An Analysis of Heat Flux-Induced Arc Formation in Residential Electrical Cables

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ABSTRACT

Electricity has long been a topic of interest in the fire investigation community. Common misconceptions about electricity have lead to the misinterpretation of electrical evidence to establish an area of origin and incorrect determinations that an appliance or wiring was the ignition source of a fire. This research was focused on improving the understanding of the mechanisms by which fire environments may trigger electrical arcs in common residential wiring. An understanding of these mechanisms will help fire investigators determine whether a given arcing event was the cause or result of a fire and how the fire progressed through a structure. In this study a cone heater was used to expose one side of an AWG 14/2 with ground non-metallic sheathed cable to a uniform radiant heat flux. A diagram of the test setup is shown in Figure 1 below. Nonmetallic (NM) sheathed cable was used for testing as it is one of the most widely used materials for residential wiring across the United States, and can be easily purchased at nearly any home improvement store. The structure of the cable can be seen in Photograph 1.

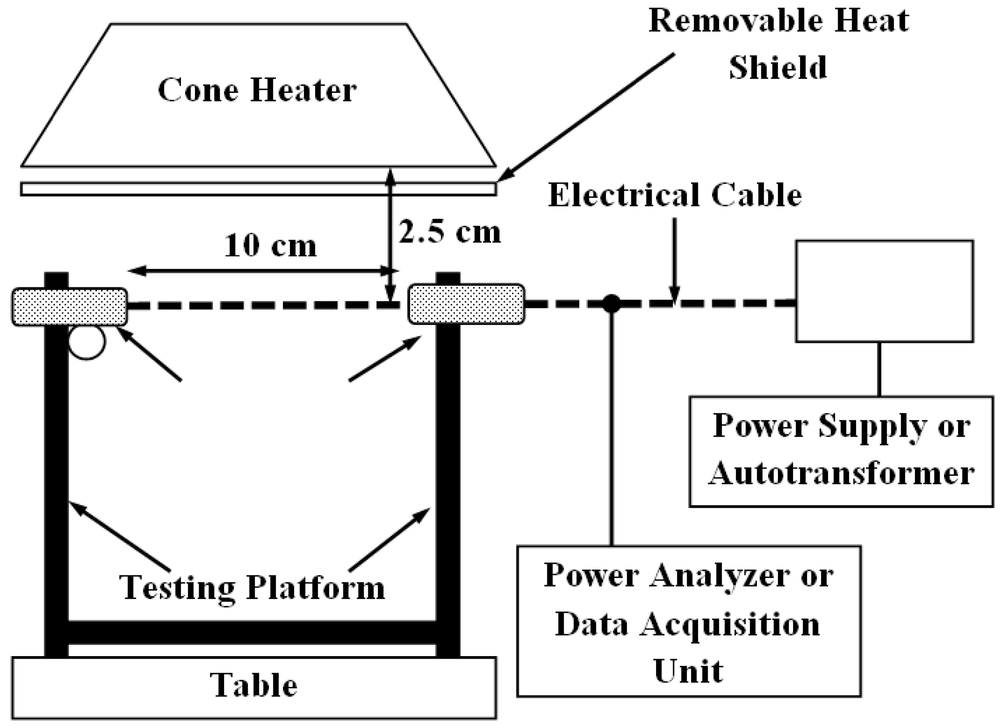
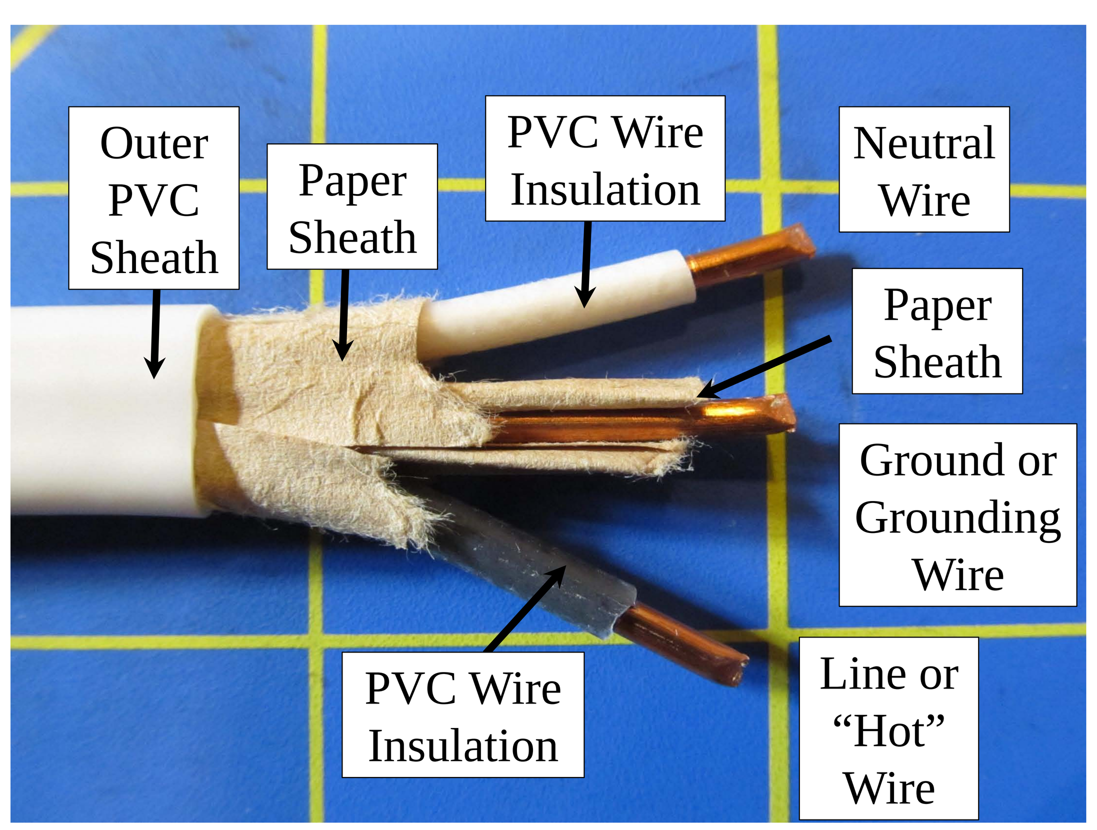


