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How do electrical wiring faults lead to structure ignitions?

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Abstract

A sizable fraction of ignitions of structures are due to electrical faults associated with wiring or with wiring devices. Surprisingly, the modes in which electrical faults progress to ignitions of structure have not been extensively studied. This paper reviews the known, published information on this topic and then to point out areas where further research is needed. The focus is solely on single-phase, 120/240 V distribution systems. It is concluded that systematic research has been inordinately scarce on this topic, and that much of the research that does exists is only available in Japanese.

Background

The latest statistics of the National Fire Protection Association [1], available for 1993 – 1997 are that 41,200 home structure fires per year are attributed to 'electrical distribution.' These electrical distribution fires account for 336 civilian deaths, 1446 civilian injuries, and $643.9 million in direct property damage per year. These figures include a proportional distribution of fires with unknown equipment involved in ignition, but do not include power cords or plugs which are attributed to specific appliances. The 41,200 structure fires account for 9.7% of total home structure fires in the period, placing electrical distribution 5th out of 12 major causes. The $643.9 million in property damage represents 14.4% of total damage, putting electrical distribution in second place (behind incendiary or suspicious causes). Earlier statistics compiled for 1985 – 1994 by FEMA [2] showed very similar results: electrical distribution was the fifth-ranked cause of fires, the fourth-ranked cause of fire fatalities, and the second-ranked cause of property loss. The electrical distribution causes [1] are itemized in Table 1.

Table 1 Causes of US residential fires due to electrical distribution

Cause of fire	Percent
fixed wiring	34.7
cords and plugs	17.2
light fixtures	12.4
switches, receptacles, and outlets	11.4
lamps and light bulbs	8.3
fuses, circuit breakers	5.6
meters and meter boxes	2.2
transformers	1.0
unclassified or unknown electrical distribution equipment	7.3

The high losses sustained due to electrical distribution fires do not imply that the systems are unreliable. There are about 270 million people in the US, occupying about 100 million housing units, with the average housing unit having 5.4 rooms [3]. This means there are 2.7 persons per housing unit, or 2 rooms per person. If there are 4 outlets per room, then the number of receptacles is $4\times2\times270\times10^6$ = 2.16 billion. A certain percentage should be subtracted for receptacles not in use. It may be estimated that half the receptacles have a device plugged in. Of the remaining half, it will be assumed that half are "daisy-chained" to another outlet, and that the other outlet is in use. Thus, the actual number of receptacles carrying current is estimated as ¾ of 2.16 billion, or 1.62 billion. NFPA statistics indicate that 4700 fires originate at "switches, receptacles and outlets," but CPSC [4] further breaks down the statistics for switches, indicating that these account for 30% of the above figure. Subtracting out the switch fires, 3290 fires per year are due to receptacles/outlets. The failure rate is then estimated as $3290 / 1.62\times10^{9}$, or 2×10^{-6}/yr. The very low failure rate indicates that electrical receptacles are highly reliable. The problem lies not with a high probability of failure, per device, per annum. Instead, the issue is that electrical distribution involves an extraordinarily high number of devices distributed throughout the built environment. Each one supplies energy, and each one can potentially fail and cause a fire.

Modes of ignition

Given that the electrical distribution ranks second in the dollar loss due to fires, one might conclude that there has been a large body of work examining the failure mechanisms that lead to ignition of fires. This proves not to be correct, and, in fact, the research has been fragmentary at best. The examination of failures can be approached in several different ways:

(a) identifying the act(s) or omission(s) leading to failure
(b) classifying failures by the functional nature of the device or part thereof that failed
(c) studying the basic physics of failures.

Both (a) and (b) are essential in reconstruction of accidents, but the focus of this paper will be on (c). This is especially important since several authors [5][6] have already reported studies along the lines of (a) or (b), but there has not appeared a systematic study of type (c).

A consideration of the failure mechanisms reveals that there are only a few main ways that electrical insulation, or combustibles close by to electric distribution components, can be ignited, although there are diverse aspects to each:

(1) arcing
(2) excessive ohmic heating, without arcing
(3) external heating.

Some ignition types involve a combination of mechanisms, so they must not be viewed as mutually-exclusive causes of fire.

Arcing

Topologically, an arc can be either a series arc (Figure 1) or a parallel arc (Figure 2).

