Examination of EWIS and Pressurized Hydraulic Lines

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An important safety consideration for the Electrical Wire Interconnect System (EWIS) is the separation between wire bundles containing power wires and other aircraft systems such as the hydraulic system. The risks of direct contact arcing to hydraulic lines have been investigated and computational models have been developed to simulate these scenarios in the Arc Damage Model Tool (ADMT), developed by Lectromec for the FAA. Even with some separation between wires and a grounded tube, a hydraulic/fuel line can sustain arcing damage as it is enveloped by the ionized arc plume. This can result in a significant transfer of arc energy to the tube (thermal energy) or even direct arcing from the wires to the tube (electrical energy).

In general, past experimentation was performed with empty aluminum tubes. This paper reports on arc testing done with aluminum tubes filled with pressurized hydraulic oil. The presence of the oil has two effects:

- The hydraulic oil acts as a heat sink for the arc energy incident to the hydraulic tube. This has the effect of reducing the hydraulic tube wall temperature rise.
- The pressure inside the tube can rupture the tube before the incident arc energy actually causes a breach in the tube wall.

This paper reports on dry arc tests done with TKT power feeder wire. The arc duration was controlled using a time delay relay with a range from 50 ms to 1 second. Separation distances of 0.5 - 2 inches were used. The inner tube wall temperature was measured using thermocouples and the time of the tube wall breach was measured with a pressure transducer. The results of these tests have been integrated into the ADMT.

1 Introduction

1.1 Pressurized Hydraulic/Fuel lines

A rupture in a hydraulic of fuel line can be a dangerous event. If the breach is initiated by an electrical arcing event, the fuel spray can be ignited creating a torch. This can have devastating effects on airworthiness of the aircraft.

The complexity and safety concerns limited the performance of experiments on target tubes with pressurized hydraulic fluids. Rather, most tests focused on arc damage testing with empty unpressurized tubes as the targets. These tests advanced the knowledge of electrical arc damage on aircraft by validating the Arc Damage Modeling Tool (ADMT) and allowing arc energy and energy transfer parameters to be defined. Experimentation performed on pressurized tubes have two key differences:

- The fluid, whether it is hydraulic fluid or fuel, acts as a heat sink for the arc energy allowing a greater level energy to be dissipated before reaching an unsafe temperature
- The pressure within the tube exerts an outward force that can cause the tube to rupture if there is tube wall strength degradation.

The research objective was to examine the energy and configuration of an arcing event sufficient to cause a hydraulic line failure at a distance. Testing was performed to define the temperature and arc energy limits from the arcing event to the hydraulic line prior to rupture. The research used aluminum tubes as the target because of its wide use in aerospace applications.

A key material property for determining the failure of hydraulic lines is the tensile yield strength at different temperatures. The reduction in tensile yield strength of metals is complex and based on duration subjected to a given temperature and it is not necessary for the tube to reach the melting temperature to rupture. An aluminum tube held at 200°C for thirty minutes will have a 70% reduction in tensile yield strength compared to the room temperature value; at 250°C for thirty minutes, the tensile yield strength reduces to approximately 50% of the room temperature value. These values are for half hour exposures at these temperatures and not short term events like arcing. To our knowledge, tensile strength reduction for short term temperatures has not been determined.

1.2 Arcing at a Distance

Past experimentation has shown the hazards of direct contact arcing between a wire and hydraulic line[i]. Limited research has been published on the effects of arcing at a distance and in these cases, the target has still been an unpressurized tube[ii].

The properties of arcing to a target at a distance are different than those of direct arcing. Because there is a gap, the arcing does not start between the target and the powered wire. Rather, the arcing begins between the wire and either a ground, such as an exposed surface or a damaged ground wire, or another power wire. The arc generates a plume of hot, ionized gas that emanates from the arc site. The arc plume develops very quickly, and can start electrical energy transfer to a target one inch away in less than 0.01 seconds.

The ionized arc plume gas causes a breakdown of the air allowing low voltages (e.g. 115VAC) to cross gaps that would be impossible otherwise. It is this process that makes it possible to cause damage at a distance in arcing events. This research was performed with positive separation of 0.5 – 2.0 inches between the aluminum hydraulic line target and the arcing wire bundle.

