Arcing Damage to Aircraft Components and Wire at a Distance

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Abstract

The paper describes the progress made in the analysis and understanding of electrical arcing damage to aircraft components and wiring at a distance. In recent years, there has been considerable new research performed on the effects and mitigation of electrical arcing. Much of this effort investigated direct contact damage (i.e. powered wire with exposed conductor striking a grounded component or structure). The testing and analysis discussed in this paper supplement and expand upon earlier damage-at-a-distance testing. These tests were performed at Lectromec and the FAA Tech Center. The scenarios investigated were damage to wire bundles, and the arcing and damage to grounded aircraft components (such as hydraulic lines). These tests were performed with a wire to target separation distances ranging between ¼" and 1". The arcing energies were quantified and a model of the energy fraction incident on the target was developed as a function of the target distance from the arc. The separation distance, the fault current, circuit protection, and material properties are important factors in modeling and mitigating arcing damage. The goal was to generate the data needed to provide insights into acceptable separation distances. This analysis is incorporated into the Arc Damage Modeling Tool that has been developed with the FAA Tech center. The analysis is of particular importance to those developing new aircraft as well as for those modifying or maintaining aging aircraft.

1 Introduction

The damage that can be caused by electrical arcing from wires is an important safety consideration and is a topic of continuing research in the aerospace industry. Past research has focused on a number of aspects of this phenomenon including arc tracking along the wire, damage to the other wires in the bundle and damage to grounded targets. This work examines the damage that can be done to aircraft components at a defined distance from the arcing event. This work was developed based on the research and conclusions of earlier work[1].

There are two scenarios of arcing damage at a distance. The first is due to natural convection. When an arc occurs, some of the dissipated energy heats and ionizes the local gas which expands creating an 'arc plume'. As this gas expands it heats and can damage nearby aircraft components.

The second scenario involves the ionized gases which reduce the dielectric strength of the air column between electrical potentials and facilitates arcing at voltage levels that exist on aircraft. Also contained in the event are ejected conductive materials (carbon, copper, and other metals) and gases that can be ignited by the arc plume. Under normal aircraft conditions, a potential difference of 115 volts is unable to jump even a 0.01 inch gap. However, if arcing has been initiated by direct contact or wet arcing, the arc plume may allow for a gap of ½" or larger to be bridged. In this case, because there is direct arcing to the target, there is the potential for greater energy transfer and damage as compared to the case of convection. The purpose of these tests was three fold:

1. To demonstrate that an initial direct arcing or wet arcing event can result in an arc over a longer distance than normally possible.
2. To show how the separation distance or arcing distances affect the energy transfer and target damage.
3. To show how fault current and wire insulation material affect the amount of energy transferred.

As there is no industry standard for the performance of this type of testing, methods were developed based on standard wet and dry initiation techniques which have been used in wire specification testing.

1.1 Test Procedures

Two test methods were used in this testing of arcing over a distance to grounded targets; a wet and dry initiation method. A brief summary of these test methods is described here.

1.1.1 Wet Test

These tests were performed using a seven-wire bundle. The insulation of the top two wires were breached with ring cuts such that the conductors of both wires were exposed with the breaches in the top two wires aligned. One of these wires was connected to the A-phase of a 3-phase 400 Hz motor/generator set and the other wire was connected to the neutral return. This created a single phase arcing scenario. The fault current for these tests was set at 250 Amp peak current (~180 Amp RMS). This circuit was protected by a standard 20-Amp thermal circuit breaker.

The three wires immediately beneath the top wire (which did not have breaches in the insulation) were connected to ground through a 50Ω resistor. This was done to provide additional data the amount of energy directed at the other wires at the bundle (this data is not presented in this paper). The bottom two wires in the bundle were not connected to the circuit and no data was measured from these wires.

Above the test sample, a grounded aluminum tube was placed at fixed distances (1/4", ½", and ¾") from the top of the wire bundle. This tube was placed parallel to the test wires. The test was initiated by placing drops of saline solution between the breaches in the wire insulation. The power was then turned on and the arcing event occurred. In each wet test the arcing was extinguished when the circuit breaker tripped.

The current going to the specimen was measured along with the current returning through the return wire and the current returning through the grounded tube. In this way, a determination could be made if and when arcing to the tube occurred. The arcing voltage was also measured so the power and energy could be calculated.

Note that a ¼" separation between a wire bundle and metallic tubing is, in general, not considered a best practice with both AS50881 and AC-43.13-1B both suggesting ½" as the minimum separation distance. In addition, wire bundles generally should not be routed under and parallel to hydraulic or fuel lines. These tests represent worst case scenarios.