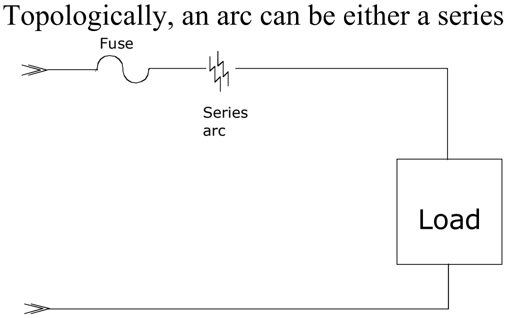

Figure 1 Series arc

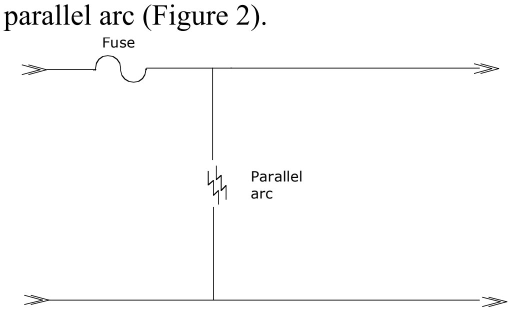

Figure 2 Parallel arc

Some authors consider a third form of arc—line-to-ground—is possible when the circuit contains a ground in addition to a neutral. But the topological arrangement is identical to that of the parallel arc, since the load is not in series with the arc. The distinction between the two basic forms of arcs is essential. In the case of the series arc, the occurrence of the arc *decreases* the current flow in the circuit. Thus, an over-current protection device cannot be expected to respond.

The causes of arcs can be many, but the primary ones are:

(1) carbonization of insulation (arc tracking)
(2) externally induced ionization of air (created by flames or an earlier arc)

(3) short circuits

CARBONIZATION OF INSULATION

In 120 VAC circuits, it is not difficult to cause sustained arcing if there is a carbonized conductive path. This is sometimes called 'arcing-across-char.' The mechanism has been known in electrical engineering for a very long time [7]. How a carbonized path gets established across an insulating material is not a trivial question. There turn out to be more than one way of creating such a path. The simplest way, used in some standard test methods [8], is to create an arc directly at the surface of the insulation, for example, by placing two electrodes on the insulator and applying a high voltage across them. Another mechanism involves the combined effects of moisture and pollutants on the surface. This process is sometimes called 'wet tracking' and has been a particular problem for aircraft wiring with aromatic polyimide insulation [9]. The combined effects of surface moisture and pollutants cause leakage currents across the surface of the insulator, which, in time, can lead to formation of carbonized tracks [10].

Insulating materials vary widely in their susceptibility to arc tracking. A large fraction of wiring in 120/240 V circuits is insulated with PVC, but unfortunately PVC is one of the less-satisfactory polymers with regards to arc tracking [10]. Noto and Kawamura [11] have reported on extensive wet-tracking experiments with PVC-insulated cables. Using the standard IEC 60112 test method [12], they documented a number of specimen types that led to flaming ignition of the cable.

When PVC is exposed to temperatures of 200 – 300ºC, it chars and the char is a semiconductor. Not surprisingly, this can lead to leakage currents and arcing. But Nagata and Yokoi [13] found that if virgin PVC was heated to the rather low temperature of 160ºC, impressing 100 V across 1 mm of insulator thickness was sufficient to cause ignition of the insulation. Furthermore, if the insulation had previously been preheated to 200 – 300ºC, then ignitions occurred when the preheated insulation was raised to only very mild temperatures during the voltage test—from room temperature to 40ºC—were found sufficient (Figure 3).