Figure 1: Setup used for the testing of electrical cables under the cone calorimeter.



Photograph 1: Components of the cable used for testing.

Four phases of testing were conducted for this project; 1) unenergized, 2) energized, and 3) energized with variable voltage, and 3) energized within an oxygen-deficient environment.

In the first series, unenergized cables were subjected to various heat fluxes while the resistance between the conductors was monitored. The results of these tests show that as the temperature climbs, at a certain point the insulation becomes a temperature-dependent semiconductor. Figure 2 shows the resistance between conductors on the cable at a heat flux of 26 kW m^{-2}. Of note from these tests is that the resistance never dropped below a value of 10,000 ohms. No significant current flow would be expected at resistances of this level.

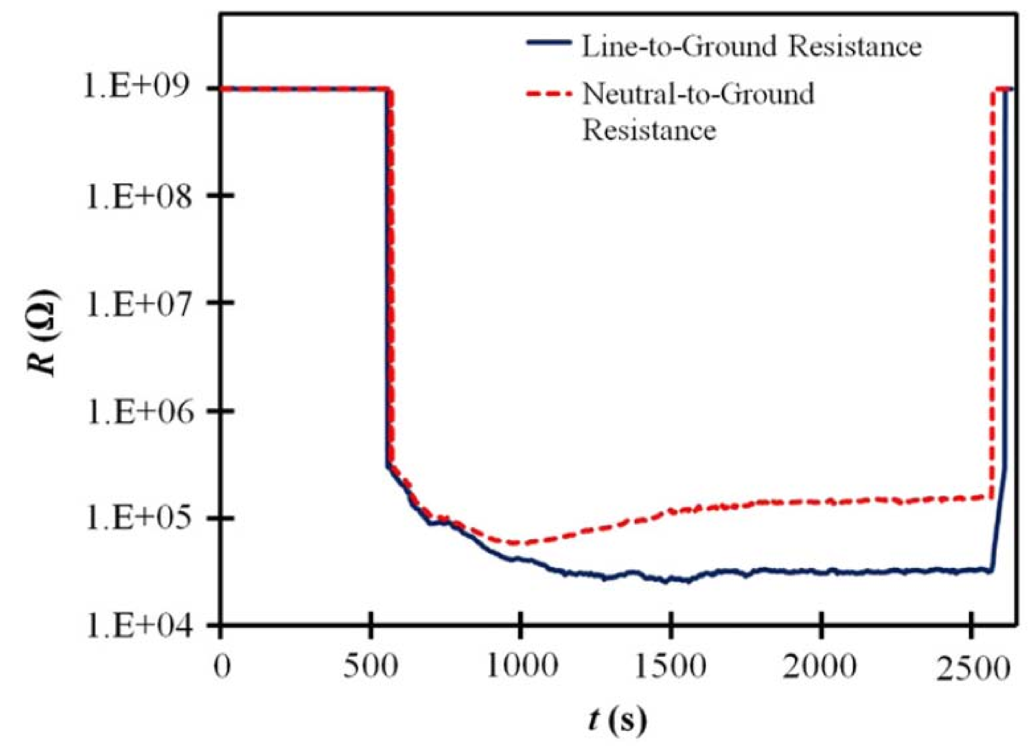


Figure 2: Graph showing the inter-conductor resistance when exposed to a heat flux of 26 kW m^{-2}. t=0 and t= 3000 s are the start and end of the test, respectively.

For the second phase of testing, cables were energized without a load and tested under heat fluxes up to 55 kW m^{-2}. The time-to-failure data are plotted in Figure 3 as a function of the radiant heat flux. The data shows an approximately linear trend when the reciprocal time to failure is plotted against the heat flux. At lower heat fluxes (22-25 kW m^{-2}) no failure was observed, despite the fact that tests were run for up to five hours. From this graph a critical heat flux necessary to cause an arcing event can be calculated to be approximately 22 kW m^{-2}. This can be drawn from Equation 1, which is from the linear curve fit (solid line) of Figure 3. The dashed lines represent 80% confidence intervals. C_{HF} and HF_{cr} are fitting parameters that were calculated to be 1.6x10^{-4} kJ^{-1} m^2 and 22 kW m^{-2}, respectively. HF_{cr} represents the estimated critical heat flux required for arcing.

