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

John J. Shea, *Senior Member IEEE*
Eaton Electrical
Eaton Corporation
170 Industry Drive
Pittsburgh, PA 15275
JohnJShea@Eaton.com

Abstract – **While there are many circumstances that can lead to an electrical fire, it is helpful to identify and document known hazardous conditions that can occur in residential electrical wiring. Conditions that can be reproduced in a laboratory, intended to duplicate 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. Failure modes for a variety of situations are described along with electrical data, photos, and video frames to show the conditions that produced a hazardous condition. Generally, the electric current produces an overheated condition in the presence of some type of combustible material. This work identifies some of the various conditions that can create the hazardous conditions and shows how wire insulation or other insulating materials, commonly used in homes, can ignite. Fires can initiate simply from exceeding the current rating of the wire or by having the wire bundled or having thermal insulation surround the wire. The types of cases explored include bundled extension cords under rugs and NM-B at the load center entrance with thermal insulation covering the wire. Other potential electrical fire hazards can be caused by broken wires or loose connections that lead to arcing or overheating. Loose wires, especially at an outlet fixture, can create glowing or overheated connections. A study of glowing connections will be presented along with overheating of PVC wiring due to series arcs. Low and high current arc energies will be discussed and compared to the combustible energy of volatile gases produced from wire insulation to illustrate the wide difference in the arc energy compared to chemical combustion energy from the decomposed PVC. Electrical wire insulation properties were also measured on various wire types to show the effects of thermal aging. Hardness of the wire insulation and cracking of the insulation was used as a measure of lifetime at 140 ^{o}C. Extrapolation to lower temperatures is described.**

***Keywords:** Arcing, PVC, Residential Circuit Breaker, Series Arcing, Parallel Arcing, Glowing Contact, Dielectric Breakdown*

I. INTRODUCTION

Electrically initiated fires can be caused by old as well as new wiring and associated residential electrical equipment. Conditions can be created, generally unintentionally and unknown to the homeowner, that can create a potentially hazardous condition, such as overloaded extension cords, loose wires on outlets, broken wires with intermittent connection, deteriorated wiring, damaged and abused cord sets, corroded plugs and sockets, damaged insulation, etc. There are also many variables, especially with portable cord sets and extension cords, that can increase the probability of starting a fire, such as rugs over cords, curtains near cords, or other highly flammable objects at the site of unintended overheating.

This work is intended to explore various conditions and mechanisms that can lead to electrically initiated fires, showing what conditions created a fire and in some cases showing the resulting current and voltage waveforms. Also covered is the study of the thermal aging effects on typical wiring used in residential applications to measure the effect overheating has on some insulating properties of common residential wire.

This work can be used to identify and prevent potentially hazardous fire conditions, quantify arcing parameters and wire insulation properties as they thermally age.

II. ARCING FAULTS

There are situations in which overheated wiring can lead to arcing and conversely, arcing can lead to overheating and subsequent ignition of the wire insulation, of decomposed gases produced from the insulation, or of nearby combustibles. These conditions can be created by either parallel or series arcing faults. In residential applications, a parallel arcing fault is formed by an arc between the line and neutral or line and ground. This generally can produce a high current fault with a magnitude that depends on the impedance of the faulted circuit. Two examples will be shown that illustrate how fires can start by parallel arcing leading to high temperatures and by overheated wiring that causes parallel arcing that leads to a fire.

A series arcing fault is an unintended arc in series with either the line side wire or the neutral wire. It is unintended because many loads normally produce series arcing (i.e. motor brushes, light switching, bimetal heater controls, high intensity lighting). An unintended series arc could be formed from a break in one leg of an appliance cord or extension cord or from a loose wire at an outlet screw down terminal, or a loose wire nut connection for example. Two conditions for series arcing faults are a glowing contact and continuous series arcing through char, both of which can be produced from unintended series arcing. It is shown how arcing can lead to overheated wire insulation that can decompose and produce ignitable gases that lead to ignition. There are many possibilities in the real world for producing both series and parallel arcing faults.

III. PARALLEL ARCING CAUSING OVERHEATING

This case would be for an arc heating the wire insulation or other nearby ignitable material. One possible situation for creating a parallel arcing fault is by accidental cutting across the line and neutral wires of a 2-wire cord or line/neutral/ground of a 3-wire cord or any combination. If the object cutting the wire is conductive, then an arc may form between the cutting object and the wires. Even a non-conductive cutter may cause the line and neutral wires to short out, depending on the motion of the cutting object and wire. The circuit impedance and the motion of the cutter and wires determine the resulting current waveforms. In many cases, the resulting current is insufficient to cause a standard electro-mechanical (E-M) breaker to trip before possibly initiating a fire. Figures 1-4 illustrate the different response characteristics of three types of circuit breakers available today; standard E-M, AFCI, and GFCI breakers. These waveforms were obtained by using the guillotine test described in UL1699 using SPT-2 appliance cord [1].

The long arcing time of the standard breaker shows how sputtering can go undetected, especially for low available currents. The intermittent, sputtering arcing, does not cause the electro-magnetic (E-M) circuit breaker to magnetically trip because the peak currents are below the trip threshold of the breaker and the current is not continuous.

As seen in Figs. 2 and 3, the time to trip is reduced and the ability to detect sputtering is achieved with the AFCI breaker [2]. The GFCI breaker, in Fig. 4, behaves similar to a E-M breaker with two wire cords, however with 3-wire cords, the GFCI tripped in less than ½ cycle of arcing as seen in Fig. 5. This fault current depended on the geometry of the wires in the cable (i.e. the ground in this case was centered in the molded wire) and which side got cut first, line or neutral and shorted to the ground wire.

The relatively high resistance of appliance cords and extension cords can result in low fault currents. A poor contact due to a light force on the broken connection can produce the relatively low parallel fault current. Ground fault protection would not activate with 2-conductor appliance cords under these condition since there is no ground wire, only parallel arc fault protective devices will sense these conditions.

Many sputtering cycles of current can flow under these conditions and result in potentially hazardous conditions with the potential to start a fire. Frequently, the arcing condition can blow itself out by melting back the copper wires or creating a separation of the conductors. This however may only be temporary and the arcing may reinitiate if the damaged connection is moved or altered in some fashion. Also, if a flammable material is located near the fault, a fire may initiate.

Reducing sputtering arcing time by reducing breaker time-to-trip is expected to reduce the probability of starting a fire.

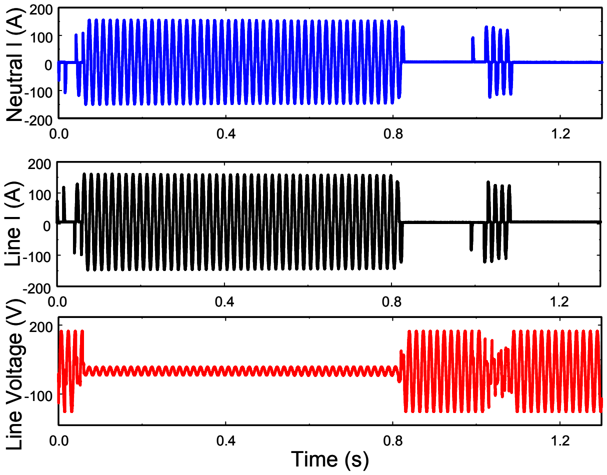


Figure 1. 2-wire fault waveforms with standard electromagnetic 20A breaker (Cutler-Hammer BR120), showing continuous sputtering parallel arcing in a SPT-2 appliance cord with 125 A_{rms} available. E-M breaker did not trip.

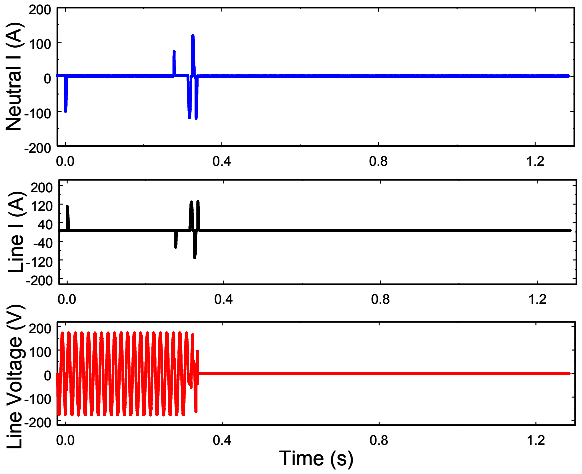


Figure 2. 2-wire fault waveforms with AFCI 20A breaker (Cuter-Hammer BR120AF with 30 mA_{rms} earth leakage), showing sputtering parallel arcing in a SPT-2 appliance cord with 125 A_{rms} available. AFCI breaker tripped (voltage goes to zero).

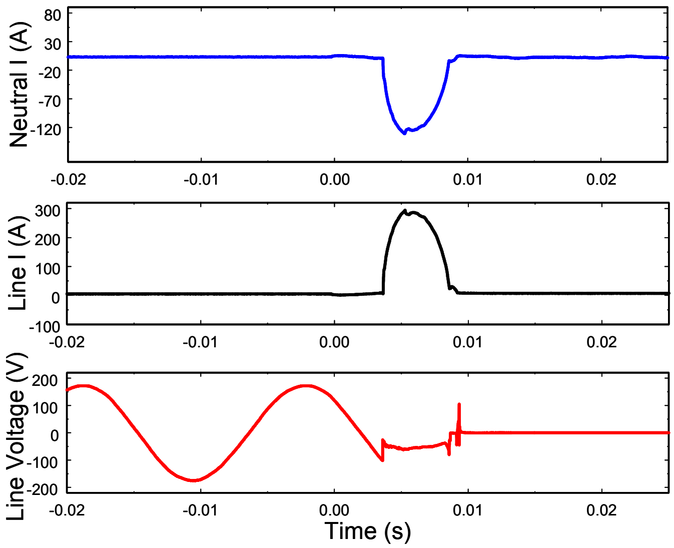


Figure 3. 3-wire fault waveforms with AFCI 20A breaker (Cuter-Hammer BR120AF with 30 mA_{rms} earth leakage), showing sputtering parallel arcing in a SPT-2 appliance cord with 125 A_{rms} available. Breaker tripped.

