Development of an Arc Damage Modeling Tool

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Abstract

This paper discusses preliminary work and plans to develop an arc damage-modeling tool. As the Electrical Wire Interconnect System (EWIS) ages; one mode of failure that is of particular concern is the arcing failure. Because of the high level of energy that can be released in an arcing event, damage can be done to structure, components, other wires in the arcing bundle and objects some distance away from the arc. In addition, heat generated by the arc can cause the ignition of fires. There have been many efforts to mitigate the damage done by arcing. These effects include introducing new wire constructions that tend to reduce or eliminate propagation of the arc, development of arc fault circuit protection, and the used of segregation and separation techniques. When one does a risk assessment, it is important to understand the possible damage that could be done by an arc and the effectiveness of the mitigation technique employed.

The approach taken to develop this tool is the quantization of energy discharged in the arcing event. Therefore, variables used in the model include source voltage and impedance, circuit protection, wire gauge and type, distance from the source voltage etc. Preliminary comparisons between observed damage and energy levels discharged do not show a direct correlation. However, it has been found that if heat conduction away from the arcing spot is modeled using a finite element method, the agreement becomes much better. The results of these tests are shown and discussed.

A project plan has been created to develop a software tool that will allow the user to model damage to a wide variety of EWIS and non-EWIS items due to arcing. The initial plans are to adapt a commercially available finite element solver for the task. There will be an initial phase in which the waveform and damage data for a number of laboratory arcing tests will be captured. This data will then be used as the basis for the development phase of the tool. It is the goal of this project that the tool can be used by design and safety engineers to predict damage levels due to arcing, set separation distances and evaluate mitigation techniques.

1. Introduction

The safe operation of aircraft well into their expected service life depends, in part, on the safe and effective transfer of power and electrical signals between aircraft electrical components. This in turn requires the enduring physical integrity of the electrical wiring interconnect system (EWIS), which is comprised predominately of wire, wire insulation, and connectors. If an EWIS failure does occur, the design of the wire bundles, contamination, and the routing of the bundles through the aircraft play an important role in assuring the hazardous effects of the failure are mitigated to acceptable levels. Electrical arcing incidents can lead to catastrophic events inside an aircraft. Damage from electrical arcing on aircraft can be the result of inadequate wire separation, segregation, contamination, and debris accumulation. Today, there are no available tools and criteria to quantify and model the damage incurred from an electrical arcing event from a wiring fault perspective

The objective of this project is to develop a user-friendly software tool that can model the damage resulting from an arcing event. The tool will be based on both analytical and empirical data and will use the concepts of energy quantification and heat transfer. The material structure and properties will be incorporated into the damage analysis. The following types of damage will be modeled:

- Damage to the source (wire) and target (structure or lines)
- Damage within a wire bundle (with and without segregation)
- Damage to targets at some distance from the arcing wires such as
  - Wire bundles (with and without segregation)
  - Structure or hydraulic lines
  - Other non-metallic objects

The program will be broken down into 4 tasks:

Task 1: Generation of Empirical Data: In this task, a matrix of arc track tests will be preformed and the resulting damage will be quantified. Emphasis will be placed on creating realistic arcs that could occur in the field. Testing parameters will be varied to represent different conditions in the aircraft (e.g. source voltage, fault current, etc.) and/or mitigation techniques such as Arc Fault Circuit Interruption (AFCI) devices, protective sleeves, etc.

Task 2: Development of Analytical Methods: In this task, damage models that are based on the energy dissipated, including the rate of energy dissipated, will be developed. The arcing waveforms generated in Task 1 with the corresponding damage will be used to develop and check the analytical models

Task 3: Development of the Modeling Tool: The models developed in tasks 1 and 2 will brought together to form the modeling tool that can be used to evaluate the potential damage caused by arcing.

Task 4: The validity of the tool will be demonstrated by how well in can model the damage in the Task 1 experiments and damage that has been done in service.

2. Task 1: Generation of Empirical Data

The goal of this task is to gather realistic data that can be used when generating the analytical approaches in task 2. This will include arcing waveforms and the corresponding damage. In general a seven-wire bundle will be used, with the insulation on the "active" wire(s) pre-damaged such that the conductor is exposed. The active wire will be powered and initiates the arc. The other wires in the bundle are the "passive" wires. They will be used to assess the damage to other wire caused by the arc.

A. Arc Initiation Methods

Two initiation methods are used for testing the damage cause by arcing to a grounded metallic object (structure, hydraulic line); they are the swing and a vibration tests. Both of these tests use metal-to-metal contact and separation to initiate the arc.

1. Swing Test

The swing test represents a ticking fault situation where a metal-to-metal contact is made momentarily and then separation occurs: for example, when a swaying bundle abrades the wire insulation and then the connector touches structure. It has been used at the Arc Fault Evaluation Laboratory (AFEL) at the William J. Hughes Technical Center for several years[*]. Using this method, damage to the structure and other wire in the bundle is easily measured and the geometry and material of the target can be

[*] Walz, M. F., Gomez, C. A. *Wire Separation and Segregation Arc Damage Assessment*, presented at 2006 Aging Aircraft Conference, Atlanta, GA. available at http://aar400.tc.faa.gov/Programs/AgingAircraft/ELECTRICALSYSTEMS.htm

modified. Because the insulation on the wire is pre-damaged, the duration of the test is short regardless of the target material. Figure 1 shows a diagram of the test apparatus. In this test the wire bundle is swung such that it exposed conductor of the active wire strikes the grounded target.

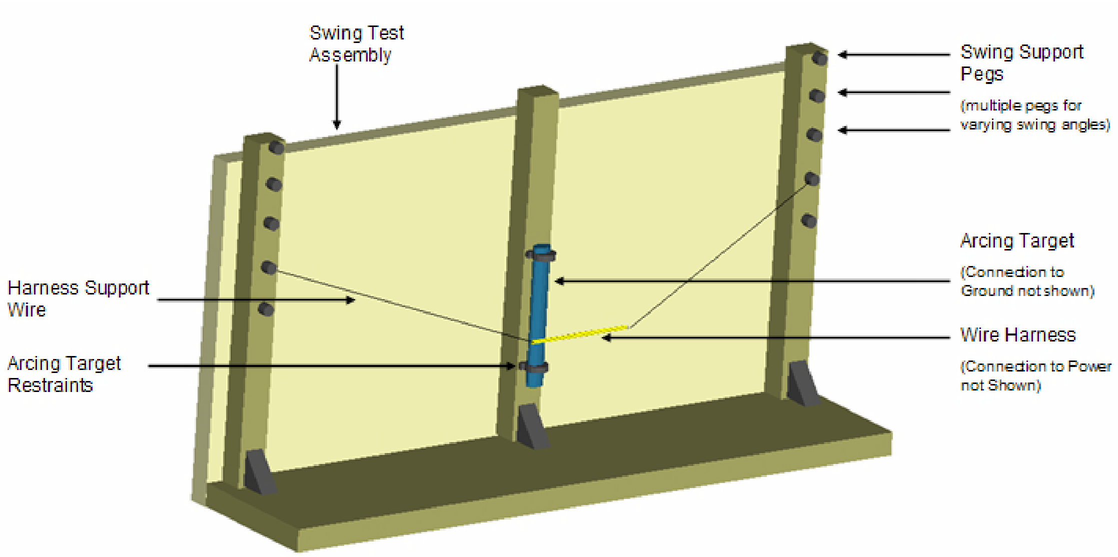

Figure 1. Diagram of swing test. Connection to power not shown.

There are several variations that can be done to influence the arcing event. These include changing the force and angle that the harness hits the target, or damaging some of the strands of the conductor.

2. Vibration

The vibration test method represent the situation on the aircraft where a wire harness has come to lie on a metal piece of the aircraft, the wire insulation is chafed through, and arcs to the metal object due to vibration.