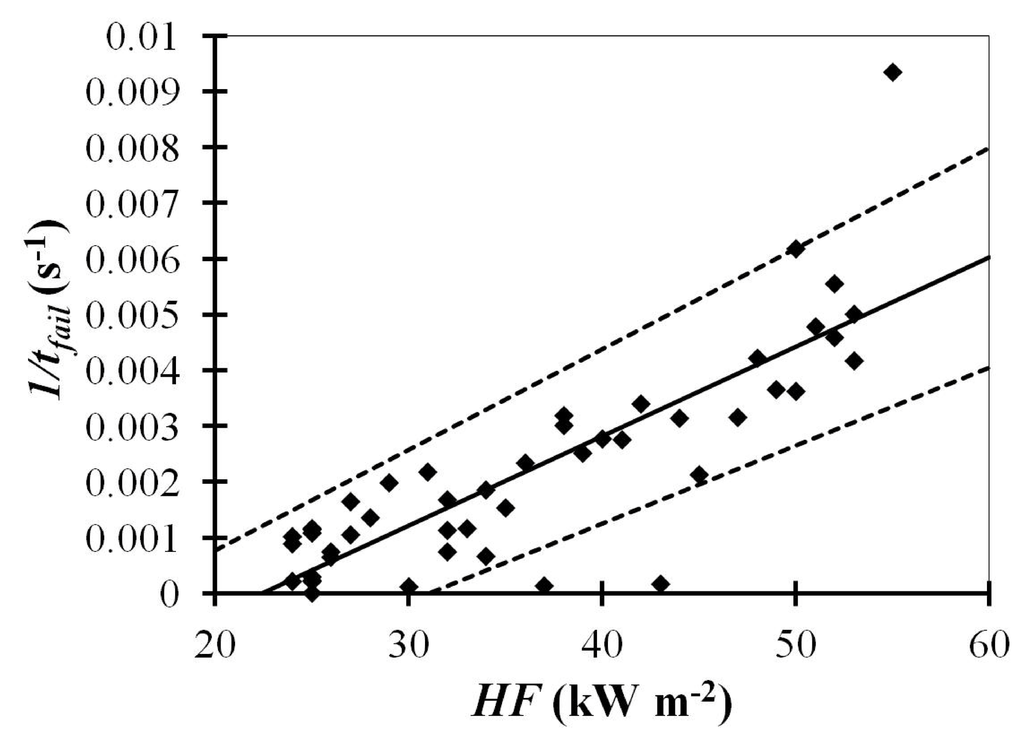


Figure 3: Graph showing inverse time-to-failure ($1/t_{fail}$) with respect to heat flux. The solid line is a curve fit, represented by Equation 1. The dashed lines are 80% confidence intervals.

$$\frac{1}{t_{fail}} = C_{HF}(HF - HF_{cr})$$ **Equation 1**

During the third phase of testing, cables were subjected to a constant radiant heat flux of 50 kW m^{-2}. However, the voltage was varied between 20 and 140 VAC using an autotransformer. The inverse time-to-failure ($1/t_{fail}$) again exhibited a nearly linear trend, as shown in Figure 4. From this linear trend, an approximation was made as to the critical voltage required to produce arcing, and is shown by Equation 2. This critical voltage, V_{cr}, was calculated to be approximately 15 VAC. The parameter C_v was calculated to be 6.0x10^{-5} VAC^{-1} s^{-1}.

