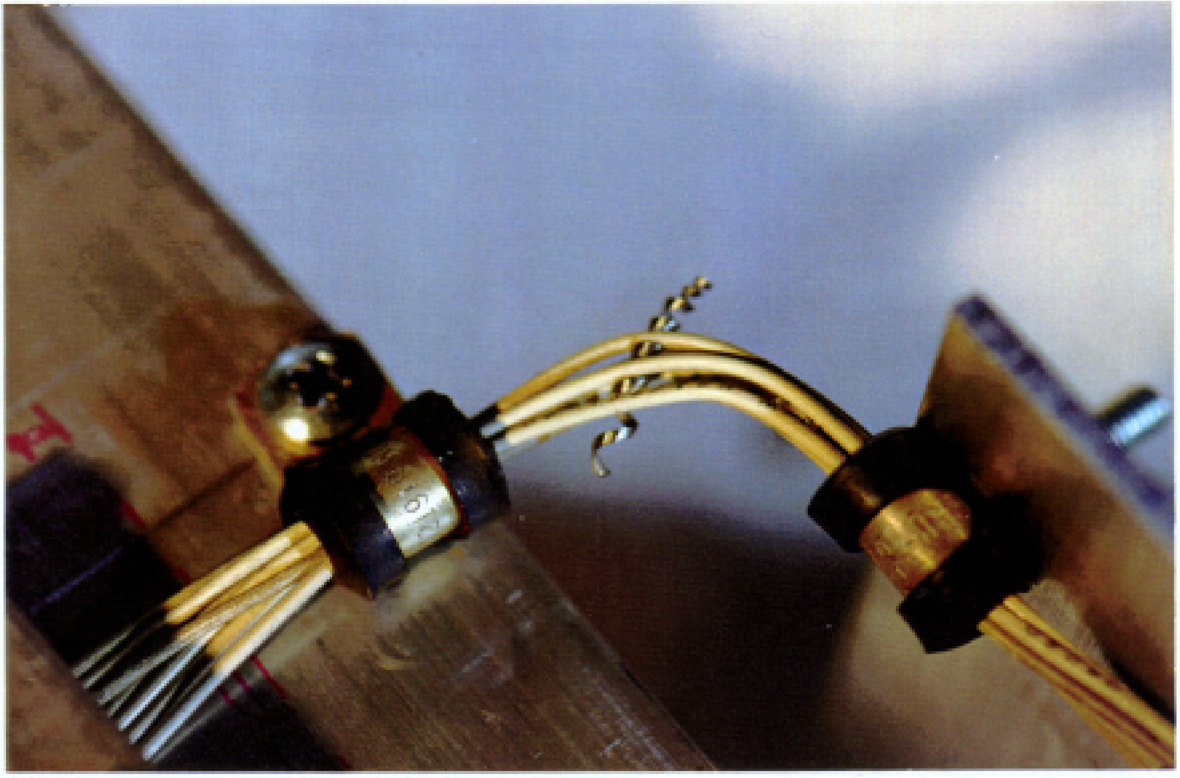


Figure 38. Test 16 A: Sample during the metal shaving abrader test 90° (right angle).