1.3 Arc Damage Modeling Tool

The Arc Damage Modeling Tool (ADMT), which was developed by Lectromec in coordination with the FAA Technical Center, is focused on the simulation of damage caused by electrical arcing events. The ADMT is a software tool that can be used to model arc damage and provide predictive analysis.

While the ADMT was developed with capabilities of handling internal fluids and pressurized tubes, this functionality had not been validated with experimental data. This research effort used the temperature and electrical information for validation of the ADMT simulations.

2 Test Configuration

The following describes the test configurations. The test circuit can be seen in Figure 1. A 20kVA, 400 Hz, 3 phase generator was used as the power source. The test circuit has no circuit protection except for a circuit control unit (CCU) to remove system power after a predetermined duration. The CCU could be set to an accuracy of ±10ms.

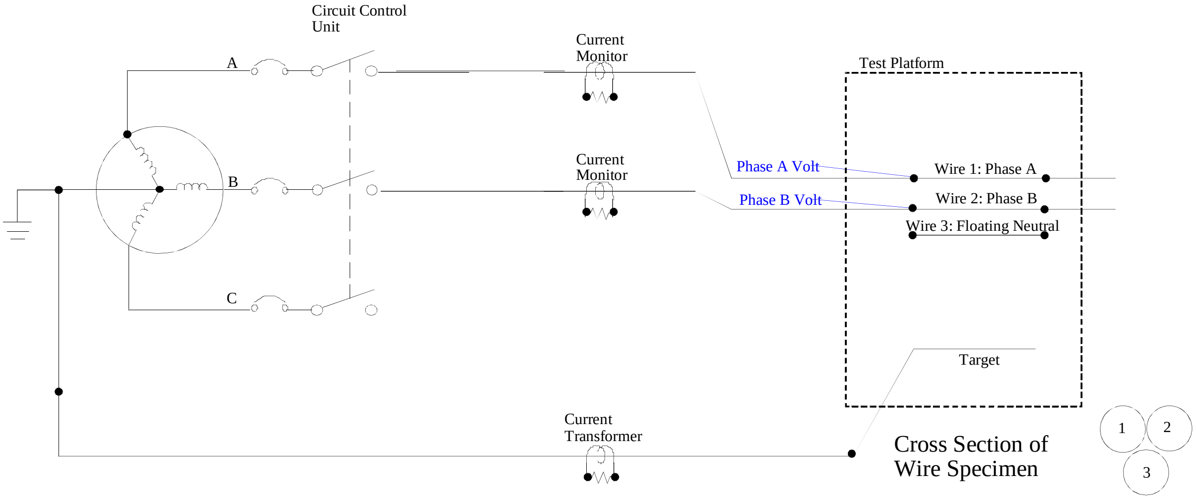

Figure 1: Circuit Diagram.

The test wire bundle consisted of three 2AWG AS22759/87 wires. Two of the wires were pre-damaged either by a ring cut (similar to the one used in the wet arc track resistance testing AS4373 Method 509 shown in Figure 2) or sliver cuts (small sections of the wire insulation removed from the wire shown in Figure 3). The third wire in bundle was floating (not connected to power). The 2AWG pre-damaged wires were connected to separate phases of a 20kVA generator. The fault current for the circuit was 550Amps.

Tests were performed with a 0.375 inch aluminum tube (Alloy 6061) connected to ground as the target. The tube had a wall thickness of 0.035 inches and rated to a maximum pressure of 1,736psi, but was only pressurized to 600psi for the testing. Temperature measurements were made by one or more thermocouples secured on the inner wall of the aluminum tube. This can be seen in Figure 2 and Figure 3.

