Progress in Developing a Software Based Arc Damage Modeling Tool

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1 Abstract

This paper reports on the progress in the development of 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 types of damage to be modeled by the tool include: damage to the source (wire) and primary target (hydraulic line, flight control cable, structure, etc.) as well as other wires in the bundle and objects at a distance.

The tool will consist of three parts. The first module is the modeling of the arc itself including the arc power (energy) and duration. These quantities will depend on the source voltage, line resistance, circuit protection, wire specification etc. For AC arcs the energy will be modeled using experimental data in which the energy in the half-cycle has been calculated for thousands of arcing half-cycles under various physical and electrical conditions.

The second module divides the arc energy into the different items that can be damaged. This can include the primary target as well as secondary targets such as source wire, passive wires in the bundle, and wires at some distance from the bundle, etc. This module will be based largely on empirical results.

The third module will model the damage to the targets due to the incident arc energy. Damage is caused by an excess of thermal energy, which is modeled using heat flow simulations that depend on the properties of the target material such as geometry, melting temperature, heat capacity, thermal conduction etc. The results of the arc damage modeling tool are compared to the damage and other measurements made in the experimental testing.

2 Introduction

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 types of damage to be modeled include:

- Damage to the source (wire) and primary target {Note: in this document primary target refers to what is being arced to (e.g. hydraulic line, flight cable etc.) and secondary targets are all other items that can be damaged by arc energy}
- Damage within a wire bundle (with and without wire bundle segregation material)
- Damage to targets a distance from the arcing wires such as
    - Wire bundles (with and without segregation)
    - Structure or hydraulic lines
    - Other non-metallic objects

The project was broken into three major tasks. Task #1, which has been already completed, consisted of more than 700 arcing tests in which the electrical characteristics of the arc and damage caused by the arc were measured over a variety of parameters related to aircraft electrical and physical environments. The parameters to these tests included variables such as the arc initiation method, the fault current of the system, circuit protection device, and several others. Task #2, which is the current active task, includes the development analytical models of the results found in Task #1. Additionally as part of this task, the framework for the Arc Damage Modeling Tool (ADMT) was developed. The ADMT, which is currently in development, has been designed to incorporate the analytical results found in Task #2 into the working model. Task #3 of this project focuses exclusively on the development of the ADMT. The software tool will be designed to be a system allowing both simplified analysis of a setup or configuration, as well as making available in-depth analysis of damage and thermal states of the target/wires.

The results of the testing are described in "Effects of Physical and Electrical Parameters on Damage Caused by Electrical Arcing" also presented at the 2008 Aging Aircraft Conference [1].

3 Description of the Tool

The tool will model damage to structure and hardware, the source (arcing) wire, other wires in the bundle and wire bundles and other objects at a distance. The tool can be broken down into a series of three separate modules as shown in Figure 1.

1. The first module is the modeling of the arc itself including the arc power (energy) and duration.
2. The second module divides the arc energy into the different items that can be damaged. This can include the primary target as well as secondary targets such as source wire, passive wires in the bundle, and wires at some distance from the bundle, etc.

3. The third module will model the damage to the targets due to the arc energy that is incident upon them. The results of this module can be compared to the damage and other measurements made in the Task 1 Tests.

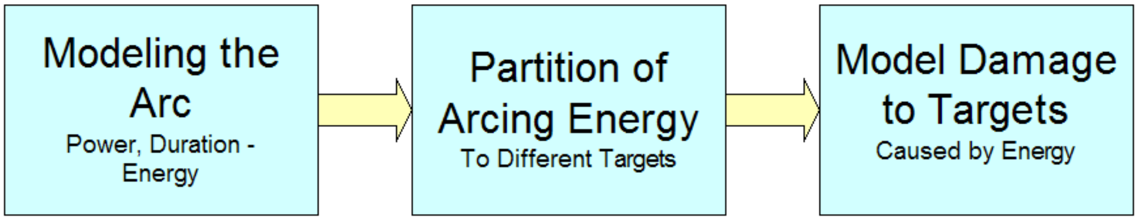

Figure 1. The three modules of the arc damage tool.

The first module determines the arc power and duration for a set of input parameters. To accomplish this, the arc waveforms from Task 1 are analyzed and the energy in each arcing ½-cycle determined. This data is added to a ½-cycle energy database along with the parameters of that test (source voltage, fault current, wire specification, etc.). An empirical fit of this data would then be used by the tool to generate the power characteristics of the arc for a given set of parameters.

In a similar way, the arc waveform data from Task 1 are analyzed to determine the current in an electrical arc event for a set of circuit parameters. This data is used with circuit protection trip curves to determine the maximum duration of an arc.

The second module, in which the arc energy is partitioned and only a fraction of the arc energy is incident on a given target, is difficult because it is impossible to measure this quantity directly. However, this partition can be inferred by using the arc power waveforms from the tests in Task 1, paired with the damage results from these tests. In this process, the power waveform for a given test is used as input to the heat transfer simulation (Module 3). The power waveform is modified by an arc efficiency factor that defines the fraction of arc energy that is incident on a given target. The arc efficiency factor is varied in multiple runs of the simulation until the best agreement between the simulated damage and actual measured damage is found. An arc efficiency database defining how the arc energy is being developed to define and store arc efficiency partition between the various targets will result from this process.

Of the three modules, the simplest one in concept is the third, in which the damage to a target is calculated once the power delivered to the target is defined. Damage is caused by the build up of excess heat energy until the target melts or is otherwise damaged. This problem is a function of the thermal properties and geometry of the target and depends on the heat capacity, thermal conductivity, melting temperature (or other phase change) and physical dimensions of the target. This type of heat transfer problem can be solved with good confidence using the finite volume numerical method [2].