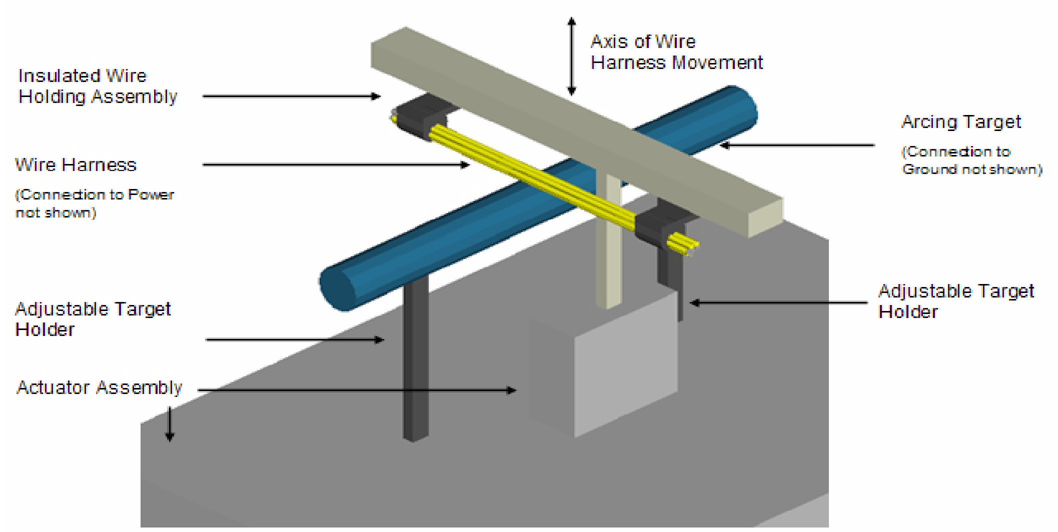

Figure 2. Diagram of vibration test stand. The electrical connections for the wire harness and the arcing target are not shown.

There are several variations that can be done to influence the arcing event. These include changing the force and angle that the harness hits the target or damaging some of the strands of the conductor.

In the vibration test, an arc is created between a pre-damage wire on the outside of the test harness and a vibration metallic target such as a hydraulic line, flight control cable or structural spar. Figure 2 shows a 3-D model of the test apparatus with the wire bundle crossing at a right angle with the target. The test apparatus can be modified so that the target vibrates against a stationary harness.

In preliminary tests, the consistency of the results was improved if some of the test parameters were controlled. These parameters include the frequency and displacement of the vibration, and the force between the bundle and target. The frequency and displacement of the vibration can be set in accordance to the RTCA manual DO160D <u>Environmental Conditions and Test Procedures for Airborne Equipment</u> (1997) or can be adjusted outside these settings. The force between the harness and target can be adjusted using the wire harness holders and can be measured using a spring scale.

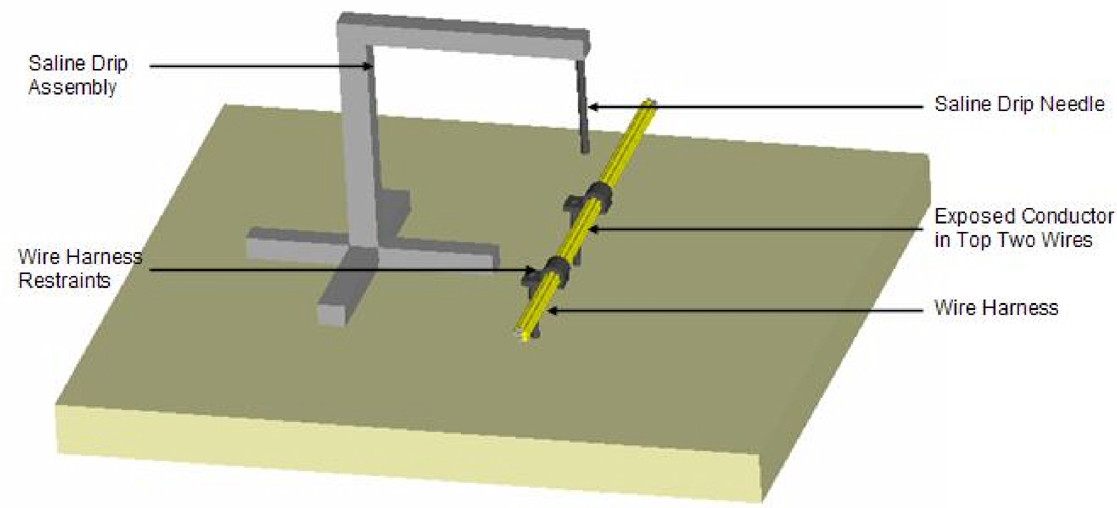

Figure 3. Wet Test Apparatus

3. Guillotine

The guillotine test used in this work follows the test method in AS5692 with modifications as needed to meet the goals of the project. One change includes the use of thicker "blades" in addition to razor blades. In these tests, aluminum rectangles that are 1/16" or 1/8" in thickness will be used. The edge of rectangles will not be sharpened so windows will have to be cut into the active wire insulation to allow arc initiation.

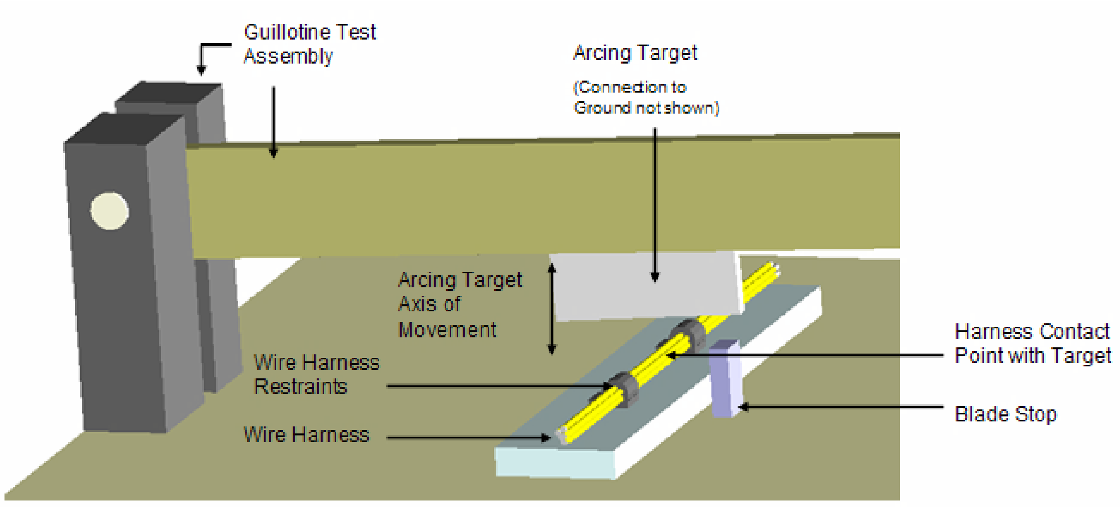

Figure 4. Guillotine test apparatus.

The use of the guillotine test is limited in the test plan but will serve several purposes. Because the target geometry differs from the other test methods, it should provide a useful data set in developing the tool. The guillotine test will be used in the testing related to the measuring the effect of dirt and debris.

B. Discussion of the variables

In addition to the various arc initiation methods, other electrical and physical parameters included in the test plan investigated.

1. Source Voltage

After reviewing the Service Difficulty Reports and accident/incident databases, the majority of the cases in which arcing have done significant damage has been on the 115 VAC circuits. Testing will also be done using 28 VDC to ground, 115 VAC to 28 VDC and 200 VAC (phase to phase).

2. Fault Currents

The fault currents depend on the voltage source and the length and gauge of wire between the source and the arc event. For 20-gauge wire on a 115 VAC circuit, a length of 175 feet corresponds to a peak hard short fault current of 100 amps, because this is near the upper limit on lengths of wire found on a commercial aircraft, this will be the lowest fault current used. The upper limit of the fault current used in these tests is 1000 amps; this corresponds to a scenario in which an arc occurs several feet from the power bus. Testing shall also include intermediate values of fault current (250 and 500 amps in the case of 20 gauge wire) so that arcing throughout an aircraft can be correctly modeled. The control of the fault current is being performed with the use of the appropriate length of wire in series before the arc.