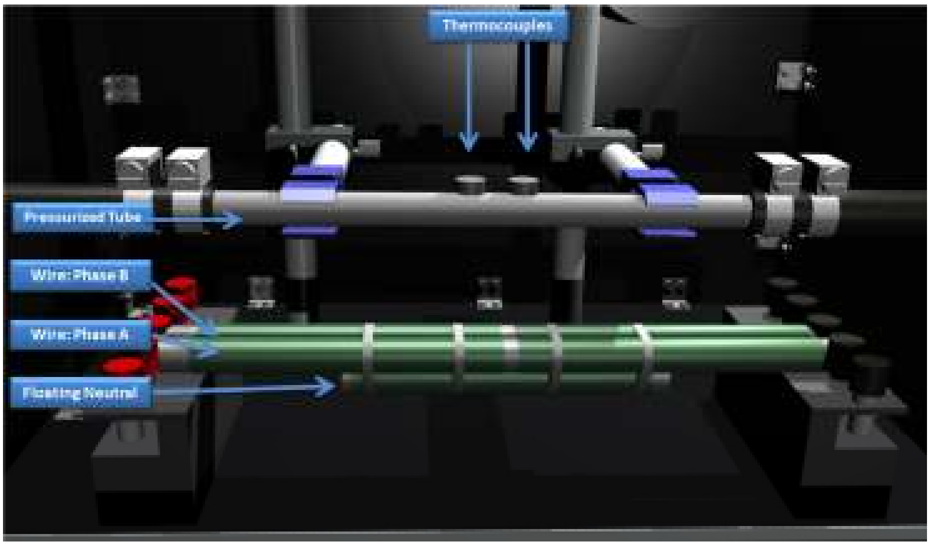

Figure 2: Configuration of Pressurized Hydraulic Tube Test with Ring Cuts in the wires.

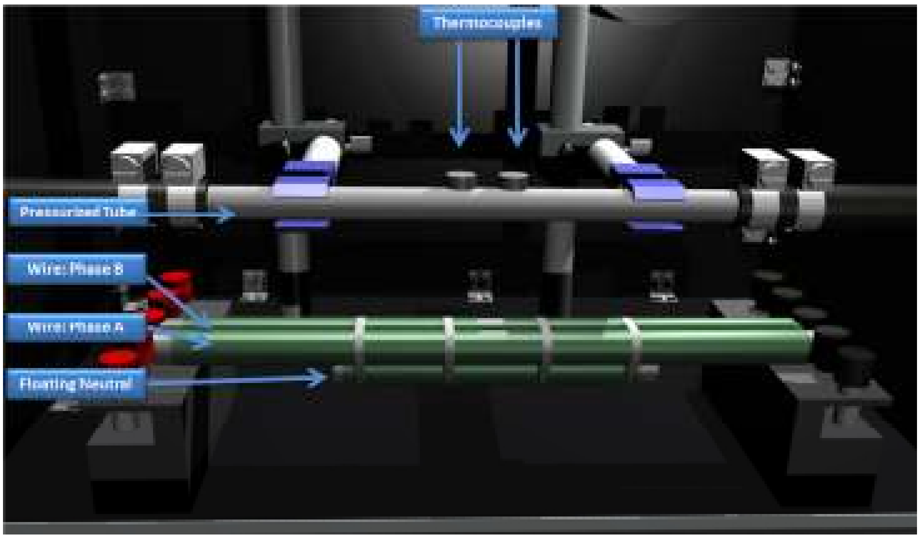

Figure 3: Configuration of pressurized hydraulic tube test with sliver cut in the wires.

Before the target was added to the experiment, the test wires were first prepared by making momentary contact between the two conductors with a grounded aluminum blade. Once the wires began to arc, the power was cut off, and the target was placed at the defined distance. The circuit control unit was then set for a defined time and the power reapplied.

Since the hydraulic system had a small amount of hydraulic fluid with no reservoir, a breach in the tube would result in an immediate drop in pressure. This limited the amount of fluid that would be ignited in the case of a breach.

A camera was placed over the experiment to monitor the direction of the arc plume. An example of this can be seen in Figure 4. Past experimentation has shown that the arc can vary more than 45° from vertical for the same configuration.