3.1 Modeling the Arc (Module 1)

The characteristics of the arc that must be modeled are the power (energy) and the duration. Because the duration of the arc often depends on the thermal circuit protection, the arcing current must also be modeled. The parameters that influence the arc power the most are the source voltage, fault current (series impedance), wire specification and, to a lesser extent, the initiation method and the target material.

3.1.1 AC Arcs

The power in an AC arc is the product of the arc voltage and current, and varies throughout the arcing half-cycle. The typical arc voltage and current waveforms are distinctive and complex to model mathematically. They also would be difficult to model from first principles due to the highly complex and random nature of arcing on the aircraft environment.

To solve this problem, the energy dissipated in the arcing half-cycles of the Task 1 test data are analyzed. This is done using in-house software that recognizes the arcing half-cycles based on voltage and current levels and crossover points (positive-to-negative and negative-to-positive). The software then integrates the power to acquire the energy in each half-cycle. The software calculates the power that is dissipated in the sample leads (in the testing performed, the voltage was measured six inches from the arc) and subtracts this from the overall energy dissipated to give the most accurate value for energy dissipated in the arc itself that can be obtained. Preliminary analysis indicates that fault current is one of the most influential parameters when determining half-cycle energy. Figure 2 shows a frequency chart for tests with fault currents of 50, 100, 250, 500 and 1100 Amps. This represents the analysis of over 35,000 arcing waveforms.

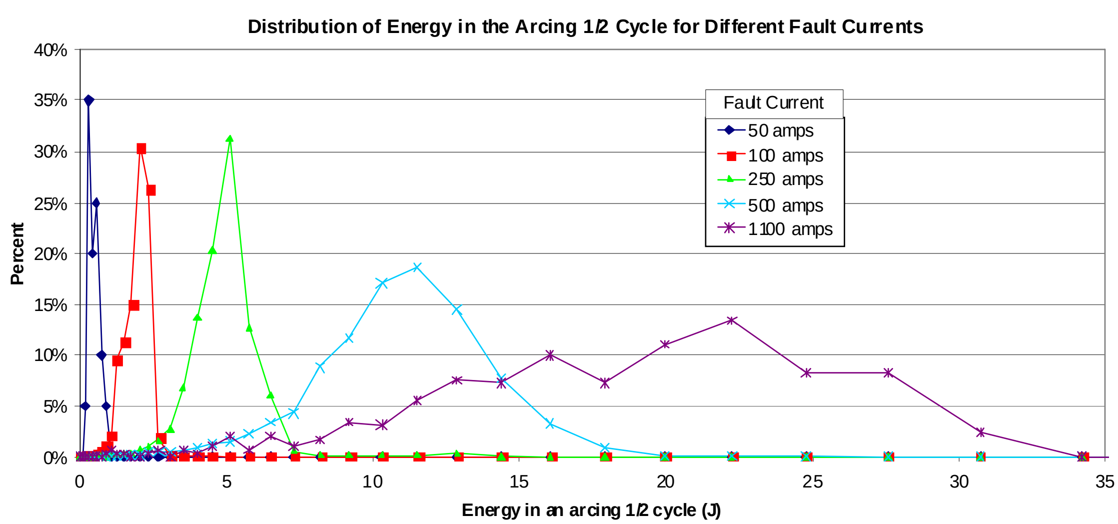

Figure 2. The normalized distribution of energy per half cycle for arc with fault current of 50, 100, 250, 500 and 1100 Amps

The distributions for some of the fault currents are broad especially at the 500 and 1100 amp level. This is in part due to the random nature of the arcs but is also due to the effects of variations of some of the other parameters such as insulation type, wire gauge, initiation method etc. While there effects are not as dominate as those of fault current they are observed, Figure 3 shows the 500 amp distribution from Figure 2 further broken down by wire gauge. While not responsible for all of the broadening it can be seen that the effects of 10 AWG wire does increase the width of the distribution.