There are two main effects on the arc introduced by limiting the fault current (i.e. introducing more series resistance). The first is that the power dissipated in the arc is reduced. This will tend to reduce the damage done by the arc. However, the second effect is because the current is reduced, and the time that it takes for the current protection to trip is increased, at least in the case of thermal circuit protection. This tends to result in a greater level of damage. It is important to understand how these opposing effects are combined to cause the resulting damage throughout the range of realistic fault currents.

3. Circuit Protection

The circuit protection will affect the arc damage by limiting the arc duration. Both thermal and arc fault circuit breakers are included in the test plan for this project. In general, the circuit breaker rating will be matched with the wire gauge, as they would be used in a typical aircraft circuit. However, in at least one test sequences smaller and higher than typical rated breakers will be used so that the effect of arcing duration can be closely examined.

4. Wire Gauge

The wire gauges included in the test plan are 10, 16, 20 and 24 AWG wire. This spans the range of wires gauges being used on commercial aircraft with the exception of large power feeders. Emphasis will be placed on testing the 20 AWG wire because 20 and 22 are the most common wire gauges used for power wires. The effect of the wire gauge on testing will be to limit the range fault currents used for a particular gauge of wire to those consistent with what is possible on the aircraft (see fault current discussion above). Also, in general, the rating of the circuit protection will be paired with the wire gauge as they are generally used (e.g., 7.5 amp for 20 AWG).

Apart from the limits on the fault current and circuit protection, it is expected that the most significant effect of the wire gauge on the damage will be that the destruction of the smaller diameter wire in high current events, as this should limit the duration of the arc and thus the damage caused by the arc. The dissipation of energy in the source wire at the arc site and subsequent damage to the conductor will be an important part of the arc model and is depended on source wire gauge.

5. Insulation Type

The type of wire insulating material used in the testing can have an impact on the amount of damage done to the target, and the wire itself. As such, the insulating materials that are to be tested include aromatic polyimide (e.g., MIL-DTL-81381), fluoropolymers (e.g., AS 22759/34), and a composite (e.g., AS22759/80-92). The insulation type will play a role in two aspects of the testing. The first is that some wire insulation materials, namely polyimide, when in close proximity to the arc will tend to increase the number of continuous arcing half cycles that make up an event. While arcs using wire with other insulation types or having no insulation near the arc site, will tend to have a lower number of continuous half cycles. However, even with the reduced number of arcing half cycles, the damage caused by these arcs can be significant.

The insulation type will also be important when measuring the damage done to the passive wires. Because the thermal characteristics of these insulation types are different, it is expected that the level of damage done by the released arcing energy will vary.

6. Target Material & Geometry

There were several criteria for chosen the targets for the arcing the structure tests.

- The target should represent something that can be found on an aircraft that could be damaged by an arc.
- The geometry should vary between the different targets to aid in the development of the tool by checking the results for accuracy when modeling the damage to different geometries.
- The thermal properties (melting temp, thermal conductivity, etc.) of the target should vary again to check the tools ability to modeling damage in different circumstances.

Considering these criteria the following targets were chosen:

- 3/8” 6061 Aluminum tube (similar to that used for hydraulic lines)
- 0.5” Titanium tube (similar to that used for hydraulic lines)
- 0.25” Military-specification flight control cable
- Aluminum Spar

In addition, it should be noted that the failure point for a pressurized hydraulic line is not the point where the wall is entirely melted through. It is the point where the temperature of the wall has increased to the softening point of the metal so that the tube ruptures. Therefore, a pressurized hydraulic line may be included later in the series of tests as a target.

C. Damage Quantification

For each of the tests performed, there will a quantification of the amount of damage that was done to other items in the experiment, whether they be the wire, arcing target, or nearby objects.

1. Damage to Wire and Dimensional analysis of the damage:

The damage quantification methods used in this project consider the damage to the wire insulation and to the conductor as separate measurements. The main method of measuring damage to a wire will be measurement of the dimensions of the damage and estimating the volume of the material removed. Post-test 1X-30X photos of the individual wires, as well as cross-sections, will aid in the damage estimates and documentation of damage. For example, using the photos in Figures 5 and 6 leads to the following estimation:

Diameter at start ~ 60 mil= 1.5 mm (radius= 30mil =0.75mm)
Diameter Post-Test (in damaged area) ~ 40 mil= 1.0mm (radius= 20mil = 0. 5mm)
Length of Damage area ~80 mil ~2 mm
0.4 of circumference damaged
Estimate of Insulation removed = $0.4*2mm*3.14*(0.75mm^2-0.5mm^2) = 0.79\ mm^3$
Estimation of Conductor removed = 0

2. Wet Dielectric Voltage Withstand Test:

If significant damage has occurred to the passive wires but the conductor in not visible, a wet dielectric voltage withstand test will be performed on the passive wires using a 1500 VAC HiPot.

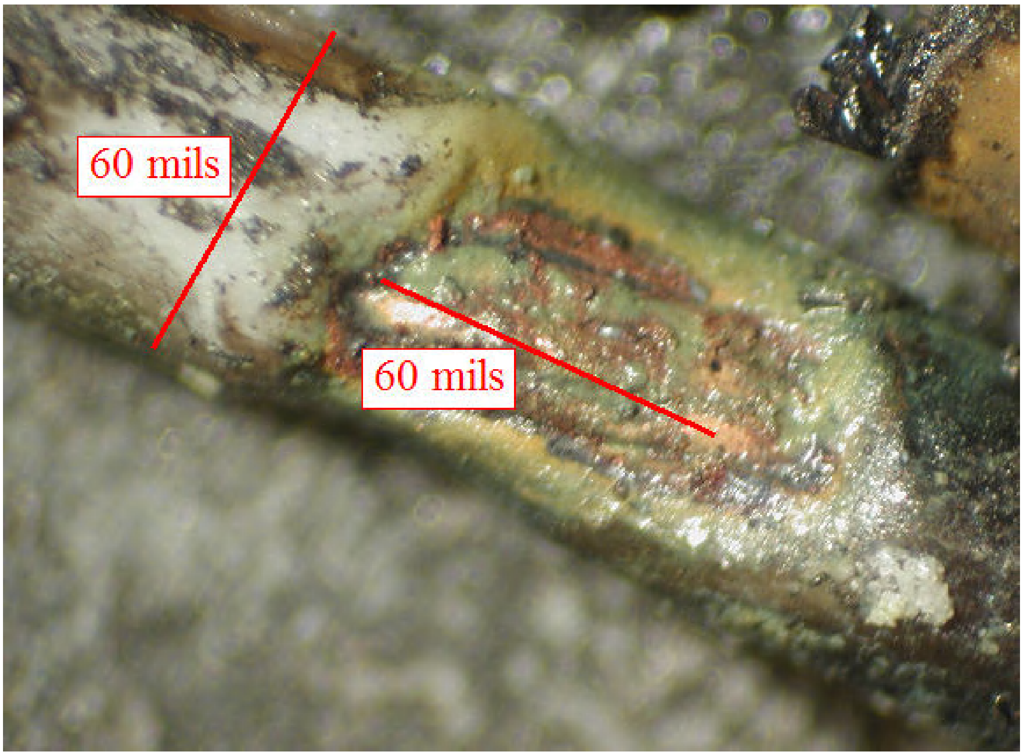

Figure 5: Post arc test photo of wire damage.