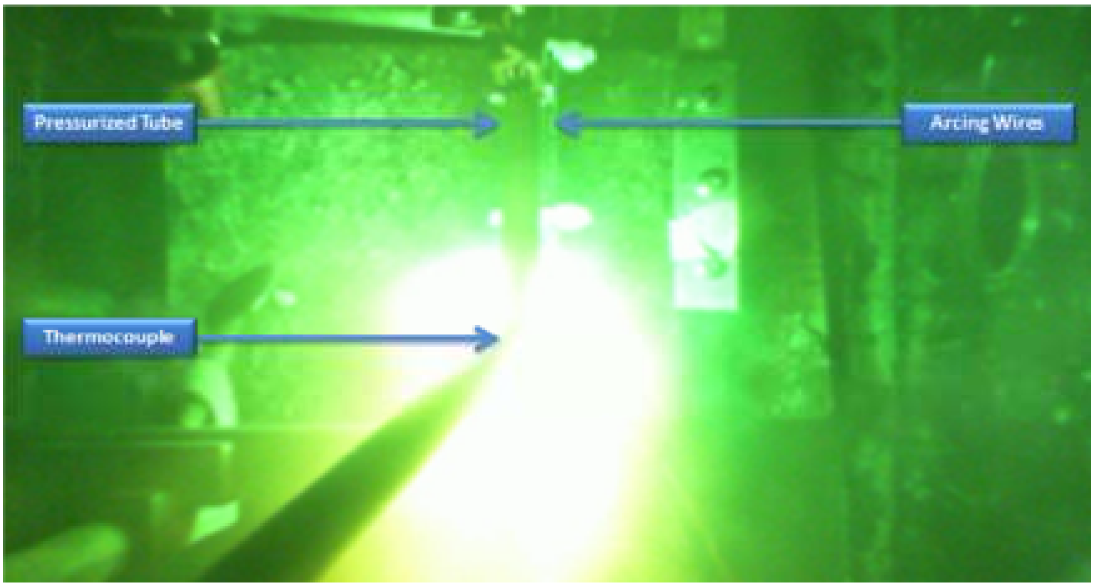

Figure 4: Overhead UV filtered image of arcing event

Figure 4 shows an example of the UV filtered arc plume. With the most energetic part of the arc blocked by the target, it was possible to evaluate the arc plume width and direction. This provided additional information for comparing similar tests and determining causes for the variability of test results.

3 Results

The research had two distinct sections: Testing was performed with different separation distances and different arc durations. Below are results of several important tests are described. The testing data was then used as input data to the arc damage modeling tool and the simulated results compared with the experimental.

3.1 Test Results - Breached Lines

During the testing phase, Lectromec performed a series of tests that examined different arc durations over different distances. The first group described here was performed with a 1.0inch separation between the pressurized tube and the arcing wires. Initial shorter duration tests allowed heat transfer parameters to be determined. One test in this series (OVH-R274-30) that resulted in a beach, had sporadic arcing lasting 200ms, energy output of 2219 Joules, and 606 Joules of direct arcing to the target. Figure 5 shows the energy and power plot for this experiment.

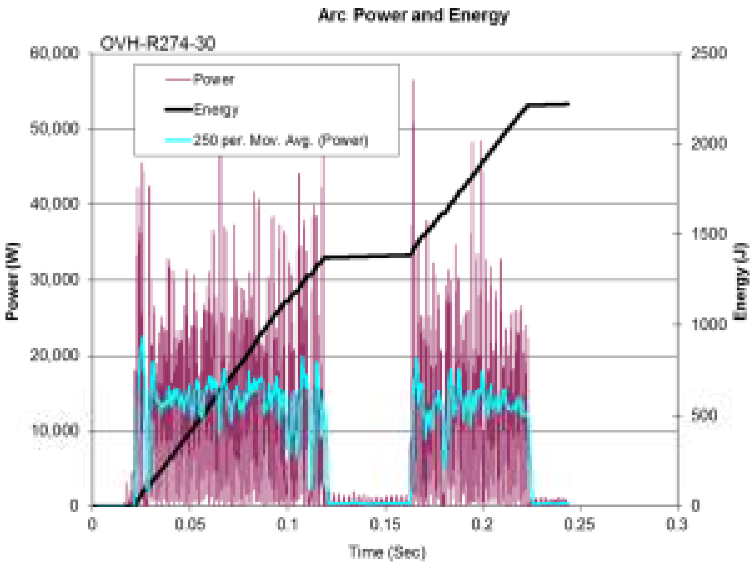

Figure 5: Power and Energy curves for the arcing event that ruptured the pressurized hydraulic tube.

Given that the thermocouples were on the inside tube wall, there was a small delay between the arc plume enveloping the tube and the thermal energy conduction through the target.

Examination of the pressure data showed that the tube wall ruptured after the end of the arcing event had occurred. This would indicate that there was sufficient energy transferred to the aluminum tube (through direct arcing and heating from the arc plume) that the outward pressure breached the wall of the tube (Figure 6).