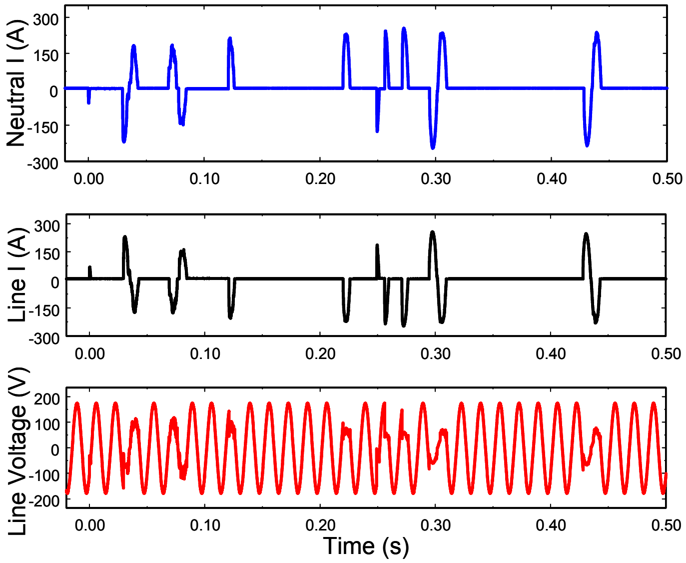


Figure 4. 2-wire fault waveforms with GFCI 20A breaker (Cutler-Hammer GFCB120 5 mA_{rms} sensitivity), showing sputtering parallel arcing in a SPT-2 appliance cord with 125 A_{rms} available. Breaker did not trip.

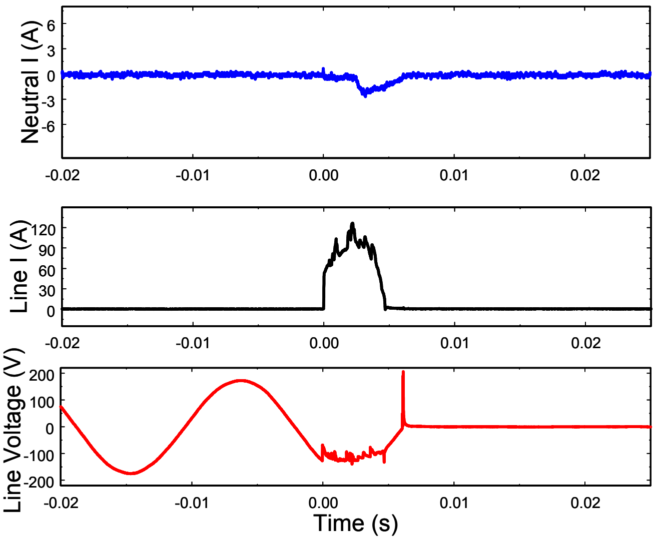


Figure 5. 3-wire fault waveforms with GFCI 20A breaker (Cutler-Hammer GFCB120 5 mA_{rms} sensitivity), showing sputtering parallel arcing in a SPT-2 appliance cord with 125 A_{rms} available. Breaker tripped.

IV. OVERHEATING CAUSING PARALLEL ARCING

Even without damage or defects, wiring can be subjected to high thermal stresses because of currents at or above the conductor rating or in combination with wire bundling and/or added thermal insulation. Two such overheating leading to arcing scenarios will be explored; an extension cord (considered temporary wiring, but frequently long term) bundled and placed under a rug and behind the wall wiring to a load center. In both cases, thermal insulation temperature ratings are exceeded, even when conducting rated current and currents at 110% of wire rating. In both examples, the overheating is due to a combination of factors that lead to excessive temperatures that results in parallel arcing.

A. Temporary Wiring (Appliance and Extension Cords)

According to CPSC fire statistics extension cords and appliance cords are subject to greater abuse and have a greater potential for damage and misapplication, when compared to fixed wiring [3]. Many electrical fires and accidents can be attributed to extension cords. Even though extension cords are temporary, many times they are used long term. They can be stepped on, crushed, cut, abraded, flexed, or subjected to many other types of abuse. These flexible cords are made up of many parallel strands of fine copper wire and can come in two or three conductor varieties with various thermal ratings on the insulation jacket and various wire gauge sizes for current ratings. Various wire insulation types and grades are may also created for higher current appliances such as HPN (neoprene) for higher current loads such as heaters, irons, air conditioners or other special applications.

A test was conducted by placing a bundled SPT-2 16/3 (3-wire) 8ft extension cord (white color Slimline model 2241 made by Woods Industries, Inc.) under a rug. 110% ($14.3A_{rms}$) of rated current was conducted for 100 hours. The initial steady-state temperature of the insulation inside the bundle was 165 °C. Shown in Figs 6 -8 are the temperature of the bundle, the waveforms at the start of fire, and the resulting fire damage to the bundle.

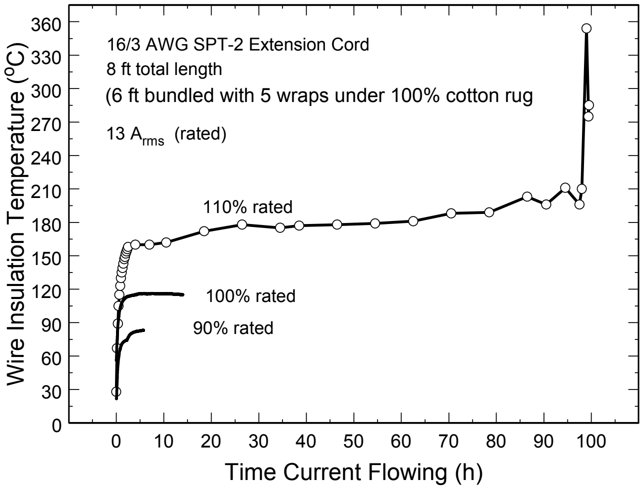


Figure 6. Insulation surface temperature measured inside 16/3 SPT-2 extension cord bundle under a 100% cotton rug.

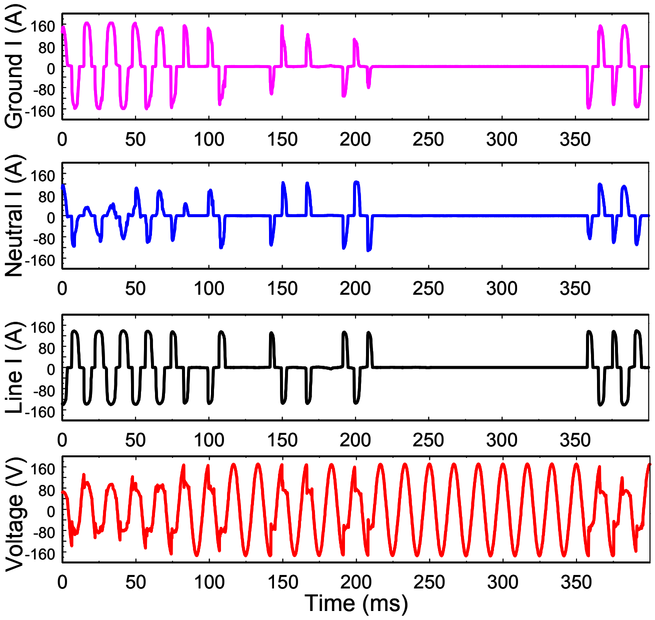


Figure 7. Rug test waveforms at the time the rug started on fire. Prior to this time, copious amounts of smoke were coming from the rug.

a). Initial flame burst from gases produced from PVC wire insulation after 100 h.

b). Second flame burst 400 ms later.

c). Large flame burst from wire insulation 433 ms later.

d). Rug burning.

Figure 8. Still frames from video footage of 3-wire SPT-2 extension cord bundled in cotton rug at ignition.

The extension cord was 8’ in length. It was wrapped into a coil of approximately 6 to 7” in length for a total of 5 loops and wire tied. Approximately 1 foot of the extension cord extended from each end of the bundle to allow the rug to be wrapped around the wire and connected to the voltage source and load.

With the wire rating on the packaging of 13 A_{rms}, a current of 14.3A_{rms} (110% of rating) was conducted approximately 8 h each day except on weekends (the work week). Temperature was measured inside the wire bundle with a type T thermocouple connected to a Fluke Hydra data acquisition unit with results as shown in Fig. 6. Temperature slowly increased over time as the wire insulation degraded. Elevated temperature increases wire deterioration, decreasing expected lifetime. The higher the temperature, the shorter the life of the wire insulation. High temperatures cause an increase in leakage current that causes the run-away effect seen in the temperature results in Fig. 6.

Eventually, the temperature becomes so high that the insulation on the wire and the rug begin to produce visible smoke in the air. ½ cycle of arcing then initiated line to ground as seen in Fig. 7. The resulting fire is shown in Fig. 8.

B. Insulated NM-B Cable

Frequently, NM-B cable, common to many existing and most new and replacement residential installations, is bundled at the load center entrance, typically at the top or bottom of the load center. Also, many applications use a short, < 24”, length of conduit per NEC, to feed the cables into the load center. This can cause the cables, depending on the number and size of the cables, to be bunched together when entering the load center possibly causing excess heating of the cables at this point, depending on currents and ambient temperatures. If the cables in this bundle happen to be carrying fully rated current and if thermal insulation is covering the wires, typical of load centers in finished rooms, then it has been found in this study, that the insulation thermal rating, 90 ^{o}C for NM-B, will be exceeded. This condition can be exacerbated by high ambient temperatures, typically found in outdoor installations in the Western United States during the summer [4].

Testing conducted on NM-B cable, consisted of simply a coil of NM-B wire of about 18” diameter to simulate bunching of NM-B cables at a load center. Thermocouples were placed in the center of the wires to measure the insulation temperature. Three different numbers of coil wraps (20, 10, and 5) were used both with and without thermal insulation (3.5” thick Owens Corning fiberglass R-13). Thermal results, shown in Fig. 9, reveal the maximum measured temperature in the middle of the wire bundle. As expected, the higher the currents and the greater the number of coil wraps, the greater the bundle temperature. Temperatures were increased with thermal insulation as expected. Surprisingly, however all cases with thermal insulation exceeded the thermal rating of the cable insulation for rated current. Also, the highest actual temperature depended on the thermocouple position in the wire bundle and thus may not have been at the hottest spot. Three thermocouples (TC’s) were inserted in the center of the bundled cables that were covered in the fiberglass. Each TC was spaced apart by approximately 8 cm. Fiberglass insulation was only wrapped around one-third of the coil as seen in Fig 11.