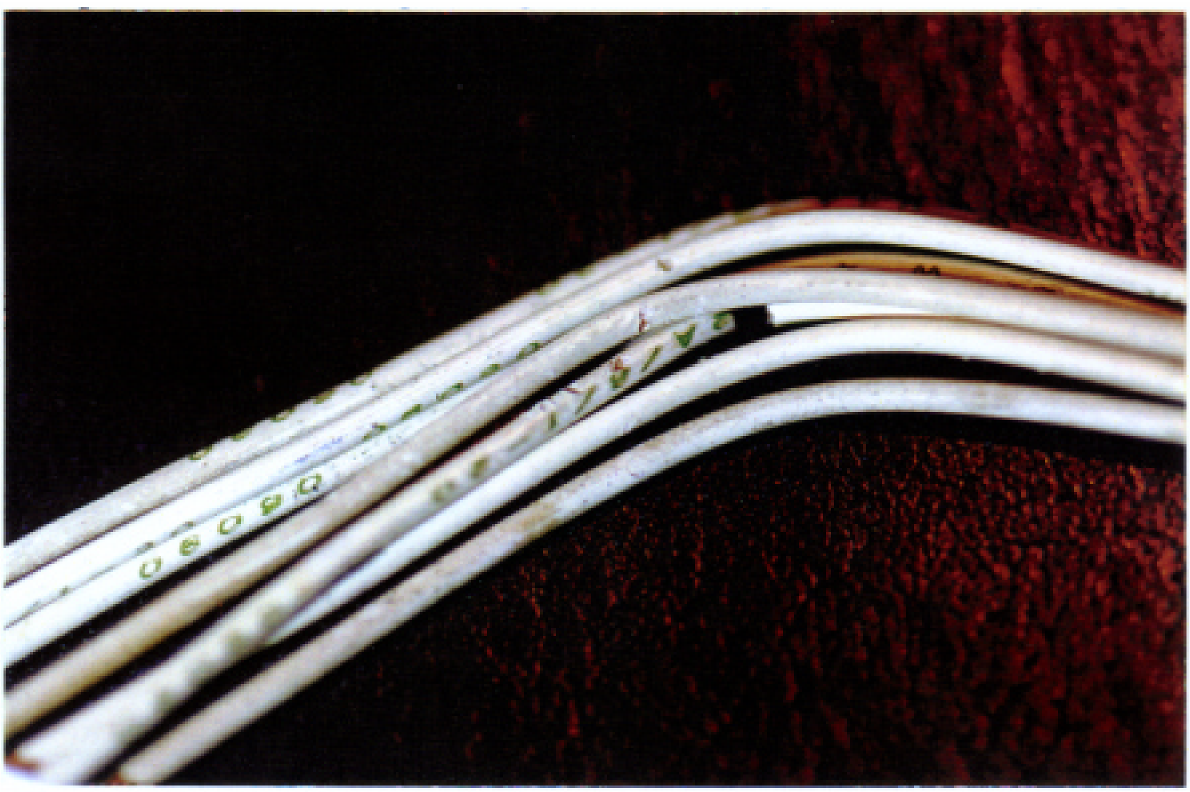


Figure 39. Test 16 A: Damage sample after metal shaving abrader 90° (right angle) test. Note that the broken wire was due to flexing and not the action of the shaving.

Test 17 & 19

2 Bundles: four wires each (three BMS 42/1/1-20; one 3 BMS 42A/8/1-18)
Metal Shaving: Two steel shavings placed ~1 apart between bundles
Circuit Resistance: 1 Ohm
Generator: 3 phase, 400Hz, 120 line to neutral (208 line to line), 10 kVA.

Observations	Test 17	Test 19
Flash	Yes	No
Strong Arcing	No	No
Circuit Breakers Tripped	No	No
Damage Length	0	0
# Wires Failing Wet Dielectric Test	2 of 8	2 of 8

In both of these tests the steels shavings did damage to the insulation that exposed the conductor. In the case of Test 17 the shaving was arranged so that the movement of a shaving between the bundles caused a steady abrasion of the insulation (Figure 40) over the course of an hour. However, before the damage reached to the conductor the shaving was disrupted slightly (by an ohmmeter probe) which caused the shaving to move via the motion of the bundles to a new location. Here, the shaving chaffed through the insulation and caused a flash in a matter of minutes (Figure 41). The flash did not turn in to strong arcing and the shaving then moved to a new location where it continued to chaff the insulation. The test was ended before the sample could flash again.

The oscillogram shows 6 current peaks of up to 75 amperes that occurred during the flash event. Examination of the sample showed severe abrasion damage and a little soot near there point where the wire flashed (Figure 42).

In Test 19 the shaving used was thinner (49 mils by 18 mils) and the abrasion patterns were more like short cuts in the insulation (Figure 43). There were no flashing events during the 4 hour duration of the test. However, two of the eight wires failed the wet dielectric test. The points of failure on these wires were at cuts that were deeper than they first appeared. From the location of the cuts it appears that different shavings made the cuts and therefore they could not cause a flash event.