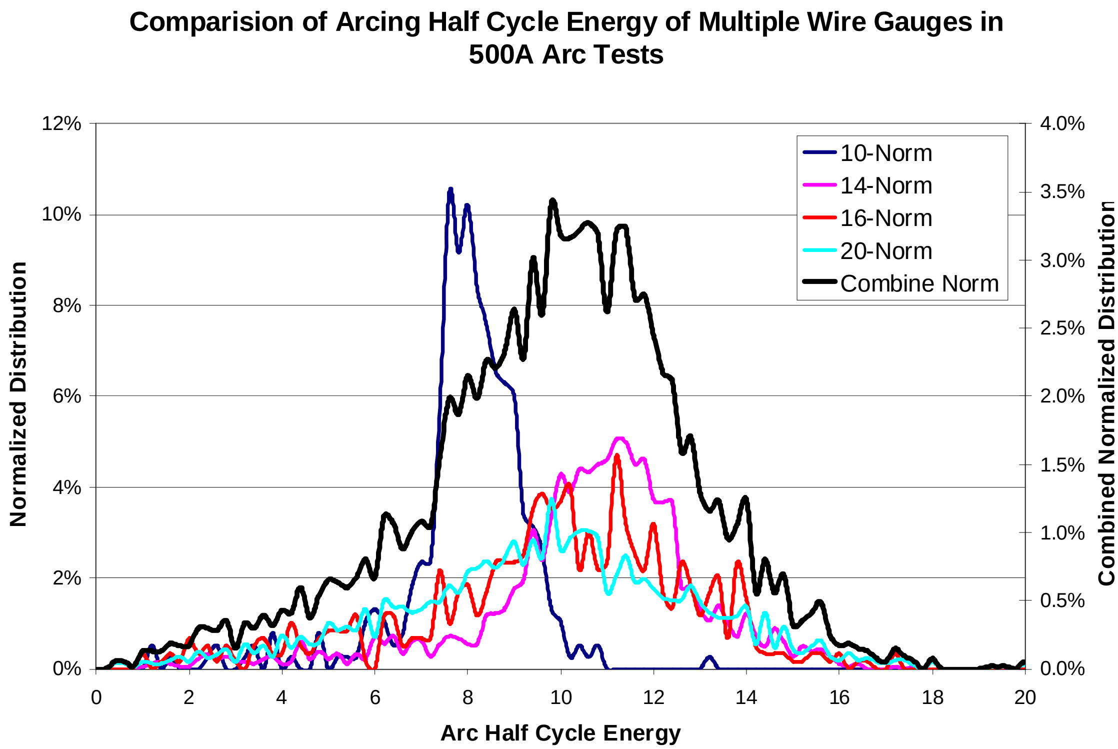

Figure 3. Breakdown of the 500 amp half-cycle energy distribution by wire gauge.

From this type data, a multivariate function is being developed for the energy in the arcing half-cycles as a function of the parameters (source voltage, fault current, wire specification, etc.). Because the tool is designed to predict the maximum damage that can be done by an arc, the average value of the half-cycle energy will not be used, instead a curve will be generated that estimates the arcing energy using the maximum values of half-cycle energy that are typically found for the given configuration.

The duration of the arcing event must also be modeled. An arcing event can end for several reasons:

- Circuit protection can trip
  - Source wire shorts to target
  - Arcing current waveform trips circuit protection
- The arcing distance can become too large for the source voltage
  - Damage done to arcing target and source wire
  - Movement of source wire in relation to the target

Of course arcs can extinguish before either of these two conditions are met due to unfavorable arcing conditions, such as relative movement of the source and target.

However, because the goal of the project is to estimate the upper limit of damage for a given set of parameters these conditions will not be assumed to exist.

The tripping of a thermal circuit breaker will depend on the integration of the current vs. time curve in comparison to the circuit breaker trip curve. The current data can again come from the analysis of the Task 1 test data. Figure 4 shows initial data for RMS currents in arcing half-cycles, along with the arc voltage, for several tests with 100 Amp fault currents. Because a thermal circuit breaker trips due to a build-up of heating within the breaker, the RMS current and arc duration will be used with the trip curves to determine the number of arcing cycles can occur before the circuit protection trips

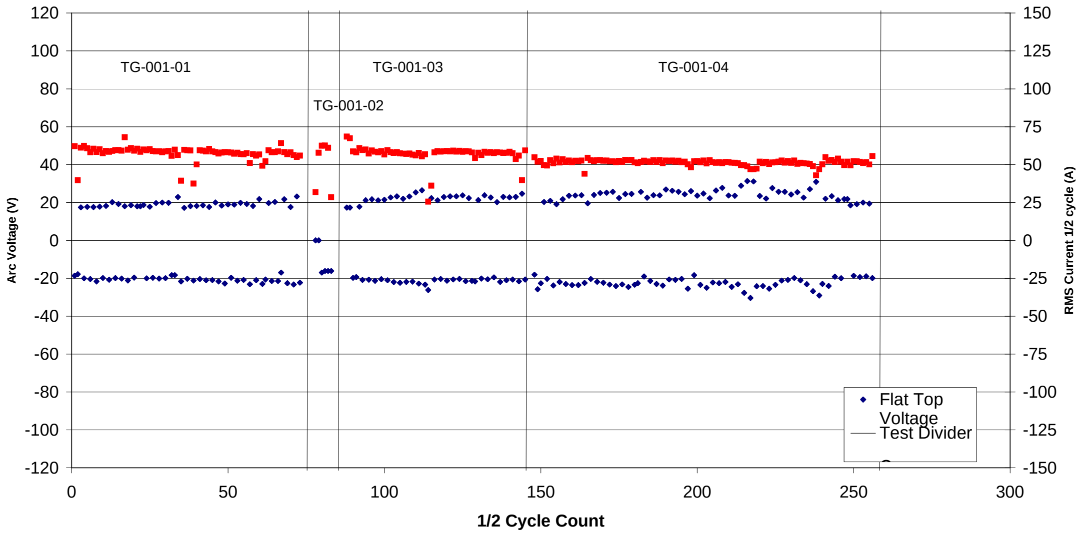

Figure 4. Peak currents and arc voltage per arcing 1/2-cycles in tests using 100 A fault currents.

An arc fault circuit breaker trips based on the number of arcing waveforms distinguished by the analysis circuit of the breaker; each manufacturer has its own proprietary algorithm. However, manufacturer information and Task 1 data (patterns of opening times for a given number of arcing half-cycles) can be used to estimate trip times for arc fault circuit breakers. The minimum specification requirements in AS5692 will also be used for a conservative number of arcing half-cycles.

A second way that an arc can be extinguished is that the source wire and target become damaged such that the arc length becomes too long. This most often occurs when the source wire conductor erodes but the insulation does not, leaving an empty insulation tube. If the insulation is removed during the arc (e.g. an arcing event with a MIL-STD-81381 type wire insulation), then the arc is extinguished only after enough conductor is eroded so that the conductor and target cannot touch or come close enough to sustain the arc. This method of extinguishing the arc is not solved by modeling the arc, but by the simultaneous simulation of damage to the target and to the source wire using the heat transport solvers in module 3.

3.1.2 DC Arcs

The approach for modeling DC arc will be same as for AC except that the average energy and currents will not be based on half-cycles energy but instead on time average energies and currents.