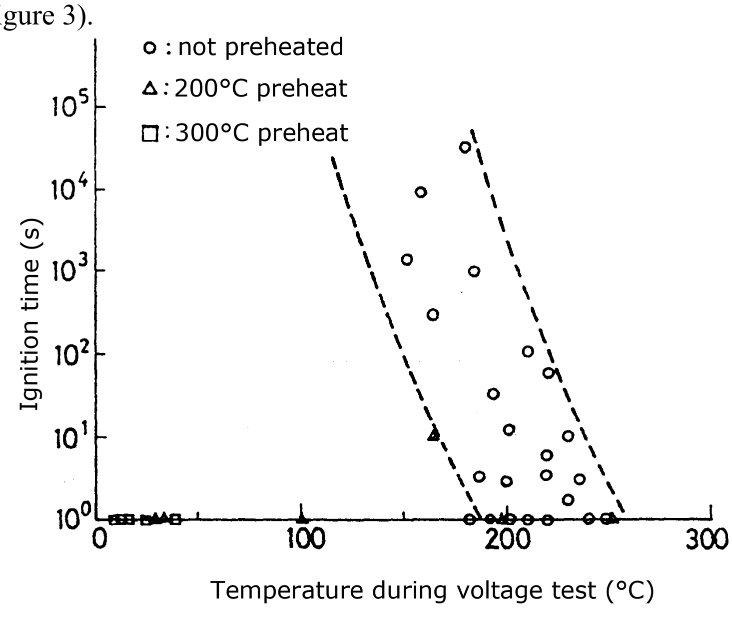

Figure 3 Effect of preheat temperature and test temperature on ignition of PVC wire insulation when subjected to 100 VAC across 1 mm insulation thickness

Hagimoto et al. [14] conducted laboratory studies on arcing faults (parallel arcing) of electrical cords. They identified that the process typically proceeds in a repetitive, but irregular fashion. They identified the following sequence of steps:

- initial current flow occurs due a carbonized layer.
- the current flow increases and results in local arcing
- the arcing causes melting of metal and expulsion of the molten pieces.

- once the molten pieces are expelled, current flow drops
- continued current flow through carbonized material eventually leads again to a sizeable current flow.

The process repeats indefinitely. The authors also measured the current waveforms during the process, and found peaks up to 250 A, but these peaks were rare, and the waveform typically showed peaks no greater than 50 A. Consequently, a long time would take before a circuit breaker would be expected to open. (Note, of course, that the actual current values will depend on the resistance of the particular circuit tested).

EXTERNALLY-INDUCED IONIZATION OF AIR

The intrinsic dielectric strength of air is high (roughly 3 MV m^{-1}, for all except very small gaps), but breakdown can occur at much lower values if the air space is ionized by some means. Two such means are flames and pre-existing arcs. If a serious arc-fault occurs in a distribution bus, a large amount of ionized gases will be ejected. These can travel a certain distance, and if they encounter another circuit, they can readily cause a breakdown and new arcing at the second location [15]. The decreased breakdown strength of air due to presence of flames has been documented in laboratory studies by Mesina [16], who showed that the dielectric strength of air drops to ca. 0.11 MV m^{-1} in flames. Mesina's study, however, only encompassed conditions at 1600 V and higher.

Fire-induced arcing is considered that the most common situation for arcing damage to be encountered in fire scenes [17]. It can involve either carbonization of insulation, externally-induced ionization of air, or both, but there does not exist a study examining either phenomenon in the case of fires involving 120 V branch circuits.

SHORT CIRCUITS

The term *short circuit* is commonly applied in the situation where a low-resistance, high-current fault suddenly develops in a circuit. This can take two forms: (1) a bolted short where a good metal-to-metal contact is made across a full-thickness section of metal; (2) an arcing short, where initial metal-to-metal contact is not sustained and current flows through an arc. In a bolted short, heating is not localized at the fault but distributed over the entire length of the circuit. A bolted short can readily be created by mis-wiring a circuit and then turning on the circuit breaker. The circuit breaker then typically trips before anything ignites. It is, in fact, exceedingly hard to create a fire in branch-circuit wiring from a bolted short [18][19].

An arcing short results from a momentary contact of two conductors. This causes melting of the material around the contact area. Magnetic forces tend to push the conductors apart, and the liquid bridge between them then gets broken. Sparking may be observed as the conductors come apart. After an arcing short, large-diameter conductors can often be seen with a notch on the surface; smaller-diameter wires may be severed entirely; both results are illustrated in NFPA 921 [20].

It is also hard to ignite combustibles from arcing shorts in normal branch circuits protected by 20 A or smaller circuit breakers or fuses. For example, Béland [17] hammered cables, armored cables, and conduits until the circuit breaker opened; these produced minimal mechanical sparks and could never ignite wood, although in some cases loose fibers from wood fiberboard insulation did ignite. On the other hand, Kinoshita et al. [21] successfully ignited cotton gauze when creating bolted shorts with wires having 1.6 mm diameter solid conductors and also with ones using 1.25 mm^2 stranded conductors. In their experiments, this required a thermal-mode-only, 20 A circuit breaker; when using a 20 A thermal/magnetic breaker, ignitions were not observed.

