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DEVELOPMENT AND ANALYSIS OF ELECTRICAL RECEPTACLE FIRES

FINAL DRAFT

Grant No. 2010-DN-BX-K218

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ABSTRACT

Laboratory testing evaluated the impact of a wide range of variables on the formation of overheating connections in residential duplex receptacles. Two types of receptacle configurations have been evaluated: 1) those focused on terminal connections and 2) those focused on plug connections. Testing included 528 receptacle trials, 408 trials with various terminal connections and 120 trials with various plug connections. Thirteen pre-fabricated wall assemblies of 36 receptacles were placed in 8 compartment fire tests and 5 furnace fire tests. The variables evaluated in the fire exposure testing included: the receptacle material, materials of the receptacle faceplate and box, terminal torque, and energized state of the receptacle. A portion of the receptacles in the fire exposure testing had overheated connections that were created in the laboratory testing. These receptacles were used to assess whether evidence of overheating would persist after a fire exposure. All receptacles were documented for damage to the receptacle, faceplate, and outlet box including any arcing, overheating, and/or melting. The results of laboratory testing indicate that only the loosest connections tend to form significant overheated connections irrespective of other variables, such as receptacle materials and installation. Forensic signatures of overheating have been identified and have been found to persist even after external fire exposure. In addition, locations of arcing within receptacles as a result of fire exposures were identified and characterized. The location of arcing is primarily dependent on the duration and intensity of the fire exposure, as well as the construction and materials of the receptacle, outlet box, and faceplate. The presence of characteristic indicators of arcing and melting were analyzed.

TABLE OF CONTENTS

TABLE OF FIGURES

Page

TABLE OF TABLES

Page

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EXECUTIVE SUMMARY

Electrical fire initiation is attributed to a large proportion of structural fires, especially large fires, in the United States. Hall [2010] reports that from 2003 to 2007, home electrical fires represented 13% of the total home structure fires, 17% of associated civilian deaths, 11% of associated civilian injuries, and 21% of associated direct property damage. Of all electrical fires, 41% involved electrical distribution or lighting equipment (i.e., wiring; outlets, receptacles, and switches; over current protection equipment; meters and meter boxes; lamps, light fixtures, light bulbs, and signs; cords and plugs; transformers and power supplies). Receptacles, cords, wiring, and plugs combined represent approximately 14% of all residential electrical fires [Hall, 2010]:

- Outlet or receptacle 5%
- Extension cord 3%
- Branch Circuit Wiring 3%
- Permanently attached power cord or plug 1%
- Unclassified cord or plug 1%
- Detachable power cord or plug 1%

An earlier study [Hall et al., 1983] of 105 residential-occupancy electrical fires showed that 37% of those fires had their origins in receptacles, cords, or plugs. Generally, the statistics reported do not include the physical mechanism that led to the device malfunction causing a fire. Most (72%) of reported home structure fires involving electrical failure or malfunction were reported with few or no details on failure mode. The two leading types of electrical failure or malfunction were unclassified electrical failure or malfunction (46%) and unspecified short circuit arc (27%). Therefore, the statistics do not provide a basis for improving fire safety. In order to use these statistics in a better context, it is important to first determine the required conditions that are needed for ignition and the subsequent forensic signatures that can be used to differentiate whether the electrical component was the cause of the fire or a victim of the fire.

There is a limited body of work addressing the mechanisms and conditions that may lead to electrical fires. The primary physical phenomena that cause electrical fires are overheating and arcing. Babrauskas [2003] provides a good review of the literature. However, there is a need to further explore these mechanisms and to establish forensic analytical methods that will provide improved reliability in making cause determinations in electrical fires.

The two global objectives of this work were to improve the forensic examination of electrical receptacles and their components and to better understand the potential causes of electrical fires in receptacles. Three primary areas of interest were explored: the development of overheating connections in receptacles (i.e., terminals and at the plug/receptacle interface), electrical and thermal damage to receptacles from fires, and forensic examination of electrically damaged and fire damaged receptacles.

Two series of tests were used to accomplish the objectives of this research: (1) laboratory testing of plugs and receptacles and (2) plug and receptacle configurations exposed to two different types of fires. Large quantities of receptacles were evaluated in each test series in order to provide adequate data for evaluating the effects of multiple variables as well as providing a substantial database to establish a quantitative understanding of the accuracy and reliability of forensic tools.

This report addresses the impact of a wide range of variables on the formation of overheating receptacle connections and overheating plug connections. The primary variables of study were the looseness of the connection (i.e., receptacle terminal torque and plug blade nominal retention force), receptacle materials, electrical load, and surrounding materials (i.e., installation in an outlet box with faceplate); only copper wiring was used. These variables were selected to be representative of a range of conditions expected to be found in the field. Laboratory testing of receptacle and plug connections consisted of 528 trials of 490 receptacles, with tests lasting up to 511 days.

A number of visual indicators of overheating receptacle connections were observed. These included oxidation, corrosion, and dezincification of metal components; and discoloration, melting, dripping, cracking, and charring of plastics. For receptacle screw terminal connections, it was found that nearly all of the loosest screw terminals (i.e., less than 3 in-lb) developed visible signs of overheating connections when subjected to loads of 15A. This is in good agreement with work conducted by Ferrino-McAllister et al. [2006] and Meese and Beausoliel [1977] who found overheating that developed in connections less than 1 in-lb and ⅛ turn loose (from 2 in-lb), respectively. When subjected to loads of 3A and 6A, regardless of the looseness of the connection, none of the receptacle connections developed significant signs of overheating. Only one receptacle subjected to a 6A current load showed some discoloration at the screw terminals. This receptacle was installed in a PVC outlet box with a Nylon faceplate, and no damage was obvious from an external inspection. When subjected to a load of 9A, approximately half of the receptacles with the loosest screw terminals (i.e., less than 3 in-lb) developed visible signs of overheating. At screw terminal torques of 3 in-lb or above, visible signs of overheating were not observed regardless of the electrical load. Based on this testing, both a very loose connection (< 3 in-lb) and a relatively high current load (9A or higher) are required for overheating to begin at a receptacle screw connection. The receptacle body material was not a prominent factor in determining whether or not a receptacle would overheat. However, the receptacle material typically affected the visual signs of overheating as the three types of receptacles (PVC, polypropylene, and Thermosets) behaved differently when heated.

Only three of the 42 back-wired push-in connected receptacles showed indicators of overheating, with one ultimately failing (0.02 failures/year). All of these receptacles were subjected to daily vibrations and were installed with one prior insertion and removal cycle for each wire. The only back-wired push-in receptacle to fail overheated to the point of flaming ignition. Despite some negative reputations in the past, likely due to early designs of back wired connections, the changes to UL486 [1986] affecting the testing of back wired push-in connections appear to have led to notable improvements of the robustness of this type of connection. Aged receptacles with back wired push-in connections were not tested in this research, but prior studies have indicated that early designs of back wired push-in connections had issues related to overheating [Biss, 1989; Oda, 1978]. Not only were loose connections and relatively high currents required to develop overheating of back wired push-in connections, but mechanical vibration of the receptacle was as well.

In addition to receptacle connections with branch circuit wiring, the connections between plugs and receptacles were systematically studied. The majority of plugs with folded brass blades and plated brass blades connected to receptacles having reduced nominal retention forces (i.e., 0.01 and 0.1 kg) showed some signs of overheating. However, the vinyl plugs with solid brass blades only showed evidence of serial arcing at the plug-receptacle connection, not overheating. This was attributed to a variety of possible factors including the blade-wire connection within the plug, the plug materials, the plug blade materials, and even the receptacle that the plug was connected to. The plugs with the folded blades and plated blades had crimp-on connections to the cord wiring with the body of the plug molded around them. The plugs with solid brass blades had a tight screw connection to the shunted wire and open space within the plug body, which helped to reduce the heat at the plug blade connections. And while receptacle screw terminal connections only overheated when loose connections were present, three receptacles having non-modified plug connections showed signs of overheating. The plugs were taken from cords with 16 ga stranded copper wire rated to 13A. Even with a modest over current of 2A (i.e., a 15A load), these receptacles still degraded to the point of visible damage to the plug without any additional thermal insulation or manipulation.

One primary mechanism leading to overheating of receptacle and plug connections was the formation of copper oxides at terminal connections involving copper wiring. Observations in this test program indicated that the oxide development in loose terminal connections followed that described in the literature whereby heat was first generated at a loose connection due to reduced contact area; then the heated copper wire oxidized; and finally the semi-conductive copper oxides formed a high resistance connection producing more heat and continuing the cycle. A second possible mechanism of overheating connections observed in this test program involved only the PVC receptacles. As the PVC receptacles were thermally degraded due to an overheating connection, they would release HCl vapors which would condense and form a white crystalline deposit on the surface of the conductors. The corrosion products may have then precipitated more heat and continue the heating-corrosion-heating cycle much like the copper oxides.

Glowing connections were formed on both plug connections and receptacle screw terminal connections. Two types of glowing were established: glowing connections with a bright orange glow over the entire screw terminal or plug connection (size ≈ 6.3 mm (0.25 in.)) and glowing connections with a small area of bright white glow (size of glow spot ≈ 1.5 mm (0.06 in.)). Both types were observed for receptacle connections, while only the overall glow was observed for plug connections. While the formation of glowing connections was limited to only the loosest screw connections (i.e., 1 in-lb and less) and plug connections (i.e., 0.1 kg (0.22 lb) and less), their development and appearance was rather inconsistent. Some glowing connections lasted for multiple days. Some would begin glowing, stop, and re-start without any apparent reason. Other overheating connections which had not glowed previously would transition to glowing immediately after the current was cycled on. Sometimes, when a connection was glowing and current was cycled off, the glow would reappear when power was cycled on even up to hours later. Other times, the glow would disappear for days before re-establishing. Despite their fickle nature, glowing connections formed at terminal torques of 1 in-lb and less without any manual intervention. This was contrary to the work published by Ferrino-McAllister et al. [2006], which stated that manual manipulation of loose connections was required for glowing connections to develop. The difference between this study and that of Ferrino-McAllister et al. [2006] is time. The development of glowing in loose receptacle connections requires time; often that time can be as long as months or years. The measured power dissipation in glowing connections was between 12 and 47 W. This was consistent with the range of power dissipations measured by a variety of researchers for copper connections.