3.2 Partition of Arcing Energy (Module 2)

The partition of energy can be found using the Task 1 arcing power data paired with the damage that the arc caused to the different targets near it. To do this the heat transfer simulation was run using the arc power data files from the test with a modifying factor called the arc efficiency percentage. Multiple simulations were run with varying arc efficiency percentages until the actual damage done to the target was accurately simulated. In this way, a database of arc efficiencies is being created for the primary targets, source wire conductor, passive wire insulation, and wire or other targets at a given distance from the arc. The steps to determine the arc efficiencies are:

1. Use experimental power waveform as input to target damage simulation (module 3)
2. Run multiple simulations using a range of arcing efficiency
3. Chose arc efficiency in which simulated damage best match experimental damage
4. Develop database of arcing efficiency for different parameters

Figure 5 shows the percent agreement between damage volume measured experimentally and those simulated using a range of values for arcing efficiency. These results are for a particular test which was a 115 VAC swing test using 24 AWG polyimide wire against an aluminum tube. The best agreement between simulated and experiment damage level is in the 38 - 40 % arc efficiency range where the difference between the simulation and the test volume loss is close to 0%. In general, arc efficiencies near this range have been found to give good agreement for the case of arcing to a metallic tube. A database of arc efficiencies is currently being populated for other targets and parameters.

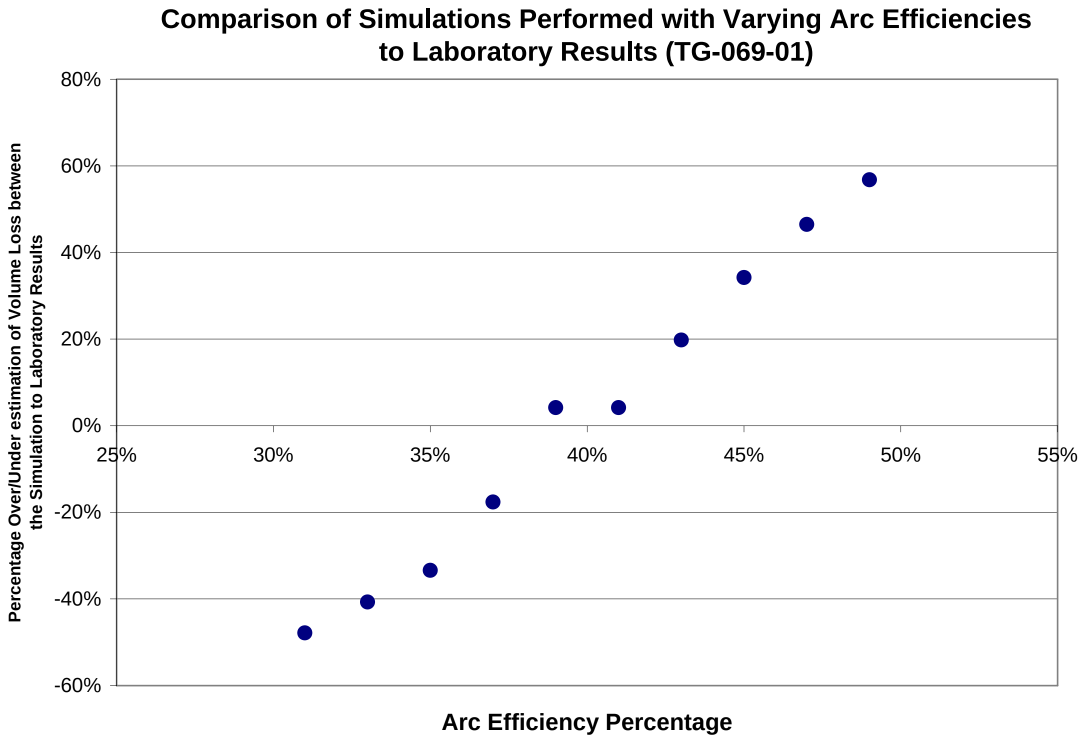

Figure 5. Percent agreement between simulated and experimental of damage levels for a range of arc efficiencies.

One parameter that is significant in determining arc efficiencies is distance from the arc for the case of damage to wires in nearby bundles. Figure 6 shows the best fit arc efficiencies for two series of tests at distances of 0.25, 0.5, 0.75 and 1.0 inch from the arc. Both series were wet initiation with MIL-STD-81381 wire with the blue series represents test using 20 AWG wire, a 7.5 thermal circuit breaker, and 500 amp fault current, and the red series test using 14 AWG wire, 20 amp thermal circuit breaker, and a 250 amp fault current. Even though the energy level (600Joules versus 6000Joules) and damage levels (topcoat damage to conductor melting) varied greatly, the arcing efficiency values are similar. The arc efficiency is reduced as distance from the arc is increased as expected. However, the rate of reduction (1/distance or less) is not a great as may have been expected. One explanation for this is the highly directional nature of the arc plume as shown by the thermal gradient stratification tests done in Task 1 (ref).