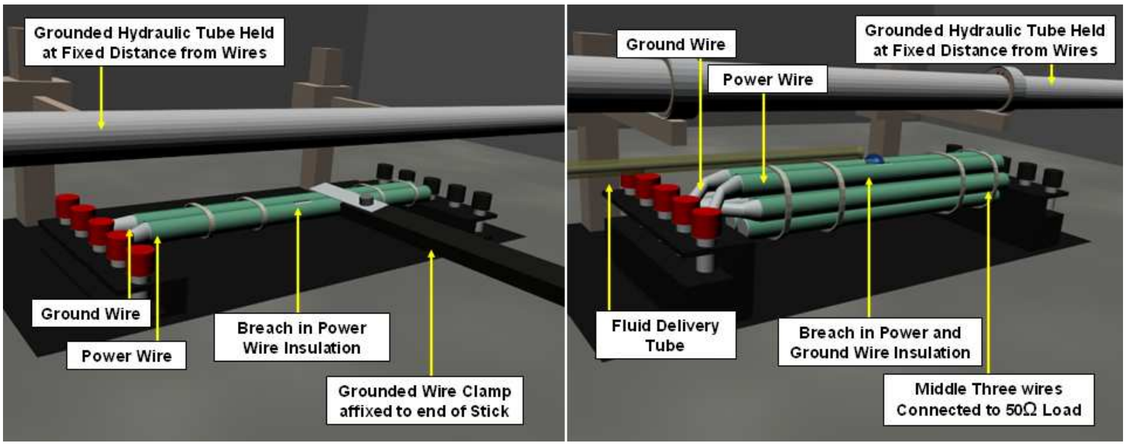

Figure 1: Test setup for both dry arc [left] and wet arc [right] initiation methods for damage at a distance.

1.1.2 **Dry Test**

The dry test method also created a single phase arc and was similar to the wet test, though there were some alterations. For the dry test, a simple two wire bundle was constructed: one power wire in which a breach was created in the insulation (this breach was about 2mm wide and 10mm in length) and one ground wire with no breaches in the insulation.

Similar to the wet test method, a grounded aluminum tube was placed at a fixed distance from the top of the wire bundle. This tube was placed parallel to the test wires. A clamp with the rubber boot removed was grounded and affixed to the end of a rod. This clamp was to serve as the means of initiating the arcing event.

After the test power was turned on and the grounded clamp was touched to the breach in the power wire insulation. The clamp made contact with the wire at a shallow angle from the wire to represent a failed clamp situation. The test proceeded until the circuit protection activated or the arc extinguished.

1.2 **Test parameters**

Electrical arcing can occur in any location within the aircraft. Because of this, there are a large number of environmental and electrical considerations that must be taken into account when developing a test. For these initial tests, past work was examined for guidance on important parameters and only a few selected parameters were selected for variation. The parameter descriptions are presented here.

1.2.1 **Fault current**

The fault current is defined as the peak current that was measured if the test circuit was shorted at the specimen. The fault currents (250 and 500 amps) were chosen to represent the range of fault currents that could be found on an aircraft.

1.2.2 **Circuit protection**

A 20-Amp thermal circuit breaker was used for the wet tests while a 15 amp thermal circuit breaker was used for all but one of the dry tests. The ratings of the circuit breakers were values that are often used for 16 and 14 gauge wire. Thermal circuit breakers were used as they allowed enough arcing half-cycles for the arc plume develop and arcing to the tube to occur.

1.2.3 **Wire Specification**

Two different wire specifications were used for these tests:

MIL-W-81381/11-14: Polyimide insulation

BMS 13-60-16: Composite (TKT) insulation.

The polyimide insulation is the worst case as its poor arc track resistance is well documented[2]. It is generally not used in new aircraft construction. However, there is still polyimide insulated wire in the aging fleet. Composite insulated wires are commonly used on new aircraft and are more resistant to arcing than Mil-W-81381 type wire.

1.2.4 **Separation distance**

An electrical arcing event is a localized event, but the arc energy heats and ionizes the local atmosphere which can cause damage to nearby targets. The separation testing started at 0.25 inches and continued in quarter inch increments to a distance of one inch which resulted in little or no target damage.

1.2.5 **Test Setup**

As identified earlier, two test methods were used in this testing: a dry initiation method simulating the type of arcing event that would occur with a clamp failure and chafing through the wire insulation of a powered wire, and a wet initiation method simulating a common cause failure. The test procedures can be found in the appendices.

2 **Test Results**

In this section several tests will be discussed in detail to illustrate important characteristics of arcing to a grounded component at a distance. The results of all of the tests are then summarized.

2.1 **Test 23: Wet Arcing - Mil-W-81381 wire**

Test 23 was a wet arc test using Mil-W-81381 wire with the separation distance between the arcing bundle and the grounded target (3/8" outer diameter aluminum tube) set at ¼". In this test, arcing was initiated between the active wire and the return wire and had a peak current of approximately 200 Amps as shown in Figure 2 (thin red line). After nine arcing half-cycles, the arc transferred from the return wire to the grounded tube at ¼" as shown by the heavy blue curve. The arcing then alternated between the return wire and tube. The arcing current to the tube was approximately equal to or only slightly reduced from the arcing current to the return wire. A total of 743 Joules of energy was dissipated in arcing directly to the tube in comparison to 4475 Joules dissipated in the entire arcing event. Figure 3 shows the extensive damage to the target aluminum tube.

This test illustrates the increase arcing distance that is possible once an arc has been initiated and the significant damage that can be caused. Without the initial wet arcing to the return wire, the ¼" gap would not have been bridged.