A bit of experimental ingenuity reveals that there are modes of parallel arcing caused by short circuits that have a high probability for ignition. Franklin [22] described that fires were readily started in blankets and in paper, when a power cord was cut with diagonal cutters. The fires ignited from the molten copper droplets which are ejected. In such a situation, a bolted-short condition persists only very briefly, since the magnetic forces induced by the short circuit push the conductors apart, converting the bolted short into an arc. He was able to create up to thirty such short circuits on a power cord before a 20 A circuit breaker tripped. Nishida [23] found that cotton and paper (but not PVC) could be ignited when a single 0.18 mm strand contacted a strand from the other leg of a stranded cable. But he concluded that ignition was occurring due to the high temperature reached by the strand and not through arc energy.

The cutting of an energized electrical cord by an electric saw can result in ignition of nearby combustibles having a low thermal inertia. UL has a 'guillotine' test which simulates a sawing accident [24]. Cheesecloth is placed nearby as the ignition target.

Excessive ohmic heating

The causes of excessive ohmic heating can be subdivided into:

(1) gross overloads
(2) excessive thermal insulation
(3) stray currents and ground faults
(4) overvoltage
(5) poor connections

GROSS OVERLOADS

It is easy to start fires by creating a gross overload in an electric cable. But the circumstances required for it do not tend to correspond to ways by which electric wiring fires normally start. The smallest power cords or extension cords in general use in the US are 18 AWG, and these are rated for 10 A. Experimental studies on the gross-overload ignition mode are meager, but they indicate that currents 3 – 7 times the rated load are needed for ignition [25][26][27]. Since branch circuits are normally protected by 15 or 20 A circuit breakers or fuses, a gross overload must be considered a rare cause of fires in branch-circuit wiring.

EXCESSIVE THERMAL INSULATION

There are simple ways in which a fire can be created with an electric cord that is neither damaged nor subjected to a current in excess of its rated capacity—loop it up upon itself several times, or provide a high amount of external insulation, or both. Laboratory demonstrations have verified that ignition readily occurs [28]; in one case, simply coiling the cord three times and covering with a cloth sufficed [29]. A special form of this hazard occurs with the old knob-and-tube wiring, which was common in the US prior to World War II. This type of wiring uses two separate conductors which are not grouped into a cable, but are individually strung on widely-spaced porcelain knobs. The current-carrying capacity is dependent on there being unobstructed air cooling of the wires, and fires have occurred when the wires were buried in thermal insulation [6].

STRAY CURRENTS AND GROUND FAULTS

Stray currents occur when circumstances cause current to flow through paths not intended to carry current. Ground faults are a well-known example [30][31]. They can occur if a conductor is abraded or damaged and contacts metal siding, roofing, etc. Kinoshita et al. [32] documented that only 5 A was required for ignition when a 3-conductor, PVC-insulated cable contacted a galvanized iron roof. An unusual mode of ignition from a ground fault is where current flows through a gas line. The current causes overheating of the metal and eventually a failure occurs [33]. In cold climates, it is not rare for individuals to thaw a frozen water pipe by attaching a welding transformer and passing current through it. Fires have resulted due the very large currents that are involved [34]. Sanderson [35] studied a case where thawing activity did not ignite the house that was being worked on, but caused ignition in six neighboring houses fed from the same power utility connection.

OVERVOLTAGE

All indications are that this is a rare form of ignition, as concerns branch-circuit wiring. The materials used for wires and wiring devices are well able to withstand the normal surges that are a regular event in a power distribution system. To experience ignitions, one of three events are generally needed:

(a) lightning strike
(b) accidental delivery of high voltage into low voltage wiring
(c) floating neutral

Lightning strikes can result in massive ignitions, not just of wiring, but of all sorts of combustibles. The problem has generally not been studied in connection with 120/240 V wiring systems. Occasional fire reports are encountered where, due to some malfunction in the power distribution network, high voltage got applied to wiring intended to carry only 120/240 V. These cases are rare enough that no systematic study exists. Floating neutral problems are a bit less rare, but again, no systematic studies exist. The basic problem is illustrated in Figure 4. A normal load, such as R_x, expects to see 120 V presented to it. But if a break in the neutral occurs, it will be presented with a voltage that can range from slightly above 0, up to almost 240 V; the exact value is determined by the other loads on the system, R_1 and R_2. Ignitions are not surprising in such circumstances.