Glowing receptacle connections produced distinct metallurgical evidence including: welded copper conductors around screw terminals, severed conductors at or near the screw head, and enlarged screw heads due to severe corrosion. These types of evidence are unique in appearance compared to melting and arcing events from external fire exposure. Arcing in stranded or solid copper wiring can sometimes sever one or more conductors involved in the arcing [NFPA 921, 2012]. However, the conductors severed due to the glowing connections were always severed near the screw terminal (i.e., within 1.3 cm (0.5 in.)) and only the severed conductor itself showed damage. In no cases of arcing from fire exposure did any of the solid copper wires sever due to the arcing. Also, all of the arcing observed in solid copper wires from receptacles was more than 1.3 cm (0.5 in.) away from the screw terminals and involved more than just one conductor. Temperatures upwards of 1100ºC at the bright glow spots on the copper conductors were measured. These temperatures were greater than the melting point of copper, which caused the copper conductor to become molten at the point of glowing. Even though the glow spot temperatures were higher than the melting points of copper and brass, in no cases did the brass receptacle contacts melt as a result of the glowing connection. This glow spot moved around the screw head, melting the copper conductor and welding it to and between the screw and screw terminal. The glow movement produced distinct curved striations in the welded conductor. This type of melting was unique compared to both arcing and melting from a fire exposure. Korinek et al. [2013] observed similar evidence for glowing connections between a copper wire and a receptacle screw. No cases were observed where fire melted copper connections were formed that were visually similar to the welded conductors produced from glowing connections. As the glow spot moved along the conductor and around the screw, it would get to the point where the conductor separated from underneath the screw head. At this point, the conductor would begin to neck at the glow spot, eventually severing and producing bead-like structures at the screw side and wire side of the parted copper conductor. Round, irregular, and flat severed conductors were observed. The severed conductors were visually unique compared to external fire induced arcing and melting damage. Whereas arc beads are generally smooth and copper colored, the round severed conductor ends were more of a round cap appearance and were dark grey in color. Irregular severed conductor ends were not tapered in the fashion that is usually observed for melted wires. And the flat severed conductor ends were distinct from the flat shaped melted conductors in that the conductors severed from a hot glow spot did not have the pitted flat surface that was found for melted wires. The round severed conductor ends were observed to have a cap of copper oxides atop a flat end; this evidence was also produced in experimentation by Korinek et al. [2013]. Glowing plug connections did not develop the bright glow spots, but tended to be an overall glow at the connection. Glowing in these connections did not produce any distinct metallurgical evidence.

Glowing connections in PVC receptacles sometimes produced what was termed an enlarged screw head as a result of severe corrosion of the terminal screw. This evidence was distinguishable by its swollen appearance and reduced size of the screwdriver notches. Cross-sections taken of the enlarged screw heads revealed that the majority of the surface corrosion was iron oxide. There was also a distinct thin copper layer at the base of the corrosion separating it from the bulk metal of the screw. It is unclear what physiochemical interaction caused the formation of the copper layer. Cross-sections and SEM/EDS chemical mapping were taken for four screws which were either enlarged screw heads or visually similar to enlarged screw heads (i.e., possible false positives). The cross-sectioned samples were an enlarged screw head (pre-fire), an enlarged screw head (post-fire), a screw with melting and corrosion from furnace exposure (Furnace

Screw X), and a screw with rust deposits. Analysis of the cross-sections and EDS mapping revealed that the enlarged screw heads were unique compared to the screw with rust deposits. While the potential false positive samples had visual characteristics similar to the enlarged screw heads formed as a result of overheating and corrosion, certain indicators clearly set them apart. In order to differentiate between these screws, comparison of multiple characteristics of the screw and corrosion (i.e., color, shape, roughness/porosity, oxidation layering, and EDS mapping) was necessary.

A number of receptacles with evidence of overheating, including welded conductors, enlarged screw heads, and severed conductors, were placed in a furnace exposure with temperatures upwards of 1000–1250ºC to simulate flashover conditions. The majority of the evidence of glowing on these receptacles remained after the fire exposure with only some changes in the color of the evidence. All of the 13 welded conductors persisted and remained identifiable after the fire exposure. On 9 out of 11 welded conductors with curved striations present, the curved striations remained and persisted after the fire. Four out of 5 enlarged screw heads persisted after the fire exposure; the fifth was only partially enlarged prior to the exposure and it was not clearly evident after the fire exposure that it had been partially enlarged. Only one of the 23 severed conductor ends (screw side and wire side combined) did not persist after the fire exposure. This one conductor had signs of melting of the copper wiring. At temperatures below the melting point of copper (1080ºC), the evidence of glowing connections persisted and remained unique compared to arcing and melting damage. Because the evidence of glowing connections primarily involves copper, copper oxides, steel, and steel oxides, the evidence will persist even at temperatures high enough to melt brass components (i.e., 930ºC).

While indicative of an issue within the receptacle or plug connection, the visual signs of overheating (i.e., melting, charring, discoloration, oxidation, and corrosion) did not always lead to a failure of the receptacle. Even though the majority (~80%) of very loose receptacle (1 in-lb and less) and plug (nominally 0.1 kg (0.22 lb) and less) connections subjected to a load of 15A showed signs of overheating, failure rates for very loose receptacle screw terminal connections (0.5 failures/year) and for very loose plug connections (0.04 failures/year) were rather low. Failures were not observed in non-modified plug connections, receptacles with torques of 3 in-lb or greater, solid brass blade plugs, folded blade plugs, or receptacles with loads of 6A and less. Only one failure event occurred for a receptacle subjected to a load of 9A. As was stated previously, the development of glowing connections took time and so did the receptacle failures. The range of times to failure for receptacle and plug connections was between 5 and 365 days; the average was 161 days. There were no trends observed with respect to the time to failure for variables including screw terminal torque, vibration, duty cycle, nominal plug retention force, or the failure mode.

The wide range of times to failures is significant with respect to implications for fire investigations both for the shortest and the longest time to failure. First, the quickest time to failure (5 days) is a rather short span of time in the expected life of a receptacle, which is typically on the order of a few decades. This implies that a specific receptacle failure could be tied to a certain event (i.e., receptacle modification, installation, addition of load, etc.). On the other hand, the longest time to failure of 365 days is noteworthy in that it suggests that failure events can be quite removed from the initial installation or modification, especially considering the receptacle and/or plug may not be in use continuously.

Multiple receptacle and plug connection failure modes were identified in the laboratory testing including: shorting of conductors, severed conductors at or near the screw terminal, series arcing at screw terminals, and flaming ignition. Approximately 19% of all failure events were flaming ignition failures (14% of receptacle failures; 100% of plug failures). Flaming ignition events were large enough to potentially ignite a range of proximate materials both in flame size and duration. Flame sizes up to 61 cm (24 inches) were observed and flaming ignition events lasted for periods up to about 6 minutes. However, the large flame sizes were only observed for the first 10% or so of the flaming duration. All of the flaming ignition events self-extinguished. Due to the additional plastics present, flaming ignition events for receptacles installed in outlet boxes with faceplates were generally larger in size. The outlet box also contributed to the likelihood of flaming ignition events. Failure rates for PVC and polypropylene receptacles (with 15A load) installed in outlet boxes with faceplates that led to flaming ignition were much higher (0.47 failures/year) compared to PVC and polypropylene receptacles installed in open air (with 15A load) that led to flaming ignition (0.07 failures year).

Evidence of arcing in flaming ignition events was not always present. Only 9 of the 17 flaming ignition events had parallel arcing evidence and only 3 of these 9 tripped a circuit breaker. While none of the flaming ignition events led to the complete consumption of the receptacle and/or outlet box and faceplate, the lack of circuit breakers tripping has significant implications for fire investigation. It indicates that circuit protection does not necessarily activate for an overheating receptacle that fails and ignites a flaming fire. Flaming ignition events occurred both with and without the distinct evidence associated with glowing connections. Some receptacles had welded conductors, some did not; some receptacles had curved striations on the welded conductors, some did not; and some of the plug connections had dezincification on the plug blade, some did not.

A number of categories of thermal damage were created for each type of receptacle, outlet box, and faceplate in order to discretize the end-state of the thermal damage observed for each item relative to the maximum exposure temperature. The methodology consisted of first evaluating the damage category for each component; second, using the maximum measured exposure temperatures for each component to determine temperature ranges for each damage category; and third, to evaluate the classification scheme by assessing a particular fire environment based on estimated temperature ranges for exposed components from their thermal damage categories. Ideally, the thermal environment would be characterized using the entire time-temperature and/or time-heat flux history for each receptacle. But, fully characterizing these temporal parameters in a concise manner proved too complex. A sample receptacle was evaluated using the methodology developed in this work. The range of temperatures for this sample did encompass the actual maximum exposure temperature, but the range was also quite large. Additional analysis of thermal damage to receptacles from a broader range of fire scenarios would strengthen this methodology for broader applicability. Further development of this method could provide fire investigators with a practical metric to describe the fire environment that is also suitable for field use and has a familiar quantifiable meaning.

The thermal damage from fire exposures was consistent in its general behavior; it tended to be uniform across the exposed face and advanced from the exposed face towards the rear of the receptacle. With respect to heating, the individual material behaviors observed in the fire exposure testing were similar to those found in the laboratory testing (i.e., melting, charring, cracking, etc.). The progression of damage from the front of the receptacle to the rear of the receptacle is consistent with observations in the literature [Babrauskas, 2003] and is quite distinguishable from the localized damage that is due to overheating. This distinction follows logically from the fact that the damage is a response to the thermal insult (i.e., fire or overheating connection) and the location of the thermal insult dictates the location of the damage. This type of visual determination of the damage location is analogous to a heat and flame vector analysis as discussed in NFPA 921 [2012]. The thermal damage to receptacles, plugs, outlet boxes, and faceplates due to overheating connections will generally remain distinguishable from damage due to external fire exposure depending on the extent of the damage. As the thermal damage from the fire exposure increases, the chances of identifying localized damage from overheating connections decreases.