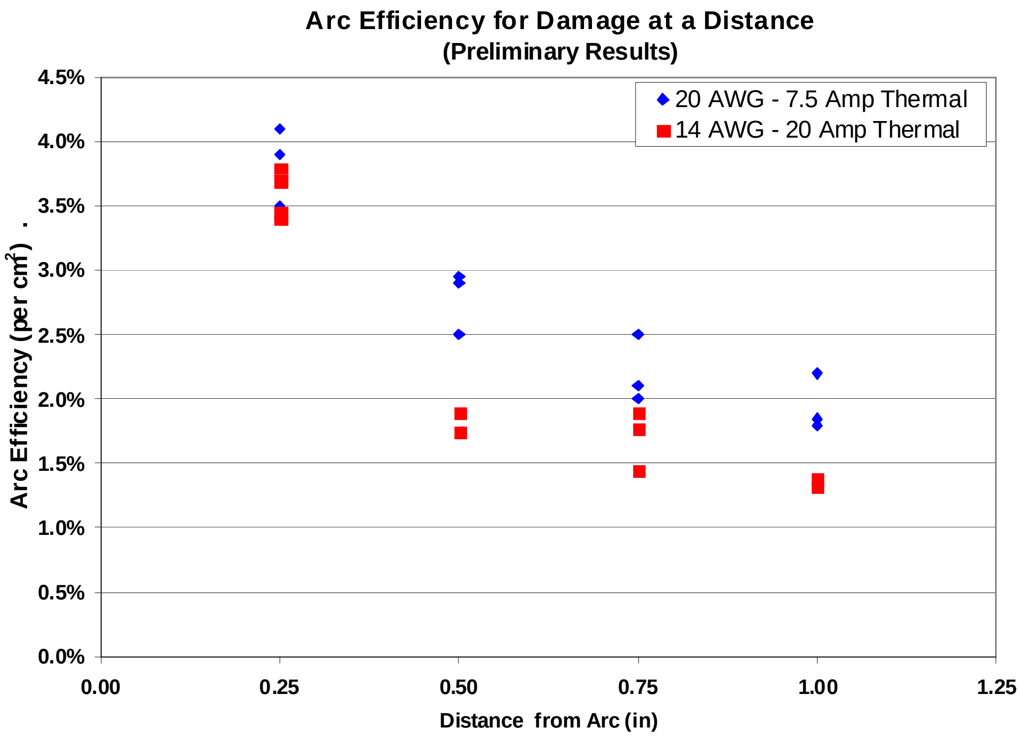

Figure 6. Arc efficiencies for energy transfer to targets at different distances from the arc.

Because the damaging arc plume of hot gas is not symmetrical around the arc, for any particular test in Task 1, it is impossible to know if the target was in the hottest part of the arcing plume. Therefore after analyzing all of these tests, the database will have a range of arc efficiencies for targets at a distance from the arc. The tool will use the higher values for arc efficiency to reflect the worst-case possibilities.

In addition to measuring the damage done by the arc, a thermocouple was placed on the target at a distance between 5 and 20 mm from the arc location. The temperature was recorded before, during, and for several seconds after the arc event. Because of the relatively slow response of the thermocouple, the initial thermal pulse caused by the arc cannot be recorded accurately. However, several seconds after the arc, as the temperature slowly approaches a steady state, the temperature measurements are more accurate. These measurements relate to the total energy that the injected into the target. By comparing the measured temperatures to the simulation temperatures at the thermocouple position, an independent method for finding the arc efficiency will be used.

For passive wires in the bundle (those wires that were not actively part of the arc), the case is similar to targets at a distance in that the fraction of energy that goes into a particular wire insulation depends on the randomness of the arc and of the relative positions of the passive wires to the arcing wire. The analysis will produce a database with a range of values for of arc efficiencies for a given set of parameters.

3.3 Modeling Damage to Targets (Module 3)

Damage to all targets, either primary or secondary, depends on the influx of energy from the arc that heats the target. If the target heated to a temperature at which a material phase change occurs, then the target is damaged. Once the energy is delivered to the target the problem is one of the thermal mass and thermal conductivity of the target. These problems can be solved using finite difference methods. The problem is different then most solved with COTS Finite Difference/Element software in that the target is expected to lose material through melting or evaporation (initial results indicate the melting is the favored way of eroding target material). This means that the geometry of the target will always be changing with energy and material leaving the system. Therefore, damage simulators have been developed for this project.

The general form of the damage simulator is the same regardless if the target is a metallic primary target or an insulator for a wire or other secondary targets. A control volume finite difference method is used to calculate the flow of heat energy. Figure 7 shows a simple flowchart of the simulation and short explanations of each of the boxes are found in Appendix A.

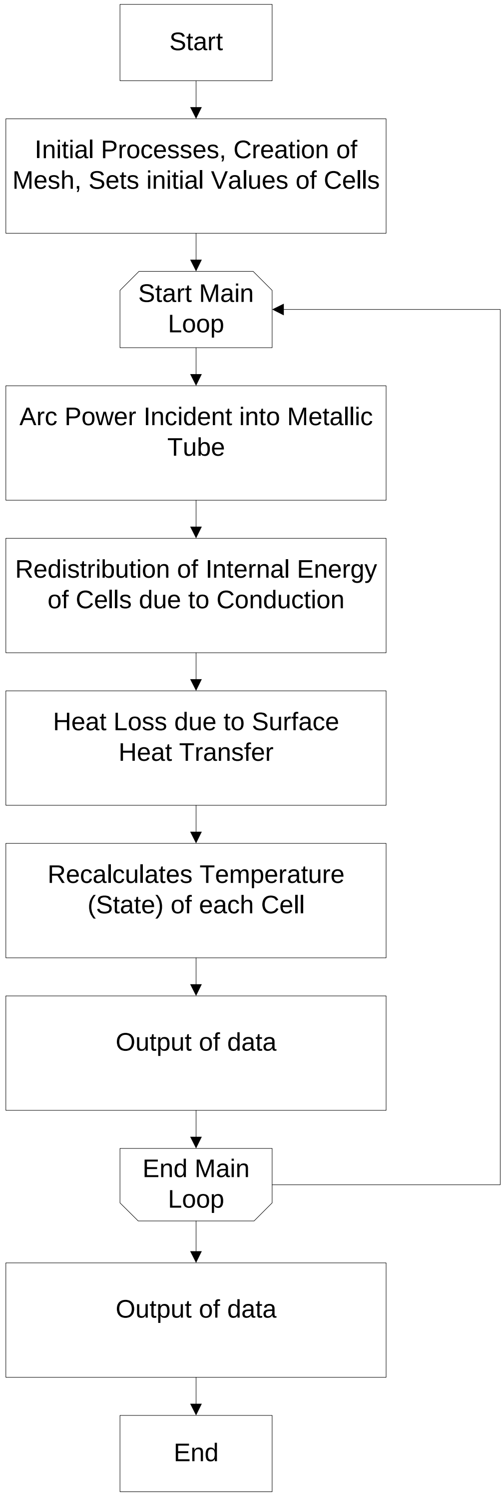

Figure 7. Flowchart of the damage simulation

3.3.1 Material Properties

The thermal properties of the targets that affect damage to the target are

- Phase Transition and Melting Temperatures

- Specific heat
- Heat of phase changes (e.g. heat of fusion etc.)
- Thermal conductivity