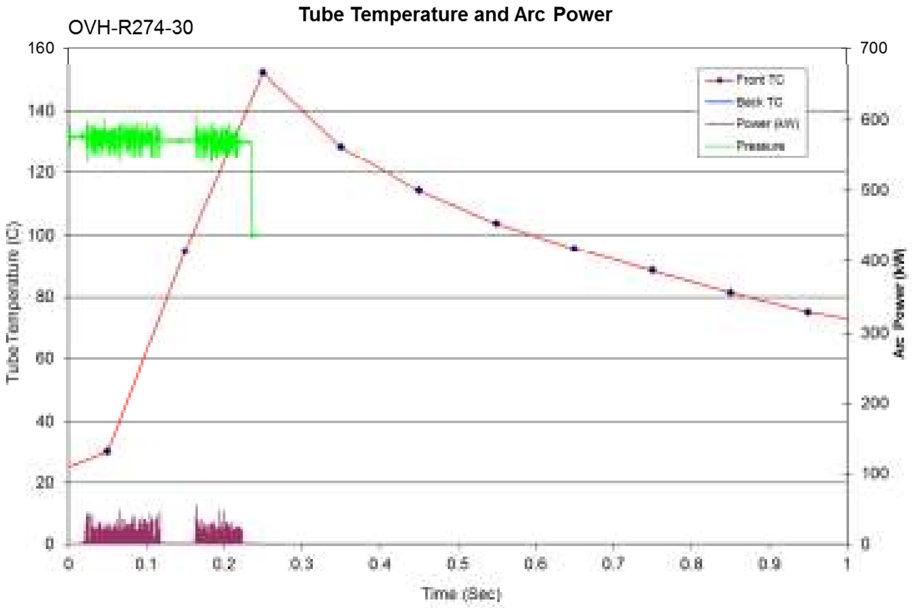

Figure 6: Pressure, temperature and power graphs for test with breach in hydraulic tube

The maximum recorded temperature from this test was 157°C, but this was not at the site of the breach. The thermocouple was 1cm away from the arc location indicating that the highest temperature location was not captured in the test measurement. The data from this test could then be used with the ADMT to determine the failure temperature of the tube.

Figure 7: Breach created in 1.0 inch separation test.

The breach shown in Figure 7 was the most pronounced of the breaches that were seen in the hydraulic tubes. Other failures were seen as stress fractures and pinhole breaches. Sometimes these holes were so small that it was impossible to detect with an unaided visual examination.

3.2 Test Results – Unbreached Lines

Some testing did not yield breached hydraulic lines. These tests helped set the upper boundary on the maximum temperature for a pressurized tube. Test OVH-R274-46 (seen in Figure 8) was performed with a two inch separation from the target. The arc duration was set to 2.4s and resulted in a total arc energy greater than 18kJ. Although this was a significantly longer event, the aluminum tube did not sustain the same level of damage as the previous example (Figure 9).

Two thermocouples were used in the test, based on comparison to the damage profile observed in the posttest analysis, and were in the most heavily damaged areas of the target tube. As such, the 200°C maximum temperature that was recorded is fairly close to the hottest temperature on the tube from this test.