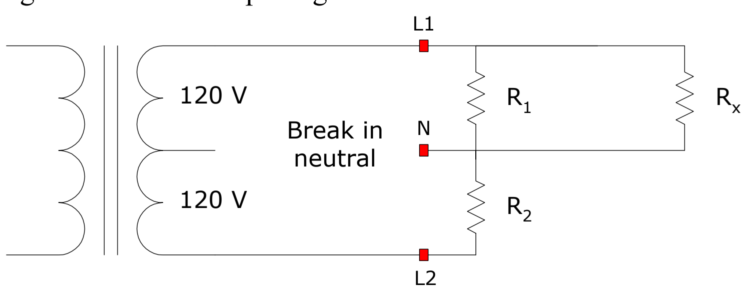

Figure 4 Floating neutral

POOR CONNECTIONS

If a connection is not mechanically tight and of low resistance, it can start to undergo a progressive failure. The process often has the quality of an unstable, positive-feedback loop. High resistance creates localized heating, heating increases oxidation and creep, the connection becomes less tight, and further heating occurs, until high temperatures are attained. At a certain stage, a poor connection can become a glowing connection which shows very high temperatures. At that point, nearby combustibles may be subject to ignition. The process generally appears to be one of ohmic heating albeit with a highly complex resistive element (but as indicted below, there is some possibility that arcing also plays a role in glowing connections).

One of the earliest efforts to study glowing connections dates to 1961 [36]. The primary results are shown in Figure 5. The connection acts as a non-linear circuit element. For currents over 10 A, drops of around 2 V were found. But for small currents, voltage drops in the tens of volts can be found. At a maximum current of 20 A, ca. 50 W is dissipated in a copper/brass connection and around 35 W for copper/iron. The study noted that the power dissipation depends only on the materials involved and not on the nominal size of the contacts. It was also found that to start the glowing process, a current of 4 – 6 A had to be supplied; glowing of freshly-made connections could not be started with smaller currents.

Subsequently, a number of research projects delved into further details of glowing connections, especially following the popularization of aluminum wiring in residential and mobile home construction in the 1970s. Hotta [37] identified a number of fire cases attributable to this cause and conducted studies where he found that approximately 15 W was dissipated in a glowing copper-copper connection drawing 1 A, and about 25 W at 2.5 A. By means of X-ray analysis, Hotta identified that the high resistance in a copper-copper connection is due to progressive formation of Cu_2O at the junction. Kawase [38] further studied the glowing process with copper-copper connections. Using an AC source of less than 100 V and 0.5 to 1.0 A currents, he noted the following sequence of events when an intermittent copper-to-copper connection is made. Initially, when the contact is made and broken, blue sparks are generated. After a number of make/break cycles, the sparks become red, instead of blue. If after this time, contact is made continuously, a "Cu_2O breeding process" begins to take place. Layers of Cu_2O begin to grow on both contacts. Along the layer of Cu_2O, a single bright filament emerges. Molten metal is located along this thin filament, which meanders "like a worm." Kawase measured the voltage-current relationship of the glowing connection and found that it cycles between high- and low-conductivity states. He interpreted the cycling as a recurring breakdown of the interface between Cu and Cu_2O. Hagimoto et al. [39] found that in AC circuits, for 1 mm wires, the minimum current necessary for glow to be sustained was 0.3 – 2 A , while for 2 mm wires, it was 1 – 2.5 A.

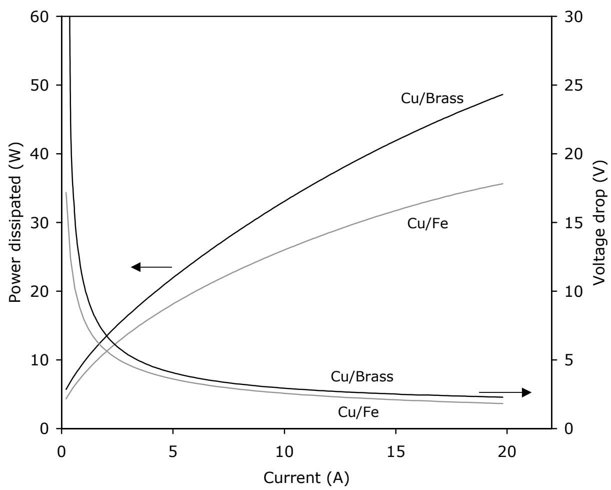

Figure 5 Power dissipation and voltage drop across glowing connections of two types