Steady-state current was applied for approximately 2 to 3.5 hours in each case. Short-circuiting occurred for the 20-wrap case with fiberglass insulation after 3.5 h. Three out of five tests, with 20 wraps, at 18 A_{rms} with fiberglass insulation produced smoke and cable fire ignition and eventually caused the circuit breaker (Westinghouse SWD BA 20 Amp) to trip after the cable arced for approximately 0.3 to 0.6 s. An example of one of the arcing waveforms, shown in Fig. 10, reveals leakage current initially in the ground wire, then after about 4 cycles, a sputtering arc develops between the line and neutral wires with a further increase in the ground current. The three temperatures shown in Fig. 9 above 200 ^{o}C at 18 A_{rms} are due to a rapid deterioration of the insulation and subsequent escalation of the temperature many seconds before actual short-circuiting occurred. Even though this particular breaker did not have ground fault or arc fault protection, it still tripped. However, there was significant smoke and heat damage to the insulation and the potential to start a fire was present as seen in the photograph, in Fig. 11, of the cable after this test.

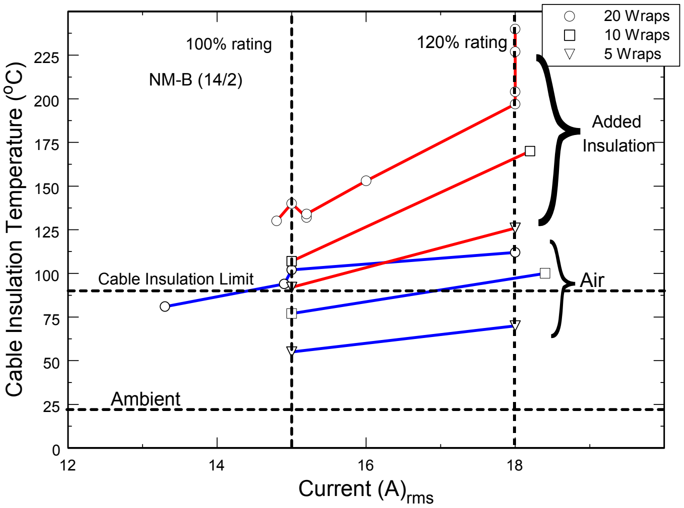


Figure 9. Temperature measured on the oxide bridge at 2.5A_{rms} as the glowing filament moved across the oxide surfa

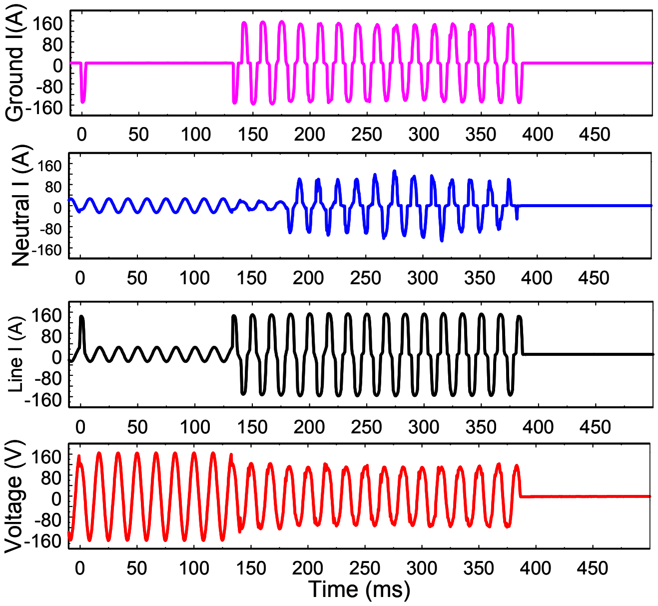


Figure 10. Waveforms from NM-B thermally insulated 20-wrap coil, showing long duration, intermittent sputtering fault currents.

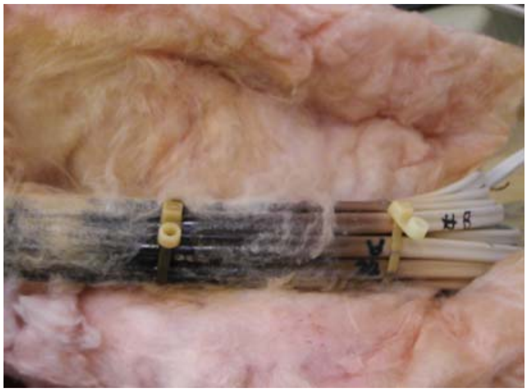


Figure 11. Photograph of NM-B thermally insulated 20-wrap coil after arcing.

III. SERIES ARCING

There are many other situations where series arcing can occur, but generally, there are two common situations: a loose connection such as a wire under an outlet screw and a break in one leg of temporary wiring (e.g. SPT-2 cord). By itself, a series arc typically has low arc energy and seemingly poses little or no fire threat. Arc energy is typically low, about 1 Joule for a half cycle of a 5 A_{rms} arc depending on the arc voltage. This is a low energy arcing condition. However, the picture changes in the presence of insulation or if a glowing condition results. Glowing contacts can be created from series arcing and can result in copper wire temperatures that exceed the insulation melting point. Series arcing in the presence of insulation can create char that creates continuous series arcing that can overheat insulation and initiate a fire.

The next two sections will describe in detail the formation and characteristics of the glowing contact and series arcing over char, both of which can lead to fires due to the decomposition of the electrical insulation to produce volatile ignitable gases. However, background on plasticized PVC insulation used on electrical wiring will be reviewed. This will show how plasticized PVC electrical insulation can create ignitable gases and produce char that allows series arcs to persist even at 115 V_{rms}.

A. PVC WIRE CHARRING AND DECOMPOSITION

The majority of modern electrical wire insulation is made from plasticized PVC consisting of PVC resin, plasticizers, and other additives. There are two factors that are identified as potential problems for electrical safety from insulation - char and ignitable smoke. Thermal decomposition, from chain stripping of the PVC molecular chain, shown in Fig. 12, creates char [5].

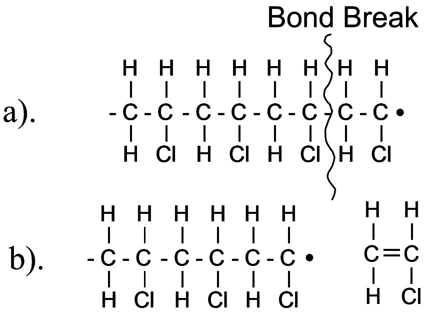


Figure 12. The chain stripping process for PVC resin. a). PVC polymer chain with one unbonded carbon. b). Thermal decomposition causes a side-chain to break away [5].

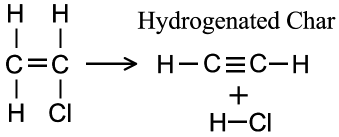


Figure 13. After stripping PVC (Fig.1), further decomposition produces hydrogenated char [5].

After the PVC polymer chains begin stripping, Fig. 13, continued heating above a decomposition temperature, generally > 180 ^{o}C, causes the stripped molecules to crosslink with side-chains to form hydrogenated char and hydrogen chloride, Fig. 13. This char is a temperature dependent semiconductor that can lead to over-surface breakdown below 115 V_{rms} [6-8].

Other additives, e.g. antimony flame-retardants can also produce char. Antimony trioxide, Sb_2O_3, is commonly added to PVC to react with halogen acid, released during a fire, to produce char, which acts as a physical barrier to flame spread. Antimony-halogen reactions in fire also keep oxygen from easily combining with fuel contributed by the polymer [5,8].

Starting at room temperature, when PVC wiring is burned, it generally chars and self-extinguishes the flame [5,6]. However, if the insulation is at an elevated temperature, particularly near or above its melting point, 180 ^{o}C, the material does not self extinguish but readily burns [5,6]. Because of the chemical composition of electrical grade PVC, when it is pyrolized in air, HCl and other gases are produced [11-14]. It is also possible that ultra-fine calcium carbonate $CaCO_3$, hydroscopic filler used in the production of SPT-2 insulation to minimize HCl production, can cause moisture to be formed on the insulation further contributing to reduced breakdown strength. Moisture can also originate from alumina trihydrate, Al_2O_3 $3H_2O$ (ATH) with a subsequent reduction in breakdown strength [5,6].

Plasticizers, used to make PVC pliable for use in electrical insulation for wiring, particularly in residential wiring (SPT-2), are listed in Table 1 along with their formulation. Many of the most commonly used plasticizers for electrical wire are phthalates. Upon heating wire insulation, phthalates can begin to decompose at temperatures as low as *105 ^{o}C* releasing gas phase compounds that, when combined with the oxygen present in air, form an ignitable fuel [5-10]. Table 2 shows a list of these possible decomposition products for DBP as an example. Increased temperatures, from the glowing contact or from arcing, can cause further breakdown of these gaseous compounds to form less complex, but still highly ignitable gases in oxygen such as those listed in Table 3.

For most pure hydrocarbons in air, the auto-ignition temperature, and the temperature at which a flammable mixture will ignite spontaneously, ranges from 540 ^{o}C for methane to 240 ^{o}C for n-decane – well below reported glowing contact temperatures of 1230 ^{o}C [11,12]. The minimum ignition energy, which is the energy from a spark or arc discharge needed to ignite an air fuel mixture, ranges between 0.1 – 0.3 mJ for most combustion fuel-air mixtures. But hydrogen is much lower – around 17 μJ. For reference, a 0.2 A_{rms} ½ cycle of arcing, even at the minimum arc voltage in air of 10 V_{rms} produces about 16 mJ of arc energy, more than enough energy to ignite these combustible mixtures [13]. For reference, the typical spark discharge energy from a human is about 10 mJ [13]. The lower explosive limit (LEL), or the minimum amount of fuel volume % needed to ignite when mixed in air, decreases with an increase in temperature. This means that it takes less fuel gas to make an air-fuel mixture flammable when the area surrounding the wire is heated. Table 3 shows the range of LEL and upper explosive limit (UEL) for some gases that are present in decomposing PVC. It will be recognized that these percentages of gas are very low, even at room temperature. The criteria for forming a combustible mixture, i.e. a mixture that lies in the range between the LEL and UEL, could be achieved when the PVC wire is overheated. For reference purposes, gasoline has a LEF of 1.2 % volume in air at room temperature [10].

Table 1. Common plasticizers for PVC wire insulation.

