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A criterion for thermally-induced failure of electrical cable

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ABSTRACT

Electrical failure of 14 American Wire Gauge nonmetallic-sheathed cable, which is used widely in residential electric circuits in the United States, was examined in a range of high temperature environments. Slow heating rates were maintained in these environments to ensure that the heat transfer inside the cable was not a significant factor in the failure process. The experiments were performed in non-energized configuration (insulation electrical resistance was measured), energized with a nominal voltage of 120 V of alternating current and no load, and energized and loaded configurations. In the case of energized experiments, the main parameter that was determined was the time to cable failure. This time was found to be highly reproducible and strongly dependent on the cable temperature. Individual cable insulation components were also examined in a range of experiments including thermogravimetric analysis to gain insight into the mechanism of the failure process. It was determined that the time to cable failure can be quantitatively linked to a particular insulation component reaching a critical degree of thermal decomposition. The use of this criterion within the framework of a thermal degradation model, which was parameterized based on anaerobic thermogravimetric analysis, produced reasonably accurate predictions of the times to failure for a range of energized cable tests.

1. Introduction

Electrical wiring is cited as the cause of a notable number of residential fires in the United States. From 2006 to 2008, about 6% of residential fires were categorized as electrical fires [1]. Of those electrical fires, an estimated 40% were attributed to wiring of the building. The rest of the electrical residential fires were attributed to cords, plugs, sockets/receptacles, lighting, and other electrical devices. Per fire, electrical fires were more deadly, caused more injuries, and resulted in more property damage than non-electrical fires from 2003 to 2005 [2]. As these statistics show, electrical fires, specifically those caused by building wiring, represent a significant problem for public safety.

While wiring-induced fires represent a significant problem, their analysis, reconstruction and prevention are still extremely difficult. In particular, determining whether an electrical cable failure is the source of ignition or simply a result of an already existent fire has been a problem for many in the fire investigation community [3]. A failure of energized cable frequently causes an arc, which is defined as an electric discharge across a gap or through a semi-conductive medium [4,5]. For residential purposes, arcing events (or faults) can be divided into two main categories: series and parallel. A series arc fault occurs within an existing loaded circuit and is frequently a result of a loose connection producing glowing contacts or continuous arcing through char [6].

The arc faults that were the subject of the current study are parallel arc faults. Parallel arc faults can be caused by a direct contact between a hot/line and ground wires of an energized (but not necessarily loaded) cable or by the formation of a conductive bridge between these wires [6]. This bridge can be produced by thermal degradation of the cable insulation. Some of the earlier studies of cable insulation degradation caused by heat were performed by Beland [7]. He found that the insulation lifetime is inversely proportional to the temperature of the cable. Detailed experiments on thermally-induced failure of a range of cable types were subsequently carried out by Hoffmann et al. [8], Ferrino [9] and Hagimoto et al. [10]. It was observed that the time to failure decreases with increasing heat flux from a radiant source simulating fire.

In several recent studies [11,12], engineering models of heat-induced energized cable failure were developed. These models describe transient heat transfer inside the cable and rely on the notion of a critical insulation temperature at which an arc fault takes place. The results of a study conducted recently by our group [13] performed on a 14 American Wire Gauge (AWG) nonmetallic-sheathed cable suggest that the timing of an arc fault is defined by a critical degree of the thermal decomposition of the electrical insulation, which is a function of both local temperature and time.

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The current work examines this hypothesis further.

The same cable type (14 AWG nonmetallic-sheathed) was subjected to the thermal environments where heat transfer inside the cable was fast with respect to the rate of environmental temperature change. These experimental conditions, which were fundamentally different from those explored in our previous study, made it possible to decouple chemical kinetics of the insulation decomposition from the heat transfer inside the cable and analyze the relationship between the decomposition and occurrence of arc faults. The cable was tested in non-energized configuration (insulation electrical resistance was measured), energized with a nominal voltage of 120 V of alternating current (VAC) and no load, and energized and loaded configurations. Cable insulation components were also examined in separate experiments to gain insight into the mechanism of the failure process. From results of these experiments, a decomposition-kinetics-based model of the cable failure was developed and its ability to predict the time to an arc fault was validated. It was shown conclusively that, at low levels of heat exposure, critical temperature does not represent an accurate criterion for the cable failure.