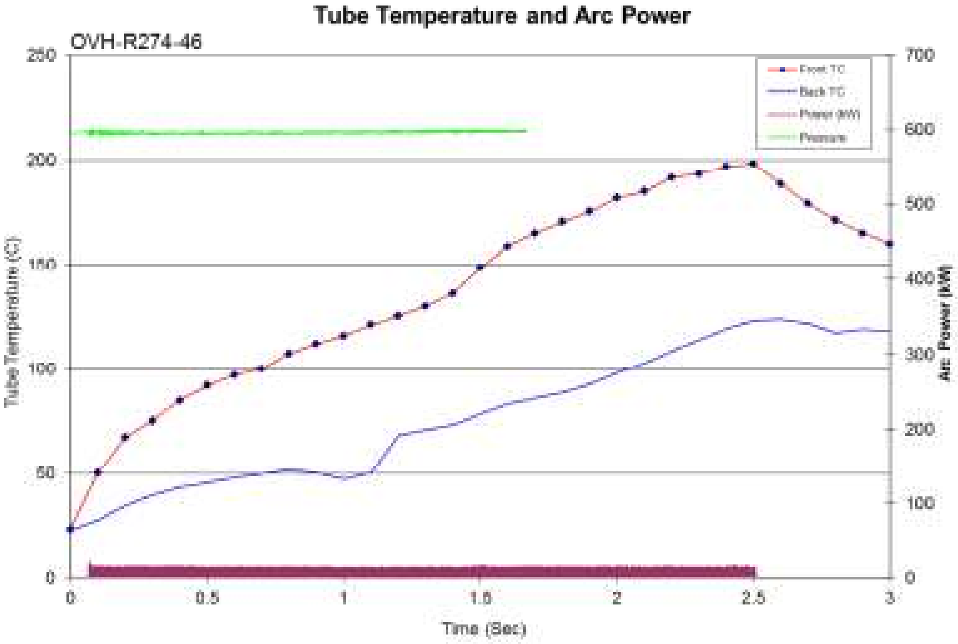

Figure 8: Temperature and power plots from 2.0 separation test

Posttest examination of the target tube showed no pitting as typically seen in cases of direct arcing. The tube did show a large amount of copper residue and splatter from the arcing between the wires which could not be easily removed.

Figure 9: Posttest photo of target aluminum tube OVH-R274-46

One of the changes that may have lowered the energy was that this test was performed with a ring cut in the arcing wires and not a sliver cut. It appears as though the direction of the arc plume is significantly affected if there is a ring cut in the wires (as in wet test specification SAE AS 4373 method 509) or if there is nick in the wire insulation.

3.3 Comparison to simulations

To gather further information on the rupture temperature of the pressurized aluminum tubes, simulations were performed using the experimental data. As noted earlier, the breach in the tube wall from test (OVH-R274-30) was measured to be 11mm from the location of the thermocouple. To identify the temperature the tube had reached before rupture, the test parameters were entered into the ADMT.

Figure 10 shows the ADMT simulation results using the arc energy waveform from the experiment. The pink, cyan and green lines show the simulation temperature at three different locations. The green line is the simulated temperature measurement 12mm from the center of the arcing event. This shows close correlation with the measured temperature (the sampling rate of the temperature data recorder was 10 S/s).

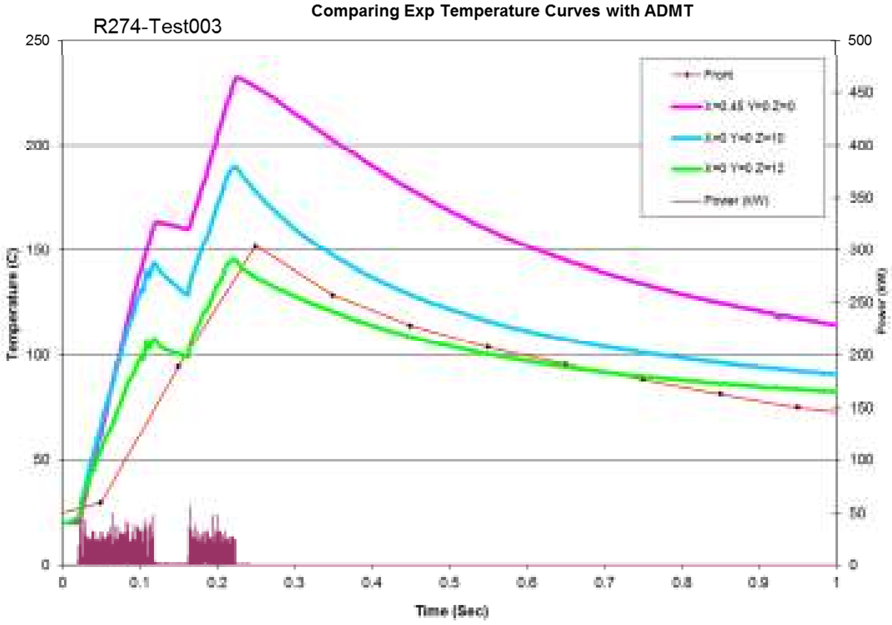

Figure 10: Simulation results of (OVH-R274-30)

At the center of the arc, the simulation suggests that the tube reached a maximum temperature of 232°C before breaching. The maximum simulated temperature indicates that this increase to 232°C is sufficient to create a breach. Simulations based on other testing showed similar limits.

Simulations were also performed on test that did not yield tube breaches. Figure 11 is an example of an ADMT simulation that as did not have a breach. In this test, two thermocouples 0.5inches apart were used. The simulations results show excellent correlation with the experimental data.