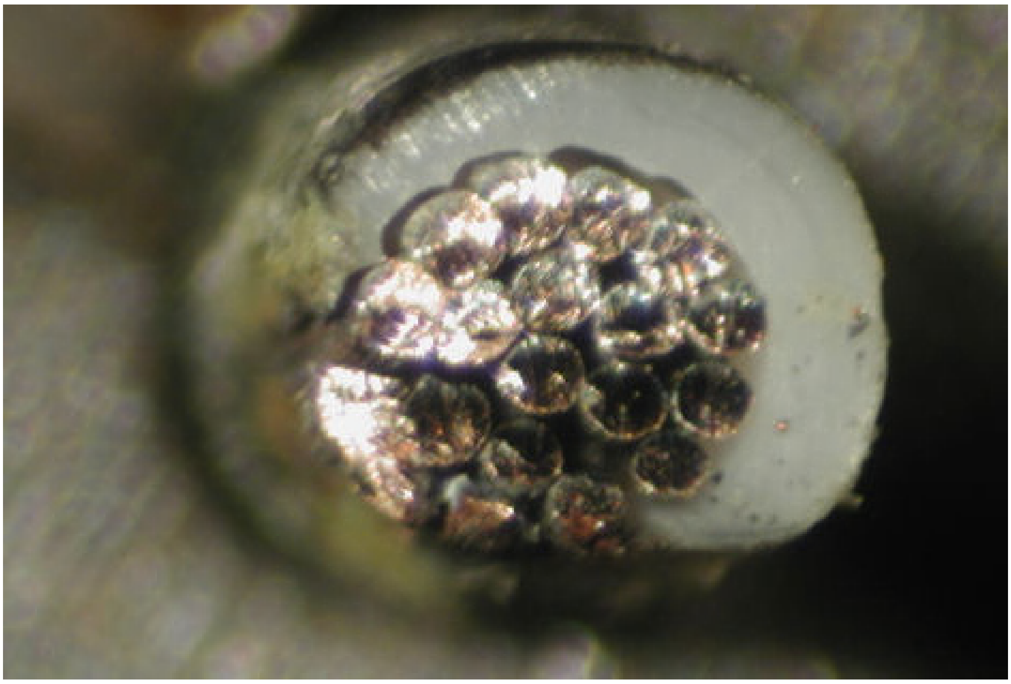

Figure 6: Cross-section photo of damage area seen in previous figure.

3. Damage to Arcing Target:

The damage done to the metal targets will be methodically measured used the depth measurement device as seen in Figure 7. Figure 8 shows a damaged tube with the red grid overlay showing the points where the depth measurements were taken. These data are then used to make a map of the volume of material that was ejected or moved by the heating due to the arc.

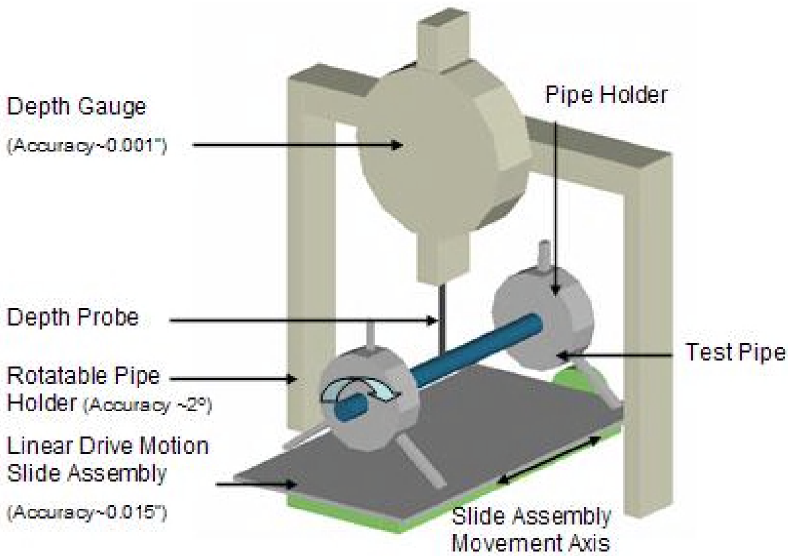

Figure 7: Apparatus for evaluating the pitting damage done to hydraulic lines and pipes during the arc damage experiments.

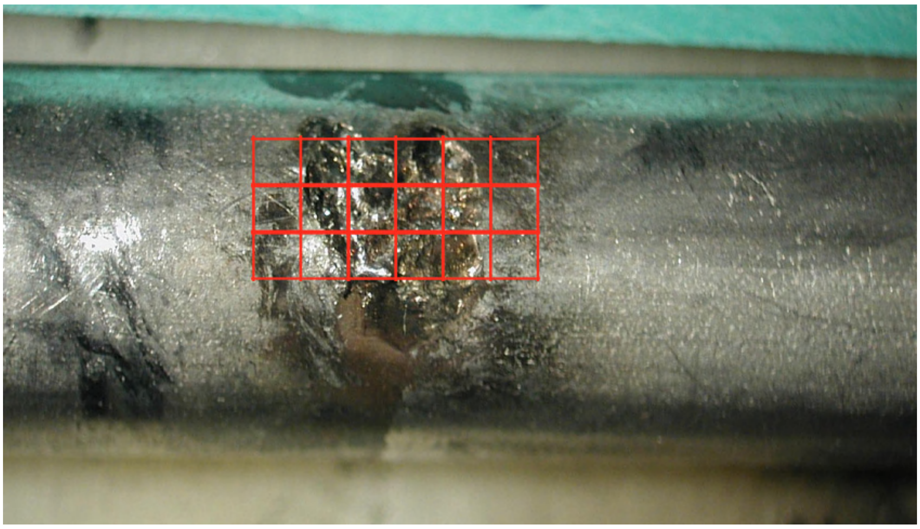

Figure 8: Photo of aluminum tube that has been damaged in an electrical arcing experiment. The red overlaid grid show where depth measurements are taken.

4. Non-Contact Damage

As part of this project, Lectromec shall also look for the quantification of spew. Spew are parts of the wire and arcing target that are damaged during an electrical arcing event and are expelled from the site. The ejection of the material is caused by the expansion of the gas heated by the arcing event. The size distribution, temperature, and effective damage radius of the spew will be considered. The amount of energy that the spew is able to deposit into other materials will be of primary importance. This work will only focus on the damage that spew might do as the result of heat transfer to other items; subsequent damage resulting from spew (i.e. chafing within a wire bundle caused by cooled spew) will not be investigated.

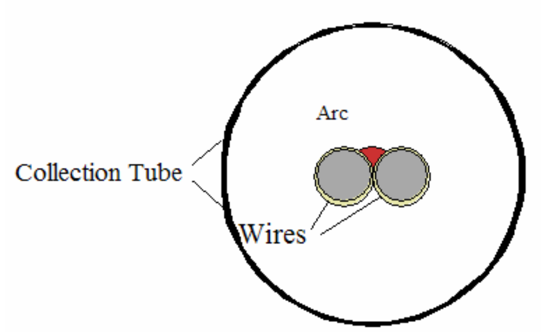

Figure 9: Proposed configuration of spew collecting cylinder to be placed around test wires.

Figure 9 shows a method of collecting molten material expelled from the arc. The volume around the arc is surrounded using a cylindrical tube. Experience has shown that some molten material expelled from the arc will cool and will stick to the walls of the plates while most of the spew will bounce around the plastic tube until coming to rest at the bottom of the cylinder. The distribution of the material on the wall can be used to determine the angle at which material is expelled. Accurate measurements of the weight of the cylinder before and after the test will quantify the amount of material expelled.

5. Thermal Gradient Stratification

As a means of assessing the temperature of the arc plume, Lectromec proposes a thermal gradient stratification method. When there is an electrical arc between the wires in the harness, some of the energy moves away from the bundle in the form of hot gas (the arc plume), radiation, and spew. To quantify this, Lectromec shall use thin metal wire strands as probes of the temperature profile of the plume. In this method, thin wire strands are supported on each side and span over the arc initiation site (an example of this can be seen in Figure 10. As the arc plume engulfs the probe wire, the wire temperature becomes that of the plume. Because the thermal mass of the thin wire is small, Lectromec assumes that the wire does not have a significant impact on the temperature of the plume. Once a section of the wire strand has reached a melting temperature, that section falls (or, if still under pressure from the expanding gas, is expelled) from the strand. The resulting profile in the strand shows where the temperature of the arc was at, or above, the melting temperature of the wire. By using wires of different metals or plastics (different melting temperatures) a profile of the arc plume temperature can be made.