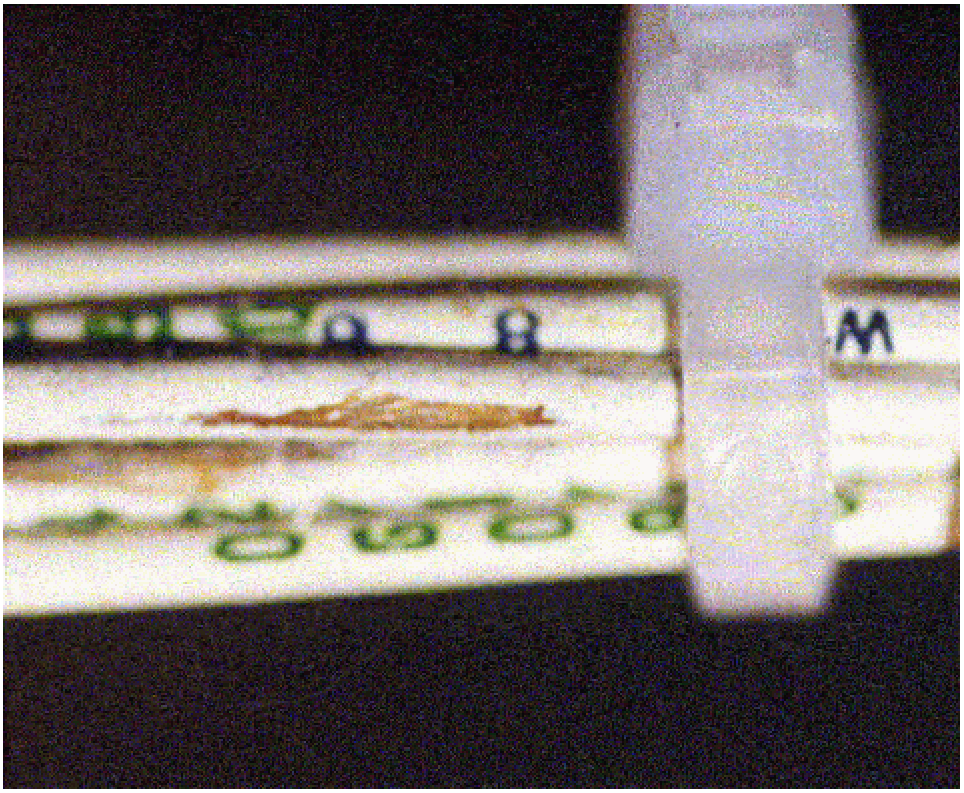


Figure 40. Test 17: Abrasion damage that did not reach to the conductor.

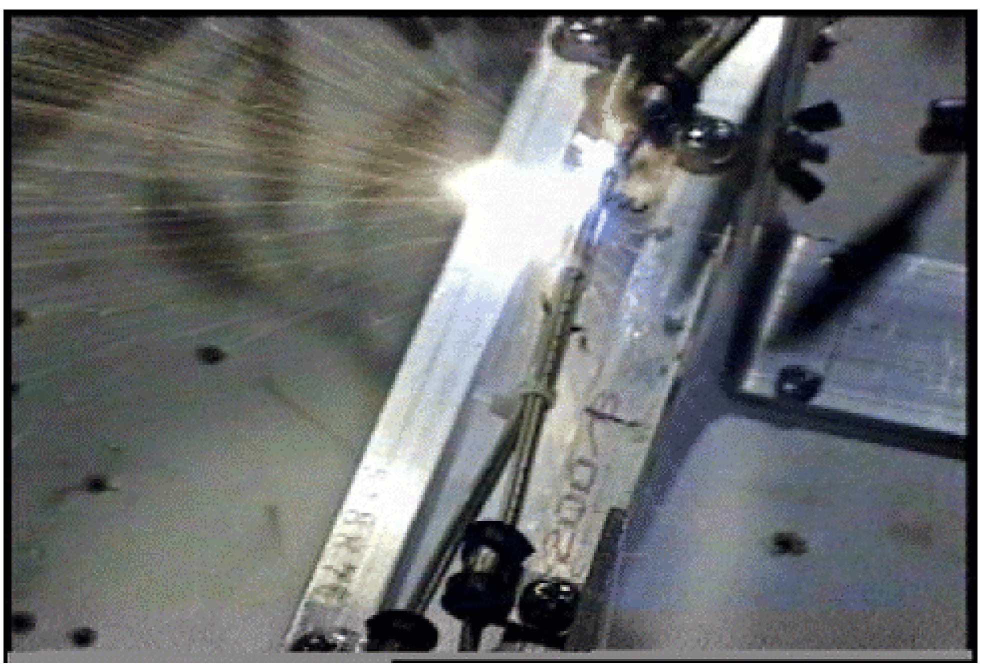


Figure 41. Test 17: Flash event during the longitudinal abrasion test.

