Conditions for Series Arcing Phenomena in PVC Wiring

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Abstract **- Under certain circumstances, unintentional series arcing, caused from damaged line cords and loose connections, can pose a serious fire and safety hazard. This work, focusing on residential 115 V_{ac} applications, shows how continuous bursts of ignited gases can be created from overheated PVC insulation created from glowing contacts with subsequent series arcing, or surface breakdown with subsequent series arcing. Also, surprisingly, these potentially hazardous fire conditions were created with currents as low as 0.9 A_{rms} at 115 V_{ac} (100 W lamp load). Little research is available about the interaction of glowing contacts, formed from loose or broken copper conductors in wiring (outlets, switches, line conductors, etc.), with electrical insulation. This work shows how glowing contacts and surface arcing can decompose PVC insulation, form ignitable gases, and that it is possible for the subsequent series arc to ignite, and burn insulation. Two conditions are identified that can create an overheated connection – a glowing contact and/or breakdown over a charred insulation surface. Mechanisms are discussed along with data for glowing contact voltage drop, photographs of glowing connections, and a gas chromatograph analysis of the evolved gases emitted from overheated PVC wiring. Selected high-speed video frames (1000 fps) taken from videos of the series arc and bursts of ignitable gasses along with synchronized current and voltage waveforms over a current range of 0.9 A_{rms} to 5 A_{rms} are presented. These findings are useful for advancing the state-of-the-art in fire protection by providing a better understanding of how electrical fires can initiate.**

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

I. INTRODUCTION

New Arc Fault Circuit Interrupter (AFCI) residential circuit breakers, mandated by the 2002 NEC for use in bedroom circuits of new construction, provide enhanced protection not present in conventional electromagnetic miniature circuit breakers (MCB's) [1,2]. AFCI's respond to low-level sputtering parallel faults and ground current faults. However, series arcing faults will not be detected by existing AFCI's unless the series arc progresses to parallel or ground, which does frequently occur. Presently, manufacturers are attempting to develop even more advanced electronic detection circuitry for series arc fault sensing. The huge challenge, faced by manufacturers, is the difficulty in reliably discriminating between undesired series arcs and series arcing that is designed to occur in distribution equipment (light switches, thermal switches, etc.) and loads (motors, etc.) over a current range of about 0.2 A (glowing lower limit) up to 20 A (typical upper MCB rating). Here it is noted that the load current may contain high harmonics or floating DC levels (switching power supplies, capacitor switching by the power company, light dimmers, high in-rush loads, compressors, etc.). To further complicate matters, there are typically parallel combinations of various loads in a home. And since parallel or series faults can occur anywhere in the system from a wide variety of causes (loose connections, damaged insulation, over-current, over-voltage, external heating, last strand heating, wire staple, broken wire, etc.), some faults, under certain conditions, can initiate fires.

This work focuses on characterizing series arcing in PVC line cord used in typical consumer devices. It is shown that glowing contacts and arcing across char are two forms of overheating, caused by series faults, which can potentially initiate a fire. It was discovered that a glowing contact and arcing over surface, under certain conditions, could overheat PVC wire insulation, leading to its decomposition and the formation of combustible gases that can be ignited from the series arc. In some cases, the gases have been observed to ignite with almost every half-cycle for up to many seconds.

These phenomena will be investigated along with an analysis of the gases emitted from PVC SPT-2 wire (S - service rated, P – parallel conductors (flat cord), T - thermoplastic, 300V rating, 18 AWG 105 ^{o}C two conductor). The phenomena will be correlated with selected frames from a high-speed video camera with current and voltage waveforms showing the ignited gas action.

II. BACKGROUND

The CPSC reports 163,000 total residential electrical fires, from which 40,100 were started from electrical distribution equipment in 1997 in the US alone with a property loss of over $676M [3]. Two potential sources for overheating wire are: glowing contacts and arcing over char. Both sources can initiate from a poor or broken conductor, but the main difference between the two conditions is that arcing over char needs insulation to bridge the gap in the broken conductor. A glowing connection can readily form between only two copper conductors with or without insulation present.