Abbreviation	Name	Formulation
DBP	di-n-butyl phthalate	$C_6H_4(COOC_4H_9)_2$
DEHP	di-2-ethylhexyl phthalate	$C_6H_4(COOC_8H_{17})_2$
DPHP	di-propylheptyl phthalate	$C_6H_4(COOC_{10}H_{21})_2$
DINP	di-isononyl phthalate	$C_6H_4(COOC_9H_{19})_2$
DIDP	di-isodecyl phthalate	$C_6H_4(COOC_{10}H_{21})_2$

Table 2. Compounds emitted from PVC insulation heated from 40 ^{o}C to 250 ^{o}C [9] and MSDS sheets.

Compound	Formulation	LEL (% vol in air)
Benzene	C_6H_6	1.3
Toluene (Methylbenzene)	$C_6H_5CH_3$	1.2
Ethyl benzene	$C_6H_5CH_2CH_3$	0.8
1,3 Dimethylbenzene	C_8H_{10}	1.1
Styrene	C_8H_8	1.1
1,2 Dimethylbenzene	C_8H_{10}	0.9
Propylbenzene	C_9H_{12}	1.7
Phthalic Anhydride	$C_8H_4O_3$	1.7
Indene	C_9H_8	?
Butylbenzene	$C_{10}H_{14}$	0.8
Diethyl Phthalate	$C_6H_4(COOC_2H_5)_2$	0.7
Dibutyl Phthalate	$C_6H_4(CO_2C_4H_9)_2$	0.5

Table 3. Ignitable gases that may be formed from further decomposition of compounds in Table 2 [10].

Compound	Formulation	LEL	UEL
		(vol% in air)	
Acetylene	C_2H_2	2.5	100.0
Ethylene	C_2H_4	2.7	36.0
Methane	CH_4	5.0	15.0
Ethane	C_2H_6	3.0	12.4
Butane	C_4H_{10}	1.8	8.4
Propane	C_3H_8	2.1	9.5
Carbon Monoxide	CO	12.5	74.0
Hydrogen	H_2	4.0	75.0

B). *EVOLVED GASES FROM PVC INSULATION*

A gas chromatograph (GC), EG&G Chandler Engineering, series 400 AGC, model 04121-SP, was used to identify and quantify some of the gases produced from pyrolyzing a sample of SPT-2 insulation in air as shown in Fig. 14. The analysis shows many gases are produced that can be highly flammable when mixed in air to meet the LEL

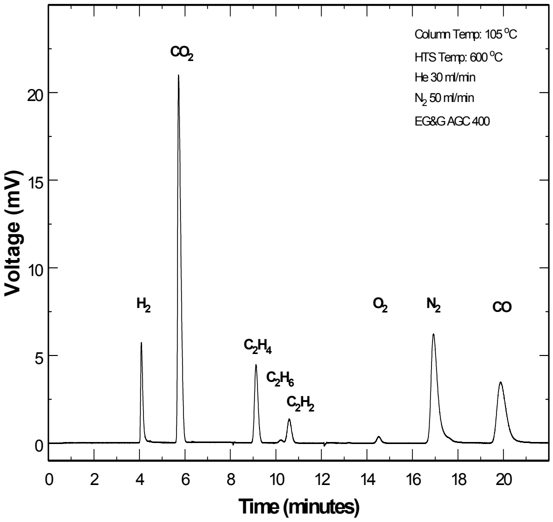


Figure 14. Gas chromatograph results from pyrolized SPT-2 PVC insulation in air shows many ignitable gases are produced.

C). *GLOWING CONTACTS*

There are many ways for electrical wires to become separated, broken, or loose and become subjected to repeated make and break action or vibration. For instance, the solid copper wire may never have been adequately torqued in an outlet receptacle and there could then be repeated motion from plugging and unplugging the male plug. A loose or broken wire connection in an outlet fixture, undergoing intermittent make/break condition under load, creates series arcing between the conductors forming a semi-conductive copper oxide, Cu_2O, film at the interface [14]. This oxide formation can lead to an overheated resistive joint that can eventually form a molten bridge of copper and copper oxide at a temperature of at least 1235 ^oC (melting point of Cu_2O) - well above the melting and vaporization temperature of polymeric insulation used in wiring [11,12]. Heat from a glowing joint can flow down the copper wires to overheat insulation not located directly at the glowing connections.

A fixture was designed and built to allow the ends of two 1mm diameter copper wires to touch and complete a resistive series circuit. One conductor was fixed and the other was moved back and forth, with current flowing, to replicate a loose arcing connection with each make/break operation. After making/breaking the connection approximately 250 times, the initial bridging filament precursor that forms just prior to glowing is seen in Fig 15a. The remaining photographs show how the glowing contact attacks the copper creating a longer and longer glowing filament. The glowing filament, c.a. 50 μm diameter, meanders around the black copper oxide formed between the wires. The wires were not moved after the glowing initiated [12,16].

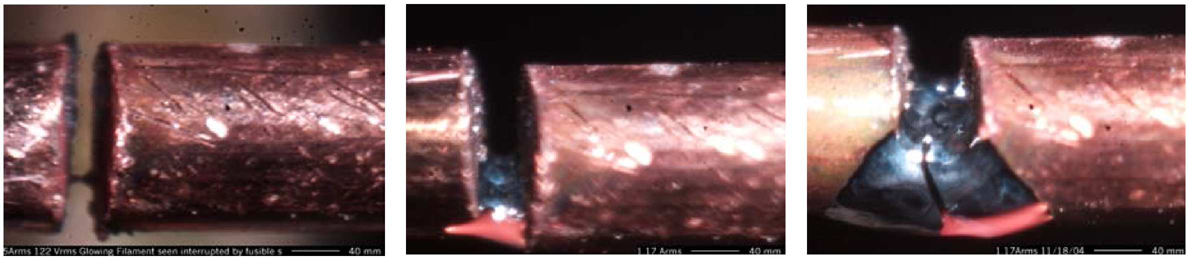
Performing different tests using a range of current levels, the glowing filament was noted to continue to persist especially at low currents (0.9 A_{rms} to 4 A_{rms}) and lengthen, along the copper wires, consuming the copper and converting the copper-to-copper oxide [12,16]. The oxide-breeding rate at 1.17A_{rms} was about 3 mm/h. Surprisingly, the lower the current, the more stable and longer lasting the glow. Glowing was much more difficult to sustain at currents above 13 A_{rms}, much more so than currents below 5 A_{rms}.

Temperature measurements of the glow, shown in Fig. 16, reveal a peak glowing filament temperature of 1200 ^oC [12]. Temperature measurements over a wide current range, seen in Fig 17, show the glowing temperature to sharply decrease below 1.5 A_{rms}, remain flat up to 5 Arms, and begin to increase above 6 A_{rms}. Any of these temperatures are high enough to decompose electrical insulation.

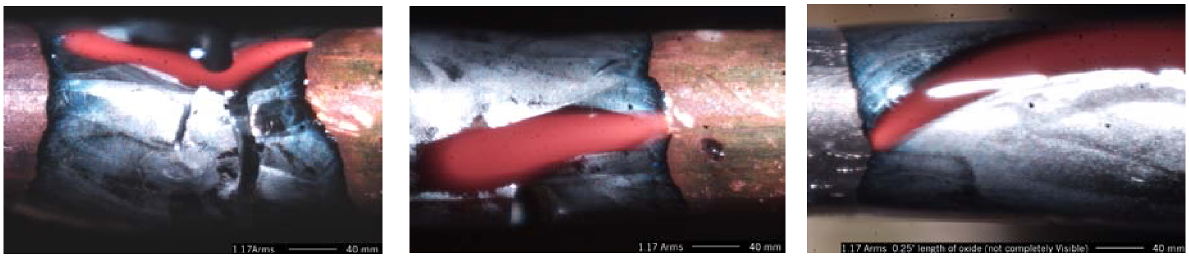
A micrograph of the remaining oxide bridge from a glowing connection in which the current was slowly lowered to extinguish the glow, Fig. 18, shows a conductive "glow track". The significance of this track was the ability for the glow to be reestablished with only the application of voltage across the connection. Typically, however once the glowing connection is extinguished, the copper oxide forms a non-conductive bridge that insulates the connection and prevents the circuit from reestablishing current flow. To reestablish current flow the oxide had to typically be removed or broken through to establish metal-to-metal contact. The "glow track" phenomenon was an exception.

The dynamic resistance of the glowing connection was measured as shown in Fig. 19 for a current of 2.9 A_{rms}. There is an interesting modulation of the resistance at the zero-crossings that corresponds to the drop in temperature of the filament when the current is low (i.e. near current-zero). High currents result in lower peak changes in resistance [12].

The average glowing contact voltage was measured at seven different current levels, at the time the glowing was initiated, to determine the average power dissipated in the connection as a function of current, as shown in Fig. 20. As the current rises from 0.9 A_{rms} to 5 A_{rms}, the wattage rises from 7 W to 25 W and remains fairly constant at 25 W up until about 16 A_{rms}. At this point the wattage rapidly increases to 50 W at 20 A_{rms}. A voltage minimum is seen near 13 A_{rms} and increases for both higher and lower currents. The voltage is also well below minimum arc voltage for copper (12 V) for all currents, with the exception of an occasional spike in the voltage, due to oxide cracking and particles ejecting from the glow region [12,16].



a). Initial Filament t= 0 min **b). Oxide Growth t= 2 min** **c). t= 8 min**



d). t= 28 min **e). t= 31 min** **f). t= 64 min**

Figure 15. Photographs showing the initial bridge formation, glowing filament (or "worm") and growth progression of the copper oxide (dark area) between two 1mm diameter, 37x magnification, stationary copper wires at 1.17 A_{rms}. Exposure time was 125 ms [16].

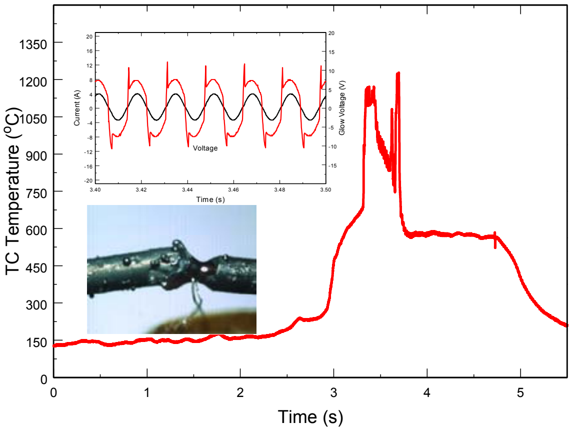


Figure 16. Temperature measured on oxide bridge at 2.5A_{rms} as the glowing filament moved across the oxide surface [12].