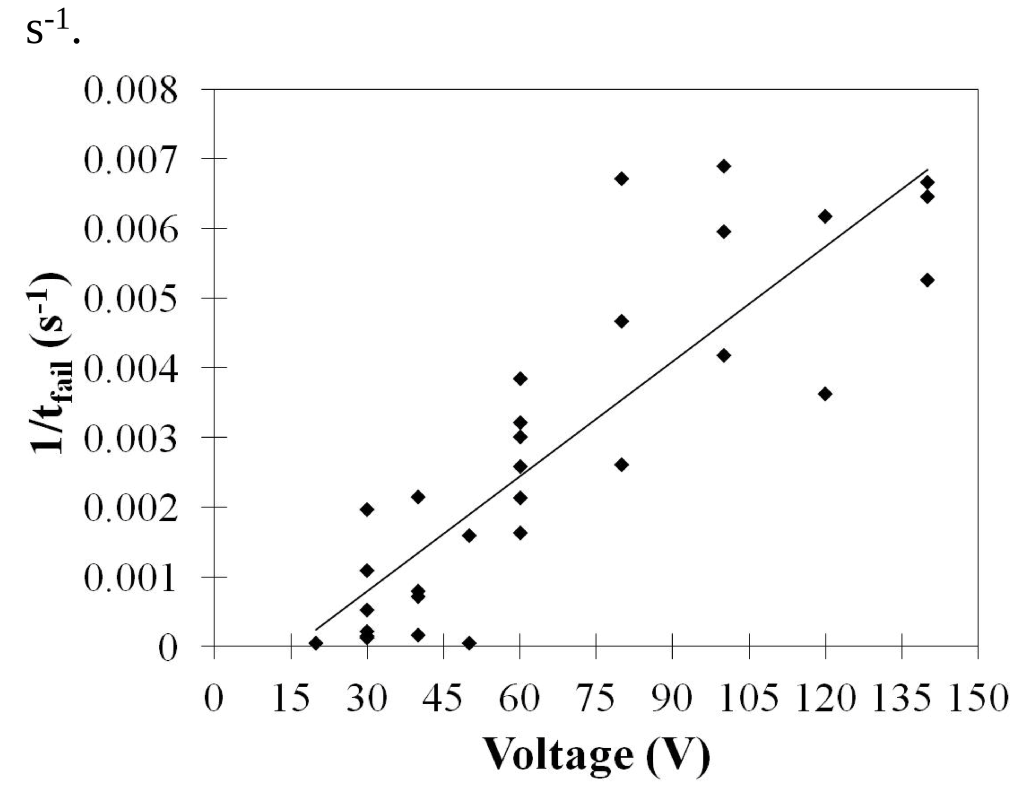


Figure 4: Graph showing the nearly linear relationship between AC voltage and the inverse time-to-failure. The solid line is a curve fit represented by Equation 2.

$$\frac{1}{t_{fail}} = C_V(V - V_{cr})$$ **Equation 2**

In the last phase of testing, cables were subjected to heat fluxes between 48 and 54 kW m^{-2}, with an applied voltage of 120 VAC. However, the tests were conducted within a nitrogen