A catalog of these values for aircraft material is integrated into the tool along with methods for inputting new data. While room temperature data is available for most of materials, the temperature dependency may not be. Figure 8 shows the temperature dependence of the enthalpy and specific heat of titanium. The variation of specific heat is around 20% from room temperature to melting.

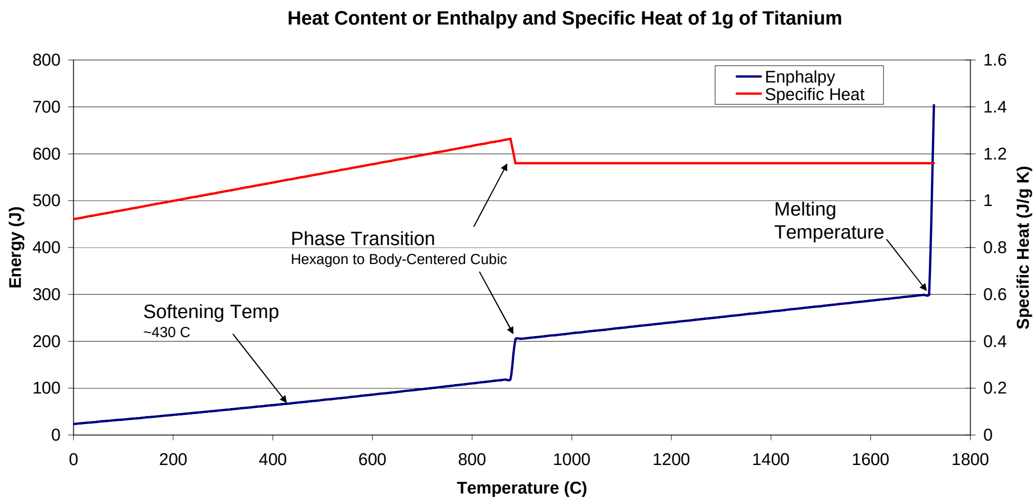

Figure 8 The heat content or enthalpy and specific heat of titanium as a function of temperature.

Figure 9 shows a screenshot of the damage simulator for a metallic tube. In the cross-section view the black area represents volume of the tube that has been melted. In the 3-D perspective view, the melted cell are shown as missing. The simulation also can output the temperature of any cells during the simulation. Figure 10 shows the simulated temperature profile of a titanium wall after an arcing event. The simulated damage (10 mils penetration of melted titanium) agrees with the experimentally measured damage. The simulation shows that the inside of the titanium tube would not reach the softening temperature of titanium (430 C) at least within the time that was simulated.

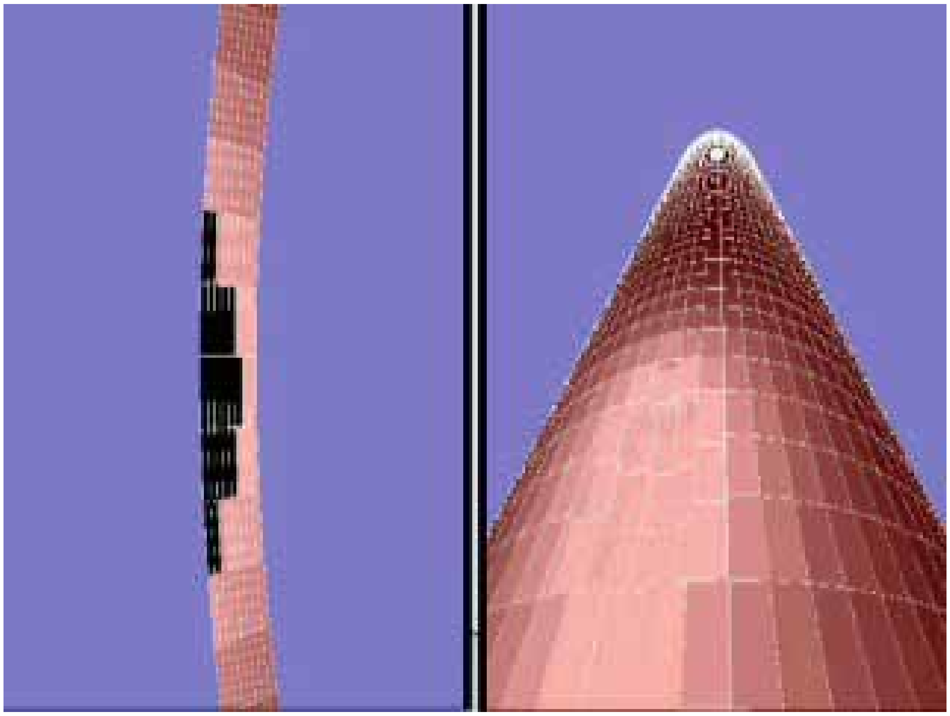

Figure 9. Screenshot of the damage simulator for a metallic tube showing the damage cross-section and 3-D perspective view.