A. Glowing Contacts

A loose or broken wire connection undergoing intermittent make/break condition under load creates series arcing between the conductors forming a semi-conductive copper oxide, CuO_2, film at the interface [4]. 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 up to 1230 ^{o}C (melting point of CuO_2) - well above the melting and vaporization temperature of polymeric insulation used in wiring [4-6]. Heat from a glowing joint can flow down the copper wires to overheat insulation not located directly at the glowing connections.

Sletbak et al. reported glowing connections in cross copper wire joints that simulated loose connections over a current range of $0.25A_{rms}$ to $6A_{rms}$ [6]. They determined that the formation of CuO_2, a semiconductor, formed by the high temperature of the arc during make and break of the loose wire that was intentionally vibrated, and the oxygen in the air, formed a nonlinear resistive connection that produced a 1230 ^{o}C glowing filament [6]. This filament was determined to be a potential fire hazard [6,7]. They also showed, over a limited temperature range, that the resistivity of the CuO_2 bridge increases then decreases as the temperature increases. This would account for the unstable nature of the glowing filament as well as the regulation of the wattage and the rectification effect of the current [4-6]. Researchers in Japan have also seen similar effects on copper contacts and other wiring materials. They reported seeing a “worm” meandering around the oxide bridge [4,5]. They were reported being able to create the glowing connection from currents as low as $0.25A_{rms}$ [6]. Aronstein has shown over many years that glowing contacts in various connector types and receptacles, especially in aluminum wiring, pose a serious safety hazard [8,9].

Decomposition of the 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.

B. Arcing Over Char

Another way in which insulation can become overheated and ignite or burn is from over-surface arcing. If two copper conductors conducting a typical load current (<20 A_{rms}), at 115 V_{ac}, part, an arc can occur between the conductors. This arc will extinguish at the next current zero in the AC waveform and not continue since the breakdown strength of a copper-to-copper electrode gap is above 327 V, following Paschen’s minimum for air [10]. This minimum breakdown voltage is above the peak voltage (170 $V_{o\text{-}p}$) for a residential 115 V_{ac} system in North America.

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 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 [10]. Continued arcing can lead to further char formation and can lead to subsequent continuous series arcing. [11-13].

C. PVC Wire Charring and Decomposition

The majority of 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 Figure 1, creates char.

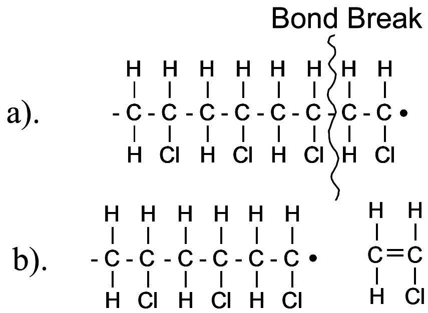


Figure 1. The chain stripping process for PVC resin. a). PVC polymer chain with one unbonded carbon. b). Thermal decomposition causes side-chain to break away [14].

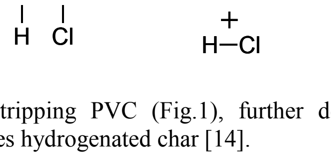


Figure 2. After stripping PVC (Fig.1), further decomposition produces hydrogenated char [14].

After the PVC polymer chains begin stripping, Fig. 1, continued heating above a decomposition temperature, generally > 180 °C, causes the stripped molecules to crosslink with side-chains to form hydrogenated char and hydrogen chloride, Fig. 2. This char is a temperature dependent semiconductor that can lead to over-surface breakdown below 115 V_{rms} [11-14].

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 [11,14].

Starting at room temperature, when PVC wiring is burned, it generally chars and self-extinguishes the flame [11,12]. However, if the insulation is at an elevated temperature, particularly near or above its melting point, 180 °C, the material does not self extinguish but readily burns [11,12]. 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 [11,12].

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 °C* releasing gas phase compounds that, when combined with the oxygen present in air, form an ignitable fuel [13-16]. 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.

Table 1. Common plasticizers for PVC wire insulation.