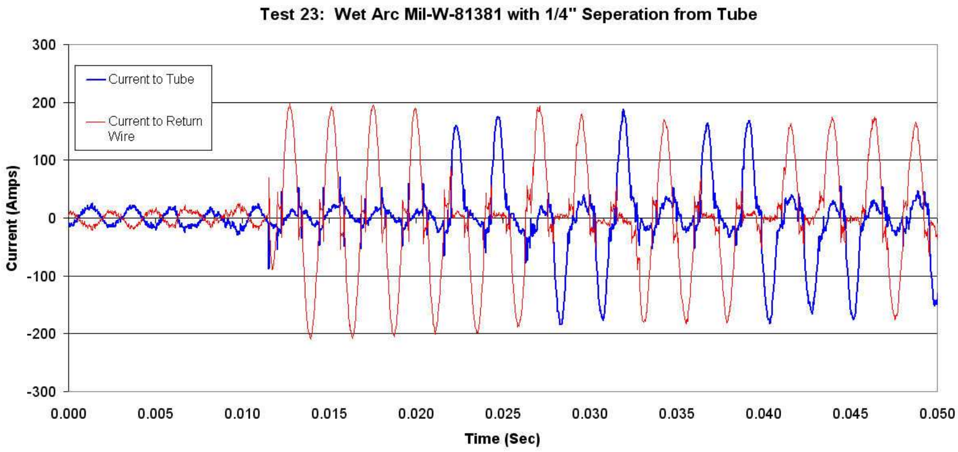

Figure 2: Test 23 Current to Return Wire and to Tube at 1/4".

Figure 3: Test 23 Damage to Aluminum Tube.

2.2 Test 3: Dry Arcing - Mil-W-81381 wire

Test 3 was a dry arcing test with a 500 Amp fault current using the Mil-W-81381 wire. The grounded aluminum tube was placed at a distance of ½" above the arcing wires. The arcing was initiated with the edge of a grounded clamp and arced only to the clamp for approximately 50 ms. At that time, arcing also began to the aluminum tube as shown in Figure 4. The magnitude of the arcing current to the tube was lower than to the clamp with peak values between 200 and 300 Amps as compared to the 400 Amps to the clamp.

The arc was extinguished after 0.13 seconds without the circuit protection tripping. There was extensive damage to the clamp and the active wire conductor; this damage created a gap between the active wire and clamp which became too long to sustain the arc. The insulation of the return wire was heavily damaged but the inner layer(s) of the polyimide remained intact so it did not become involved in the arc.

Figure 5 shows the damage to the tube for Test 3. Approximately half or 20 mils of the tube wall was eroded by the arcing. There were also large deposits of copper from the wire conductor visible on the tube wall. Of the 934 joules in the entire arc event, 190 Joules of energy dissipated directly to the tube.

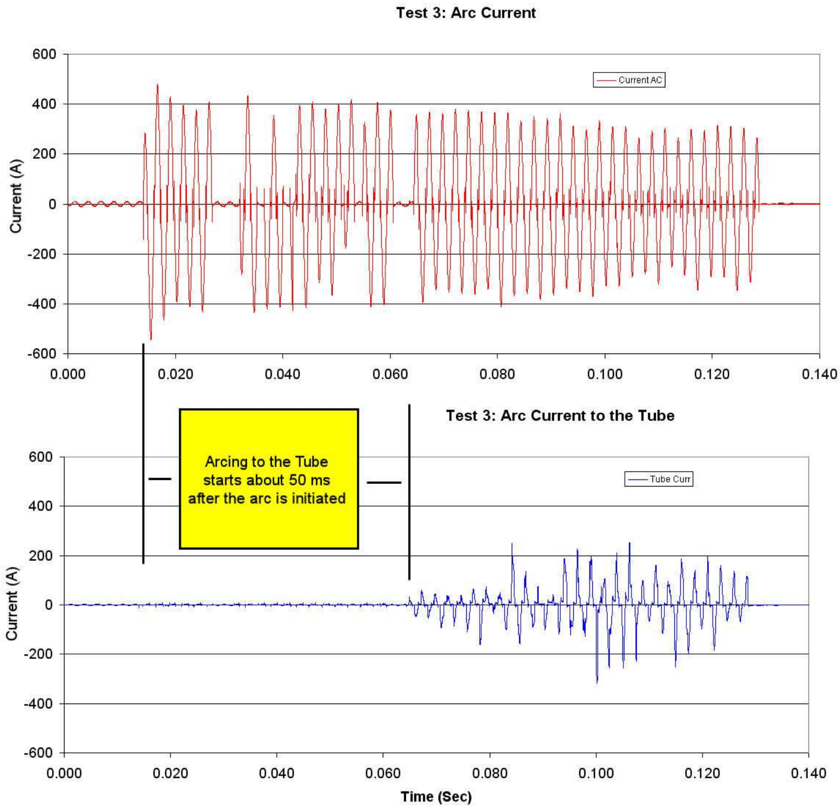

Figure 4: Test 3 - Total Arcing Current (upper) and Arcing current to the tube (lower).