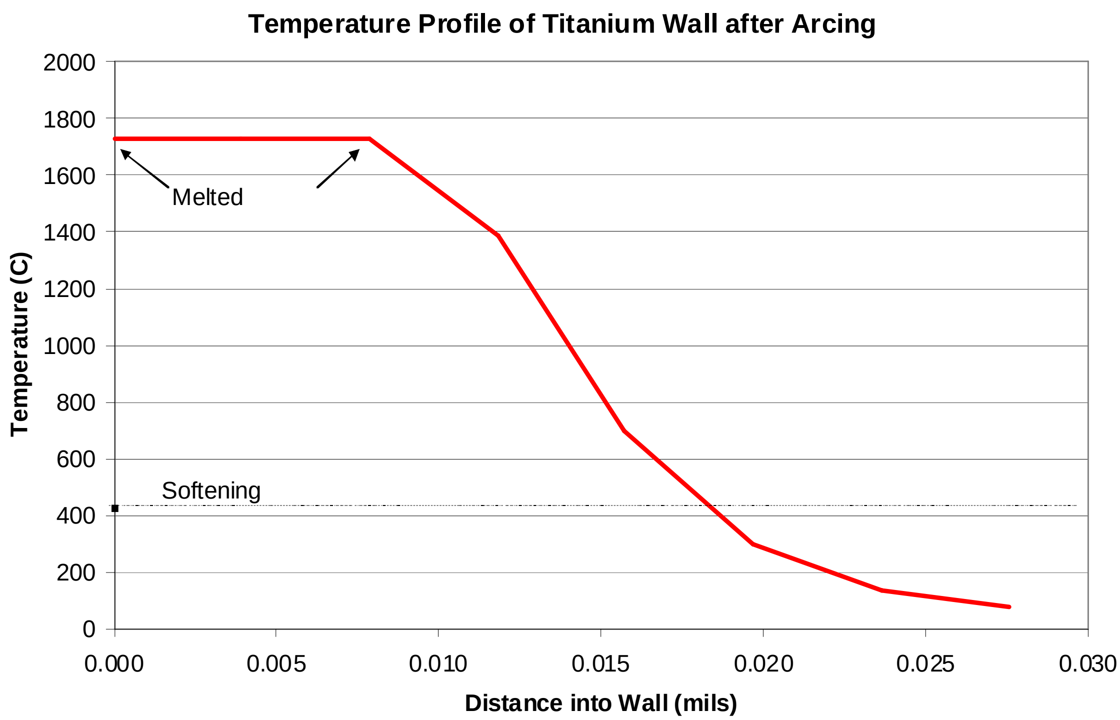

Figure 10. The simulated temperature profile of a titanium wall after arcing.

Figure 11 shows the simulated temperature profile of the insulation of Mil-W-81381 wire for a test found using the 1-D insulation damage simulator. In this case, the arc energy is coming from the left and is incident on the layers of insulation. The topcoat (TC) originally started at distance 0, but a little less than half of it has been destroyed. The other layers of the insulation consist of several layer of 1 and 2 mil polyimide (PI) tape, with FEP adhesive in-between, fill the distance to 0.22 mm (8.5 mil). The temperature in the layer is show by the black curve. For this simulation, once the temperature of the insulation reaches the temperature of 900^{o}C, it is removed from the model. This value is an estimated based on literature and experimental data for polyimide and probably is high for the topcoat and FEP materials.