Abbreviation	Name	Formulation
DBP	di-n-butyl phthalate	$C_6H_4(COOC_7H_{19})_2$
DEHP	di-2-ethylhexyl phthalate	$C_6H_4(COOC_8H_{17})_2$
DPHP	di-propylheptyl phthalate	$C_6H_4(COOCH)_2$
DINP	di-isononyl phthalate	$C_6H_4(COOC_7H_{19})_2$
DIDP	di-isodecyl phthalate	$C_6H_4(COOC_{10}H_{21})_2$

Table 2. Compounds emitted from PVC insulation heated from 40 °C to 250 °C [15] and MSDS sheets.

Compound	Formulation	LEL (% vol in air)
Benzene	$C_6H_5CH_2$	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	$C_2H_4(CO_2C_2H_5)_2$	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 [16].

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_2H_5	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

For most pure hydrocarbons in air, the auto-ignition temperature, the temperature at which a flammable mixture will ignite spontaneously, ranges from 540 °C for methane to 240 °C for n-decane – well below reported glowing contact temperatures of 1230 °C [4-6]. 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 [17]. For reference, the typical spark discharge energy from a human is about 10 mJ [17]. 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 [16].

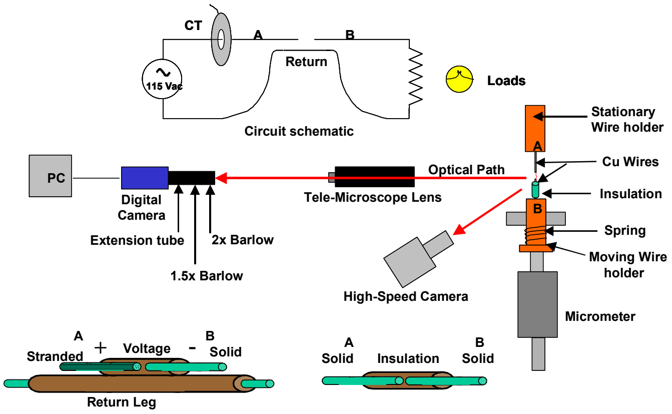
III. EXPERIMENTAL SETUP

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. Or, 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.

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 the conductors. The make/break action leads to the glowing contact and/or charred insulation, a precursor to continuous series arcing and flashes from ignitable gases.

A repeatable, yet realistic, method was needed to reproduce a broken wire connection that can result from real-life long term flexing and stressing of line cords in for example hairdryers, vacuum cleaners, toasters, etc. Wire damage especially can occur at the strain relief or at the end of the molded plug on a cord due to repeated pulling of the wire from an outlet or from mechanical damage of the cord. Long-term stress like those described can cause eventual breakage of copper wire strands creating a potential series arc. Since it was very time consuming to break wire strands by flexing, broken wire strands in a bundle were replicated using two different geometries.

The first geometry, Fig. 3a, used two wire SPT-2 cord. A break was made in one of the conductors, and the return current path was through the adjacent leg as shown in the circuit drawing. This geometry was used to check whether the observed phenomena were due to low current arcing phenomena in one leg, or whether the phenomena were associated with a progression to higher current arcs between the parallel conductors.



a). Geometry 1

b). Geometry 2

Figure 3. Sketch of glowing contact circuit and optics used to image glowing contacts. a). geometry 1 (stranded wire with solid moving wire). b) geometry 2 (single leg on solid wires).

Thus the first geometry, Fig. 3a, was made to test this condition by cutting one leg of the wire and then pulling back the wire bundle leaving an air space to insert a solid 1mm diameter copper wire (99.9% pure Alfa Aesar) to form a stranded copper-to-solid copper joint. To insure that the wire bundle slid out of the insulation uniformly, the ends of the copper wires, on that leg, were soldered together prior to sliding. This setup, shown in Fig. 3, was developed to hold the wire sample and produce the make/break action of the copper joint. The stationary wire holder was replaced with the two-conductor cord only for geometry 1. The micrometer (Mitutoyo 1 μm resolution), insulated with a delrin bushing from a moving copper wire holder, was used to manually move the solid wire back and forth, against the adjacent copper wire bundle, to create arcing at the interface while drawing load current. Depending on the test, the load consisted of power resistors (non-inductive carbon and wire wound) or a 150 W lamp load.