Since overheating connections were highly correlated to the screw terminal torque, an effort was made to evaluate whether a post-fire terminal torque measurement could be used to estimate the pre-fire terminal torque. There has been no study of this type of forensic examination method in the literature. In this work, limitations to this process were identified, including softening of brass due to heat exposure and measurement dependence on the amount of grit, grime, melted plastic, or char that was on the terminal. Under specific conditions (i.e., terminals without much debris), measurement of the loosening torque can be useful to rule out overheating by demonstrating a high torque. However, the reverse is not true; due to the uncertainty in the measurement and the effects of heating and handling potentially causing connections to loosen, post-fire loosening torques are not reliable for indicating pre-fire loose connections.

Melting of brass and copper receptacle components due to external fire exposure was only observed in the furnace fire exposure tests. The maximum exposure temperature in any of the compartment fire tests in the vicinity of the receptacles was 903ºC, which is less than the melting point of brass (930ºC). The melting evidence for receptacles exposed in the furnace was identified using the naked eye or low powered microscopes. There were no strong trends relating the receptacle material or faceplate material with whether or not melting occurred for a particular receptacle.

In general, melted brass and copper receptacle components exhibited similar characteristic traits. The melting of brass and copper components generally occurred uniformly across the exposed area of the receptacle. For brass receptacle components, the following were frequently observed: effects of gravity, thinning of brass components, holes through brass components, pitting of surface, and round globules. The following were observed for stranded and solid copper wiring: gradual necking of conductor, surface pitting, effects of gravity, terminal screws separated from the conductor, and fusing of wire strands. In most occasions, more than one characteristic was observed for a melted component. With the exception of holes forming in brass components, the melting characteristics observed in this work are consistent with the literature [NFPA 921, 2014]. The holes that formed from melting were unique to the brass internal receptacle contacts. Although these holes are not specifically called out in the literature with respect to being a characteristic trait of melting, this is mostly due to the fact that the literature has been primarily focused on arcing and melting in copper wires.

In every case where melting of copper was identified in a receptacle, melting of brass components was also evident. This result is intuitive because the melting point of brass is approximately 150ºC below that of copper. As such, in a receptacle with brass components and copper wiring, the brass should melt before the copper does. Observations of thermal damage to receptacles from external fire exposures indicate that the damage progresses from the front of the receptacle to the rear. Because the brass components in a receptacle are typically at the front of the receptacle with the wiring extending towards the rear, it follows that since the damage progressed from front to back, the items in the front melted first.

A Scanning Electron Microscope (SEM) was used to document some of the forensic evidence gathered in the laboratory testing and fire exposure testing. In particular, the SEM was used to image two damaged break off tabs from PVC receptacles; one from melting and the other from arcing (brass-steel). A visual examination of these break off tabs showed notches with a clear line of demarcation between the area of damage and the undamaged area. Distinguishing between arcing and melting was accomplished in this case using SEM and chemical analyses. The chemical analysis revealed significant iron on the break off tab having arcing damage, but very little on the break off tab having melting damage. If the arcing is between two different metals (i.e., brass and steel), this method of analysis may be used to determine whether transfer of metal, a typical occurrence during arcing, is identified. Care must be taken when conducting this type of analysis as alloying or dripping of metals can cause one metal to appear to have been deposited on another due to arcing [NFPA 921, 2011]. However, in the cases where metals with higher melting temperatures are deposited on metals with lower melting temperatures, such as steel onto brass, alloying and dripping may be ruled out.

Arcing evidence in the post-fire examinations for compartment fire and furnace fire tested receptacles was identifiable using low powered microscopes. The process of identifying arcing damage consisted of first determining that the damage was not from fire melting and second, determining which conductors were involved in the arcing. In the compartment fire testing and furnace fire testing, there were a combined 251 receptacles that were energized. Of these 251 receptacles, 201 receptacles tripped the circuit breakers during the test; all receptacles with extension cords installed tripped the circuit breaker. Arcing damage associated with parallel arcing was identified in all but 23 of the receptacles that tripped circuit breakers. For the receptacles that did trip the circuit breaker but did not have evidence of arcing, there was often significant melting of copper and/or brass that potentially destroyed arcing damage or the melted and/or charred remains of the receptacle potentially covered the arcing damage. In all of the 50 energized receptacles that did not trip the circuit breaker, arcing evidence was not found. This data suggests that fire induced arcing in receptacles will cause circuit breakers to trip, but also that evidence of arcing may not be able to be identified even if the circuit breaker trips.

Even though the fire induced arcing in this test series always caused circuit breakers to trip, the literature states that parallel arcing does not always trip circuit breakers [NFPA 921, 2011; Twibell, 2004; Babrauskas, 2003]. This phenomena was observed through monitoring of several fire induced arc faults. Twelve receptacles were instrumented with a Hioki power meter to record the voltage and current associated with arcing events. Ten of the 12 receptacles had an arc fault that tripped the circuit breaker during the fire exposure test. Three of these 10 receptacles had two arc faults separated by between 1 and 13 seconds. There were no visual differences between the arcing damage from only one arc fault or the arcing damage where two arc faults occurred. The first arc fault, which was typically lower in current than the second arc fault, did not trip the circuit breaker, but in all cases the second arc fault did. This means that fire induced arcing in a receptacle that does not trip a circuit breaker is a plausible scenario.

There were a number of locations of arcing that were common through all of the fire exposure tests. The locations of arcing were characterized as a pair of locations: the primary location (i.e., hot conductor) and the secondary location (i.e., neutral or ground conductor). The primary arcing locations included the female plug contacts, the break off tab on the female plug contacts, receptacle wiring (solid) and extension cord wiring (stranded). The secondary arcing location is a conductor involved in the arcing other than the hot conductor such as part of the ground system (i.e., steel faceplate, metal outlet box, ground strap, or ground wire) or the neutral wire. Arcing damage on the steel faceplate was confirmed in 76 out of the 133 energized receptacles with steel faceplates where arcing damage was identified. Arcing damage on the outlet box was present in only 8 out of 161 energized receptacles with steel outlet boxes where arcing damage was identified. When examining a receptacle for signs of fire induced arcing, it is not enough to only examine the receptacle; the whole installation (i.e., receptacle, wiring, outlet box, and faceplate) should be examined.

The majority of literature focuses on electrical arcing in copper wiring, both stranded and solid, with some attention paid to steel (i.e., conduits), and relatively little mention of brass. This is despite the relatively equal presence of copper, steel, and brass in receptacles and similar devices. Proposed changes to NFPA 921 [2012] for the upcoming 2014 edition of the guide include the addition of locally enlarged grain size [Murray and Ajersch, 2009; Lewis and Templeton, 2008], resolidification waves [Murray and Ajersch, 2009], and high internal porosity [Buc, 2012; Lewis and Templeton, 2008] as additional characteristic traits of arcing. Enlarged grain size was not examined because this trait could not be examined using visual methods alone.

Arcing in overheating connections (i.e., non-flaming ignition failure events) and external fire induced arcing in receptacles were rather similar in size, shape, and location. The size of arcing damage from overheating connections and fire induced arcing was typically limited to a single arc location resulting from a single point of contact. However, in some cases of arcing from flaming ignition events, the damage was extended beyond just one arcing location, with significant damage to the conductors. Other than by visual indicators, there was no attempt in this work to distinguish between external fire induced arcing and arcing that could have been the source of the fire. There has been research into this topic [Man et al., 2011; Anderson, 1996], but such work has yet to provide a conclusive determination of fire cause vs. fire effect [Babrauskas, 2004].

Distinguishing between arcing and thermal melting damage was based on the presence of visual indicators of arcing and/or melting in the evidence as listed in the proposed changes to NFPA 921 [2014], with some additions. A portion of the receptacles from this test program was evaluated for the presence of the aforementioned characteristic traits of arcing and fire-melting damage. The purpose of this exercise was to assess which characteristic traits were effective in assessing potential arcing damage on receptacle components and wiring.

Corresponding damage on the opposing conductor, localized damage with a sharp line of demarcation, and tooling marks outside of the area of damage were observed on significant portions of arc damaged conductors and small numbers of conductors with melting damage;

these characteristics were found to be strong indicators of arcing. This was expected as these traits are fundamentally tied to the physical attributes of arcing, including very high temperatures, high temperature gradients, and quick time scales for melting and cooling. Corresponding damage and a sharp line of demarcation are widely accepted in the literature as indicators of arcing [NFPA 921, 2012; Babrauskas, 2003; Murray and Ajersch, 2009; Lewis and Templeton, 2008; Twibell, 2004]. Tooling marks, including copper drawing lines, sharp edges or stamped letters and numbers, were a parallel method of determining whether localized damage with a sharp line of demarcation was present.

Resolidification waves and spatter deposits were observed in limited conductors with arcing damage; however, no fire-melted conductors were observed with resolidification waves and melting would not be expected to produce such attributes. Therefore, these characteristics were very distinct from fire melting damage and are considered strong indicators of arcing. Although internal porosity was not systematically evaluated, a number of conductors with arcing damage were observed to have significant porosity. Various researchers [Lewis and Templeton, 2008; Buc, 2012; Levinson, 1977] have shown that arcing and melting can cause porosity to form in metals, typically creating greater porosity for arcing compared to melting. However, because there has not been any rigorous study which quantifies the size and percent by volume of voids in arc beads or melted conductors, the value of this characteristic trait in an arc damage determination is limited. A round, smooth shape; small beads and divots; and localized round depressions were observed in limited numbers on arc damaged conductors and similar characteristic traits were observed in fire-melted conductors. Due to the lack of clear definitions in the literature, these three characteristic traits were poor indicators of arcing. A small portion of receptacles with arc damaged conductors also had fire-melting observed in the receptacle. Typically, this melting was either not close to the arc damage location or was on a metal with a lower melting temperature.