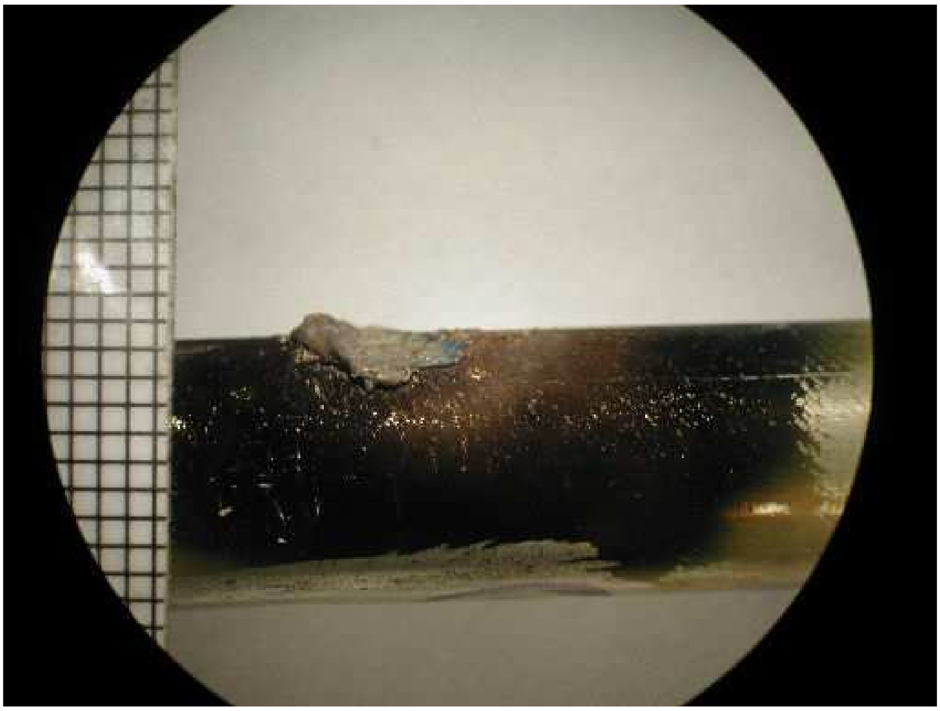

Figure 5: Test 3: Heavy damage to the aluminum tube but no penetration.

2.3 **Test 9: Dry Arcing - Composite wire**

Test 3 was a dry arcing test with a 500 Amp fault current using the composite wire. The grounded aluminum tube was placed at a distance of ½" above the arcing wires. The arcing was much more sporadic when using composite wire as compared to Mil-W-81381 wire (Test 3). As shown in Figure 6, there were several bursts of 2 to 6 arcing half-cycles over a period of 0.25-seconds. After that the arc was extinguish because the arcing distance separation between the clamp and wire became too great due to erosion of both the clamp and active wire conductor (Note that the circuit breaker did not trip). Note that a second initiation was done after 4 seconds (not shown in Figure 6) which also resulted in sporadic arcing. Because continuous arcing was not established, there was little arcing directly to the tube. In this case, only one half-cycle arced directly to the tube with a cumulative energy transfer of 13.2 Joules out of a total of 460 Joules in the arcing event. This was much less energy than similar tests done with polyimide insulation.

Figure 7 shows the damage caused by the arc to the target aluminum tube in Test 9. While there was blackening of the tube and some copper or steel transfer, there was very little damage to the tube.

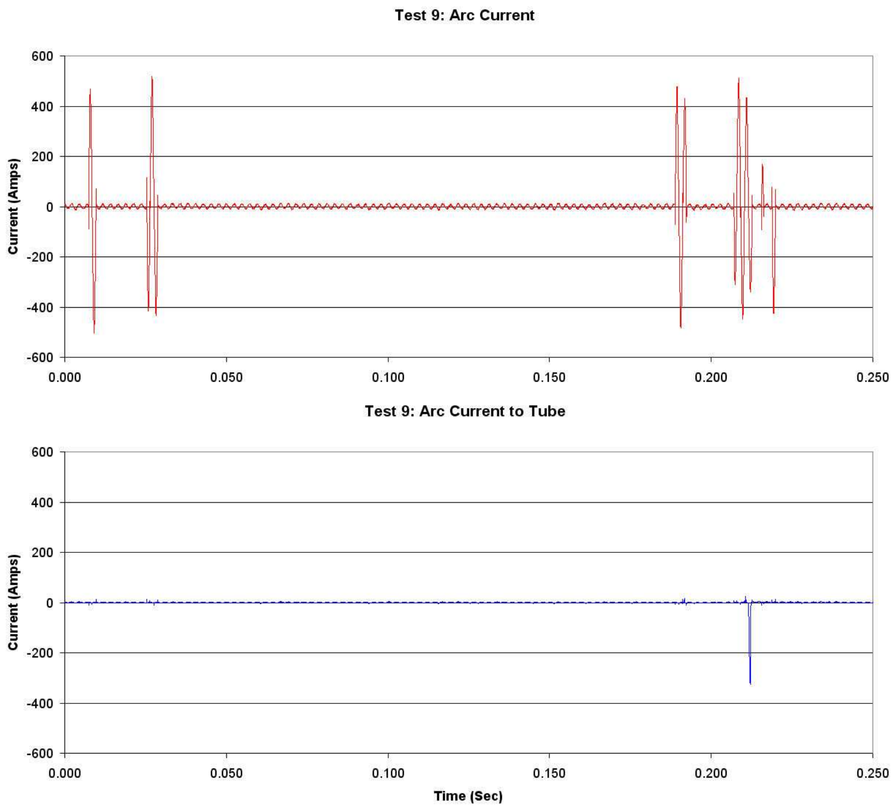

Figure 6: Test 9 - Total Arcing Current (upper) and Arcing current to the tube (lower).