It was determined that the series arcing in this first case was not affected by having the adjacent return leg attached. The current remained low and did not progress to a higher current arc between the parallel conductors. As a result, a single piece of insulation was used for a second case, and subsequent experiments. This allowed for an easier setup and a quick evaluation of materials. This second case, Fig. 3b, used only a single piece of insulation slid over two solid 1 mm copper wires. The insulation was obtained by removing the wire bundle from one leg of the SPT-2 cord and cutting the insulation to the desired length, about 3 cm. The return leg was not attached to the insulation sample in this case.

The moving electrode was spring loaded with about 1 N of spring force. The make/break action was obtained by manually turning the micrometer with light force until current flowed. Initially, the make break action was rapidly (~3 Hz) performed in order to condition the copper wire surface. When a glowing condition began to form, as detected by an increased voltage across the gap and by drag on the micrometer, the make break frequency was reduced. At this point the micrometer was slowly turned out to extend the glowing bridge as long as possible without breaking.

Typically, the bridge would break and had to be reformed by subsequent make/break action. Frequently, it was not possible to remake current flow due to the insulating nature of the copper oxide bridge. If this happened, the wires and insulation sample were replaced and testing restarted.

Numerous tests were also performed without the insulation covering the joint to image the glowing bridge with the optical setup shown in Fig. 3. A tele-microscope (Questar QM1) and a digital color camera (Polaroid model PDMC-2) were used to record 37x images of the glow.

IV. RESULTS

A). GAS IGNITION

Two typical examples, one for each geometry, illustrating the sequences of events that can occur during the formation of a series arc in PVC are presented in this section.

Figure 4 shows selected frames from the high-speed video camera, (Redlake MotionScope 8000S), at 1000 fps, of geometry 1, 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 4 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 lower level (highly resistive but not visibly glowing) to increased levels as seen in Fig. 4a) labeled full 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 4b (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. 4b. The paper indicator located about 4 cm above the insulation, eventually ignited (Fig 4c) in the burnout phase. This series arc never did transition into a parallel arc as verified by increase in current and by no visible damage to the neutral leg after the test. The leg with the series arc had a punch-through hole directed downward toward the base of the fixture.

The second geometry, select images shown in Fig. 5, 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

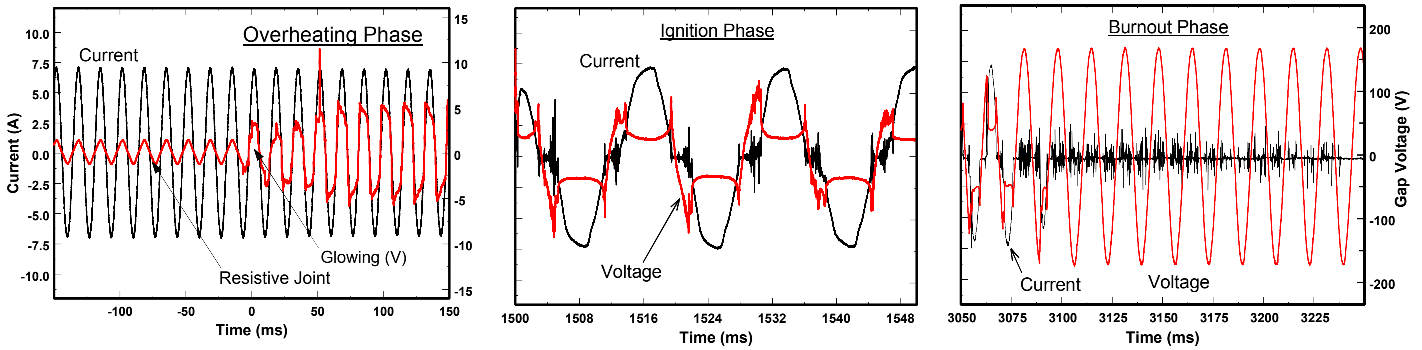
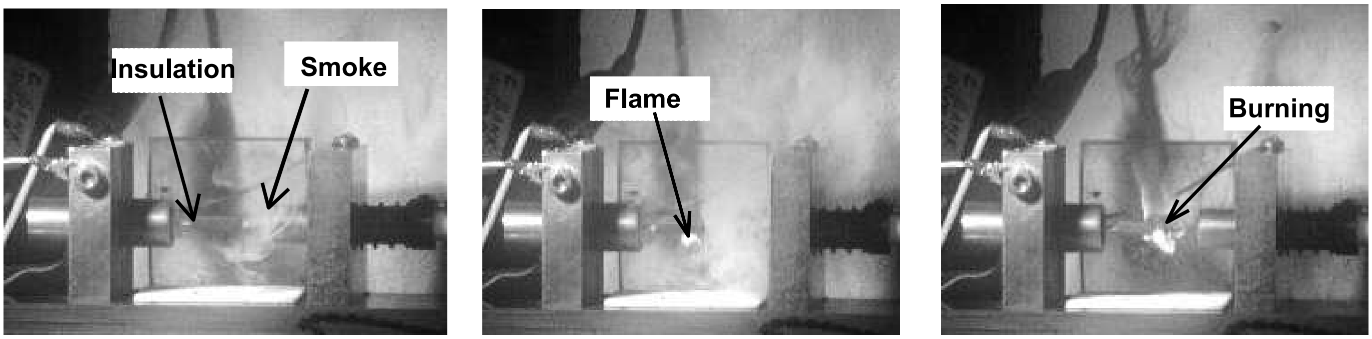