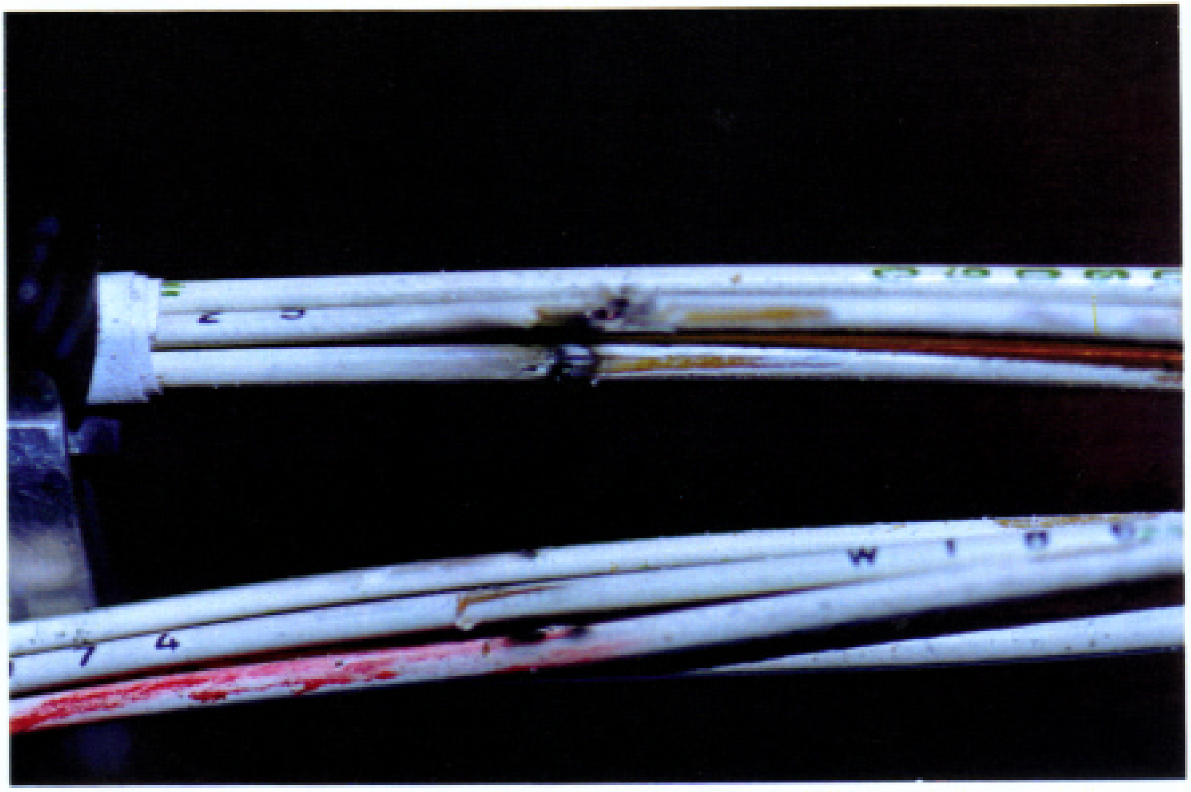


Figure 42. Test 17: Damage to wire bundle in the area of the flash.

Figure 43. Test 19: Cut damage to the insulation which in some cases reached to the conductor.

Test 18 & 20

2 Bundles: four wires each (three BMS 42/1/1-20; one 3 BMS 42A/8/1-18)
Metal Shaving: Two Aluminum 7075 shavings placed ~1 apart between bundles
Circuit Resistance: 1 Ohm
Generator: 3 phase, 400Hz, 120 line to neutral (208 line to line), 10 kVA.

Observations	Test 18	Test 20
Flash	No	No
Strong Arcing	No	No
Circuit Breakers Tripped	No	No
Damage Length	0	0
# Wires Failing Wet Dielectric Test	0 of 8	0 of 8

These tests were similar to tests 17 &19 except that aluminum 7075 shavings were used instead of steel shavings. One problem encountered was that, even with relatively thick shavings (i.e. 47 mils by 28 mils), the shaving tended to break and crumble when the two bundle were being made. Further, when the abrader was turned on, the remaining shavings tended to break and fall out of the bundles more frequently than steel shavings. However, in Test 20 one shaving stayed in the bundle for the full four hours of the test.