Limited numbers of fire-melted conductors were found with blisters on the surface, effects of gravity, gradual necking, pitting, thinning of the conductor or holes formed in the conductor. These characteristic traits were rarely observed in arc damaged conductors and were fair indicators that the damage present was due to fire-melting. Some conductors with fire-melting damage were observed to have characteristic traits of arcing (i.e., localized damage with a sharp line of demarcation or corresponding damage on the other conductor). A number of instances were observed where accepted characteristics of arcing were found in melted copper conductors. These characteristics included a clear line of demarcation between damaged and undamaged areas and copper drawing lines visible outside of the arc damaged area. In this case, a myopic examination of the evidence with respect to these characteristics could cause a false indication of arcing. In cases such as this, other evidence of melting in the receptacle (i.e., in close proximity to the area in question) would preclude confirmation of arcing. It is easy to see why errors such as this could be made. Much of the research into characteristics of arcing and melting presents discussion of one or two characteristics individually [Murray and Ajersch, 2009; Lewis and Templeton, 2008; Buc, 2012; Hussain, 2012]. As such, this type of research often does not examine the evidence in its entire context as would be expected in a practical fire investigation. The myopic examination of individual characteristics of arcing and melting is required for fundamental research, but it is a potential pitfall that should be considered in a forensic examination.

The characteristic traits of arcing and melting are qualitative and most are not well defined in NFPA 921 [2011], which leads to more subjective evaluations. However, some characteristics such as porosity have the potential for being quantitative characteristics if further research is conducted. And though some characteristic traits were strong indicators of either arcing or melting, an investigator should never rely solely on the presence of one characteristic trait for arcing vs. fire-melting determination. Using multiple characteristic traits and contextual information for arcing vs. fire-melting determination provides greater confidence in the evaluation of damage. In addition, visual examinations were found to be reliable indicators of both arcing and fire-melting for most conductors. However, there are some cases which would benefit from more advanced examination techniques including SEM/EDS examinations, X-ray, CT scanning (X-ray computed tomography), cross-sectioning and polishing, or other metallurgical methods.

Implications for policy and practice:

The results of this study establish a baseline for post-fire assessment of whether electrical receptacles may have had an overheating event that lead to an electrical fault. New forensic signatures have been identified along with techniques for evaluating post-fire evidence to differentiate between electrical overheat/receptacle fire signatures and damage resulting from an external fire exposure. Conclusions from this study are being submitted to the NFPA 921 Technical Committee on Fire Investigations for inclusion in the next edition of the document. It is anticipated that the forensic signatures identified in this work will be utilized by forensic laboratories in assessing electrical receptacle fires.

Implications for further research:

Due to the small fraction of actual occurrences of overheating events that lead to electrical faults and the potentially long times required to form such faults, more long term testing would be useful in providing a larger database. This study did not address various contaminants that may affect the development of overheating conditions in electrical connections. Consequently, work addressing a systematic study of potential contaminants would expand the understanding of conditions that can lead to electrical faults and possible fire events. An expansion of the analysis of arc locations and overheating signatures to include additional cross-sectioning and polishing, SEM/EDS analysis, CT scanning (X-ray computed tomography), or other metallurgical examination techniques would expand the understanding of what specific (non-visual) characteristics are associated with these pieces of evidence.

1.0 INTRODUCTION

Electrical fire initiation is attributed to a large proportion of structural fires, especially large fires, in the United States. Hall [2010] reports that from 2003 to 2007, home electrical fires represented 13% of the total home structure fires, 17% of associated civilian deaths, 11% of associated civilian injuries, and 21% of associated direct property damage. Of all electrical fires, 41% involved electrical distribution or lighting equipment (i.e., wiring; outlets, receptacles, and switches; over current protection equipment; meters and meter boxes; lamps, light fixtures, light bulbs, and signs; cords and plugs; transformers and power supplies). Receptacles, cords, wiring, and plugs combined represent approximately 14% of all residential electrical fires [Hall, 2010]:

- Outlet or receptacle 5%
- Extension cord 3%
- Branch Circuit Wiring 3%
- Permanently attached power cord or plug 1%
- Unclassified cord or plug 1%
- Detachable power cord or plug 1%

An earlier study [Hall et al., 1983] of 105 residential-occupancy electrical fires showed that 37% of those fires had their origins in receptacles, cords, or plugs. Generally, the statistics reported do not include the physical mechanism that led to the device malfunction/causing a fire. Most (72%) of reported home structure fires involving electrical failure or malfunction were reported with few or no details on failure mode. The two leading types of electrical failure or malfunction were unclassified electrical failure or malfunction (46%) and unspecified short circuit arc (27%). Therefore, the statistics do not provide a basis for improving fire safety. In order to use these statistics in a better context, it is important to first determine the required conditions that are needed for ignition and the subsequent forensic signatures that can be used to differentiate whether the electrical component was the cause of the fire or a victim of the fire.

There is a limited body of work addressing the mechanisms and conditions that may lead to electrical fires. The primary physical phenomena that cause electrical fires are overheating and arcing. Babrauskas [2003] provides a good review of the literature. However, there is a need to further explore these mechanisms and to establish forensic analytical methods that will provide improved reliability in making cause determinations in electrical fires. Possible conditions that induce the mechanisms that lead to overheating and arcing conditions are summarized in Table 1-1.

Table 1-1. Summary of Possible Mechanisms That Lead to Overheating and Arcing Conditions.

	Cords	Plugs	Receptacles
Arcing	- Mechanical damage - Thermal damage	- Mechanical damage - Contamination leading to arcing - Excessive electrical loads - Hot plugging - Improper insulation	- Contamination leading to arcing - Mechanical damage - Thermal damage
Overheating	- Loose terminal connections - Over current - Lack of air flow	- Improper crimping - Poor blade contact - Loose terminal connections	- Contamination - Loose terminal connections

Understanding required conditions that are needed for ignition and the subsequent forensic fire cause and fire effect signatures will allow the fire investigation community the ability to properly evaluate fires involving electrical components. The purpose of this research was to better understand the accuracy and reliability of potential signatures of electrical fires, to provide a quantitative basis for validating the utility of diagnostic forensic tools, and to characterize the conditions that lead to overheating and arcing in electrical receptacles which can cause fires.

1.1 Literature Review

A review of the literature relevant to this study has been performed. The subsequent sections summarize the body of work that has been conducted related to the electrical phenomena of arcing, arc tracking, overheating connections, and glowing connections. Specifically, the works summarized herein provide insight and data describing the formation of overheating connections with aluminum, copper, and other metals in experimental setups and in receptacle connections. Receptacle connections including screw terminals, back wired push-in terminals, and plug-receptacle connections; parameters such as screw terminal torque, plug blade retention force, and current load; and work examining arcing and overheating as ignition sources as well as the forensic examination of electrical components are discussed.

1.1.1 Codes and Standards

In order to provide the public with an adequate level of safety, certain codes and standards exist which regulate the design, manufacture, and installation of electrical components in the US and abroad. Underwriters Laboratory standards UL 498, Standard for Attachment Plugs and Receptacles and UL 817, Standard for Cord Sets and Power Supply Cords provide construction and testing requirements which serve as the primary approval method for these electrical devices in the US. In addition, Federal Specification (Fed. Spec.) W-C-596 is also used for some receptacles and plugs. NFPA 70, the National Electric Code (NEC) is the basis for regulation of the installation of electrical systems and components (i.e., switches, receptacles, electrical distribution wiring, breaker boxes, etc.) for residential, commercial, and industrial buildings and is used throughout the United States. Some jurisdictions choose to modify the NEC to fit their specific needs. The aforementioned codes and standards form a minimum set of requirements for electrical devices and their installation.

Testing in accordance with UL 498 for attachment plugs and receptacles covers a wide range of performance characteristics including plastic flammability, thermal degradation, temperature rise, product durability, and electrical insulation. While this standard does ensure a reasonable level of safety for the majority of receptacles and plugs in use, it would not be practical to evaluate every eventuality that may occur. However; time, damage, improper installation, alteration, and other conditions can degrade the level of safety provided. Over the years, as the use of electrical and electronic devices has become more prevalent, the NEC has increased the number of electrical receptacles required per linear foot of wall space in new construction. This number can only be expected to increase in the future as there are no signs of the growth of the use of electrical and electronic devices slowing.

According to the NEC, all electrical receptacles installed in accordance with the code must be listed products. According to UL 498, receptacles can either be listed as general grade or hospital grade. Hospital grade receptacles, in addition to complying with general use requirements of UL 498, have additional requirements. These additional requirements, while increasing the consumer cost of the individual device, provide better grounding, durability, strength, and assembly integrity. Federal specification (W-C-596) receptacles and plugs have additional requirements pertaining to markings, construction, performance, and durability requirements beyond those in UL 498. “Commercial,” “Heavy Duty,” “Spec. Grade,” and other designations are used by device manufacturers to market some of their product lines. These designations often mean that the products are more robust and are constructed of better components such as screw and clamp type terminals. However, these designations are not tied to any additional safety testing or construction requirements in accordance with their UL 498 listing.

1.1.2 Arcing

An electrical arc is a high-temperature (>5000°C) electric discharge between two conductors across an air gap or a medium such as char, degraded insulation, or a wet surface [Babrauskas, 2003]. Arcing across an air gap must occur either over a very small gap or using a very high voltage due to the high dielectric strength of air (3×10^3 V/mm) [Twibell, 2004]. More information regarding the dependence of arcing on the air gap distance and the breakdown voltage can be found in Babrauskas [2013].

An arc between two conductors can either be a series arc or a parallel arc. Series arcs occur in a circuit in series with the load (see Figure 1-1, left). The current through a series arcs is limited to that of the connected load. But, series arcs will not cause a circuit breaker or fuse to trip because they, in fact, decrease current draw [Babrauskas, 2003]. This does not apply to arc fault circuit interrupter (AFCI) devices which are specifically designed to detect series arcing [Babrauskas, 2003]. Parallel arcing is arcing between the two legs of a circuit; a load does not need to be present for parallel arcing to occur (see Figure 1-1, right). The current of a parallel arc is only limited by the resistance of the circuit, which is typically very low. This current is termed the available short circuit capacity; calculation of this current requires information of the impedance of each portion of the circuit including the transformers feeding the building. Parallel arcs, where the available short circuit capacity is larger than the magnetic trip value of the circuit breaker (see Section 3.3.8), will typically cause circuit breakers and fuses to trip. Where the available short circuit capacity is not able to trip the circuit breaker, sustained arcing may occur. Sustained arcing can fuse or melt metal conductors, cause ejection of molten particles, or pyrolyze and ignite combustible materials. Circuit breakers may not operate in time to prevent fires associated with parallel arcing [Babrauskas, 2006].