atmosphere (nearly 0% oxygen). The inverse times-to-failure ($1/t_{fail}$) are shown in Figure 4. The solid line is the approximation from phase 2 and denoted by Equation 1 for tests in ambient air. From this data we can see that it actually took less time to form an arc in a nitrogen environment, however the artifacts left behind were identical to all others.

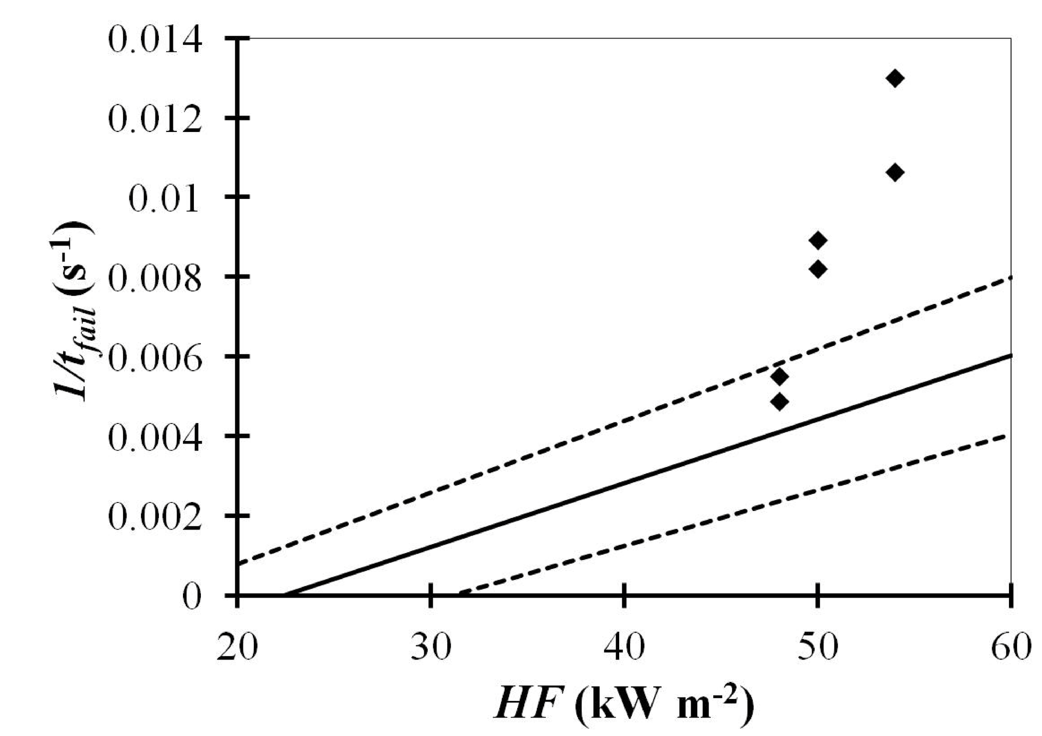
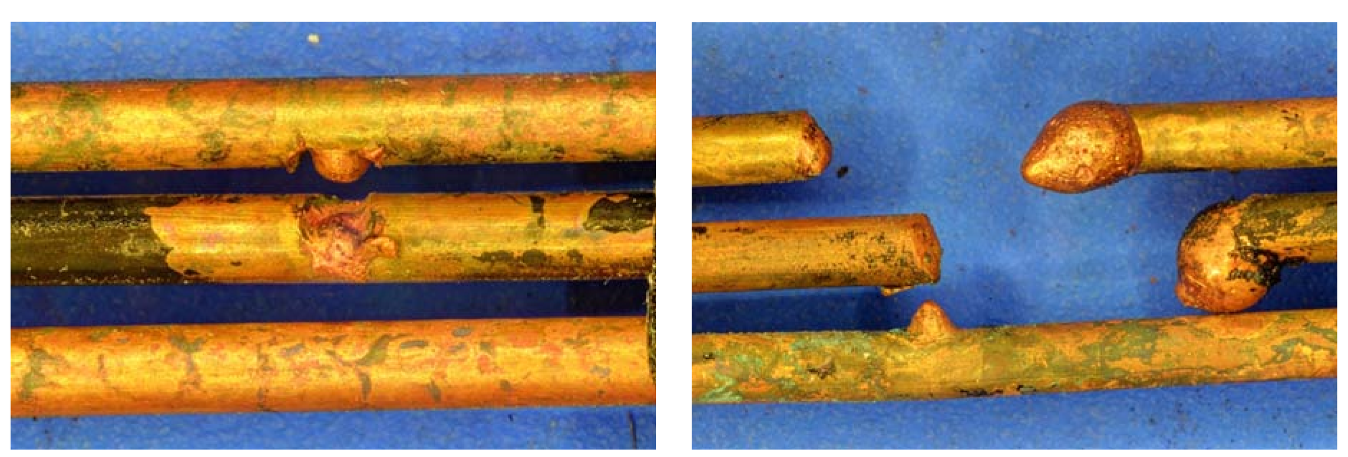