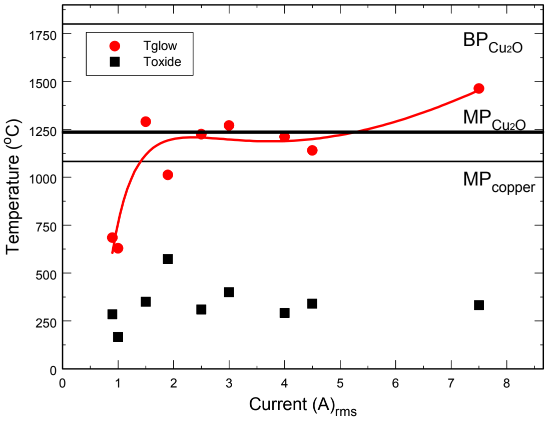


Figure 17. The measured glowing filament temperatures were typically near the melting point of Cu_2O and increased above 7.5 A_{rms} [12].

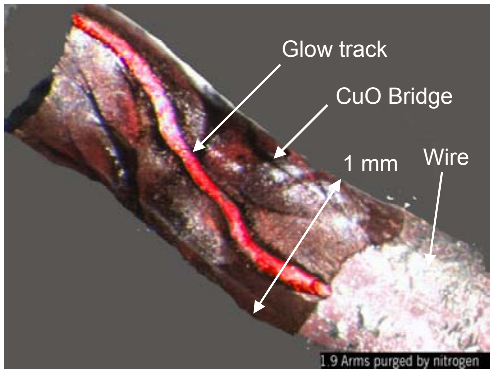


Figure 18. An optical image of open circuit glow track impression on bridge [12].

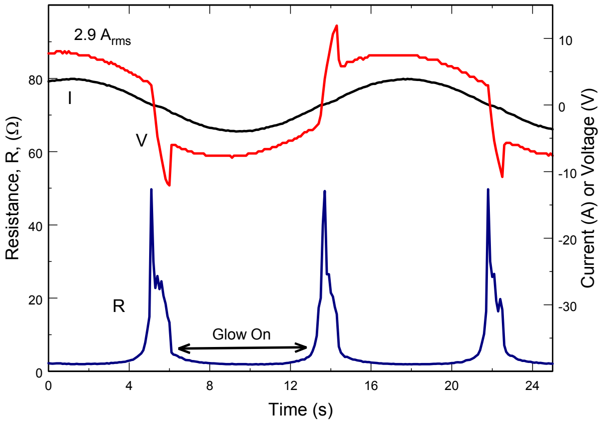


Figure 19. Dynamic resistance of glowing contact (2.9 A_{rms}, 1mm diameter copper) shows large increase in resistance near current zero [12].

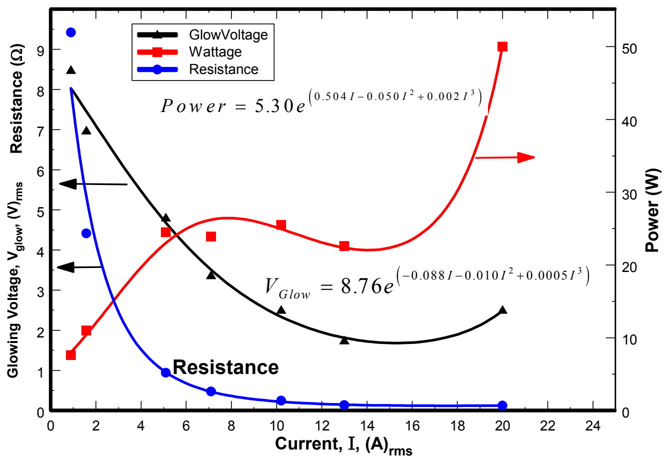


Figure 20. Typical average glowing contact voltage and power dissipated in contact for 1 mm diameter copper wire pair. Measurements taken just after glowing contact formation stabilized [16].

D. SERIES ARCING INITIATED BY GLOWING CONTACTS

Many electrical fires and accidents can be attributed to extension cords. Even though extension cords are temporary, many times they are used long term. They can be stepped on, crushed, cut, abraded, flexed, or subjected to many other types of abuse. These flexible cords are made up of many parallel strands of fine copper wire and can come in 2 or three conductor varieties with various thermal ratings on the insulation jacket and various wire gauge sizes for current ratings. Appliance cords are also similar in design and materials and can be also subjected to the above-mentioned abuses.

Tests were conducted on SPT-2 cord (60 °C rated) to illustrate how when one leg of the cord is broken, this can cause series arcing and can lead to a fire. It was also show under these conditions, that continuous series arcing persisted and did not form a parallel arcing condition. Furthermore, these fires were started with currents as low as 1.7 A_{rms} [16].

It is shown that the decomposition of PVC wire insulation, caused from a glowing contact, can create flammable gases that can be ignited by an arc initiated by a break in the glowing contact.

This set of experiments is intended to show that it is possible to produce hazardous fire conditions when the copper wire strands in one leg are broken and there is subsequent “make and break” of conductors. The make/break action can lead to a glowing contact, a precursor to continuous series arcing and flashes from ignitable gases.

A test fixture, described in [16], was used to create a glowing connection between two copper wires, used to replicate a broken conductor in one leg of SPT-2 wire. Two copper wires, 1mm diameters, were inserted into a leg of SPT-2 insulation that had the stranded wire removed. The adjacent leg of the wire remained intact and current was monitored to measure if the series arc progressed into a parallel fault condition. After repeated make/break operations at 5 A_{rms}, a glowing contact was created. The glow progressed into a series arc as seen in the waveforms in Fig. 21. The series arcing, inside the SPT-2 insulation, heated the insulation to decomposition temperatures, causing volatile, ignitable gases to be produced in the air surrounding the wire. The arcing ignited the gases and caused fireballs and flame too be produced for many seconds from the insulation. The flames were caused from the volatile gases and not from arcing. The arc only ignites the gases.

Figure 21 shows selected frames from the high-speed video camera, (Redlake MotionScope 8000S), at 1000 fps illustrating an example of the three phases that were identified during the formation and life of a series arc – overheating, ignition, and burnout for a glowing connection causing the overheating. After approximately 1000 make/break operations, the glowing contact was self-sustaining (time zero) and the setup was undisturbed. Approximately 30 s later, visible smoke appeared as seen in Fig 21 a) (overheating phase). The current waveform, measured with a current transformer (CT) (F.W. Bell model BB25), appeared fairly sinusoidal and continuous during this period, just prior to time 30.060 s, and voltage was distorted but continuous, indicative of a glowing connection. The glowing voltage, in many cases, transitions from a resistive (not visibly glowing) to fully glowing. The wattage dissipated at full glowing corresponds to a clearly visible orange colored glowing filament in the wire gap.

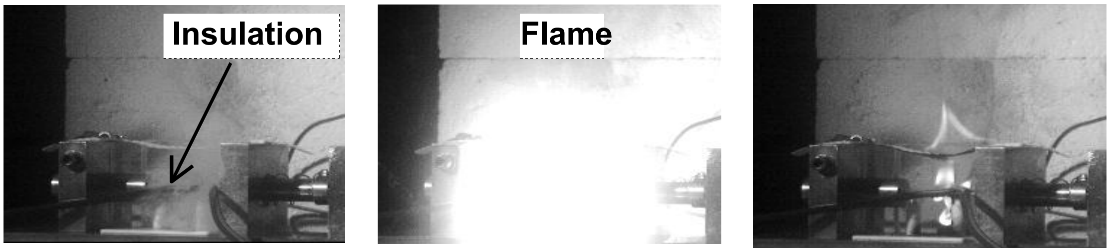
At 30.232 s a visible flame first appeared outside the insulation (not shown). 1 ms later a bright flash occurred and subsequently continued with almost each half cycle. Figure 21b (31.508 s) illustrates the current and voltage wave shape during the gas ignition phase. Arcing across the break in the conductors is occurring with each half-cycle. Some sensor blooming is likely producing a larger flash than may be actually occurring as seen in Fig. 21b. The paper indicator located about 4 cm above the insulation, eventually ignited (Fig 21c).

It was determined that the series arcing, initiated in one leg of SPT-2 insulation did not necessarily break though to the adjacent leg and create a high current parallel arc condition.

In the case of a PVC line cord, the wire strands break internally at the end of the molded strain relief from repeated pulling on the wire cord or from mechanical pinching or cutting. Damaged wiring (one leg broken, line or neutral), loose connections, etc. in $115V_{ac}$ applications, can create series arcing from the make/break action of the damaged connection. This series arc, even though it is low in current, typically < 20 A_{rms}, still results in a plasma hot enough (2000 to 5000 ^{o}K) to char insulation located in close proximity to the arc. This charring can deposit onto the copper wire making it a good thermionic emitter. Charring on the inside of the insulator surface, between the two conductors can also occur. A carbonaceous path between the contaminated conductors can result in intermittent arcing between cracks formed in the char on the insulation surface or directly across the contaminated conductors. Carbon, on the wire, heated by an arc initially formed from mechanical contact of the two conductors, continues to arc because of the thermionic emission properties of the carbon [17]. Continued arcing can lead to further char formation and can lead to subsequent continuous series arcing. [12-16].

