

# Identifying Causes for Certain Types of Electrically Initiated Fires in Residential Circuits

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***Extended Abstract*** – While there are many circumstances that can lead to an electrical fire, it is useful to identify and document potentially hazardous conditions that can occur in residential electrical wiring. Conditions that can be reproduced in a laboratory, intended to replicate real-life conditions, can be used to increase knowledge for augmenting fire forensics and as a guide for manufacturers to develop safer, more fire resistant electrical systems. Electrical faults can be either series (a break in one leg, either line or neutral) or parallel (line-neutral, line-ground) or a combination of both.

Residential wiring can be classified into two groups, behind the wall (fixed wiring and portable wiring (appliance cords, extension cords, etc.)). Each class can have its own set of circumstances that can lead to potentially hazardous conditions, including damage, misapplication, loose connections, harsh conditions, and wire aging. Some examples for fixed wiring arcing failures include loose connections at an outlet, a staple or drywall screw bridging conductors, and excessive self-heating by current flow leading to wire insulation degradation and failure. Examples of portable wiring faults include cut wires, broken strands, abraded wire insulation, loose connections, and self-heating. All these conditions can occur for old as well as new wiring. Aged wiring and in particular fixed wiring, since it is much more costly to replace than portable wiring, may fail due to insulation degradation, especially if rework or retrofitting has disturbed the wiring. Moving and bending old wiring that has become embrittled from age, can crack the insulation and expose conductors possibly leading to arcing.

Traditional electro-magnetic (E-M) circuit breakers are designed to protect against overloads and high current parallel faults. However, studies by the CPSC have shown many cases in which appliance cords or extension cords or other types of sputtering arcs started fires but the E-M breaker never tripped. This type of study spurred the development of the arc fault circuit interrupter (AFCI). Extension cords or appliance cords can greatly reduce the available fault current with resulting sputtering or intermittent arcing currents that are below the magnetic trip threshold of E-M breakers. These are parallel arcing faults that can persist long enough to potentially cause fires. The other possible fault condition is a series arcing fault. This, for example would be when one leg of a wire is broken and

unintended arcing occurs with resulting glowing connection and/or carbonization. At first sight, this condition is not as dangerous as the sputtering parallel arcing fault due to the lower arcing energy per half-cycle and the thought that the arc would extinguish after  $\frac{1}{2}$  cycle. Also, the series arcing current is determined by load impedance unlike the parallel case where the source and line impedance determine the fault current. It was however discovered that low current series arcs with associated ignition of evolved gases and charring of insulation could also be potential fire hazards.

This work shows examples, and the underlying mechanisms, of how electrical fires can start in both fixed and portable new wiring. Results are also provided from highly accelerated life testing of various types of residential wiring to illustrate how aged wire may fail.

Three cases of parallel arcing faults are described. The first case is cutting across energized conductors. Current and voltage waveforms are shown for six different configurations. These include the type of circuit breaker protecting the circuit, and the type of wire cut (2-wire or 3-wire). Depending on the available fault current, waveforms show that the sputtering arcing fault, created by cutting the wire, depends on the breaker type (standard E-M, AFCI, GFCI) and wire type (SPT-2 2 conductor or 3 conductor). The second parallel arcing case illustrates how a bundled extension cord under a rug, a common misapplication, can lead to parallel and series arcing faults that can start a fire. The third case shows how fixed wiring (NM-B) cable, bundled and thermally insulated at a load center, can become overheated due to self-heating and cause wire insulation failure that leads to parallel arcing.

In explaining how series arcing faults can initiate fires, the paper draws on extensive PVC wire insulation background regarding common plasticizers used and the deterioration and decomposition mechanisms that occur when PVC wire insulation is heated and exposed to arcing. Gas analysis measurements have revealed that flammable gases can evolve from pyrolyzed PVC insulation. There are three examples presented showing how series arcing can initiate fires. Two examples illustrate a broken conductor in SPT-2 cord that is arced repeatedly. Over time, this repeated arcing of the conductor causes either a glowing connection to form or charring of the surrounding wire insulation. Both of these conditions lead to a fire because of the evolved gases created by the decomposition of the wire PVC insulation. The insulation decomposes because of the high temperature produced by arcing over char or the glowing connection. Glowing connections, arcs, and hazardous gas evolution were created at currents as low as  $0.9 A_{rms}$ . Extensive studies will be presented on the properties of glowing connections along with waveforms and corresponding high-speed video images of the fire initiation process. The third example shows how NM-B cable can char a 2x4 wood stud when a steel staple cut the neutral wire, forming a bridging connection across the neutral wire, to create a glowing connection.

The paper also contains data on accelerated aging of various types of residential wiring. Wires were placed in an oven at 100 °C and 130 °C to accelerate the aging process. Measurements of the insulation properties - ac high voltage resistance, capacitance, dc resistance,  $\tan(\delta)$ , and weight loss - were performed over time to show how properties of the various wires changed. A second experiment was performed to measure the flexibility of the wire insulation. Again, using an oven to accelerate the aging process of the wire insulation, a life model using a WLF equation for polymers, was developed. As the wire insulation was aged in the oven, it became more brittle. The time it took to cause the insulation to crack, when flexed around a radius, was used to develop the model. Time to embrittle the insulation at room temperature could then be predicted based on the accelerated life tests assuming that cracked insulation could lead to parallel arcing within the wire sheath. While this oven heating was intended to take new wires and accelerate the aging process, to replicate average conditions found in a home over many decades, one can see from the self-heating results, that even new wires can be subjected to temperatures well above their service rating in a very short period of time and with resulting degradation to failure.

*Keywords: Arcing, PVC, Wiring, NM-B, SPT-2, Residential Circuit Breaker, Series Arcing, Parallel Arcing, Glowing Contact, AFCI, GFCI, WLF equation*