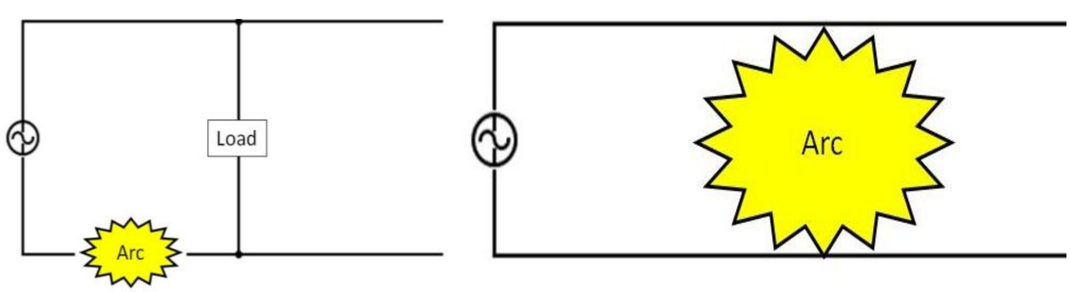


Figure 1-1. Schematic of a series arc (left) and a parallel arc (right).

1.1.2.1 Arc Tracking

When subjected to mechanical damage, moisture, salts, or excessive heat, wire insulation can break down, causing leakage currents between two conductors previously separated by the insulation [NFPA 921, 2011]. These leakage currents generate heat, which causes a carbonized path to form on the insulation between the conductors. This process is called arc tracking. In time, an arc may occur between the two conductors along the carbonized insulation pathway. These types of arcs are typically referred to as arcing thorough char. Several test methods, including UL 746A [2000], ASTM D3638, and IEC 60112 [2003], assess the relative propensity of insulation materials to arc tracking [Beyler and Gratkowski, 2006]. These test methods usually use wet tracking methods whereby drops of a saline solution are deposited onto the insulation between two electrodes at specified intervals of time up to a maximum number of drops. The end of a test is determined by the operation of a circuit breaker or a maximum measured current flow through the circuit. Depending on the method, tests can be conducted using AC or DC sources at a specified voltage or a range of voltages. These test methods produce comparative results and do not establish the limits on when tracking is possible [Beyler and Gratkowski, 2006].

There are varying opinions in the literature of the prevalence of arc tracking as a fire cause. Yereance [1995] claims it is a major cause of residential fires, but provides little support. Noto and Kawamura [1978] were able to create arc tracking with ignition in half of their cases. Beyler and Gratkowski [2006] have performed studies that showed that arc tracking across damaged conductors from a low voltage circuit (12–14V) is capable of starting a fire.

1.1.3 Receptacle and Plug Connections

Because electrical receptacles are the primary access point for obtaining electricity in most settings, a major point of study is the potential for electrical heating and arcing at connections in receptacles. In a typical residential setting, the most numerous type of circuit is a 120V AC branch circuit. These circuits are used to power a wide range of devices including computers, televisions, lighting, electronics, refrigerators, and other appliances. A common type of receptacle used on the branch circuits are duplex receptacles, i.e., those having two outlets. Receptacles are made up of non-permanent connections, meaning ones that can be removed, loosened, or changed without damaging the system. Permanent connections, such as crimps and soldering provide a connection that must be destroyed during modification [Rabinow, 1978]. For receptacles, there are connections between the receptacle and fixed branch circuit wiring as well as between plug prongs/blades and the internal plug terminals. Some studies have been conducted which examine the mechanisms which lead to both arcing and glowing connections in receptacles (see Section 1.1.3.1) and plugs (see Section 1.1.3.5). However, few if any of these explore the conditions that lead to the ignition of electrical components and proximate materials.

1.1.3.1 Overheating Receptacle Connections

A common physical mechanism leading to receptacles fires is the occurrence of an overheating connection, formed as a result of a loose terminal connection. In a receptacle there are electrical connections between the plug blades and the receptacle as well as between the receptacle and branch circuit wiring. Connections between the receptacle and branch circuit wiring can be various types, including side wired screw terminals, back wired push-in terminals, and back wired compression terminals, the latter being less common (see Figure 1-2). All types of connections have the potential to overheat if installed improperly. In addition, due to the practice of installing receptacles in series in some installations,a receptacle does not necessarily have to have a load plugged directly into it in order for there to be current passing through it and potentially creating an overheating connection.

Figure 1-2. Three types of receptacle terminals (from left to right: side wired screw terminal, back wired push-in terminal, and back wired compression terminal).

1.1.3.1.1 Aluminum Connections

In the 1950s and 1960s, aluminum wiring was introduced for use in branch circuit wiring for residential applications due to its lower cost than copper [Rabinow, 1978]. Aluminum wiring had extensively been used in many industries without major issues up to this point, however, the wiring connections used in these industries tended to be specifically designed for use with aluminum wiring [Rabinow, 1978]. On the other hand, the aluminum wiring used in residential applications was used as a drop-in replacement for copper. This was done without redesigning the connections that were originally designed for copper wiring [Rabinow, 1978]. Because of its tendency to creep and loosen in pressure terminals when heated by electrical current, overheating connections were found to be more prevalent in aluminum (compared to copper) [Rabinow, 1978]. After this problem was recognized, there was an increase in research on aluminum connections in residential applications in order to understand and mitigate the hazards.

Meese and Beausoliel [1977] performed an exploratory study on overheating connections in receptacles with aluminum and copper wire and noted various parameters affecting the temperatures. These parameters included the length of conductor wire in the outlet box, outlet box material, face plate material, wall insulation, wire-binding screw material, etc. Glowing connections were obtained in a variety of situations with both severe and minimal mechanical interactions. Their study noted that wire insulation, PVC outlet boxes, wood paneling and wood insulation were all susceptible to charring but did not investigate the conditions leading to flames capable of involving surrounding combustibles. They also found that plugs were susceptible to ignition. Based on voltage drop measurements, the longest continuous glow in aluminum wiring in open air occurred for a period of 129 hours; the extended duration testing was only conducted for one receptacle. The average power dissipation over that period was 20 W, with a peak of 35 W. In the majority of experiments by Meese and Beausoliel [1977], receptacles were never energized for more than 9 continuous hours. This relatively short exposure duration does not account for situations where current flow is continuous.

Aronstein [1983] studied branch circuits using aluminum wire and identified several ignitable materials inside an outlet box, such as braided type NM cable sheathing and insulated twist-on connectors, and ignitable materials outside the junction box, such as wood paneling and wallpaper. He was able to quantitatively correlate the heat dissipation from overheating connections that could lead to ignition of furnishings (28 W), receptacle faceplates (30 W), and wood studs (35–50 W). He also found that molten aluminum could be ejected from outlets to ignite surrounding combustibles (45–50 W) and that glowing connections could ignite vapor barriers and attachment plugs and cords, but did not give details on the conditions necessary for such occurrences. Similar results from a previous study by Aronstein [1977] on aluminum wired field sample receptacles, reported in Babrauskas [2003], are noted in Table 1-2.

Table 1-2. Power Dissipation in Glowing Aluminum Connections [Aronstein, 1977].

Power dissipated in connection (W)	Results
4	Newspaper over face, slight charring
0.5-35	Charred bedspread
34-57	Wire melted, wallpaper charred
23-46	Insulation melted, cotton towel against face charred
4-9	Insulation melted
14-20	Cotton towel against face ignited (flaming)
12-46	Bedspread against face smoldered then ignited (flaming)
28-32	Bedspread ignited
29	Ignition of wood members after 1 hour

Newbury and Greenwald [1980] simulated loose aluminum wiring connections in duplex receptacles and an experimental apparatus. The experimental apparatus used by Newbury and Greenwald consisted of a test wire wrapped around a screw removed from a commercial receptacle. A current of 15 A was applied to the connection and the screw was loosened until a glow developed. This apparatus was used to produce specimen used to examine the initial phases of glow development. The second set of tests examined residential receptacles with screw connections tightened to 4 in-lb. A current of 40 A was applied and the power was cycled (10 minutes on, 10 minutes off) until a glow developed. Newbury and Greenwald did not measure the power dissipation for any of their glowing connections. Examination of cross-sections of the glowing aluminum connections produced by Newbury and Greenwald revealed iron-aluminum intermetallic compounds at the interface of the aluminum wire and iron screw. These compounds were thought to have formed as a result of arcing. The authors stated that the intermetallic compounds could have a resistivity more than 10 times greater than the pure metals. Newbury and Greenwald proposed that the intermetallic compounds, rather than aluminum oxide formation was the primary mechanism for the formation of the glowing connections.

1.1.3.1.2 Copper Connections

Overheating and glowing connections are not unique to aluminum and have been studied in copper wiring by a variety of authors, including Ferrino-McAllister et al. [2006], Ettling [1982], Aronstein [1983], Sletbak et al. [1992], Kim et al. [2006], and Korinek et al. [2013]. The primary mechanism for the formation of overheating and glowing connections in copper wiring is the formation of a semi-conductive oxide layer between two conductors.

In all electrical circuits, current flow through a conductor creates heat due to the inherent resistance of the conductor. This is called ohmic heating. Even when operating at or over a conductor's rated ampacity, most heat generated is dissipated into the environment. Ohmic heating also occurs for current flow through a connection where the heat generated is due to the contact resistance. When two electrical conductors make firm contact over a large surface area relative to the cross-sectional area of the conductors, a good connection is formed and ohmic heating at the connection is minimal. However, loose terminal connections typically result in reduced contact area between conductors. The passage of current through a loose copper connection (i.e., a reduced contact area) heats the contact area causing the formation of oxide layers between the contacts. Copper oxides are semi-conductive materials and as the layer of oxidation builds between the contacts, a high-resistance connection is formed. This high-resistance connection will heat up and exacerbate the formation of additional copper oxides. Eventually the connection can heat to the point of glowing which can persist for minutes, hours, or days [Meese and Beausoliel, 1977]. The rate of oxide production is based on the density and type of oxide film that is formed (i.e., porous oxide, nonporous, adherent oxide, and spalling, non-adherent oxide) and the temperature at which the oxide is formed [Askeland, 1989]. Below approximately 1100°C, CuO [cupric oxide] is formed and above this temperature Cu_2O [cuprous oxide] is formed. CuO is generally dark black in appearance, while Cu_2O is a reddish color; both are semi-conductive materials.