E). SERIES ARC OVER CHAR

The second geometry, select images shown in Fig. 22, illustrates an over-surface charring condition, rather than a glowing contact, that produced the initial overheating of the insulation. This is apparent in the corresponding waveforms



a). Overheating 30.060 s b). Gas Ignition 31.508 s c). Burnout 33.096 s

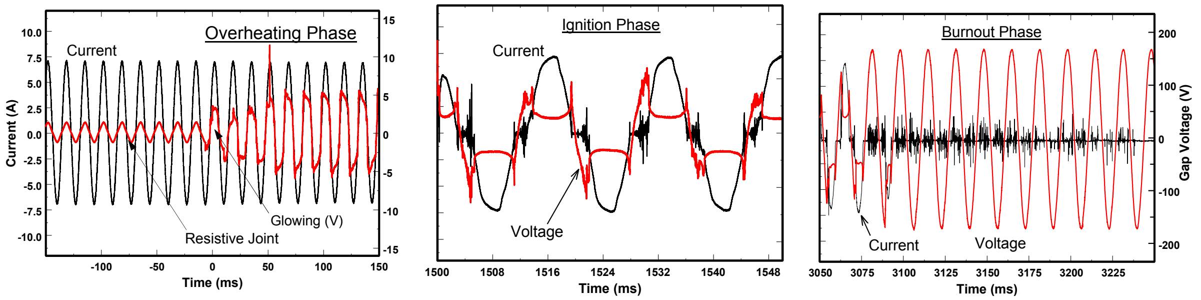
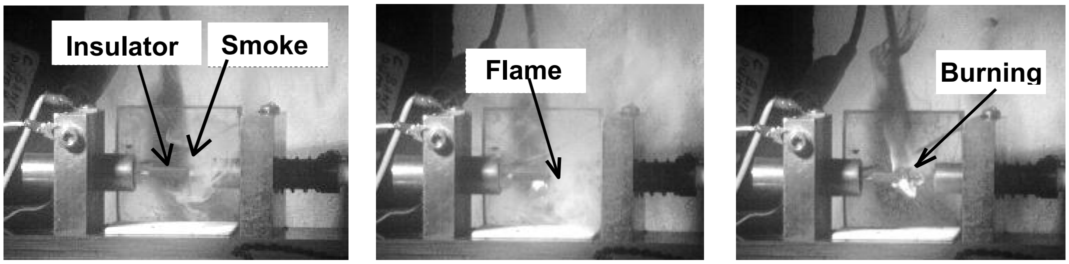


Figure 21. Selected high-speed video images showing gases being ignited at 5 A_{rms} from SPT-2 PVC line cord. Waveforms illustrate a). overheating from a glowing contact, b). gas ignition, and c). burnout of PVC insulation. Waveforms are not synchronized to images but are representative of typical waveforms seen over many tests. Voltage scale is right axis (glowing voltage scale shown amplified). Waveforms acquired approximately 30 s after overheating condition established. Total acquisition time of images was 4 s [16].



a). Overheating b). Ignition c). Burnout

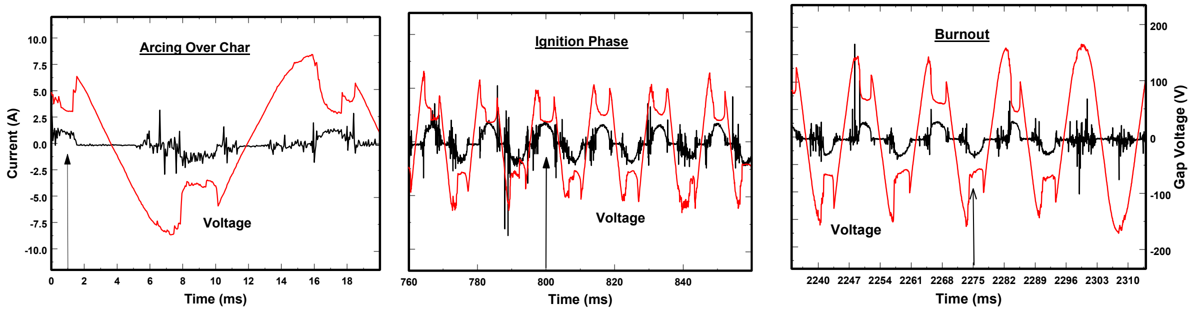


Figure 22. Selected synchronized high-speed video frames and waveforms showing a). overheating via over surface charring b). ignition, and c). burn out for 1.67 A_{rms} PVC insulation. Arrows indicate time of image [16].

for the overheating phase (Fig. 22a). The current consists of high frequency bursts of arcing rather than a smooth continuous waveform as compared to Fig. 22a. This low level intermittent arcing, during the overheating phase, continued for about 250 ms. The current then transitioned from intermittent arcing into continuous arcing (half-cycles of current with "shoulders" around current zero as shown in Fig 22b). The first visible flame appeared outside the insulation at 800 ms (Fig 22b). After approximately 2296 ms, the series arcing transitioned to low level high frequency sputtering, as indicated by the waveforms in Fig. 22 c) at burnout.

This shows that series arcs can initiate fires with currents as low as 1.7 A_{rms} and possibly lower.

F). ARC ENERGY VERSUS CHEMICAL ENERGY

Calculations comparing series arc energy to parallel arc energy to chemical energy from volatile gases produced by overheated PVC wiring show just how low series arc energy is when compared to the other two. However, series arcs, even below 5 A_{rms} are not to be ignored, since they still can produce hazardous conditions as seen in the glowing contact section and in the upcoming series arcing section.

Parallel Arc Energy

This is the high current mode, thus producing high arc energy that depends on the available fault current and how the fault is made. A parallel fault current, seen in Fig. 1, produced a sputtering arc of 125 Arms, below a typical electromagnetic MCB magnetic trip threshold of around 195 A_{rms}. Using, this current and the arcing voltage of 13 V_{rms} gives an arc energy per half-cycle of 60 Hz current of 13.5 J or ***1620 J/s***. The total arcing energy in Fig. 1 was about 1300 J.

Series Arc Energy

This is compared to a series arc, which is dictated by the load. Typical load currents in a home can range from around 0.7A_{rms} up to 20 A_{rms} steady state for 115 V_{rms} circuits. So for arcing energy for a series arc the range, per half-cycle, would be 0.18 to 5 J (using 30 V_{rms} as a typical series arc voltage). Series arcing however can be continuous for many seconds and thus produce energies high enough to support combustion (120 half-cycles/s times 0.18 to 5 J/half-cycles equates to 22 to 600 J/s). This can also be compared to glowing connection wattage of around ***8 to 50 J/s*** (over minutes to hours) depending on the current level and stability of glowing connection.

Chemical Energy

In contrast to the low series arcing energy, the chemical energy of gases from decomposed PVC wire have substantially more potential energy and capacity for starting a fire with only a short duration arc to initiate the combustion. The flame shown in Fig. 4 can be obtained by estimating the diameter of the fireball (5cm) and assume it is round. Then, using hydrogen gas as an example, the energy released with each gas ignition can be calculated using the heat of combustion for hydrogen (141.8 kJ/g) and the density of hydrogen (0.089 g/l at 0 °C). The volume of gas would be $4/3\pi r^3$ or 65 ml. The energy released is 820 J/half-cycle, assuming an unrealistic complete burning of the fuel. This energy could be released about every half-cycle or during times of combustion, depending on the rate of vaporization of the fuel source (i.e. wire insulation or other nearby combustible). Thus, ***98 kJ/s*** could be produced. In reality, this will be lower because of non-stoichiometric ratios of fuel to oxygen and not every half-cycle causing ignition.

Still, even a reduced number is significantly greater than the energies from arcing or glowing. Obviously, the gas will consist of a mixture of gases and the heat of combustion will depend on the mixture and the amount of oxygen available. It is important to note that, the released amount of chemical energy is significantly higher when compared to the series or even the parallel arc.

IV. THERMAL AGING OF WIRING

A. INSULATION ELECTRICAL MEASUREMENTS

Accelerated aging studies were conducted on various types of common wiring used in residential applications to determine how the electrical parameters change over time. This was used to establish a general trend since these measurements are very difficult to make on actual wires rather than prepared laboratory samples of insulation. But they were done to get a measure of the variation in real world wiring and to maintain the actual sample conditions.

An oven was used to heat the wire samples at a known temperature, 100 °C and 130 °C, for a known time to accelerate the aging process of the electrical insulation. Various electrical parameters were measured to determine how these parameters changed as the wire insulation aged.

Insulation measurements included ac impedance at 1500Vac and 60 Hz, dc resistance at 500 Vdc, Tan(δ) at 1kHz, and capacitance at 1 kHz. Testing consisted of removing the wire samples from the oven at regular intervals. After cooling, measurements were made and the samples were returned to the oven. Results are summarized graphically in Figures 23 and 24. Six wire types were tested (SPT-2 white, SPT-2 Brown, BX old, BX new, NM-B, and SJTW). For each wire type, three identical samples

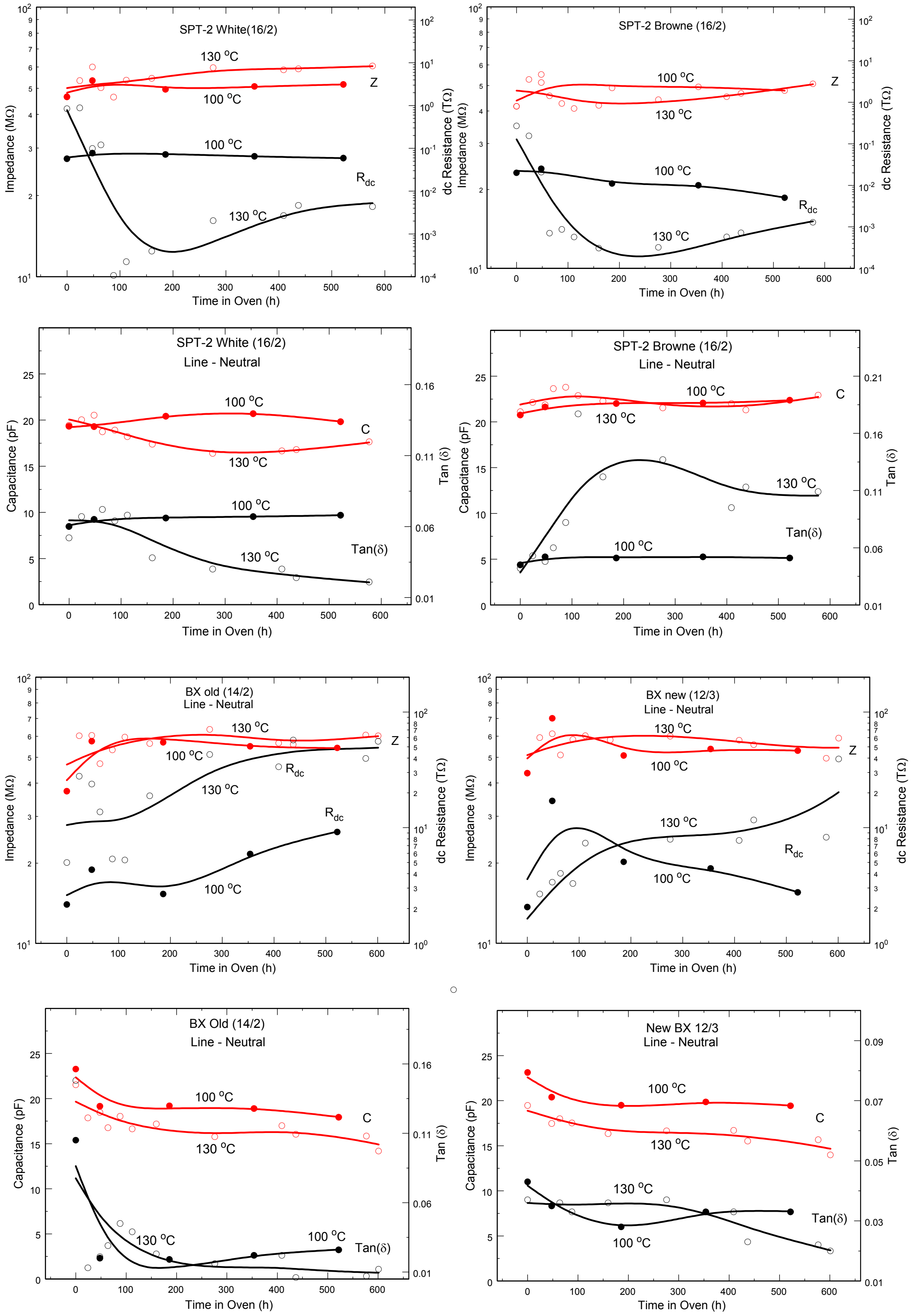


Figure 23. Accelerated thermal aging results from various types of residential wiring. Each data point is an average taken from three samples.