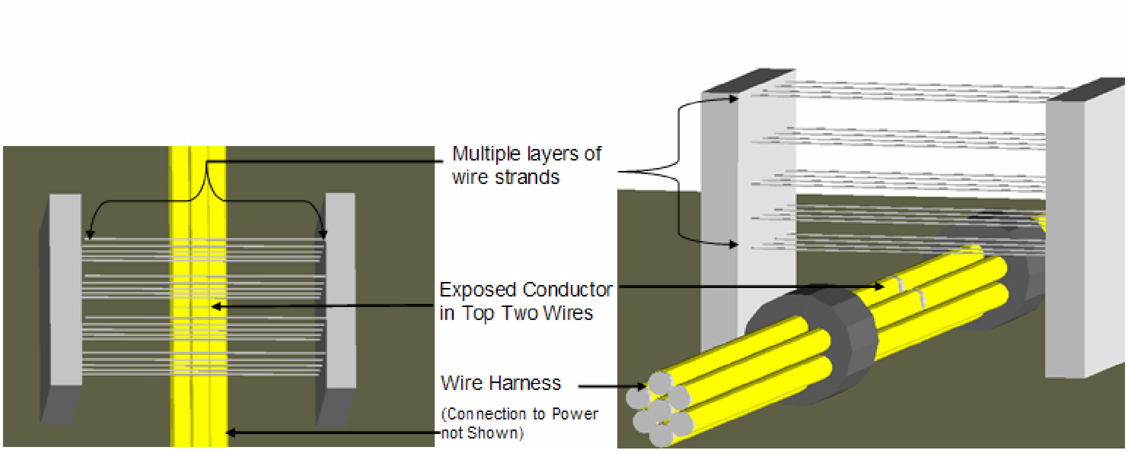

Figure 10. An example of how the thermal gradient stratification method would be employed on an arc damage test bundle.

Figure 11 is a post test photo of an arc test with this damage with a distance quantification method. Though only a single array of wire strands was used, one can see the direction at which the energy left the initiation site. In this test the probe wire farthest away from the arc was a little less than half an inch. This means that the plume temperature was at least 1058°C at this distance and, judging is how much of this strand was melted, probably at still at a greater distance.

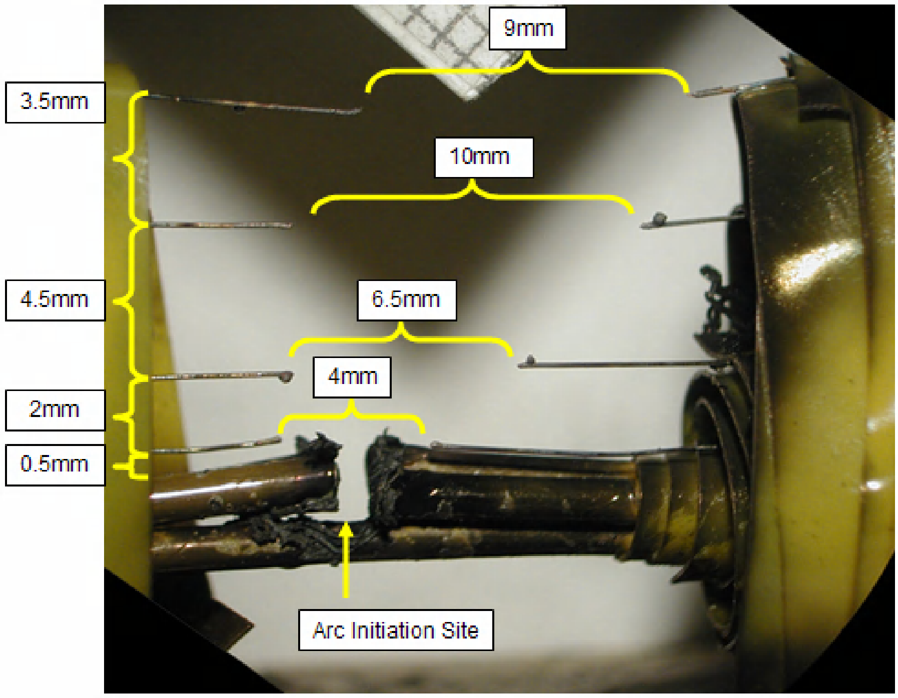

Figure 11: Example of the type of damage profile that can be seen using the thermal gradient stratification method. The scale at the top of the photo is 1mm x 1mm

When applying this methodology during actual experiments, a greater number of wire strands will be employed for the thermal gradient evaluation. Further, additional layers of wire strands will be added vertically until consistent test results show that there is an upper limit to the damage profile imparted upon the wires.

The device shown in Figure 10 is an example of how this method could be applied to the wet arc initiation method. A similar approach could be utilized with the other initiation methods. This method provides a number of benefits over other methods that we have investigated.

- There is physical evidence of the temperature and energy that was present near the arcing site.
- This provides a means of evaluating the physical distribution of energy from the site.
- There is no need to have concern for capture rates from digital devices.
- The small cross sections of the wires limit the interference to higher layers of wire strands.

The thin wire strands serve as a probe of not only the temperature of the area, but also of the energy in the immediate area. For those spans of the wire strands that are lost after the test, one cannot be certain if they have been melted, evaporated, or were undamaged, but were pushed away by the expanding gas. However, we can be certain that at ends of the remaining strands were subject to temperatures that were sufficiently high enough to bring the temperature of the wire strand to the melting point.
Utilizing this method, the distribution of energy from the site can be approximated and can be applied to other parts of the damage-modeling tool.

3. Task 2: Development of Analytical Methods

The goal Task 2 will be to develop analytical models that correspond to the physical phenomenon observed in experiments from Task 1. This approach will take into account the variables that were utilized in the testing and will examine the correspondence between the experimental parameters and the resultant damage. Modeling the arcing and resulting damage will require three different aspects to be modeled:

- The power and duration of the arc
- The division of the arc energy between the
  - Target
  - Source wires
  - Other wires in the bundle and objects at a distance from the arc
  - Loss to the environment
- Damage Models

A. Modeling the Power and Duration of the Arc

The instantaneous power in the arc is the arc voltage multiplied by the arc current ($P_{arc} = V_{arc}*I_{arc}$). The parameters that affect these values the most are the source voltage (V_s)and the impedance between the source and the arc. This impedance (X_b) will include the source impedance and the resistance of the wire connecting the arc location to the voltage source. Even with the impedance defined, the arcing voltage and current is not defined and could theoretically be any combination of values defined by the $V_{arc}=V_s-I_{arc}X_b$. The arc power therefore is also not defined.

A conservative approach would be to assume the maximum power is dissipated in the arc given the constraints of source voltage and series impedance. A basic rule of power transfer states that this occurs when the arc impedance equals the series impedance. This results in the arc voltage being half of the source voltage or 62.5 Volts for a 115 VAC circuit. However, in practice the arc voltage is not that high.

Figure 12 shows a typical current (red) and voltage (blue) waveform for an arcing event produced by a swing test. A classical arcing waveform is observed and, in this case, the arcing voltage was between 15 and 20 volts. In general, the arcing tests show that the arc voltage is normally between 15 and 30 volts and therefore the arcing power will not the maximum power possible.