Sletbak et al. [40] studied additional details of the Cu_2O breeding process and found that the filament glows at 1200 – 1300ºC. The process is able to sustain itself, since copper continues to be oxidized underneath. The high temperatures attained can readily lead to ignition. With a current of 1 A, values of 200 – 350ºC were recorded at a 10 mm distance from the glowing point. If a temperature of ca. 1250ºC is taken to be as typical for the hot part of a glowing Cu-Cu connection, it can be noted that it is very close to 1230ºC, the melting point of Cu_2O. Hagimoto et al. [39] explain that the pulsing waveform found for glowing connections is accounted for by spatter (mechanical sparks) that is emitted from the connection. The spatter ejects material and this causes a momentary fluctuation in current.

Meese and Beausoleil [41] conducted a series of experiments specifically focusing on glowing at the screw terminals of an AC duplex outlet. Glowing connections readily occurred when the screw was not tightly tightened. Visible glow occurred for currents carrying as little as 0.3 A in a 120 V circuit and also in low-voltage (3 – 4 V) circuits carrying less than 1 A. In low voltage applications, glowing connections could be established in circuits with a voltage of less than 10V. A poor connection which is glowing can re-establish the glow if the current is cut off and later turned back on. There does not appear to be any time limit for glows; in one experiment Meese and Beausoleil saw a connection glow for 129 h. In a circuit carrying 20 A, a glowing connection was seen to dissipate 20 – 40 W; this is contrasted with 0.08 – 0.2 W for a good connection at 20 A. A glowing connection in a typical residential duplex outlet may be dropping only about 1 – 2 V across it—this is why the problem may not be noticed at an early stage. Meese and Beausoleil also found that steel screws are much more likely than brass screws to produce a glowing connection.

An interesting question is whether some pairs of metals might be immune to glowing. Several research groups have made claims that a particular pairing cannot lead to glow. But a different research group typically succeed in eliciting a glowing connection with the selfsame pairing of metals. At the moment, there does not appear to be any confirmed non-glowing pairs of contact metals.

Complicating matters somewhat, UL [24] has proposed, on the basis of unpublished experimental work, that a phenomenon identified as 'micro arcing' is involved in a glowing connection. When two metals are separated by a metal-oxide layer, conduction is essentially nil across the layer, which is a dielectric. But the applied voltage can cause a breakdown of the oxide layer. This discharge can cause a fine metal bridge to be created across the dielectric. Substantive current will flow through the metal bridge, but because of its limited current carrying capacity, it shortly overheats, melts, and breaks apart. The process then continues, but because of the high temperatures being created locally, oxide layers are further built up. There does not appear to be other researchers that prove or disprove this hypothesis.

IEC [42] and Sandia National Laboratories [43] both developed different test methods intended to simulate a glowing connection as a means of testing the ignitability of electric wires and cables from this source, but neither method has been validated for ignition of building components.

CPSC has found that, in a flagrant violation of both regulations and good sense, a number of fires which were caused by amateurs who made connections to building wires by simply twisting two wires together, and neither soldering nor using a wire nut on the connection [6]. Similarly, individuals sometimes repair electric cords simply by twisting the wires together and insulating them with electrical tape. This leads to a poor connection, and Hijikata and Ogawara [44] measured the characteristics of some joints of this type at currents of 10 – 20 A. They found that the temperature of the joint increased linearly with current, typically being 50 – 95ºC for 10 A, and going up to 130 – 300ºC at 20 A.

Long-term failures of twist-on connectors was studied by Béland [45]. When two copper wires were joined by a twist-on connector without adequate tightening, he found that failures commonly occur due to metal loss, but this always occurred "several inches" away from the connector, not at the connector itself. This was discovered to be a corrosion problem. Overheating of the connector liberates HCl gas from the PVC wire; the gas is corrosive and attacks copper. Over long periods, metal loss occurs to the point that a connection can be completely severed.

IGNITIONS FROM POOR CONNECTIONS

A glowing connection might typically be found in a wall cavity, where the closest combustibles—thermosetting plastics used as case materials for outlets or switches, along with wood studs—are high-thermal-inertia substances unlikely to be easily ignited. Thus, the question arises as to what exactly a glowing connection in one of these electrical devices can ignite. On this crucial question, only three very limited, unpublished studies can be found. Aronstein [46] states that he successfully ignited:

- low thermal inertia furnishings (bedding, drapes, upholstery) placed directly against the face of an outlet, from a connection dissipating 28 W.
- thermosetting-plastic receptacle cover plates, from a connection dissipating 30 W (thermoplastic cover plates, however, were prone to melt away rather than to ignite).
- wood studs, from a connection dissipating 35 – 50 W.