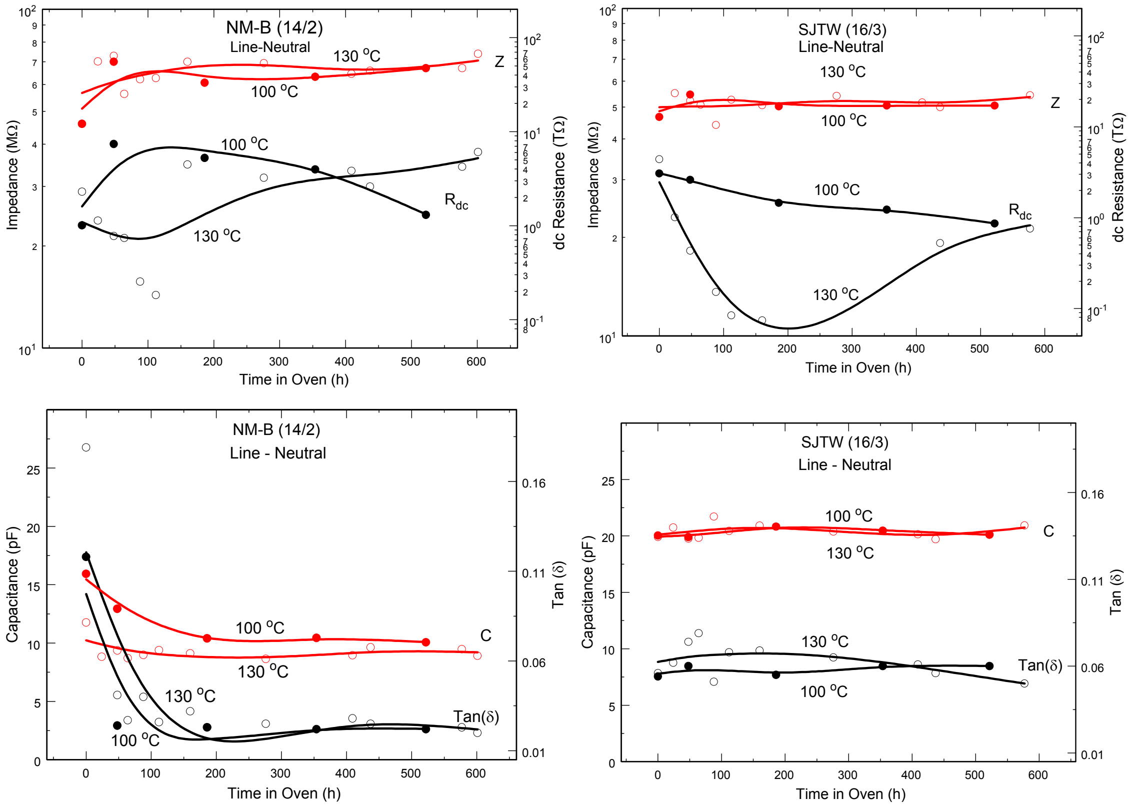


Figure 24. Accelerated thermal aging results from various types of residential wiring. Each data point is an average taken from three samples.

were used. Initial measurements were made on all the samples. Each data point shown in the Figures represents an average of the three readings, one from each of the three wires from that type. All wire lengths were 30 cm. The old BX wire (cloth covering a black rubber insulation), taken from a residence, was estimated to be 60 years old. All other samples were new PVC insulation types. Measurements reported are for connections made between line and neural wires, however, all combinations were measured for three wire cables (i.e. line-neutral, line-ground, neutral–ground). A smoothing function was used to show the general trends in the data.

A Keithley 6487 picoammeter, with two 22MΩ-quieting resistors in series and a ground shield, was used to make 500Vdc resistance measurements. A Stanford Research Systems model SR720 LCR bridge was used to measure the capacitance and tan(δ). A Slaughter dielectric breakdown tester, model 1106-5, was used as the 1500V$_{rms}$ 60 Hz ac source for measuring ac impedance along with a Fluke model 83V multimeter for measuring current. Durometer was measured using handheld gauges made by Rex Gauge Co. model A-07496 (Shore A scale) and model D-02013 (Shore D scale).

While there was difficulty in obtaining reliable and repeatable results, due to using real wires rather than prepared insulation samples, of all the measurements, the dc resistance appeared to be a somewhat reliable indicator of insulation condition. The dc resistance, for example in the SJTW wire in Fig 24, measured between the line and neutral wires, clearly shows an initial drop in insulation resistance for the first 100 hours at 130 °C. The resistance then slowly increased over time as the wire became embrittled. All the other parameters remained relatively flat.

The initial fall in resistance was attributed to the initial softening of the polymer. Softer polymers would have more mobility in the polymer chains and increased volume to allow greater electronic conduction and thus lower resistance. The rise in resistance was attributed to the decrease in the polymer volume due to a loss of plasticizer with aging. Lower volume would restrict molecular motion and reduce electronic and ionic conduction. The measurements where further complicated by the fact that many PVC wires contain calcium carbonate as filler. Calcium carbonate is hydroscopic and when the wires were removed from the oven for measurements, differing amounts of water can be absorbed by the wire depending on the room humidity and length of time at room temperature. Other types of fillers can also be hydroscopic and effect the electrical measurements.

It can be seen that the ac impedance (i.e. the resistive and capacitive components) did not vary much. Also, the capacitance and the tan(δ) remained relatively constant. In some other wire types, it was noted that the capacitance and tan(δ) dropped within the first 50 hours of aging. This could be attributed to the decomposition of plasticizer from the insulation.

To summarize the results, the 130 °C temperature had a greater effect on all the parameters than the 100 °C tests. The impedance, in some samples increased slightly with time at 130 °C as is reflected in the decrease in capacitance but generally did not change significantly. The dc resistance showed how aging changed the charge carrier properties of the insulation. Initially, thermal aging causes a significant amount of plasticizer to evaporate from the PVC insulation.

It can be concluded that there is no definitive end-of-life that can be made from this type of electrical data. The wires, especially the SPT-2 wires were extremely brittle, and could crack if bent or shatters if struck. It was shown that a sputtering parallel arcing could result by cracking the insulation of one of the SPT-2 wires. However, without cracking the insulation all the wires could still carry current and withstand line voltage and 1500 V_{rms}.

Many of the problems with aged wires can occur when brittle wires are disturbed either when replacing outlets, switches, etc., or when wiring is moved for whatever the reason. The insulation can crack and expose bare copper wire that can create a shock hazard or even cause a glowing or a parallel fault.

B. INSULATION HARDNESS MEASUREMENTS

Another set of aging tests was also performed on a set of various wire types, shown in Figs. 25-29, to show how the durometer or hardness of the insulation on the wires changes with accelerated thermal aging. Depending on the durometer of the insulation, either the Shore A (model 1500-A-07496) or Shore D (model 1500-D-02013) scale durometer, made by Rex Gauge Co., was used for measurements. The wire samples were removed from the oven and allowed to cool prior to making a measurement. The spring-loaded indenter head of the handheld durometer was pressed into the wire insulation and the depth of the indenter indicated the durometer. The wire was then wrapped around a 0.5” diameter mandrel to determine if the insulation was brittle enough to crack. A new section along the length of the wire was used for each bending test to eliminate fatigue failures. An equation was developed, based on measured values of Shore A versus Shore D scales, to convert Shore A results to Shore D . This conversion, shown below, allowed for continuous curve fit plots to be made as seen in Figs. 25 – 30. There was little change in durometer at 110 °C. However, at 140 °C durometer changed significantly. It is

$$ShoreD = 0.00525e^{(0.283ShoreA-0.0035(ShoreA)^2+1.63E-5(ShoreA)^3)}$$

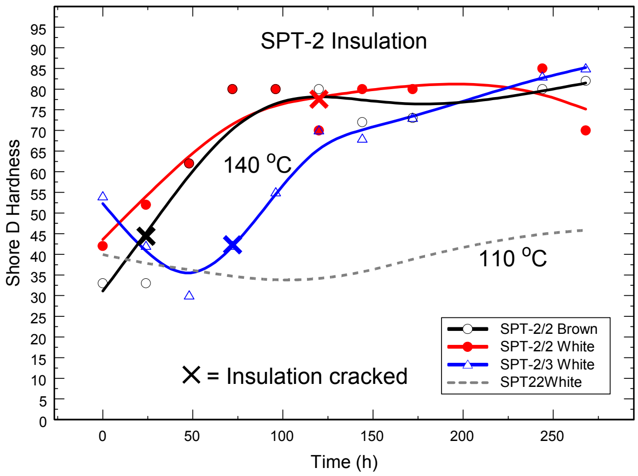


Figure 25. Durometer results of accelerated aging of various SPT-2 wires at 140 °C and 110 °C.

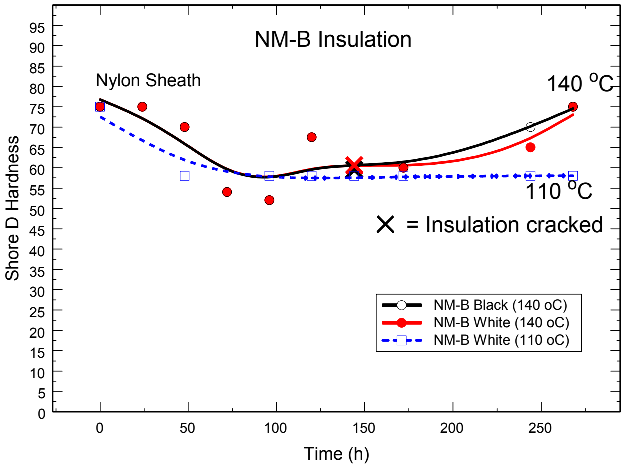


Figure 26. Durometer results of accelerated aging of NM-B wire at 140 °C and 110 °C (line and neutral wires).