Figure 7: Test 9 - Slight damage to the aluminum tube

3 Summary of the Test results

Table 1 is a summary of the test results showing a qualitative tube damage assessment and the calculated energy dissipated by arcing directly to the tube. In addition, the table shows the number of arcing half-cycles that occurred before arcing to the tube began as well as the peak arcing current.

Because there are a limited number of tests (1 or 2) for each configuration, the results should be considered preliminary. However, there are several trends in the data that can be observed:

- In the tests in which there was arcing directly to the tube, there was a delay from the initiation of arcing to the initiation of arcing to the tube. This varied from nine half-cycles at 1/4" separation to many half-cycles for larger separation distances. This delay was likely caused by several factors which may include:
    - The need to erode the primary arcing target (e.g. clamp or return wire) so that arc length becomes long and arcing to the tube is preferred or at least allowed as compared to arcing to the clamp.
    - The arc plume with ionized gas needs to be established and expanded to envelop the tube.

  Because of this delay, arc fault circuit protection may be effective in mitigating this type of damage.

- For arcing with polyimide insulated wire, it was relatively easy for an arc to transfer from its original target to a grounded target with a separation distance of ½" or less. This was observed in 7 out of 7 tests which included both wet and dry initiated tests.

The amount of damage done by the arc energy can vary greatly. In one test (Test 2), 147 Joules were transferred to the tube with only slight damage.

- When the separation distance was increased to ¾" or 1", the amount of arcing directly to the tube was significantly reduced although some energy was transfer. This is shown in Figure 9. In addition the magnitude of the current when a arcing ½ cycle did occur was reduced.

- When the arc was initiated using composite wire, the amount of arcing directly to the tube was significantly reduced although some energy was transfer. This is also shown in Figure 9. This reduction was likely due to the sporadic nature of arcing involving composite wire and that the arc was extinguished when the arc length because too long. The increase in arc length was due to erosion of the clamp and conductor of the active wire..

Table 1: Summary of Test Results

Test Set-Up						Arc Details			Tube Damage			
Test #	Initiation Method	Target Distance (inch)	Active Wire	Fault Current (A)	Circuit Protection	CB trip (y/n)	# Arcing 1/2 Cycles	Arcing - Energy Dissipated (J)	Damage Qualitative	Energy to Tube (J)	# of 1/2 Cycles before Arcing to Tube	Peak Current to the Pipe (A)
1	Dry - Clamp	0.5	PI-14	250	15 A	Y	463	1375	Moderate	260.7	42	150
2	Dry - Clamp	0.5	PI-14	250	15 A	N	171	901	Slight	147.4	60	145
3	Dry - Clamp	0.5	PI-14	500	15 A	N	86	934	Heavy	190	32	312
4	Dry - Clamp	0.5	PI-14	500	15 A	Y	93	857	Slight	28.2	25	151
5	Dry - Clamp	0.5	PI-14	500	20 A	Y	121	1312	Slight	49.8	25	100
6	Dry - Clamp	0.5	TKT-16	250	15 A	N	23	81	None	0		
7	Dry - Clamp	0.5	TKT-16	250	15 A	N	98	348	None	0		
8	Dry - Clamp	0.5	TKT-16	500	15 A	N	31	264	None	0		
9	Dry - Clamp	0.5	TKT-16	500	15 A	N	46	420	Slight	13.2	13	323
10	Dry - Clamp	0.75	PI-14	250	15 A	N	280	1442	None	0.8	108	19
11	Dry - Clamp	0.75	PI-14	250	15 A	N	357	1844	None	0.4	107	16.4
12	Dry - Clamp	0.75	PI-14	500	15 A	N	52	547	Slight	12	22	270
13	Dry - Clamp	0.75	PI-14	500	15 A	Y	69	735	Slight	0.6	24	22
14	Dry - Clamp	0.75	TKT-16	250	15 A	N	36	145	None	0		
15	Dry - Clamp	0.75	TKT-16	250	15 A	N	15	53	None	0		
16	Dry - Clamp	0.75	TKT-16	500	15 A	N	35	348	None	0		
17	Dry - Clamp	0.75	TKT-16	500	15 A	N	8	80	None	0		
18	Dry - Clamp	1	PI-14	500	15 A	Y	96	1049	None	1	54	47
19	Dry - Clamp	1	PI-14	500	15 A	Y	45	520	Slight	0.1		
20	Dry - Clamp	1	TKT-16	250	15 A	N	45	152	None	0		
21	Dry - Clamp	1	TKT-16	500	15 A	N	25	229	None	0		
22	Dry - Clamp	1	TKT-16	500	15 A	N	26	239	None	0		
23	Wet	0.25	PI-14	250	20A	Y	778	4475	Penetration	743	9	189
24	Wet	0.5	PI-14	250	20A	Y	826	4701	Penetration	223	27	133
25	Wet	0.75	PI-14	250	20A	Y	875	5579	Slight	47	32	46