Unfortunately, Aronstein gave few details of his experimental work. He did note that the burning of the thermosetting cover plates was a flameless, glowing combustion, and that a lightweight material (e.g., drapes) would have to be contacting the cover plate for further propagation to take place. In the case of ignitions of studs, again he found that initial ignition was of a glowing type or smoldering type, but that this turned into flaming when it broke to the other side of the stud, or, in the case of wood paneling, when it broke through the front face of the paneling. Aronstein also reports that glowing connections were able to ignite:

- male plugs, cords, and small transformers plugged into the outlet,
- vapor barriers inside the wall cavity,

but he gave no details about the conditions needed for these ignitions to occur. He also found that a connection glowing at a 45 – 50 W level was able to melt aluminum wiring, and the gobs of molten aluminum could ignite a cardboard box filled with papers.

Ontario Hydro [47] conducted a series of tests using duplex outlets wired with aluminum wire and previously exposed to a modest overload of 27 A. The outlets were cycled using a 15 A load applied for 3.5 h, then off for 0.5 h. A mockup up stud space was built, including thermal insulation inside the cavity and combustibles placed at the face. No male plug was used, the current being drawn by a daisy-chain connection. The results are summarized in Table 2.

Table 2 Results from Ontario Hydro testing of duplex outlets with poor connections

Wall paneling	Insulation	Covering over outlet plate	Wiring method	Results
wood	cellulose	cotton blanket	screw	scorching only
wood	cellulose	cotton blanket	back-wired	wood paneling and cellulose insulation ignited after 4 cycles
wood	cellulose	cotton blanket	back-wired	fuse blew in 4^{th} cycle; paneling and insulation ignited after current flow had ceased
gypsum wallboard	fiber glass	cotton drapery	back-wired	no ignitions after 42 cycles; plastic outlet parts charred

Hagimoto [48] reports one unpublished experiment where a glowing connection was made in a knife switch. The switch was housed in a molded plastic case and attached to a wood board. After about 5 h of carrying 10 A, the wood had partly carbonized and a piece of plastic from the case melted, dropped onto the hot conductor, and ignited. This, in turn, caused the wood board to ignite.

Combined effects

A number of fire scenarios can involve a sequence of two steps: overheating first, followed by arcing and ignition. For example, a wire may become heated either due to excessive current or due to a poor connection. This may soften the insulation sufficiently, so that a short circuit occurs at a place where the wire is bent or passes a metal edge.

The most important of the combined-effects situations is perhaps the last-strand problem. A number of fires occur either at the junction between a cord and the male plug, or at another place along the cord where repeated bending has taken place. This has been studied by several groups of researchers. Typically, it has been found that ignition of a plug or cord is associated specifically with the breakage of the last strand. Mitsuhashi et al. [49] created failures of PVC-insulated cords so that only one strand remained. Using test cords of 30×0.18 mm strands (rated 7 A) or 50×0.18 mm strands (rated 12 A), they found that for ignition to occur, the load current had to be within a relatively narrow range. Ignition of the PVC insulation occurred only if the current was between 10 and 20 A. Currents smaller than 10 A equilibrated to steady-state temperatures of 100ºC or less and did not lead to fusing of the last strand and ignition of the PVC. Conversely, currents over 20 A caused a rapid fusion of the strand, and consequently did not deliver sufficient energy into the already-broken strands to raise their temperature sufficiently to ignite the insulation. PVC used for electric cords is moderately resistant to ignition—applying local flames or hot temperatures normally does not lead to a propagating fire of the polymer. But this changes if the material has been preheated. Thus, Mitsuhashi discovered that the overheating must not be too rapid. The sequence of events, then, is: overheating → fusing → arcing → stopping of current flow. The ignition occurs initially at only a tiny spot, but because a certain portion of the cord has been preheated to over 100ºC, rapid flame spread can occur away from the ignition location. The authors did further heat transfer modeling and concluded that a gap of at least 1 mm is needed for ignition to occur. Nagata [50] also conducted experiments and theoretical modeling and came to broadly similar conclusions. UL uses the last-strand problem in their 'rotational flexing' test [24], where a stranded electrical cord is rotated enough times that one of the conductors suffers a break, and it is then examined whether cheesecloth, used as an ignition target, will ignite.