Sletbak et al. [1992] conducted experiments with pairs of small (cross-sectional area: 1.5 mm^2) vibrating wires which produced glowing connections between the wires. Sletback et al. proposed that arcing resulting from making and breaking of the connection due to vibration precipitated the formation of Cu_2O on the conductors. As current flow through the oxide layer exceeded approximately 0.15A, the current became concentrated in a thin glowing filament (~1235°C) at the surface of the oxide. The glowing filament precipitated more oxidation growth on the conductors to a point where a solid physical and electrically conducting oxide bridge was formed between the two conductors. This series of events was termed the "Cu2O breeding process," the details of which have been studied by various authors including Kuroyangi et al. [1981], Shea [2006a], and Kawase [1977]. In particular, Shea [2006a] found that glowing connections could not be formed in environments of dry nitrogen. Even when there was a glowing connection already present, when the partial pressure of oxygen dropped below 12 kPa (90 Torr), the glowing connection could not be restarted or maintained. Shea hypothesized that without enough oxygen, the production of Cu_2O that caused the glowing connection could not be maintained.

Experimental data from glowing connections in copper wiring from Ettling [1982], Aronstein [1983], Sletbak et al. [1992], and Kim et al. [2006] is presented in Table 1-3. These studies used different methods to initiate a glowing connection and examined a wide range of currents (0.5–20 amps) and voltages (120–220 volts, AC). Ettling [1982] created a glowing connection between copper wires (14 AWG) and a steel nail which ignited pyrolysis vapors from the nail's wood substrate. Sletback et al. [1992] and Kim et al. [2006] used small diameter (1.3–1.5 mm) oscillating wires to obtain glowing connections. In general, the range of power dissipations from glowing copper connections was similar to glowing in aluminum connections (see Table 1-2). Meese and Beausoliel [1977] stated that power dissipations from glowing connections could be as low as 5 W (at 0.8A) and greater than 35 W (at 15A). However, these authors studied both copper and aluminum connections and it is unclear which material the range of power dissipations is for. Regardless, wide ranges of power dissipations from glowing connections were observed in both copper and aluminum connections at a variety of currents.

Table 1-3. Power Dissipation by Glowing Copper Connections.

Source	Power Dissipation (W)	Current Draw (A)	Line Voltage (V)
Ettling [1982]	20	Not Stated	120
Aronstein [1983]	0.5 - 57	12-15	120
Sletbak et al. [1992]	17	1	220
Kim et al. [2006]	19-31	1.6	220

Korinek et al. [2013] recently studied overheating in poor connections between copper wiring and nickel plated steel receptacle screws. To produce glowing on short time scales, the connections between the wire and screw were made by laying the wire on the screw head rather than having the wire wrapped around the screw. These researchers found that glowing connections (comprised of copper, iron, and oxygen) would melt and re-solidify in layers forming a "nugget." The glowing area was observed to move along the interface of the wire and screw; necking of the glowing conductor was also observed. These researchers observed a "burn-open" of the wire which stopped current flow (i.e., severed conductor) at the point of the glowing liquid copper oxides. A chapter on electrical fires from a fire investigation book [Twibell, 2004] has also noted that "many overheating connections burn themselves out and break the electrical circuit without causing the fire." Though it is unclear whether this particular statement was substantiated by personal experience or specific research, it mirrors the behavior observed by Korinek et al. [2013].

A large body of work has studied the corrosion of copper and other metals used in electronics and electrical components. Glass et al. [2011] exposed electrical receptacles and other electrical devices to hydrogen sulfide (H_2S) and electrically tested them. They found no increase in electrical resistance, evidence of overheating, or degradation of cross sectional area. It is possible that other corrosive environments, which have not yet been studied in this context, could lead to overheating connections.

1.1.3.2 Other Glowing Connections

The glowing discussed in Sections 1.1.3.1.1 and 1.1.3.1.2 was for connections between aluminum and steel and copper and steel, respectively. Copper and aluminum connections, primarily due to their tendency to oxidize at moderately elevated temperatures, have been shown to form glowing connections with a variety of other metals commonly used in electrical devices. Meese and Beausoliel [1977] obtained sustained glowing (i.e., >5 minutes at 15A) with the following material combinations:

- Copper wire and steel block;
- Aluminum wire and steel block;
- Copper wire and aluminum wire;

- Copper wire and copper wire; and,
- Aluminum wire and aluminum wire.

However, Meese and Beausoliel [1977] were unsuccessful in obtaining glowing connections between copper wire and brass blocks or between aluminum wire and brass blocks. Ettling [1982] performed experiments with contact between a copper wire and a zinc plated steel nail in which a glowing connection did not form. Sletback et al. [1992] was able to form glowing connections between copper and brass and copper and tin plated brass wires.

1.1.3.3 Screw Terminal Torque

The torque on receptacle screw terminals has been use by some studies as a measurement of the looseness of receptacle connections. Work by Ferrino-McAllister et al. [2006] explored glowing connections in copper wire connections in residential receptacles to study the factors that lead to their formation, such as initial screw torque, screw loosening, current, apparent wire contact area, contamination, vibrations, and other mechanical disturbances. Ferrino-McAllister et al. [2006] found temperature changes of approximately 38°C or less with terminal torques more than 4 in-lbs and up to approximately 80°C at torques below 1 in-lb. Tests were conducted at 12.5A for between 2 and 8 hours. These conditions did not initiate a glowing connection or rapid oxidation of the conductors. It was found that movement of the loose connection by hand was required to initiate a glowing connection. The length of wire in contact with the binding screw head did not have an impact on the temperature of the conductor. Meese and Beausoliel [1977] conducted tests with screw terminal connections loosened by 1/8 turn from a torque of 2 in-lb to produce their glowing connections. And a NIST study, using 14 AWG conductors, showed that minimum heating can occur for a screw torque of 6.2 in-lb [Burns et al., 1978].

Newbury and Greenwald [1980] studied glowing connections in aluminum wired residential duplex receptacles. These receptacles had connections tightened to 4 in-lb. A current of 40A was repeatedly cycled (10 minutes on, 10 minutes off) to induce glowing. Four receptacles were sampled in the testing by Newbury and Greenwald. Two of the four receptacles developed glowing connections after 36 cycles, with maximum temperatures of 350°C measured at the break off tabs. Glowing for these receptacles was sustained for 4 hours before the tests were terminated. Two other receptacles did not develop glowing connections after 12 and 16 cycles. The receptacles that did not develop glowing were interrupted prior to glowing in order to examine the sequence of events leading up to glowing.

The typical torque that is used for field installations of receptacles is not readily apparent and is dependent on the person performing the installation. UL 498 [2008] use a torque of 9 in-lb for 14 AWG or smaller wires (15A or less) and 14 in-lb for 12 AWG or larger wires (more than 15A) for their temperature testing. However, this is not an installation requirement. UL 498 also requires that all screw terminals withstand a maximum tightening torque of 16 in-lb before thread stripping occurs. The NEC suggests, in an informative annex, that installers of receptacles use manufacturers recommended torques or in absence of these torques, a minimum value of 15 in-lb is recommended for connections with 10 AWG and smaller wires. This annex does not form part of the NEC requirements and is only for general connections, not specifically for receptacles. Some receptacle manufacturers state that the terminals should be “sufficiently tight” and do not specify a torque to be used. Otherwise, there are no specific tightening torque requirements for the installation of receptacles.

1.1.3.4 Back wired Push-in Connections

The fire hazards of receptacles employing back wired push-in terminals have also been the subject of much debate in the literature. Earlier studies had shown that these connections are susceptible to overheating, and many failed the UL 498 [1986] temperature test requirements for receptacles after as little as one removal and reinstallation of a back-wired conductor [Aronstein, 1993], or even after being exposed to a year of normal cyclic loading using 15A and 20A currents [Biss, 1989]. Oda [1978] also found that back-wired push-in receptacles were more likely to ignite proximate materials than side-wired receptacles. These and other studies prompted changes to the 11th edition of UL 498 [1986] for testing requirements for back-wired receptacles, yet there has been no subsequent study to determine any consequent improvements [Babrauskas, 2003].

As part of the current UL 498 [2008] listing process, receptacles with back wired push-in connections undergo a battery of temperature testing. Prior to testing, a wire is inserted and removed three times for each of the back wired push-in connections. A new wire is inserted the fourth time. Each conductor is then subjected to a 20 lb pull force perpendicular to the plane of insertion for a period of 1 minute. After this, the receptacle is installed in a wall mockup with aluminum heat reflectors installed on the back of the wall before conducting the four part temperature rise test. The first part of this UL 498 [2008] test consists of a standard temperature rise test at a current of 15 A, similar to that which is used for side wired screw connections. Second, a current cycling test is conducted at 22.5 A which consists of 168 four hour cycles with 3-½ hours with current and ½ hour without current. Third, each conductor attached to the receptacle is moved through an arc of approximately 90 degrees and returned to the horizontal position two times. The final part of the temperature testing is a repeat of the standard temperature rise test similar to that which is used for side wired screw connections. In this test, the temperature rise must be no more than 30°C above ambient when the device is carrying its maximum rated current [UL 498, 2008]. The testing regimen for back wired push-in connections is quite severe when compared to the testing for side wired screw terminals. The screw terminals are tested at relatively tight conditions; torques of 9 and 14 in-lb are used for 14 and 12 AWG conductors, respectively. Also, the screw terminal connections go through one test only and do not have any manipulation of the conductor or terminal.

1.1.3.5 Overheating Plug Connections

A plug provides an interface between a receptacle and an electrical cord via male blades. The connection inside the plug, between the blade and the cord, is typically either crimp or screw and pressure plate type. Ignition mechanisms have been better characterized for plugs than for receptacles. Several studies have quantitatively examined failure modes for plugs including: electrical contact and insulation degradation due to heating, mechanical damage, manufacturing defects, loose contacts, and contamination leading to arc tracking. Ignition in plugs can be caused when arcing occurs through insulation charred by either heat or arc tracking through surface contamination. Ashizawa et al. [1997] proposed an ignition mechanism by which heating due to poor connections or mechanical damage will lead to a breakdown of PVC insulation, one of the byproducts of which is $CaCl_2$, with calcium coming from a common PVC filler material. This hygroscopic compound attracts water to the surface, which leads to severe arc tracking and ultimately ignition.