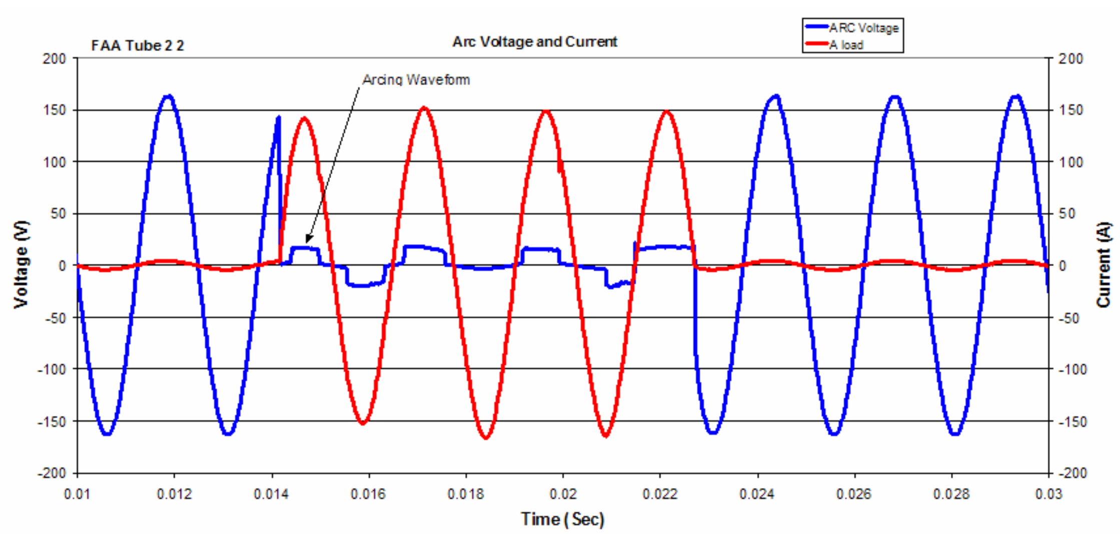

Figure 12. Current and voltage waveforms for an arcing event during a swing test (FAA Tech Center)

Therefore the power in the arc will be modeled using empirical curves for the arcing power as a function of fault current and perhaps other testing parameters. Figure 13 shows the power (purple) and energy (black) traces for the waveforms shown in Figure 12. The empirical power curves will be created by analyzing the waveforms generated in Tasks 1 and calculating the energy dissipated in each arcing half cycle.

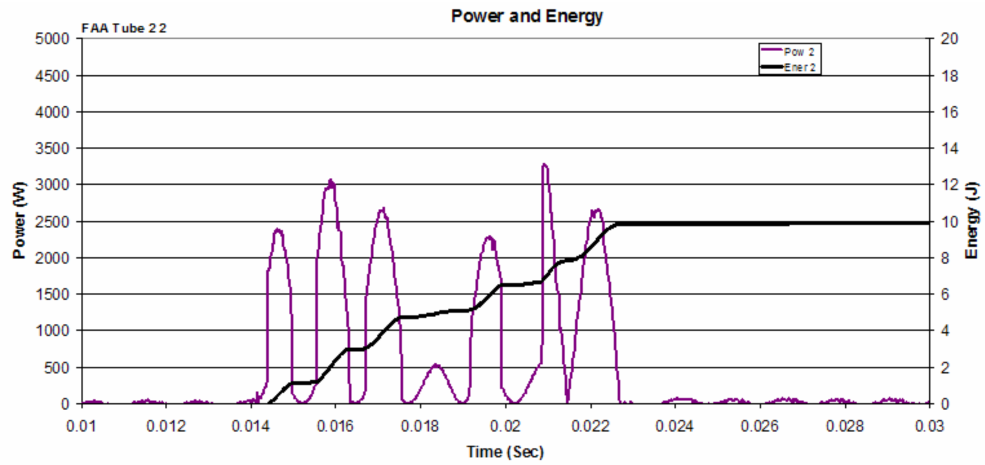

Figure 13. The power and energy waveforms for the test shown in Figure 12.

B. Division of the Dissipated Energy

Much of the energy that is dissipated in an arc enters the target of the arc, and this energy proceeds to heat and damage that object. However, all of the imparted energy does not do this as evident by the melted and missing pieces of conductor of the source wire, the damage to other wires in the bundle, and the spew and hot gas that emanate from the arc area. How this energy is divided is therefore important to the overall understanding of the damage done by the arc.

1. Ejected Molten Material

When an arc occurs it is common to see glowing points of light ejected from the arcing area as seen in figure. These are melted bits of metal emanating from either the target or the source wire conductor. Quantifying the mass and energy of this material is important for two reasons:

- The molten metal may damage nearby objects;
- The ejection is part of the damage process of the target or wire and represents energy leaving the arcing area.

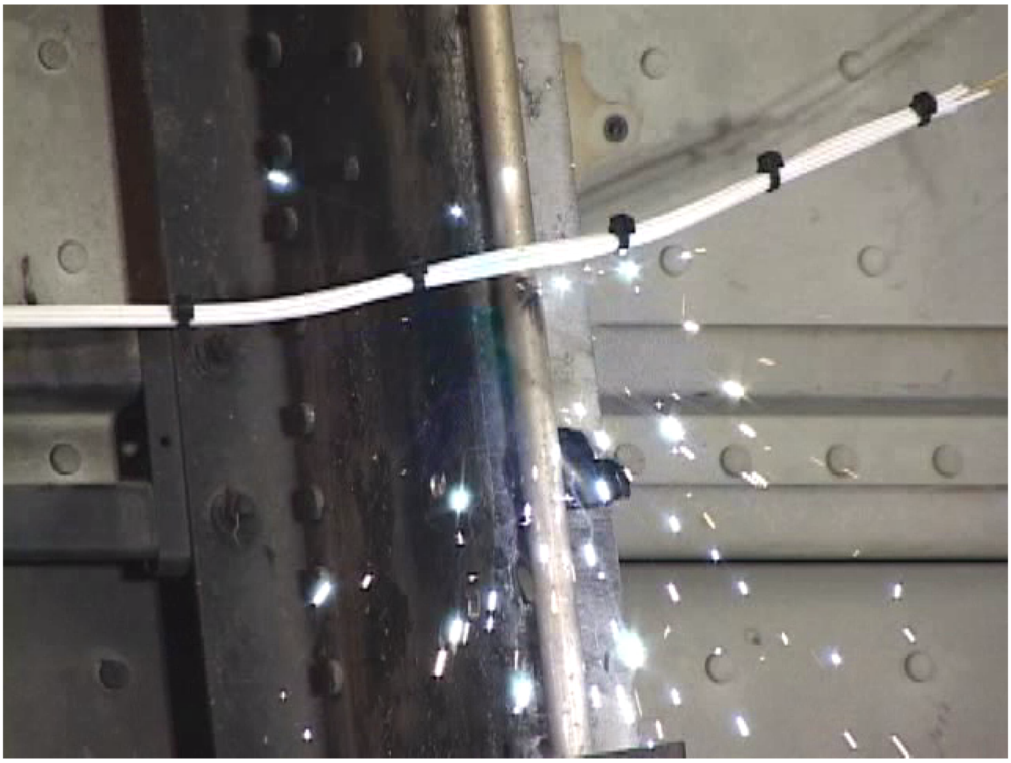

Figure 14. Material ejected from the arc whose waveform is shown in Figure 12

As described earlier, one method of capturing this material is to perform the arcing test in an enclosed tube. Figure 15 shows the material recovered from a test in a collection tube, while Figure 16 shows a large piece of ejected material that was struck in the wall of the collection tube. It was the largest of 3 pieces that had melted into the wall of the cylinder. In this case the material was the result of a phase-to-phase wet arc. Using the 7 mil diameter wire strand for scale, the range of diameters for the ejected material can be estimated as between 2 and 35 mils. If we assume the temperature of the ejected material was above the melting temperature but below the evaporation temperature of copper, then the range of energies for the ejected material is between 3 mJ and 30 J depending of the size of the piece as shown in Table 1.