2. Experimental

2.1. Electrical cable

The electrical wiring analyzed in this study was Southwire Romex SIMpull 14 AWG nonmetallic-sheathed cable, also classified as “thermoplastic construction” [12]. This cable is widely used in residential circuits in the United States. These circuits are typically powered by 120 VAC. As shown in Fig. 1, this cable consists of 3 solid copper conductors: the line conductor, neutral conductor, and grounding conductor (or ground). The first two conductors are identified by black and white insulation, respectively. The electrical insulation of these conductors is composed of polyvinylchloride (PVC) and a thin outer layer of clear polyamide (or Nylon), according to the manufacturer. The grounding conductor is wrapped in paper sheathing. The conductors are laid parallel to each other and wrapped with another layer of paper, followed by the outer PVC sheath. For simplicity, the paper and outer PVC are referred to as electrical insulators despite the fact that it may not be their primary functionality.

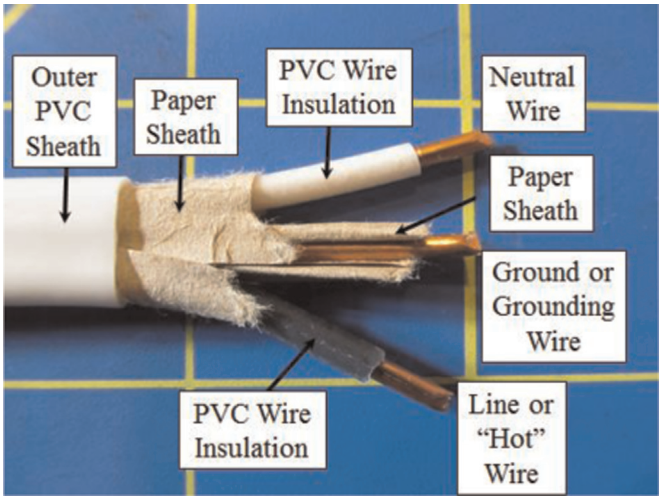

Fig. 1. 14 AWG electrical cable tested in this study.

2.2. Thermal environment

The cable and cable component experiments were performed using a Memmert UFE 500 convection oven. The temperature inside the $71 \times 76 \times 50\ \text{cm}^3$ oven chamber was monitored using 1.5 mm diameter, type K thermocouple probe suspended in the middle of the chamber. This temperature was controlled with a built-in proportional-integral-derivative controller. The atmosphere inside the chamber was air. The heating programs utilized in these experiments consisted of approximately 6 °C min^{-1} ramp followed by a plateau. Most of the experiments were performed using 3 temperature programs shown in Fig. 2 with plateaus at 200, 210, and 230 °C. Relative durations of the ramps and plateaus are indicated on the figure. These temperature programs were selected to achieve cable failure within a reasonable and reliably detectable period of time ranging between tens of minutes and several hours. The temperature inside the chamber was examined for spatial uniformity and reproducibility using a separate thermocouple. This temperature was found to vary by less than 3 °C among different positions inside the chamber, and was highly reproducible, less than 2 °C variation from experiment to experiment at a particular position and time.

2.3. Cable test setup and procedure

In preparation for oven testing, 127 cm long segment of the cable under study was mounted on a Kaowool insulation board using glass-wool-insulated metal brackets as shown in Fig. 3. A single 1.5 mm diameter, type K thermocouple probe was subsequently inserted into the cable, beneath the outer PVC insulation. Extreme care was taken not to penetrate the paper sheathing of the cable. The insertion position of the thermocouple was varied from test to test to examine potential variability in the cable temperature. Only one thermocouple was used in each test to minimize mechanical damage to the cable insulation.

Non-energized cable testing was performed by connecting a Fluke NetDAQ data acquisition system to the cable and measuring electrical resistance between the line and ground wire. A small voltage of 0.5 V of direct current was used for the resistance measurement. The cable mounted on Kaowool board was placed inside the oven chamber, connected to the data acquisition system and subjected to a heating program. The start of the heating program corresponded to the start of experiment. Both electrical resistance and cable temperature were recorded as a function of time with a frequency of 2 Hz. Only one oven temperature program corresponding to the highest, 230 °C, plateau was used in these experiments. The total of 7 non-energized cable tests were carried out to accumulate statistics.

Energized cable testing was first conducted without load. The cable was energized with 120 VAC by connecting it to a wall outlet via a larger capacity, 10 AWG cable. The circuit was protected by a 20 A fuse. The short circuit capacity of the power source was estimated at 300 A. The current and voltage in this circuit were monitored using a Hi-Techniques Synergy P power analyzer and recorded at a frequency of 1000 Hz. The time of failure was identified by a spike in the current and/or light and sound produced by an electric arc. The cable temperature was measured and recorded in the same manner as in the non-energized cable experiments. All 3 oven heating programs described in the previous subsection were utilized in these tests. 7 tests were conducted for each temperature program.

Energized (120 VAC) cable was also tested in loaded configurations to determine whether the presence of electric current impacts the time to failure. The load was provided by a bank of incandescent light bulbs. The number and power of the bulbs was selected to produce either 12 or 18 A of root mean square current