Figure 8: Summary of the Test Results

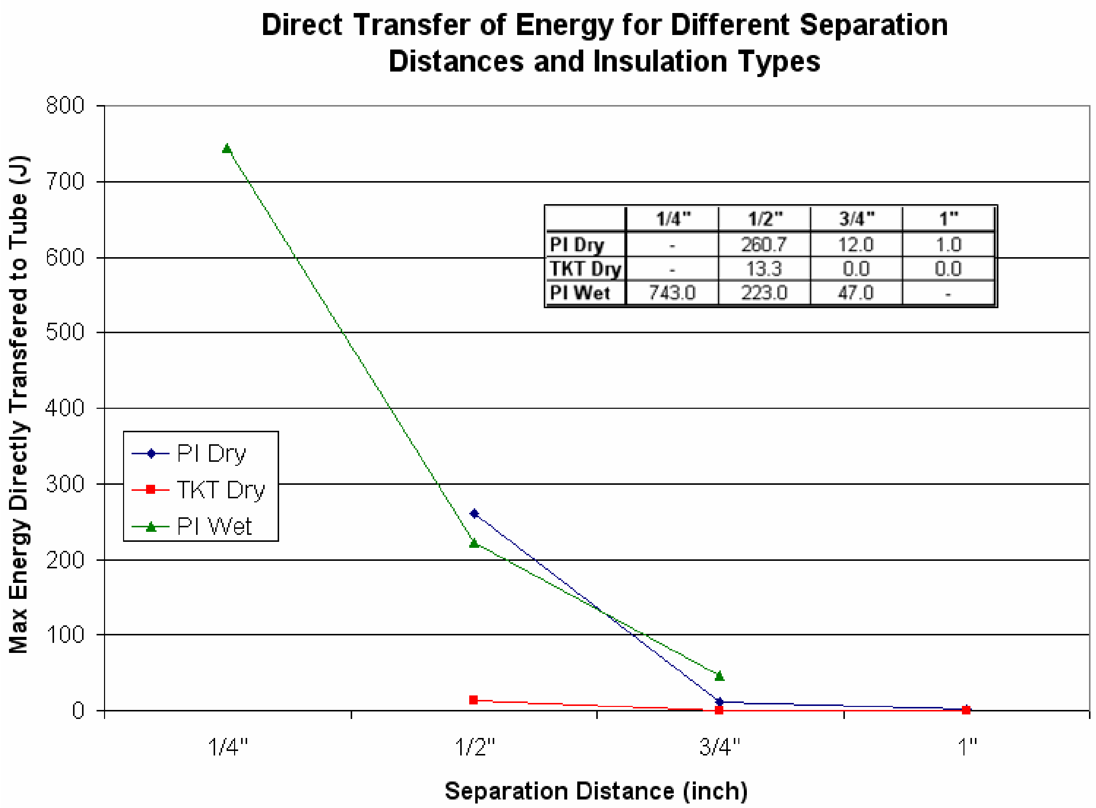

Figure 9: The amount of arcing energy directly to the tube for different separation distances and wire types.

4 Application to Aerospace Systems

The results of the testing have a direct impact on the aerospace industry, particularly those requiring certification to FAA rule 25.1709. FAA requirement 25.1709 requires that an Electrical Wire Interconnection System (EWIS) evaluation include the analysis of the "…possible physical failures of EWIS that can cause damage to co-located EWIS or other surrounding systems or structural elements.[3]"

This testing of damage at a distance shows that there can be energy transfer, and it is up to the designer to provide sufficient evidence to the FAA in certification that, "The intensity and consequence of the arc and its mitigation should be substantiated."

5 Conclusion

This testing shows that an arc can bridge a longer gap than normally considered possible if there is a preliminary initiation (wet or dry) which establishes an arcing plume of ionized gas.

Although the limits of energy transfer and damage have not been established, the experimental trends indicate that increasing the separation distances to greater than ½" or using a composite wire will significantly reduce the energy transfer and damage to grounded components significantly. With careful selection of the circuit protection, wire type, separation and fault current, the consequences of an electrical arcing event are reduced.

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[1] Walz, M., Linzey W., Traskos M., Gomez, C. and Bruning A., “Development of an Arc Damage Modeling Tool”. 2007 Aging Aircraft Conference, Palm Springs, CA, April 17, 2007

[2] Linzey, W. G., McCutchan, M., Traskos, M. T., Gilbrech, R., Cherney, R., Slenski, G., and Thomas, W., III, “Evaluation of Risk and Possible Mitigation Schemes for Previously Unidentified Potential Hazards”, Ninth Aging Aircraft Conference, Atlanta, GA, March 2006.

[3]United States, Department of Transportation, Federal Aviation Administration “Advisory Circular: Certification of Electrical Wiring Interconnection Systems on Transport Category Airplanes”, AC # 25.1701-1, December 4, 2007

Appendix A Electrical Arc Initiation Test Method for Examination of Damage to Targets Separated from the Initiation Bundle

Developed by Lectromechanical Design Company

A.1 PURPOSE

A.1.1 The purpose of this test is to show the effectiveness of separation and/or protective sleeves to prevent damage caused by dry arcing of powered wires. This test supposes a scenario where a clamp that is holding the wires is misaligned. This then leads to the clamp to chaff through the rubber boot and wire insulation resulting in an arc event as the metal clamp touches the wire conductor.

A.2 TEST EQUIPMENT

A.2.1 A transparent screen to protect laboratory personnel from molten metals. UV radiation and other debris that may be ejected from the test specimen.