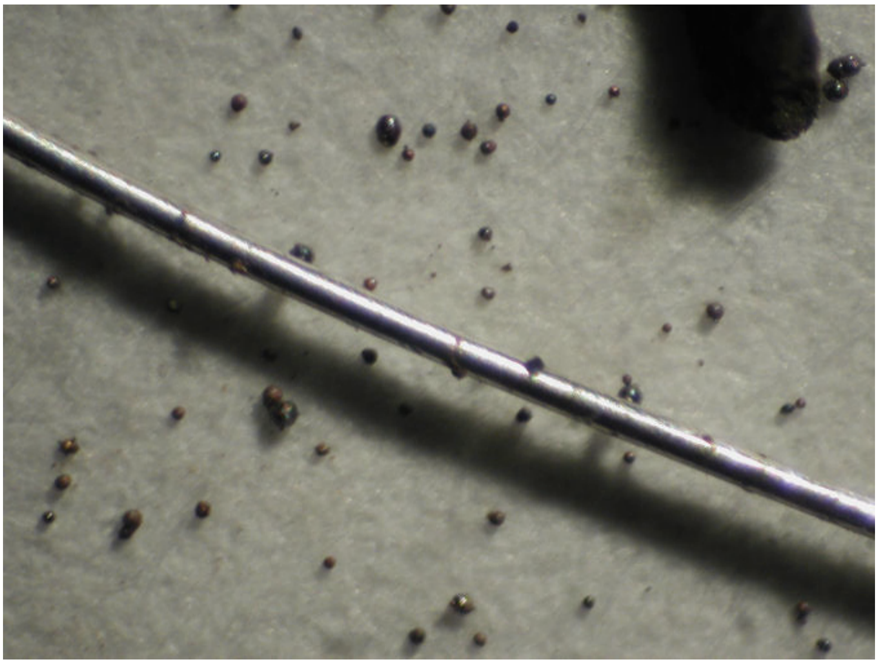

Figure 15. Material ejected from an arc. The wire strand is 7 mils (about 0.18mm) in diameter.

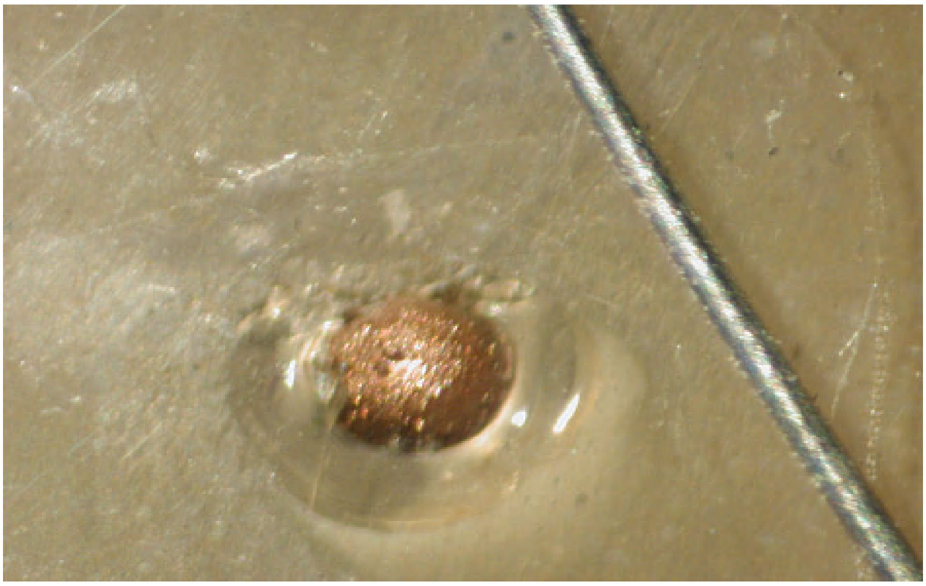

Figure 16. Large piece of ejected material; the wire strand is 7 mils in diameter.

Table 1. Volume and energy calculations for ejected material starting from room temperature.

Diameter of Copper Ball		Volume	Mass	Energy to Melt Copper	Energy to Raise Copper to Evap. Temp	Energy of Copper
Mil	mm	mm^3	g	J	J	J
35	0.875	2.805	0.02513	15.40	29.62	22.51 ± 7.11
20	0.500	0.523	0.00469	2.90	5.57	4.23 ± 1.34
7	0.175	0.022	0.00020	0.123	0.237	0.180 ± 0.057
2	0.050	0.0005	4.69E-06	0.0029	0.0056	0.0042 ± 0.0014

C. Damage Models

After both the energy dissipated in the arc and the division of energy are modeled, then the damage done as the result of that energy must be modeled. A simple correlation between the total energy released and the damage has been observed. Figure 17 shows the damage to an aluminum blade caused by an arc. The red square represents the amount of aluminum that would be melted if all of the energy dissipated in the arc were used to melt aluminum.

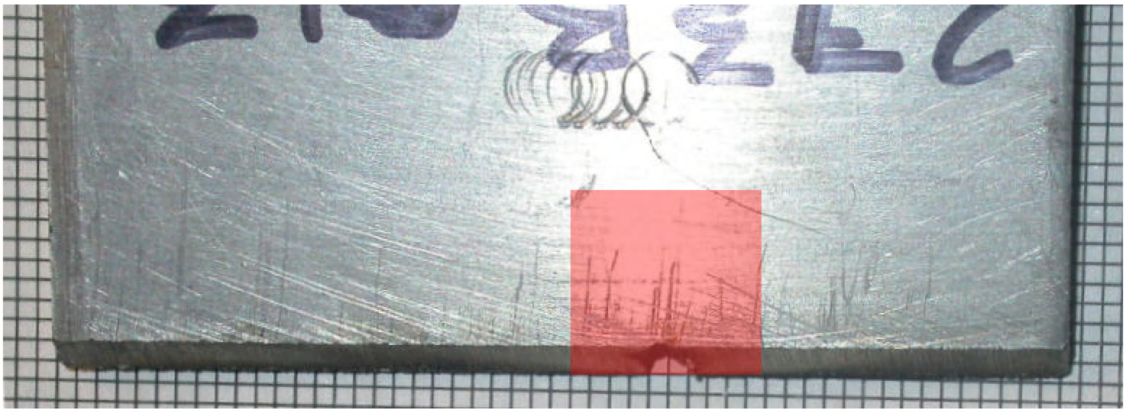

Figure 17. Comparison of actual blade damage to theoretical damage (red square) if all the arc energy was used to melt the aluminum blade.

One aspect that is not considered in the above analysis is the thermal conductivity of energy from the site of the arc. When the blade is modeled with a control volume formulation†, which includes the thermal conductivity, the results agree much better with observation. In Figure 18 the dark red/brown squares represent melted aluminum. Here the time dependent power curve of the energy dissipated in the arc was used as the energy source term for the cell at the arc site.

† Patankar, S. V. *Numerical Heat Transfer and Fluid Flow*. Taylor and Francis 1980

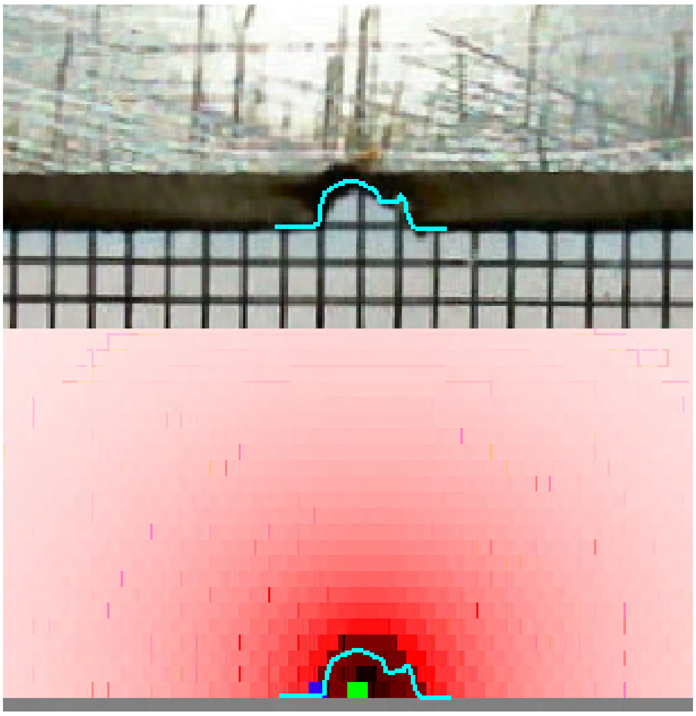

Figure 18. Comparison of blade damage with that predicted by control volume simulation.