Figure 4: Graph showing the inverse times-to-failure found in a nitrogen environment. The solid and dashed lines are from the energized tests in normal air, shown for comparison.

The arcing damage created in each series of tests exhibited characteristics found in various fire investigations texts, including *NFPA 921: Guide for Fire and Explosion Investigation*. These characteristics include a sharp line of demarcation and highly localized area of damage, with corresponding damage on adjacent conductors. Examples of this arcing damage are shown in the photographs below.



Photographs 2 and 3: Arcing damage created during testing. Nearly all arcing damage was consistent throughout the project, and exhibited characteristics described in *NFPA 921* and other fire investigation texts.

Computer pyrolysis modeling was used to determine if extrapolations could be made regarding the time it takes to create a failure in a fire environment. This was done using Thermakin, a one-dimensional model developed at the Federal Aviation Administration (FAA). For these models, cables were assumed to be laying flat on the surface of 3/8 inch gypsum wallboard. On the other side of the wallboard, fires of various intensities were modeled with heat fluxes of 50, 60, 100, and 150 kW m^{-2}. Failure times under these conditions (assuming that the gypsum wallboard did not fail) were approximately 18.5, 13.9, 8.4, and 6.3 minutes, respectively. Simulations were also conducted at 33 kW m^{-2}, which is representative of conditions at the ceiling in a compartment at the onset of flashover. Under these conditions, no failure (i.e. arcing) was obtained in over one hour. From this data, it can be postulated that in order for a failure to occur within a period of investigative interest (i.e. minutes versus hours), the gypsum wallboard must physically fail or be exposed to flashover conditions for six minutes or more.