Figure 4. Selected high-speed video images showing gases being ignited at 5 A_{rms} from SPT-2 PVC line cord. Waveforms illustrate a). overheating from a glowing contact, b). gas ignition, and c). burnout of PVC insulation. Waveforms are not synchronized to images but are representative of typical waveforms 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 is 4 s.



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

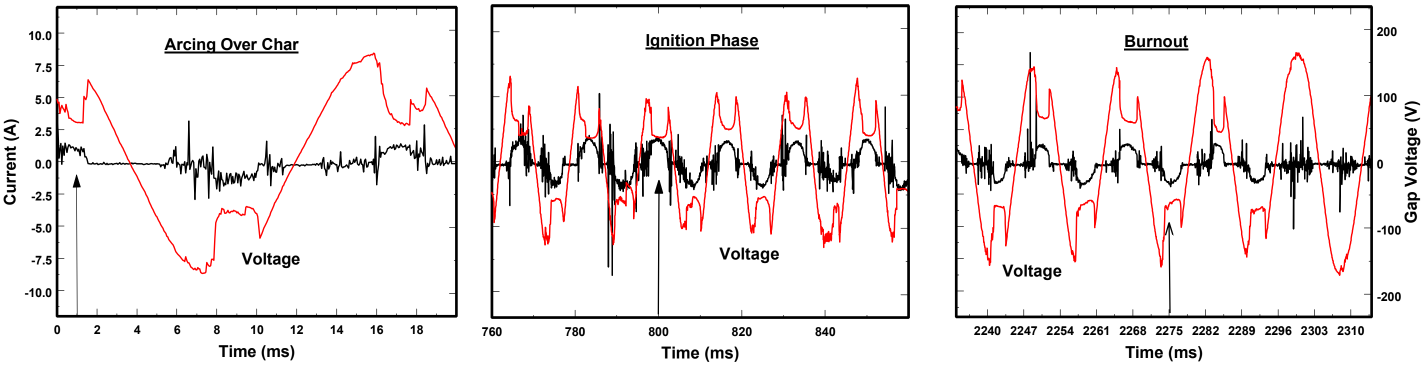


Figure 5. Selected synchronized high-speed video frames and waveforms showing a). overheating via over surface charring b). ignition, and c). burn out for 1.67 A_{rms} PVC insulation. Arrows indicate time of image.

for the overheating phase (Fig. 5a). The current consists of high frequency bursts of arcing rather than a smooth continuous waveform as compared to Fig. 4a. 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 5b). The first visible flame appeared outside the insulation at 800 ms (Fig 5b). After approximately 2296 ms, the series arcing transitioned to low level high frequency sputtering, as indicated by the waveforms in Fig. 5 c) at burnout.