The controlled volume formulation will be a technique that is further developed as an analytical tool. Preliminary work can be illustrated using the results from the test whose current and voltage waveforms are shown in Figure 12. This was a swing test in which a hole was made in a 3/8” aluminum hydraulic line with a 40-mil thick wall. Figure 19 shows the damage to the aluminum tube. Note that the hole was enlarged when the bundle rebounded and struck the tube for a second time.

The steps for the control volume formulation is as follows:

1. The aluminum tube is approximated as a collection of orthogonal cells or volumes.
2. The internal energy (enthalpy) of each of the cells is calculated assuming that the tube starts out at room temperature.
3. The arc energy for one time step (10^{-5} sec) is added to the internal energy of the cells at the arcing site.
4. The temperatures of the cells are recalculated reflecting the change in internal energy.
5. The internal energy is now allowed to redistribute taking into account thermal conductivity.
6. Steps 3-5 are repeated for the duration of the arcing event.

Figure 19. Post Test photo of damage to the aluminum hydraulic line.

Figure 20 shows the results of a simulation of damage to the aluminum tube. The arc energy is calculated directly from the current and voltage as shown in Figure 13. In this case, 80% of the arc energy was chosen as the amount of energy incident on the tube with the other 20% presumably damaging the source wire or being dumped into the arc plume. At this point, the percentage is somewhat arbitrary, but with the empirical data of Task 1 the confidence in the percentages should improve. For this example, the arc energy was divided evenly among a 3x3 square of cells on the outside of the tube.

The results show that damage is similar in size and shape to that found in the test. Again the reddish/brown squares represent melted cells and the green squares represent evaporated cells (yellow cells have reached the evaporation temperature but have not yet evaporated).

There are some additions that will be made to the model. These include addressing the issue of expelled molten metal from the arc area. This allows a hole to be created. In the current simulation, because no material was ejected, the same cells were heated, cooled and reheated during successive arcing half cycles, which will tend to limit the simulated damage

Figure 21 shows the temperature of the cells in the outside layer, middle layer and inside layer of the tube. These values are important when considering a pressurized tube. In this case, the tube does not have to melt before it ruptures, but rather, reach a temperature where the metal softens. This fracture process of can be calculated by evaluating the hoop stress on the tube.

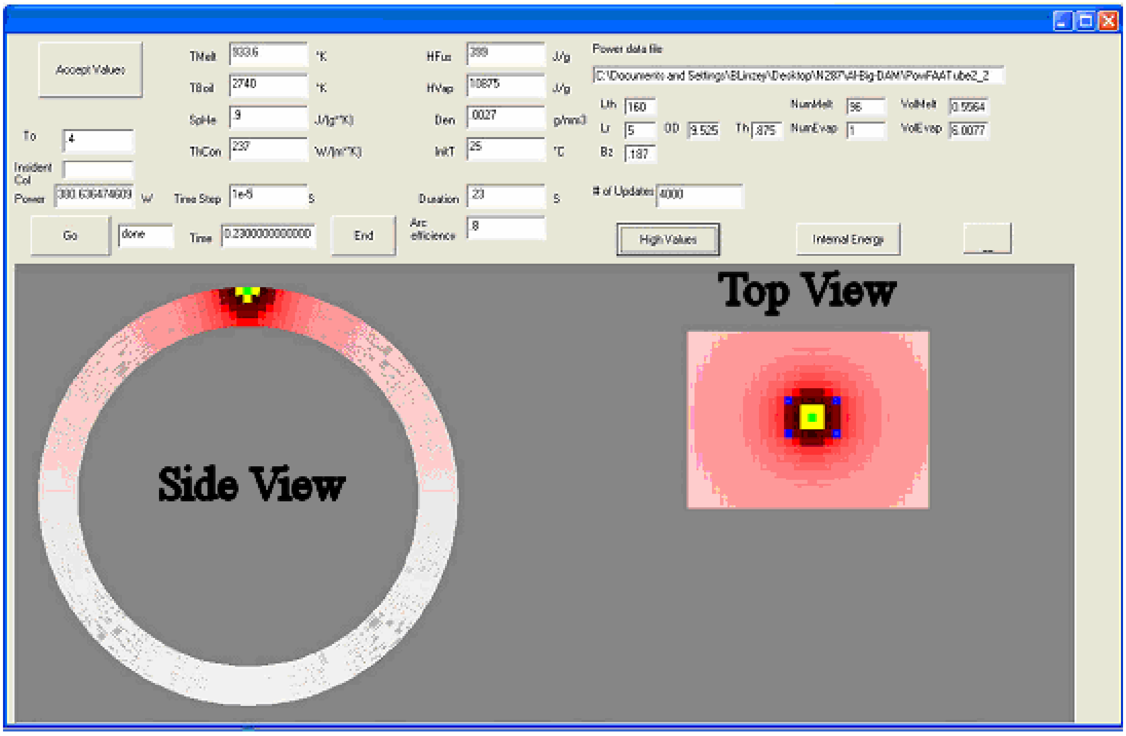

Figure 20. Results of a simulation of the heating of an aluminum tube by an arc event.

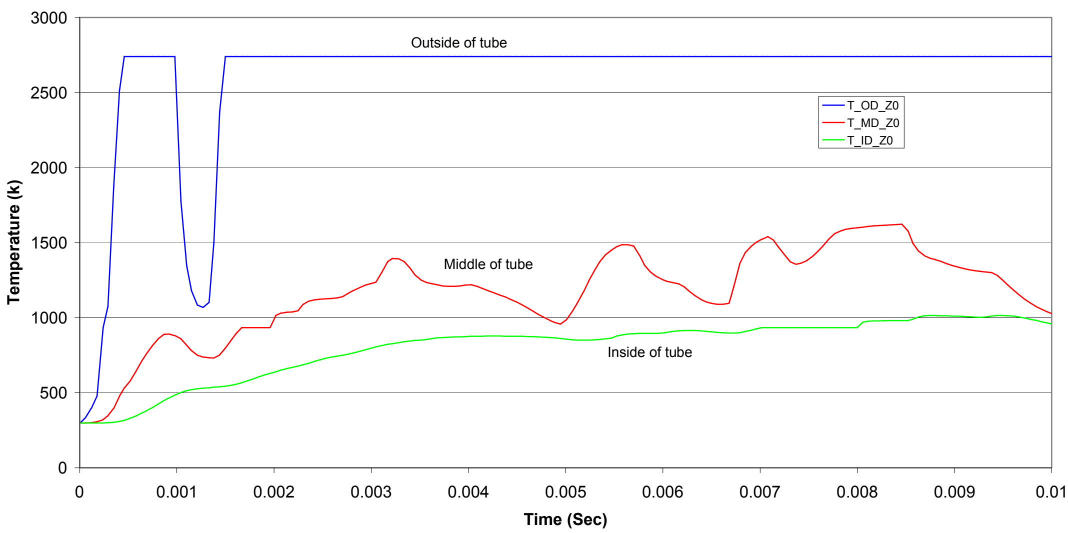

Figure 21. Temperature of the cells on the outside, middle and inside of the tube during the arc simulation.

4. Tasks 3 and 4: Development of Modeling Tool and Demonstration

The models developed in Tasks 1 and 2 will be brought together to form the modeling tool that can be used to evaluate the potential damage caused by arcing. It would be desirable to translate the damage simulation described above to commercially available finite element software. This would simplify the development as these programs come equipped with a range of features such as importation of CAD models and automatic mesh generation as well as graphic presentation of results. However, they generally are not designed to simulate a changing specimen as will occur with ejection of metal caused by the arc.

The validity of the tool will be demonstrated by how well it can model the damage in the Task 1 experiments and damage that has been experience on in-service aircraft. In addition an arc demonstration kit will be used to show how the tool functions.

5. Conclusion

A tool is being developed to model the damage resulting from an arcing event. The tool will use both empirical and analytical models, and be based on the quantification of the energy dissipated in the arc. It is the goal of this project is a tool that can be used by design and safety engineers to predict damage levels due to arcing, set separation distances and evaluate mitigation techniques.