A.2.2 A test apparatus that clamps the wire in place and allow a target (wire bundle, metallic tube composite structure etc.) to be placed a known distance from the arc area. A grounded clamp with the rubber boot removed shall be affixed to the end of a rod capable of being rocked, vibrated, or otherwise moved, so that the metal edge of the clamp will contact the conductor of one of the powered (non-neutral) test sample wires. A small portion of the insulation of test sample cable can be removed to allow the clamp-conductor contact.

A.2.3 A three phase wye connector power supply, grounded at wye, derived from a rotary machine or solid state power source of not less than 20kVA rating, delivering 208 line-to-line at 400Hz.

A.2.4 Appropriate circuit protection devices.

A.2.5 Variable load and fixed load resistors.

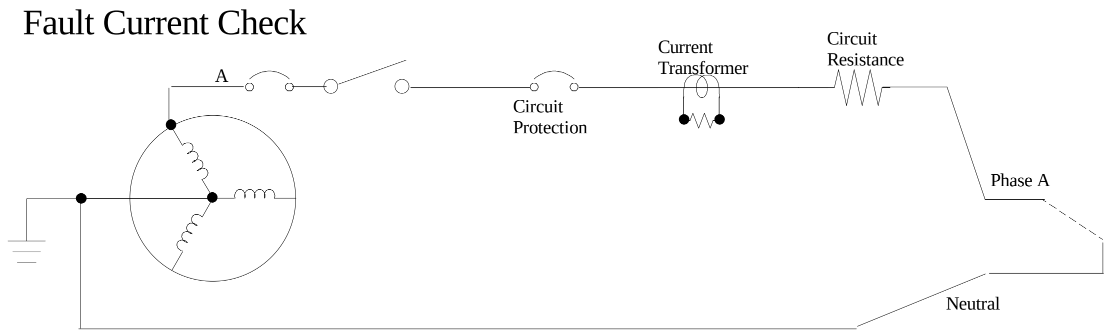
A.2.6 Lacing tape.

A.3 TEST SAMPLES

A.3.1 A test sample for one configuration consists of at least 2 wires.

A.4 TEST PROCEDURE

A.4.1 Setting the Fault Current: The fault current is set using the circuit shown in Appendix Figure 1. The fault current is measured during line to neutral short circuit. The circuit resistance is adjusted until the desired fault current is obtained. The fault current is measured using an oscilloscope or data logger to measure the current transformer output after the sub-transient response. For example, the RMS current measured from the 6 to 10 shorting cycles.

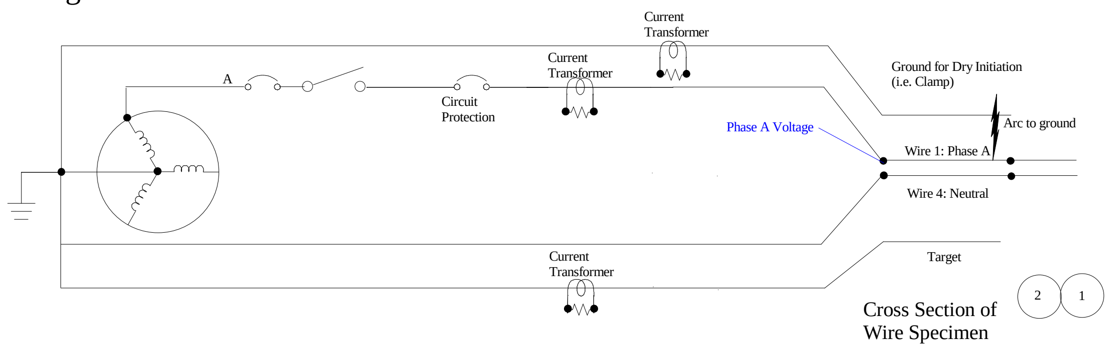


Appendix Figure 1. Circuit used to check fault current.

A.4.2 Preparation of Bundles: Conduct a 2500 volt Wet Dielectric test on 100% of the wire in accordance with the Wet Dielectric test procedure described in MIL-STD-2223 method 205 before the test is performed. Discard any failed sections of wire. Cut the wire into segments 10.0 – 13.0inches in length. Clean the cut wires using a cloth saturated with isopropyl alcohol. Strip both wire segment ends. Use these stripped ends for making electrical connections. These wire segments will be called "Active Wires". Using a sharp blade cut a grove completely around (360 degrees) the insulation of one wire at its midpoint to expose the conductor. This wire will be identified as the "damaged wire". For the dry arc test there is only on "damaged wire" which must be one of the powered phases. If testing fluoropolymer-polyimide hybrid wire, use an angled cut (~ 45 °) so that the polyimide layer is visible. The width of the exposed conductor should be between 0.5 mm and 1.0 mm. Use lacing tape that is certified for aerospace applications to hold the test bundle together. Clean the assembled bundle using a cloth saturated with isopropyl alcohol prior to installation in the fixture.