B). GLOWING CONTACTS

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. 6. 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}.

Figure 7 shows images, 37x magnification, of the formation and progression of the glowing contact measured using the setup in Fig. 3. After making/breaking the connection approximately 250 times Fig. 7a. shows initial bridging filament precursor that forms just prior to glowing. 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 in Fig. 7b. As indicated, this process can last for over an hour and could have subsequently lasted longer. The oxide breeding rate 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}, were more much more so than currents below 5 A_{rms}. There appears to be a cathode or anode spot (bright white spot on copper) visible, in Figs. 7b and 7c.

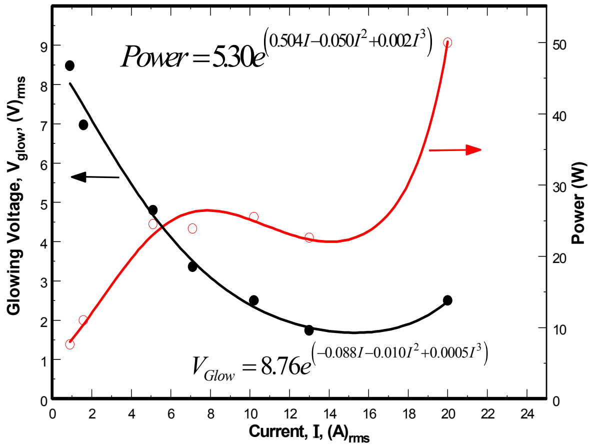
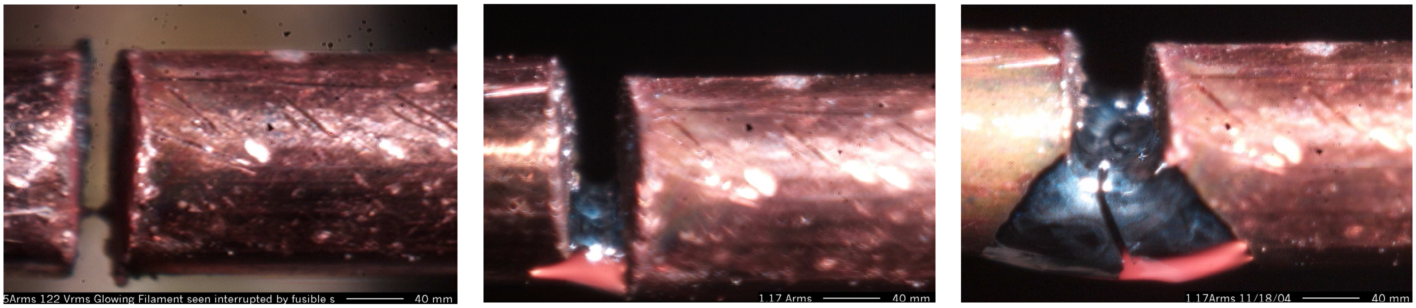
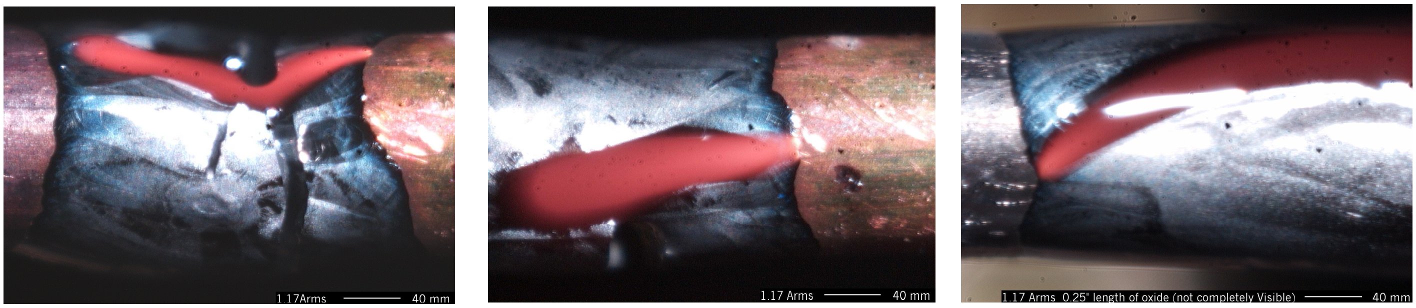


Figure 6. Typical average glowing contact voltage and power dissipated in contact for 1 mm diameter copper wire pair. Measurements taken just after glowing contact formation stabilized.