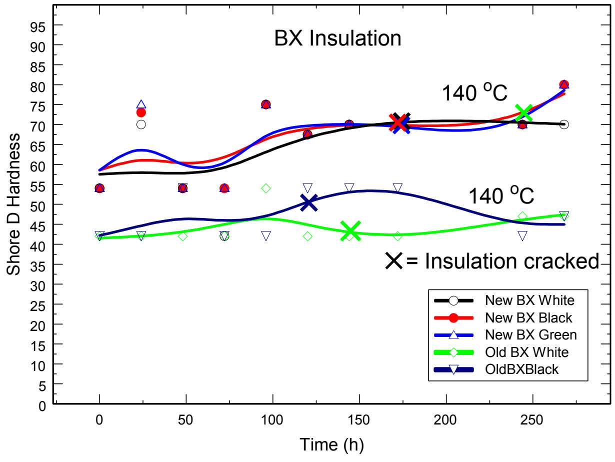


Figure 27. Durometer results of accelerated aging of BX wire at 140 °C.

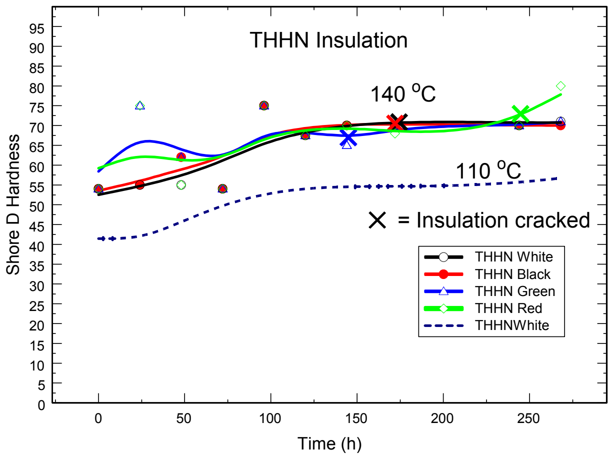


Figure 28. Durometer results of accelerated aging of THHN wire at 140 °C and 110 °C

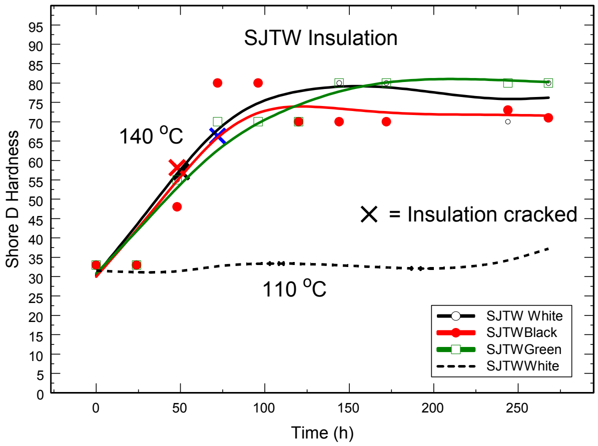


Figure 29. Durometer results of accelerated aging of SJTW wire at 140 °C and 110 °C

indicated where the insulation initially began to show signs of cracking. Some of the wires (NM-B, THHN, and New BX) had an outer nylon cover that cracked first but the end-of-life was taken to be when the underlying PVC cracked, exposing copper wire. This outer layer was initially harder than the underlying insulation.

Hardness may be a good method for determining cable lifetimes. Typically the polymer modulus is measured at an elevated temperature and then the WLF (Williams, Landel, Ferry) equation is used to time shift the curve, thus giving end-of-life at room temperature conditions or whatever temperature is desired. This may also be possible with this hardness data.

VI. CONCLUSIONS

Electrical fires can be initiated from a wide range of conditions. Many conditions, loose or corroded plugs/outlets, last strand, back wired outlets, high resistance connections, component failure, wire insulation moisture absorption, surge and lightning voltage charring insulation and others, have not been discussed in this work and need to also be recognized as potential sources of fire hazards.

Some of the potential hazards identified in this work include extra thermal insulation over wires, currents near or above wire ratings, parallel arcing faults below the magnetic trip level of a traditional circuit breaker, glowing connections from loose joints or broken wires, and unintended series arcs from motion of broken stranded or solid wires.

The following can be concluded: AFCI type breakers may reduce the likely-hood of starting a fire by reducing the effective “magnetic trip” level and recognizing sputtering arc patterns.

Overloading and bundling an extension cord under a rug or other thermal insulator is not a good idea! This is known but many times ignored. Wire insulation temperature ratings are easily exceeded even at 90% rated currents.

Bundled NM-B wire at the load center has the potential for overheating, especially if added thermal insulation covers the wires. Careful wiring practices need to be observed, especially in high ambient environments, to insure wire insulation temperature ratings are not exceeded.

Glowing connections alone can cause overheating of electrical wire insulation at currents as low as 0.9 A_{rms}. Glowing can initiate continuous arcing and can lead to series or parallel arcing.

Intermittent series arcing can produce char on electrical insulation that can lead to continuous series arcing and ignition of insulation. Series arcing can initiate fires at currents of 1.7 A_{rms} and potentially lower. Both series and parallel arcing can cause PVC insulation to decompose and produce ignitable gases. The decomposition gases, when ignited, release significantly higher amounts of energy than the series or parallel arc.

Residential electrical wiring insulation becomes brittle with accelerated thermal aging. Arcing faults may result from cracking and breakage of the brittle wire insulation even though electrical properties, including withstanding $1500V_{rms}$ are maintained. Hardness testing on aged wire insulation generally correlated well with end-of-safe-life as determined by insulation cracking when flexed. For PVC based wire insulation, hardness maybe a convenient method for determining wire life. This type of data could be time and temperature shifted to show expected lifetime at room temperature conditions.

All these hazards identified may be mitigated by observing prudent practices - not loading wires to capacity, not bundling wires together, not adding excessive thermal insulation, insuring good connections, and not using damaged wires.

However, accidents and unexpected results still happen. Unintentional series or parallel arcing or glowing has the potential to produce fires in aged as well as new residential wiring. While it may not always be feasible or practical to continuously check wiring condition, fault and shock hazard protection can be enhanced through the use of GFCI and AFCI type circuit protection.

Continuous improvements in connection methods, insulation materials, installation standards, and arc fault detection/protection and insulation monitoring are needed to reduce residential fires.

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REFERENCES

[1] UL Standard for Safety for Arc-Fault Interrupters, UL 1699, First Ed., Feb. 26, 1999.

[2] National Electric Code (NEC), 2002.

[3] J. Mah, L. Smith, K. Ault, “1997 Residential Fire Loss Estimates,” CPSC, 1997, *www.cpsc.gov/LIBRARY/fire97.pdf*

[4] Temperature of Bundled Electrical Cables Installed in Bore Holes in Residential Wood Framing, Copper Development Association, Inc., 260 Madison Ave., New York, NY 10016

[5] C.L. Beyler and M.M. Hirschler, ***Thermal Decomposition of Polymers***, SFPE Handbook of Fire Protection Engineering, 3rd edition, 2002.

[6] V. Babrauskas, “Mechanisms and Modes for Ignition of Low-Voltage PVC Wires, Cables, and Cords,” Fire and Materials Conference, pp.291 – 309, San Francisco, 2005.

[7] V. Babrauskas, ***Ignition Handbook***, Fire Science Publishers Society of Fire Protection Engineers, Issaquah, WA, 2003.

[8] V. Babrauskas, “How Do Electrical Wiring Faults Lead to Structure Ignitions,”. Fire and Materials Conference, pp.39-51, London, 2005.

[9] T.J. Lever, “Evolved Gas Collection from a Thermo-gravimetric Analyzer and Identification by Gas Chromatography – Mass Spectrometry”, Proceedings of the 28th Conference North American Thermal Analysis Society, Oct. 4-6, 2000, Savannah, Georgia.

[10] Matheson Tri-gas catalog, p. 437, www.mathesontrigas.com

[11] J.J. Shea, “Glowing Contact Physics,” proceedings 52nd Holm Conference on Electrical Contacts, Montreal, Canada, 2006.

[12] J. Sletbak, R. Kristensen, H. Sundklakk, G. Navik, and M. Runde, “Glowing Contact Areas in Loose Copper Wire Connections,” IEEE Trans. CHMT, vol. 15, no. 3 1992.

[13] D. Bjerketvedt, J.R. Bakke, K van Wingerden ***Gas Explosion Handbook***, Chapter 4, GenCon, www.gexcon.com/index.php

[14] Y. Hagimoto, K. Kinoshita, T. Hagiwara, “Phenomenon of Glow at the Electrical Contacts of Copper Wires,” NRIPS (National Research Institute of Police Science) Reports-Research on Forensic Science -, Vol. 41, No. 3, August 1988.

[15] List of translated Japanese papers detailing glowing contacts, http://members.ozemail.com.au/~tcforen/japan/

[16] J.J. Shea, “Conditions for Series Arcing in PVC Wiring,” 51st Holm Conference on Electrical Contacts, Chicago, IL, 2005.

[17] P.G. Slade, Electrical Contacts, Marcel Dekker, New York, NY, 1999.

AUTHOR BIOGRAPHY

John J. Shea Received the Ph.D. degree in electrical engineering from the State University of New York at Buffalo in 1989. He is currently a senior specialist engineer with Eaton Electrical where he is involved in the research and development of advanced current limiting and arc detection technology for power distribution components. He presently holds 27 patents on various arc interruption and power distribution component designs, written 20 journal articles and 20 conference proceedings in arcing technology, is Chairman of the 2007 Holm conference, a member of the Holm technical and steering committees and the book review editor for the IEEE Electrical Insulation Magazine. He was awarded the 2006 Eric O. Forster service award, and the 2002 IEEE Erle Shobert Prize paper recipient, 2001 Cutler-Hammer Innovation Award, a Hughes Fellowship recipient, senior member of IEEE, and member of the Applied Physical Society, Tau Beta Pi, and Eta Kappa Nu.