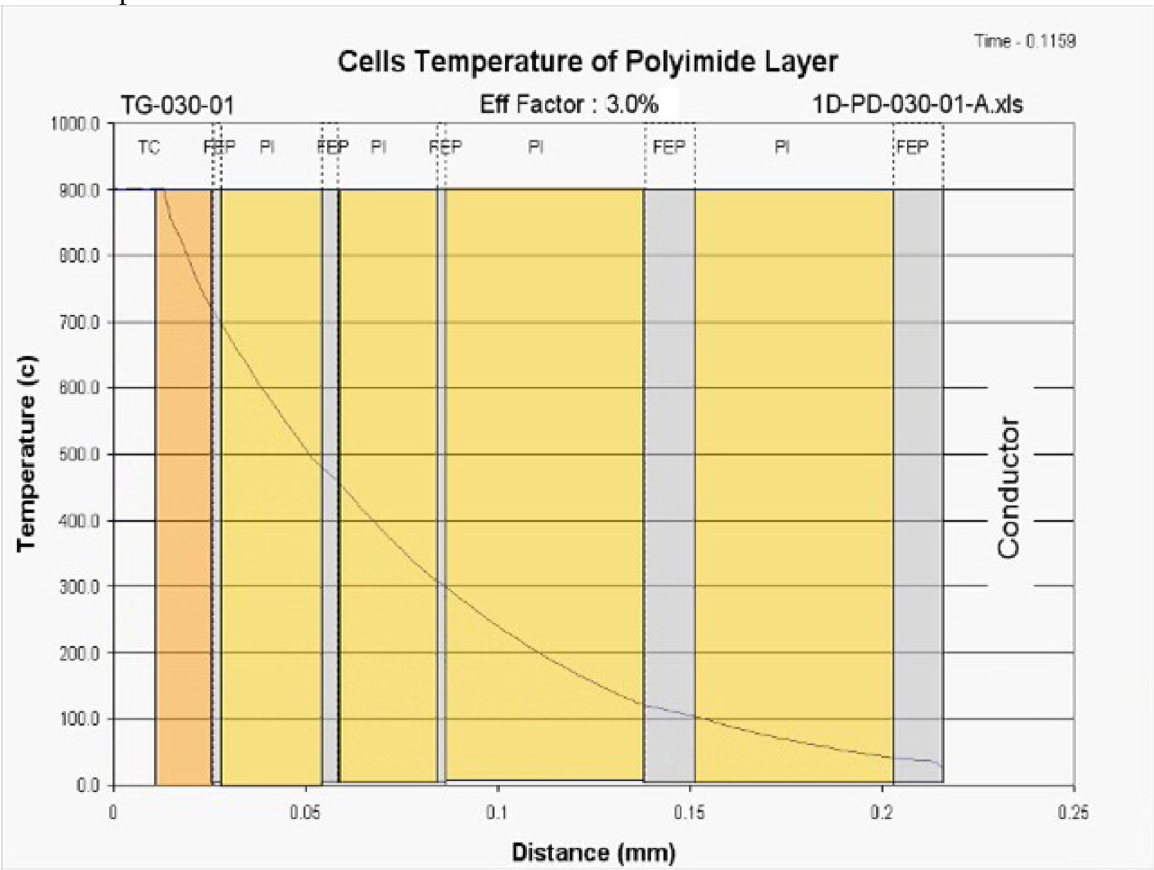

Figure 11. The temperature and damage profile found using the insulation damage simulator.

4 Conclusion

A user-friendly software tool is being developed that can model the damage resulting from an arcing event. The tool is based on both analytical and empirical data from over 700 arcing tests. The analysis will use the concepts of energy quantification and heat transfer to model damage. The tool will be comprised of three modules:

1. Modeling the Arc
2. Partition of Arc Energy
3. Modeling of Damage to Target

Preliminary results indicate that there is good agreement between the experimental damage measured and modeled damage.

The tool can be used as a stand alone tool or can be integrated into and safety assessment using the EWIS Risk Analysis Tool that has previously been developed by Lectromec for the FAA [3]. Lectromec expects the completion and delivery of the ADMT to the FAA in December 2008.

5 References

[1] Walz, M., Linzey W., Traskos M., Gomez, C. and Bruning A., "Effects of Physical and Electrical Parameters on Damage Caused by Electrical Arcing". 2008 Aging Aircraft Conference, Phoenix, AZ April 21-24, 2008

[2] Patankar, S.V., *Numerical Heat Transfer and Fluid Flow*, Hemisphere Publishing, 1980.

[3] Linzey, W., Development of an Electrical Wire Interconnect System Risk Assessment Tool, Report Number DOT/FAA/AR-TN06/17, April 2006.

Appendix A: Explanation of Simulation Flowchart

Initial Processes, Creation of Mesh, and Initial Values of Cells:

The mesh (the computation process to breakdown the target/wire into finite sections for evaluation) uses the most appropriate orthogonal coordinates for the creation of the cells that represent the target. The enthalpy (internal energy) of each cell is calculated based on the initial temperature, cell volume, material density and heat capacity. Note that the heat capacity and thermal conductivity of many of these materials are temperature depended. Where these temperature dependences are known (CRC handbook of Chemistry and Physics, etc.), they will be used in the simulation.

Start Main Loop:

The simulation is a series finite time steps, repeating the processes in the main loop for a given length (time step) that continues for a preset duration.

Arc Power Incident into Metallic Tube:

A test data file of the arc power is used as the input energy that heats and damages the target. The power is modified by the factor, the arc efficiency, that represents the fact that not all of the arc energy enters target: some energy melts the source wires, some heats the air creating a plume of hot gas and some is loss via radiation. The arc power is incident to (injected into) a number of cells on the surface of the target (causing their internal energy and therefore temperature to rise). The shape and dimensions of this area are determined by the damage that is recorded post-test. Once a cell is removed from the simulation because of melting or evaporation, the energy that was destined for that cell is instead injected into the cell below.

Redistribution of Internal Energy of Cells due to Conduction:

As stated above the introduction of the arc energy causes an increase in temperature of some of the cells. This temperature gradient causes the redistribution of this energy via conduction between cells that share a common boundary (surface). The energy that flows between two between adjacent cells (A & B) is given by the equation

$$E_{A-B} = \frac{kA(T_A - T_B)\Delta t}{\Delta x}$$

Where

k is the thermal conductivity of the metal

A is the area of the surface shared by cells A & B

$(T_A\text{-}T_B)$ is the temperature difference between cells A & B

Δt is the length of the time step (in seconds)

ΔX is the distance between the centers of cells A & B

This calculation is made for each surface of the cells (making sure that the heat flux is only calculated once for each surface) during each time step. The surfaces that define the boundary of the target do not conduct heat by this process.

Heat Loss due to Surface Heat Transfer:

Energy is lost from the target to the atmosphere by the process of surface heat transfer. For the cells that have a surface that define the external boundary of the target energy is loss from the cell using the equation

$$E_{loss} = hA(T - T_i)\Delta t$$

Where

h is the Coefficient of Surface Heat Transfer

$(T-T_i)$ is the temperature difference between the cell and the surrounding air which remains constant and is taken as the initial temperature. For an object in nonmoving air, *h* is between 5-10 W/m^2 K.

Recalculate Temperature (State) of each Cell:

After the energy has been redistributed, the temperatures of the cells are recalculated and the state of the cell is determined. Once the temperature of the cells has reach is melting temperature, the cell remains at that temperature until the internal energy is raised to the point that the heat of fusion is passed; the cell is then melted. Once a cell is melted it is considered lost to the system and heat is no longer transferred in or out of the cell. The energy in the cell is trapped and no longer interacts with any other cells. Note in some simulations the cell and its energy is considered lost only after the cell is vaporized.

Output of data:

Periodically and at the end of the simulation, certain data is exported to the display or to a text file. This data includes the temperature, internal energy, state of damage of some or all of the cells. Output at the end of the simulation includes the volume of the target that has been melted and the high temperature reached in any given cell.