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 7. Photographs showing the initial bridge formation, glowing filament (or "worm") and growth progression of the copper oxide (black area) between two 1mm diameter, 37x magnification, stationary copper wires at 1.17 A_{rms}.

C). EVOLVED GAS ANALYSIS

A gas chromatograph was used to identify and quantify some of the gases produced from pyrolyzing the insulation in air as shown in Fig. 8. The analysis shows many gases are produced that become highly flammable when mixed in air to meet the LEL listed in Table 3.

V. DISCUSSION

The 1 mm diameter wires used in this work were chosen to easily fit inside the PVC SPT-2 insulation to represent a wire bundle. It is noted, however, that glowing conditions are also known to occur on receptacles and other devices that have larger wire diameters and at metal interfaces such as plug receptacles.

The number of make/break operations needed to create a glowing contact or charred insulation depended on a number of factors in this experiment, with the dominant factor being the current level. Generally, the greater the current, the less the number of make/break operations required to either generate a charred insulation on the inner surface of the SPT-2 leg or to create a glowing connection. Other factors included the amount of force applied to the connection. Typically, just enough force at very low speed was found to create the glowing connection with the least number of operations. Insulation materials were also a factor.

The present investigation has focused on SPT-2 insulation. Other insulation types may be much more difficult to ignite (e.g. HPN thermoset cord) due to higher decomposition temperatures and less volatile gas production.

VI. CONCLUSIONS

Unintentional series arcing has the potential to produce serious fire hazards. Two modes of overheating have been identified – glowing connections and over surface char. Both of these can cause overheating of copper wires and surrounding insulation. The overheated PVC insulation can decompose and produce ignitable gases. These gases can ignite with each half-cycle of subsequent arcing until the fuel source is removed or used up. Surprisingly, fires, due to the ignition of evolved gases, were started with currents as low as 0.9 A_{rms}, which is equivalent to about a single 100 W light bulb.

New methods are needed to mitigate the effects of low current series arcs and glowing contacts on electrical fires. This could include improved circuit protective devices for detecting arcs with resulting fire mitigation, together with better heat resistant insulating materials that do not easily produce combustible gases.

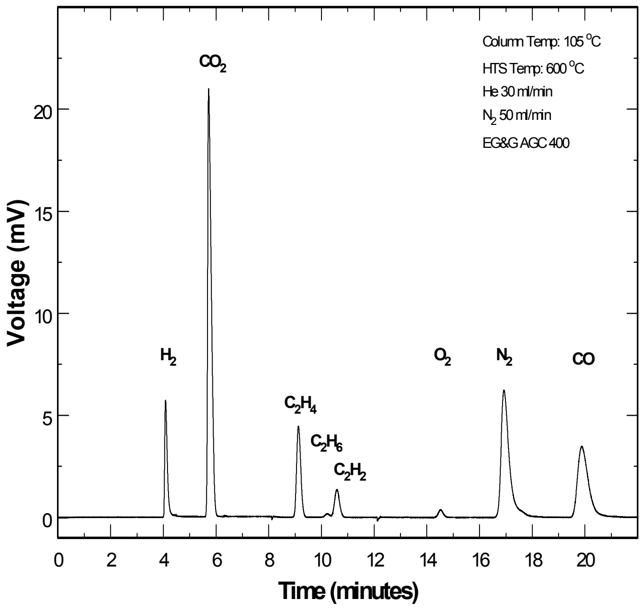


Figure 8. Gas chromatograph results from pyrolized SPT-2 PVC insulation in air shows many ignitable gases are produced. Instrument not set up to detect other gases including those in Table 2 and butane, propane, and HCl

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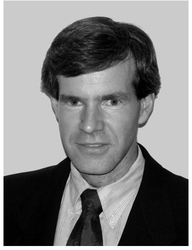

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