Aronstein [1993] concluded that after as little as 100 insertion and removal cycles, male plug blades could cause deformation of female contacts in some receptacles that would result in poor grip in the connections. These poor connections led to charring and melting of the receptacle face, however ignition of nearby materials was not discussed. UL 489 [2008] testing of plug-receptacle connections requires that the static force necessary to remove a standard plug from a receptacle is greater than 1.36 kg (3 lb) and less than 6.80 kg (15 lb). Hagimoto et al. [2001] reported that excessive heating due to loose plug connections to receptacles was a problem in receptacles with low retention forces (< 0.1 kg) and high amperage loads (20 amps). Okamoto et al. [2003] reduced the retention force between one of a receptacle's female contacts and plug blade from 1.5 kg to <0.02 kg which caused an increase in temperature of between 120 and 210°C at the terminal from a 100 VAC, 20A source. Okamoto et al. [2003] also noted that reducing the retention force for both plug blades from 1.5 kg to <0.02 kg caused an increase in temperature of between 190 and 210°C (100 VAC, 20A). However, when the current draw was reduced to 15A, maximum temperature increases of only 60°C were observed. However, testing was only conducted for periods up to 25 hours. These retention forces are quite small compared to the minimum retention force of 1.36 kg (3 lb) required by UL 498 [2008].

Uchida et al. [1981] studied mechanical failures, but not ignition, of screw-attached wires due to cyclical plug removal by pulling on the cord and found a wide-disparity between different plug types. For two different type plugs made from urea formaldehyde, when the conductor attachment screw was loosened by 180°, one exhibited a 450°C temperature rise inside the plug, while the other only had a 20°C temperature rise inside the plug. However, when terminal screws were loosened only 90° these two types of plugs only had between a 10 and 20°C temperature rise inside the plug. A rubber plug with the screw loosened by 90° failed after 60 hours of testing at a temperature of 248°C. The load for plug terminal screw tests was 100VAC and 12A. Uchida et al. [1981] also repeatedly inserted and removed various plugs from a receptacle. These plugs had between 0A and 12A loads. For some conditions, breakage did not occur in 20,000 cycles. However, if the wire was not properly terminated at the plug, breakage of conductors due to insertion and removal took approximately half the number of cycles for electrically loaded cords (~2000 cycles) compared to non-loaded cords (~4000 cycles). The authors attributed this to arcing occurring at the damaged cord-plug interface.

Shimizu [1984] and Katayama et al. [1981] have studied and quantified electrical cycles-to-ignition after mechanical failures were induced in plugs due to mechanical stresses which broke the cord/plug junctions. Loading the cord with a 1 kg weight, Shimizu [1984] bent the cord back and forth over a +/- 70° arc until all strands broke. For a molded plug, 2000 cycles were required to break all strands while for two do-it-yourself plugs, one broke after 2000 cycles and the other 250 cycles. Shimizu conducted similar experiments with cords carrying up to a 1000 W load, bending the cord back and forth by hand at approximately 30 times per minute. No flaming ignition was seen for PVC plugs and PVC cords. PVC plugs with rubber/cloth or neoprene insulated cords did attain flaming conditions for up to two minutes. Katayama et al. [1981] loaded a PVC plug and PVC cord with a 0.5 kg weight and bent the plug over +/- 60° until all conductor strands were broken. Various levels of electrical load were applied to the broken cord-sets and the cords were bent by hand to successfully induce arcing and ignition.

Okamoto et al. [1999] found that the susceptibility of plug insulation materials to arc tracking was dependent upon the material and the degree of aging. The later study by Okamoto et al. [2003] showed that, when heated in an oven, the tracking resistance (as measured by the Comparative Tracking Index [CTI]) of most plug materials decreased as the heating temperature increased and as the duration of heating increased (see Table 1-4). Although mechanisms for plug failures have been identified, the ability to discern forensic indicators of actual ignition sources needs to be studied.

Table 1-4. Comparative Tracking Index (CTI) of PVC That is Thermally Degraded, Okamoto et al. [2003].

Heating Time	Heating Temperature		
-	200˚C	150˚C	100˚C
0 hour	>600	>600	>600
1 hour	459	>600	>600
3 hours	238	>600	>600
5 hours	113	>600	>600
30 hours	-	516	>600
150 hours	-	124	>600

1.1.4 Arcing and Overheating Connections as Competent Ignition Sources

In a fire investigation, it is not enough to know whether arcing or an overheating connection was present, but it must be determined whether or not that electrical event was able to cause a fire. Arcing and overheating connections have been well recognized in the literature as electrical hazards, but documentation of their function as competent ignition sources for practical combustibles and arrangements has been rather limited. A few studies which explore the conditions leading to ignition from short-circuit arcing used readily ignitable materials such as wood shavings or cotton balls [Beland, 1984; Hagimoto, 2007], providing a lower bound on the competency of wiring as an ignition source. Others only consider ignition of materials (e.g., PVC insulation) contained in the electrical wiring itself [Keski-Rahkonen, 1999]. A study by Aronstein [1977] describes the wattages dissipated by glowing electrical connections which led to ignition of certain combustible materials (e.g., wood stud adjacent to junction box, receptacle cover plates, thermal insulation and vapor barriers). These values are listed in Table 1-2. However, these tests used electrical receptacles that had overheating connections not created by the researcher. It was not known what exact conditions led to the overheating connections. Hagimoto et al. [2001] and Uchida et al. [1981] demonstrated that loose connections (between 90 and 360º loosened) internal to the plug can produce temperatures upward of 400^{o}C at the connection. Both researchers noted that parts of the plugs and faceplates would melt and char, but did not explore whether these conditions would lead to ignition of proximate materials such as cellulosic insulation, wood studs, or plastic receptacle face plates. Twibell [2004] stated that "many overheating connections burn themselves out and break the electrical circuit without causing the fire." The discussion of overheating connections by Twibell [2004] seems to be substantiated more by personal experience rather than specific research.

Shea [2006] demonstrated arc tracking and ignition of PVC insulation experimentally by using bundled NM sheathed wiring wrapped in wall cavity insulation. Babrauskas [2001] noted that arcing in electrical wiring has been shown to ignite proximate materials by Franklin [1991]. Franklin ignited blankets and paper with parallel arcing/short circuits using a power cord that was cut with diagonal cutters. The fires ignited from molten copper droplets ejected from the cord due to the short circuits. Other types of mechanical damage such as hammering a wire has been shown to cause violent arcing and ignition of wood shavings [Beland, 1984]. Glowing electrical connections produced by two wires touching a nail were shown to ignite pyrolysis vapors from the wood that the nail was in [Ettling, 1982].

1.1.5 Forensic Examination of Electrical Components

Often after a fire has occurred, many of the electrical components are burned, charred, or melted. It is generally difficult to determine whether a damaged electrical component was a cause of the fire or damaged as a result of a fire, especially if the damage is extensive. NFPA 921 [2011] is the preeminent guide for the investigation of fire and explosion incidents. This guide contains a scientific-based methodology used for the determination of fire and explosion incident origin, cause, responsibility, and prevention. Chapter 8 of NFPA 921 [2011] is concerned with electricity as it relates to fire; from lightning damage to arcing and overheating connections. At the time of this report, there are proposals for the 2014 edition of NFPA 921 which are aimed at improving the discussion of arc beads and melting of conductors by fire. This is a significant step in providing fire investigators with state of the art research regarding this topic. The majority of this discussion, however, is focused on arcing and melting of copper conductors. At present, there is only one section in NFPA 921 [2011] regarding overheating connections. This is a basic discussion in which the causes, indicators, and physical evidence from overheating are presented:

> *8.10.4* Overheating Connections. Connection points are the most likely place for overheating to occur on a circuit. The most likely cause of the overheating will be a loose connection or the presence of resistive oxides at the point of connection. Metals at an overheating connection will be more severely oxidized than similar metals with equivalent exposure to the fire. For example, an overheated connection on a duplex receptacle will be more severely damaged than the other connections on that receptacle. The conductor and terminal parts may have pitted surfaces or may have sustained a loss of mass where poor contact has been made. This loss of mass can appear as missing metal or tapering of the conductor. These effects are more likely to survive the fire when copper conductors are connected to steel terminals. Where brass or aluminum are involved at the connection, the metals are more likely to be melted than pitted. This melting can occur either from resistance heating or from the fire. Pitting also can be caused by alloying. (See 8.10.6.3.) Overheating at a connection can result in the thermal damage and charring of materials adjacent to the connection. Heat can be transferred along conductors attached to the overheated connection, resulting in charring or loss of the conductor's insulation. The charring or loss of plastic insulation may allow arcing to occur. Such arc damage may survive the fire.*

The annex of NFPA 921 [2011] does contain a reference to some early work by Ettling [1982], but no additional explanatory material or photographs are presented.

Some attempt has been made by Babrauskas [2003] and others to identify differences between receptacles which exhibited overheating connections (i.e., potential ignition sources) and those that were damaged due to fire. He observed that damage from a fire decreases progressively from the exposed face to the back of the receptacle and is not concentrated near terminal screw connections, while damage from an overheating connection exhibits a radial pattern of damage spreading from the overheated terminal. The same observations could be extrapolated for plugs (i.e., localized damage appears in the vicinity of overheating plug-receptacle connections). Beland and Saucier [1986] observed that pitting and other evidence that may point to electrical activity at a connection were produced in fires with non-energized receptacles. There has not been any rigorous experimental study of forensic signatures of overheating connections with respect to thermal damage to the receptacle.