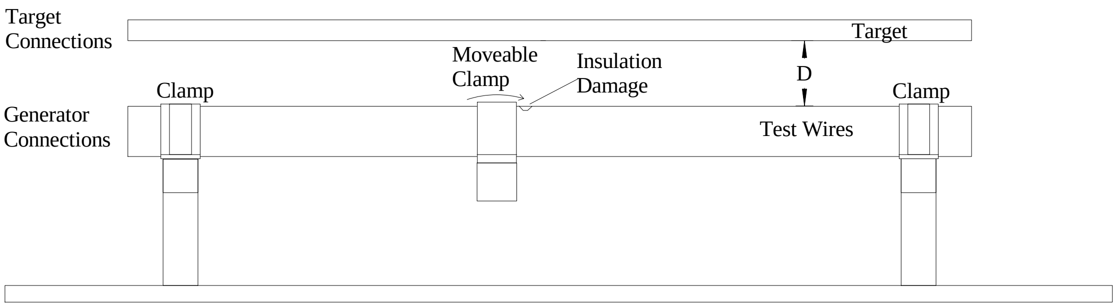
A.4.3 Electrical Connection: Connect the test bundle to the power supply and circuit resistance using the schematic circuit shown in Figure 2. Connect one end of each active wire to the appropriate phase of the power supply as shown in Figure 1. The circuit resistance is the same that was used when setting the fault current.

A.4.4 Ballast Resistors (Recommended): The ends of wires are each connected to a ballast resistor (Rb). The other ends of the ballast resistors are connected to the neutral return. The ballast resistors are to be non-inductive and sized to allow 10-15% of the rated generator current to flow in the circuit.

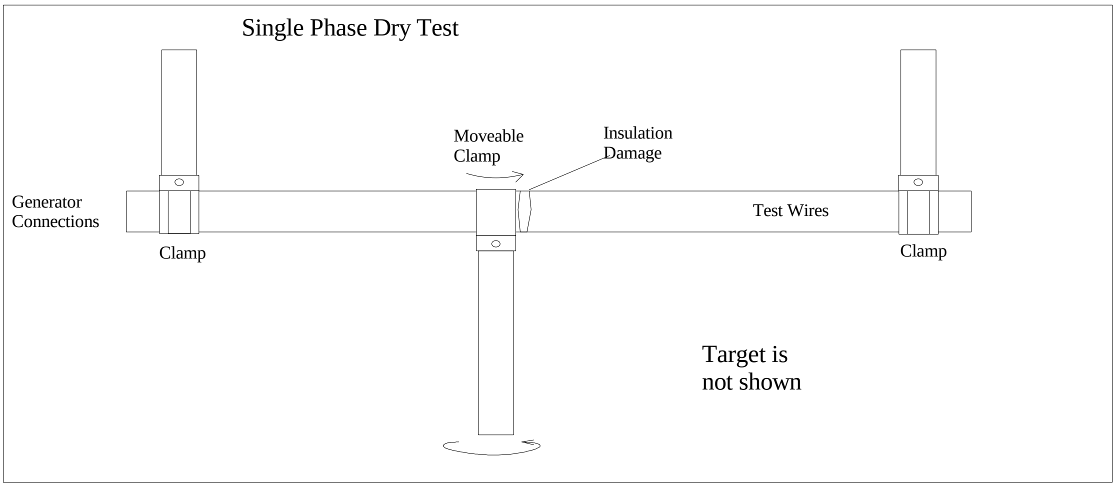


Appendix Figure 2. Test Circuit

A.4.5 Installation of the Test Bundle: The test bundle should be installed as shown in Appendix Figure 2. The damaged wires should be facing the target as much as possible.



Appendix Figure 3. Installed test bundle and target



Appendix Figure 4. Plan view of installed test bundle (Target not shown).

A.4.6 Target: The target can be another wire bundle, a metallic tube or structure, or composite tube or structure as defined in the test plan. The distance between the bundle and target and the use of a protective sleeve(s) is also defined in the test plan. The target is placed above the arcing wire. This is generally considered the worst case and is to be used unless a different position is defined in the test plan. The test can be instrumented as shown in Appendix Figure 3 as an option. Also thermocouple or other probes can be used as desired.

A.4.7 Initiation of Test: Position the protective screen to shield operator from ejected objects and UV radiation. Close all circuit breakers. Apply three phase 400 Hz power. Trigger the arc by causing the ground surface (i.e. clamp) to come in contact with the exposed conductor of the damaged wire. This movement can be accomplished through vibration or manual motion but should by done in a way that produces the most energetic arc event. The specimen and initiation should be arranged so that the plume of the arc is directed toward the target as much as possible. Some trial and error will be needed to establish this technique. Care must be taken to ensure the safety of the personnel running and/or observing the test.

A.5 **RESULTS**

A.5.1 One of the following conditions should be used to conduct and complete the test.

A.5.2 The first time the circuit protection in any powered wires trips:

A.5.3 Disconnect power from the specimen and reset the circuit protection.

A.5.3.1 Wait 3 minutes from the time of the circuit protection trip and reapply power. Rock the clamp to strike the conductor again if possible. The clamp may be so damaged that this is not possible. If this is the case, then end the test.

A.5.4 The second time the circuit protection trips for any circuit, end the test.

A.5.5 If a flash event occurs without trip the circuit protection, move the clamp again to try to create another flash event. If this is not possible due to damage to the clamp, then end the test.

A.6 **DAMAGE EXAMINATION**

A.6.1 Cable Examination: The damage on the power feeder cable should be measured and recorded with photos using magnification as necessary.

A.6.2 Target Examination: The damage on the target should be measured and recorded with photos using magnification as necessary.

A.6.3 The target should be stored so that further testing can be preformed as needed.

A.6.4 Further damage evaluation can be defined in the test plan.

A.6.4.1 If the target is a wire or wire bundle, a wet dielectric test shall be performed.