Damage caused by the shaving was mainly limited to the topcoat with some superficial damage to the Poly X layer (Figure 44). If the test was allowed to run longer it is possible that the shaving may have eventually abraded through to the conductor. However, in general when an aluminum shaving got into a position where it was forced into the insulation, it tended to break and was no longer an abrasion threat.

Figure 44. Test 20: Damage done in longitudinal abrasion tests with aluminum 7075 shavings

APPENDIX B: Different Experiment Configurations for the Metal Drill Shaving Abrasion Test.

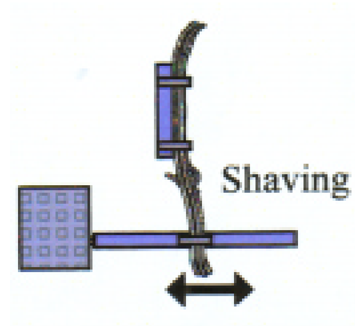
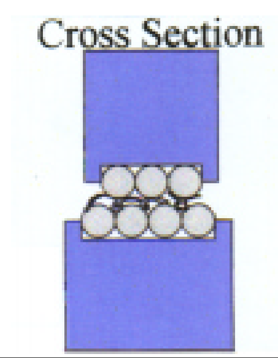
There were several different configurations of metal drill shaving abrasion test experimented with before the apparatuses described in the main text were decided upon. They caused varying degrees of damage to the insulation. Some of the configurations were objected to because it was thought that they did not to represent a realistic situation that could occur on an aircraft. A short description of these configurations is given in Table 7.

The cross sectional size and shape of the metal shavings have a large effect on the results of a given configuration. The most obvious reason for this is the mechanical strength of the shaving. Often a thin shaving would simply break apart and fall out of the test bundle. Also important is the shape of the shaving and how that effects the interaction of the shaving with the individual wires of the bundles.

The size of the shaving also affects the current carrying capacity of the shaving. If a shaving has a relatively large cross section will be able to support a larger current without evaporating and thus opening up the circuit. However, if the cross section is too large the circuit breakers will trip before enough heat is generated to initiate an arc.

The ability to control the size and shape of the shaving is more of an art than a science at this point. All of the shaving used in this project were produced using a 3/16" drill bit. The type of material is important with the grade 5 steel tending to produce longer, stronger shaving as compared to the aluminum 7075. A shaving with a larger cross section can be produced by drilling a pilot hole before drilling the hole the produces the shaving.

Table 7. Description of alternate abrasion configurations

Description	Results	Comments	Illustration
Two Bundles that are aligned much like the longitudinal abrader describe in the main text but in this case the metal shavings are glued to one of the bundles with a epoxy.	This test results in damage to the insulation with relatively thin shavings. Flash events can occur.	The gluing of the shaving may mimic the adhesion of the shaving to bundle by anti-corrosion fluid found in the field . However, the introduction of a foreign agent such as epoxy is undesirable .	
In this test a shaving is placed between the wires in a bundle. One end of the bundle is fix while the other is moved back and forth perpendicular to the axis of the wire bundle.	While there is some relative motion of the wires to the shaving it is small and does not produce much damage. There were no flashing events during these tests.	This test is appealing because one can visualize this situation to be found on an aircraft.	
The test is a longitudinal type abrasion test with two pieces square bar stock with a shallow channel acting as wire holders. The lip of the channel hold the wire in place with shaving placed between the two rows.	The amount of damage to the wires depends on how much force is holding the two wire holders together. A flash event occurred when a spring loaded clamp is used.	The wire holder supports the wire much like a large bundle would. However the wire holder and clamps used are not found on aircraft which makes the setup undesirable .	
In this test two row of wire are wrapped around a 3" mandrel with shaving trapped between. The top row is squeezed into then loosened from the bottom row by the oscillating bar.	The squeezing did cause damage to the insulation and in one case caused a small flash.	Again the wire holder and clamps used are not found on aircraft which makes the setup undesirable .