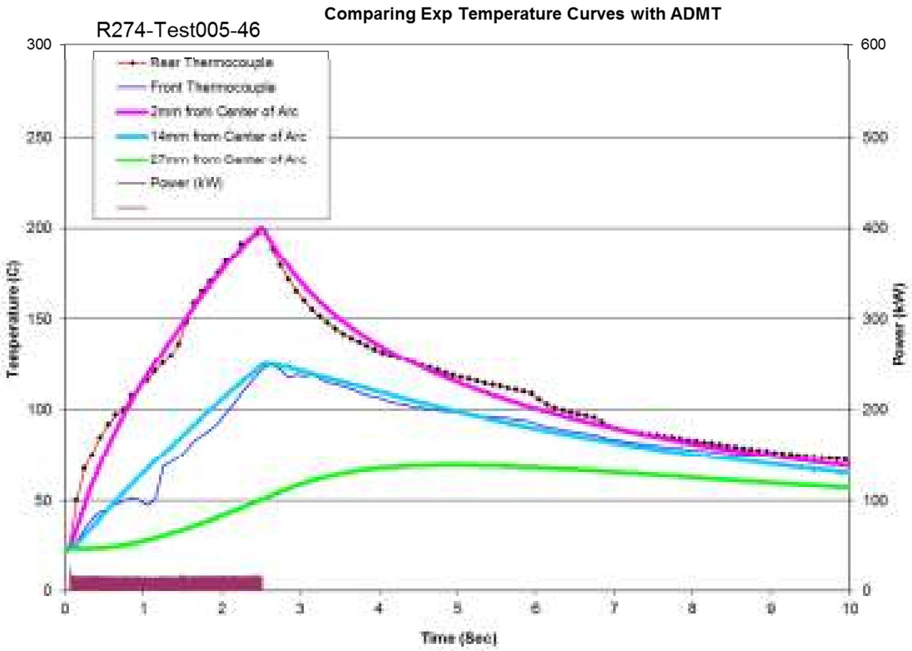

Figure 11: Simulation results of (OVH-R274-46) [no breach of hydraulic line]

While there was significant energy transfer to the target, the target temperature was not high enough to cause a breach. The long duration of the arc event resulted in energy being thermally conducted away from the areas within the arc plume to the cooler areas. Further, the simulation shows good correlation with the experimental results at times long after the arc has completed. This was not the case in tests with breaches as the simulation does not account for the effects of moving fluids.

4 Conclusion

The presence of pressurized hydraulic fluid in a tube makes a significant difference in the amount of energy necessary to create a breach in the tube wall. Even without direct contact, it is possible to transfer sufficient energy to cause a breach of a pressurized line. The effects of hydraulic fluids should be considered in any analysis to determine safe separation distances.

The tests covered in this report were configured such that the wires are below the hydraulic line (against industry standard practice). However, it is unlikely that the orientation has a significant difference impact on the results as the plume from the arcing wires is pushed outward from the initiation site. The test could have been configured in any direction; the experiments were easier to perform with the configuration used.

It is possible to model the development of the arc, arc energy, arc plume, and damage to a target. The simulations have shown excellent alignment with the laboratory data and have been presented in this paper. Further testing is necessary to ensure validation of the simulation results.

The arcing scenarios investigated in this research were hazardous, but could be recreated in an aircraft environment. Aircraft with larger generators or many smaller gauge wires could easily create scenarios with damage at greater distances.

In experiments with longer arc events, the thermal conductivity of the target material plays an important role in limiting the damage. The testing described in this report used aluminum tubes as the target with a thermal conductivity of $235\frac{W}{m*K}$ (58% copper's thermal conductivity). Other tube materials, such as titanium, have a thermal conductivity of $22\frac{W}{m*K}$ (5% copper's thermal conductivity) and would be more susceptible to damage from arcing events. Material parameters should be considered when defining separation requirements.

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[i] Linzey, W. G., Traskos, M. G, Bruning, A. M. et al. "Progress in Developing a Software Based Modeling Tool", 10th Aging Aircraft Conference, April 2008.

[ii] Linzey, W. G., Traskos, M. G, Bruning, A. M. et al. "Arcing Damage to Aircraft Components and Wire at a Distance", 11th Aging Aircraft Conference, April 2009.