A PVC male plug can be ignited by repeated 'hot plugging' while carrying a heavy load. Blades [51] demonstrated this using a 1500 W space heater as the load. The effect appears to be somewhat similar to the last-strand problem, in the repeated hot-plugging erodes the contact material, creates a poor connection, and heats up the PVC locally. Finally, arcing is able to cause ignition. The general problem of ignitions due to poor connection at the plug/receptacle interface has only been studied to a limited extent [52], and systematic studies are not available in the English-language literature to describe conditions needed for a structure ignition. Several studies have been conducted in Japan, however. Based on laboratory studies, Ashizawa et al. [53] concluded that the steps leading to ignition are:

(a) overcurrent and poor connection
(b) thermal degradation of PVC
(c) release of HCl gas from PVC
(d) absorption of moisture by hygroscopic action of calcium carbonate filler
(e) initiation of surface and internal scintillations
(f) formation of carbonized paths in the PVC, both on the surface and internally
(g) arcing
(h) ignition.

Okamoto et al. [54] also conducted laboratory studies and came to a roughly similar conclusion. Uchida et al. [55] studied the problem of failures in plugs where attachment of the wire is by means of a screw connection.

A poor connection, followed by arcing and ignition can be created when a nail or staple splits apart a conductor in a nonmetallic cable. This, again, is a low probability event, but at least two researchers have documented it in laboratory experiments. Roberts [56] demonstrated this by splitting 12 and 14 AWG nonmetallic cables with a nail. Brugger [57] used a staple to split a nonmetallic cable and reported that a glow occurs first.

External heating

Most cases of external heating involve the wire or wiring device as 'victim' of fire and not as the initiator of fire. But some situations do exist where external heating of wiring serves as the initiating event. In many cases, arcing occurs after sufficient overheating. Chavez [58] examined the electrical failure of two cables as a function of oven heating. Electrical failure was considered to be a short circuit or a low-resistance condition developed across the line; experiments were not conducted to actually elicit ignitions. A cable with cross-linked polyethylene insulation failed at 270ºC, while a cable with polyethylene/PVC wire insulation and PVC jacket failed at 250ºC. A NIST study on lighting fixtures [59] examined the effect of over-temperatures on 60ºC-rated normal building wiring. When overlamping of a fixture created 202 – 205ºC temperatures in the electrical junction box, failure occurred in less than 65 h. The wire insulation became brittle, cracked, fell away from the conductors, and this led to a short circuit.

Conclusions

In 1974 the author of a textbook on electrical insulation [60] wrote: "The fundamental breakdown processes are not understood; not for lack of experimental observations but because our background knowledge is too crude." Unfortunately, even today this statement remains true, as concerns wiring and wiring devices in buildings.

Claims are sometimes made that a significant fraction of fires assigned to electrical causes has been mis-investigated [61]. But, despite the recent efforts in NFPA 921 to make high quality information available to the investigator, this is very hard to do in the absence of adequate published research studies.

It is surprising how little systematic research has been done to elucidate and quantify the mechanisms whereby electric wiring faults lead to structure ignitions. Almost all of the experimental papers that could be found studied problems only of a very narrow scope. In addition, a number of them (mostly not reviewed here) have approached the topic by attempting to prove that certain modes of ignition "cannot happen." This, of course, is hardly good scientific methodology, but is an easy trap to fall into, when it is realized that failures of highly reliable devices are involved.

Not a single paper from a US university was found on the topic, nor is there any agency or research institute in the US that has carried on long-term research on these problems. It might be noted that in Japan, elucidating the nature of electrical ignitions has been considered to be a problem of national priority, and several institutes and universities have done considerable long-term research, but these studies are generally available only in Japanese.

Without adequate laboratory studies documenting and quantifying electric-wiring-related fire ignition scenarios, little progress can be expected either in improving fire investigations or in reducing fire losses of this origin.

In the US, the safety of wiring and wiring devices is generally assessed according to UL standards, but there exists almost no published material from UL that would document their studies of ignition mechanisms, nor to provide a basis for judging whether their test procedures have a traceable connection to field failure modes.

Aging of plastic materials can lead to increased failures. This has been studied in other electrotechnical areas (e.g., aircraft wiring), but no studies exist for building wiring.

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