Some attention has been given to the examination of oxide development in overheating electrical connections using scanning electron microscopes (SEM) by Kim et al. [2006]. Kim et al. [2006] examined the cross-section and surface of an oxide bridge formed between two oscillating conductors. They found that the surface had a composition of 84.02% Cu, 12.28% O, and 3.70% C, and its cross section had a composition of 87.94% Cu and 12.06% O. This implied that carbonization and oxidation occurred on the outside of the oxidized area and only oxidation on the inside of the oxidized area. However, it is not clear whether these values were averages over the surfaces or point measurements and whether there was any variation of these values over the surfaces. The use of this method to determine if an overheating connection existed prior to any fire exposure has not been explored. Twibell [2004] reported that in the later stages of glowing connections, the contacts may partially melt or become separated by a short distance. These observations appear to be founded in personal experience and no specific research was cited by this author. In addition, Twibell [2004] does not discuss the visual or other forensic characteristics of the melted or separated contacts.

Arc mapping is a technique that is sometimes used to determine or narrow down the area of origin of a fire. This methodology is explained in NFPA 921 [2011], West and Reiter [2005], and Churchward and Cox [2010]. Arc mapping relies on determining the locations of any arcing (i.e., arc beads) in electrical circuitry (e.g., branch circuit wiring, appliance cords, and extension cords). The methodology requires that the investigator be able to differentiate between arcs, melting, and mechanical damage to wiring and cords. This is a difficult task as these types of damage are often confused and easily misinterpreted. Arc mapping for individual appliances has also been used to aid in fire origin and cause determination [Shanley, 2008]. In addition, the presence of arcing is often used as an indication that the particular conductor was energized at the time of the fire. This may have implications for determining whether or not certain items could have been the cause of a fire. Both arcing and melting of conductors arise from thermal events. The underlying reasoning behind why there should be any differences between an arc site and damage from melting are the differences in temperature and time between these two types of events. Individual arcs last for times on the order of 1 second or less whereas melting from fire usually occurs over much longer times (i.e., minutes or longer). Also, arc temperatures are much higher (> 5000°C) and have steep temperature gradients compared to fire temperatures (~1100–1300°C max).

The majority of research into the evidence produced by arcing has been focused on arcing in stranded and solid copper conductors. Arcing events can produce damage on copper conductors having round beads, notches, or severed conductors [NFPA 921, 2011]. Stranded conductors may have some or all of the strands severed or fused together. Arcing through char can produce several points of arcing or severing of small segments of wire. NFPA 921 [2011] suggests that arc beads exhibit a clear demarcation between the bead and the adjacent undamaged wire and that a projection of porous copper may exist at the arcing location. However, NFPA 921 [2011] does not attempt to differentiate between arcing that caused a fire or was caused by the fire. The characteristics of melting in copper conductors are also discussed in detail in NFPA 921 [2011]: fire melting of copper wiring can produce thinning, tapering, and blistering of the conductor; globules may form on melted copper conductors, but these globules may show effects of gravity (i.e., dripping); and melting of copper wiring from fire may also obliterate the copper drawing lines, formed as a result of the manufacturing process, outside of the damaged area.

The proposed changes to NFPA 921 [2012] for the upcoming 2014 edition of the guide, which are yet to be accepted at the time of this report, attempt to reinforce the current description of arcing evidence with the findings from recent research [NFPA 921, 2012]. Some characteristics of arcing damage that are proposed for inclusion are: re-solidification waves, locally enlarged grain size, and high internal porosity. Re-solidification waves were discussed by Murray and Ajersch [2009] who proposed that the waves arise as a result of the rapid re-solidification of the metals involved in the arcing which had been rapidly vaporized to a plasma state by the arc. The rapid re-solidification was attributed to the large temperature gradient between the metal plasma and the solid, un-melted metal. Re-solidification waves appeared as concentric rings emanating from the arc location and were observed on both steel and copper.

Murray and Ajersch [2009] also observed changes in the grain size of the base metals at the point of arcing. This was observed for arcing in aluminum and copper wiring. For copper, the grains affected by the arcing showed an oriented and linear shape. For arcing between aluminum and steel, the grains were larger in the interaction area between the two metals. Lewis and Templeton [2008] found a region of non-directional grain growth in the vicinity of the arc location for all of their 51 cases of arcing. They referenced the grain size of the base metal (#6–#7 based on ASTM E112) but did not measure the grain size near the arcing. None of the research regarding grain size in damage to conductors from melting or arcing has yet to characterize the grains in any quantitative manner with respect to grain size distribution or location of the grains.

Lewis and Templeton [2008] observed significant levels of porosity in arc beads and concluded that this characteristic was a definitive feature of arced copper conductors. In arc damage, the authors observed various sizes and shapes of pores and a line of demarcation between the areas having pores and those not having pores. Buc [2012] also states that internal irregular porosity and an internal line of demarcation are key indicators of arcing damage. However, Levinson [1977] observed substantial porosity in both non-arc melted and arc melted copper as long as the molten material was in contact with carbonaceous reducing agents and solidification occurred rapidly. None of the research regarding porosity in damage to conductors from melting or arcing has yet to characterize the porosity in any quantitative manner with respect to pore size distribution, pore quantity, or location of the pores. Both porosity and grain size characteristics are rather qualitative and dependent on the person conducting the examination. Therefore these characteristics should not be used as the sole criteria in judging whether a piece of evidence is from arcing or melting.

Many attempts have been made to characterize the metallurgical changes that take place during arcing and as a result of fire. Babrauskas [2004] provides a review of some proposed methods for evaluating beads that occur on wires as a result of arcing. Some of these methods include surface and metallurgical examination of the bead using scanning electron microscopes

(SEM), Raman spectroscopy, and auger electron spectroscopy (AES) techniques. Overall, his assessment is that these methods are unable to provide conclusive determination of whether the bead is indicative of the cause of the fire or was a victim of the fire. His criticism is based in part on claims that the methods have been based on extremely small number of experiments and that the work has not been independently validated. Even though authors continue to search for a defining characteristic of arcing that will aid in the determination of fire cause versus fire effect, there has been no successful method developed.

Recent work by Man et al. [2011] has attempted to use SEM, AES, and Energy-dispersive X-ray Spectroscopy (EDS) to determine whether an arc occurred in a normal atmosphere or a fire atmosphere. The work showed that for arc beads in copper wiring that occurred due to a fire, on average the surface and subsurface concentrations of oxygen and carbon were approximately two to three times higher than for arcing occurring in air. The authors did mention that the insulation was adhered to the arc melted copper after the fire exposure. However, it was unclear whether any surface cleaning of the arc beads was performed after the fire. Also, it does not appear that the arc beads from arcing in air were subjected to subsequent fire as would be expected of an arc that was the fire cause. A similar method was proposed by Anderson [1996]. The presence of oxygen and carbon in the arc bead was predicated on the belief that some of the surrounding atmosphere would be absorbed in the molten metal during the arcing process and that for arcing in a fire environment this would primarily be CO_2, CO, etc. However, as Babrauskas [2004] pointed out, this methodology does not take into account that even for arcing not in a fire environment; wires are typically insulated with some plastic, usually PVC, which may be vaporized regardless of whether the arcing was a cause or victim of the fire. At present, there are no metallurgical examination methods which can conclusively determine whether an arc bead was the cause of a fire or created as a result of fire exposure.

A study by Carey and Daeid [2007] conducted experimental research with electrical wiring installed in test compartments and exposed to fire. The non-metallic sheathed cabling used in this testing was installed at the ceiling of the test compartment. This cabling was either supported by pairs of screws or wood blocks. This location of the wiring within the compartment and the support methods are highly irregular. Carey and Daeid [2007] classified nine types of arcing damage for energized wiring based on the physical appearance of the arc beads, but did not note any evidence of conductors melting. These researchers also claimed to be able to differentiate between arcing damage occurring because of a short and damage from arcing through char. Their substantiation for this claim was based on an observation that arcing through char occurred more when the wiring was supported by wood block rather than metal screws which could short the wiring. Carey and Daeid [2007] did not discuss fire induced melting, pitting, or other wire damage which could have occurred during testing.

1.1.6 Aged Receptacles

Since the modern duplex outlet was developed in the early twentieth century, there have been relatively few major changes to its design and construction. In the mid 1920's, receptacles were required by electrical codes to be polarized. The design change called for a wide neutral prong on one side so that a plug could only be inserted in one orientation. This design change was made in order to reduce electrocution hazards. Until the early 1960's grounding receptacles, were not required in most construction [Dini, 2009]. According to the U.S. Census Bureau

[2008], only 30% of existing households were constructed prior to 1960, making grounding receptacles the most used type of residential receptacle. Over the years, the materials and manufacturing methods of receptacles have gone through a number of changes. In the past 20–30 years, there has been a shift from the use of Thermosets, such as Bakelite and urea formaldehyde, in receptacles to plastics such as PVC, Nylon, and polypropylene. In addition, ultrasonic welding techniques have made the production of receptacles easier and cheaper. The internal contacts and screw terminals have also changed, from predominately flat-head screws in years past to Phillips head screws over the last few decades.

The age of a device can affect a variety of parameters including the materials it is constructed of, any prior damage or deterioration, looseness of connections, or other improper installation. Dini [2008] found using the UL 498 temperature rise test that for receptacles gathered from houses dating back to before the 1930s, 88% had a temperature rise of over 20ºC, but after tightening of screw terminals and cleaning of blade contacts (through multiple insertions), only 14% had a temperature rise of over 20ºC. This would suggest that the installation conditions (screw tightness) and some surface contamination were the primary cause for temperature rise and not the age related deterioration of the device. Dini [2008] did not publish the maximum temperature rise measured for the devices.

1.2 Motivation for Testing

While there has been some research providing insight into the formation of overheating connections in receptacles [Ferrino-McAllister et al., 2006; Oda, 1978; Okamoto et al., 2003; Meese and Beausoliel, 1977], that research has lacked the characteristics necessary to form a complete picture of the hazards associated with loose connections and the forensic analysis of receptacle connections. The aforementioned research limited the duration of receptacle testing to hours or days. This limitation caused the natural (i.e., without human interference) development of electrical failures, a process that can take up to months or years, to be overlooked. The quantity of receptacles tested in most research programs was limited to tens of receptacles. These limited data sets are inadequate to develop a quantitative basis for the probability of different failure modes or for the potential of an overheating/glowing connection to become a competent ignition source. Some research has been conducted which examined the mechanisms leading to oxide growth and formation of glowing connections for wires [Ettling, 1982; Sletback et al., 1992; Kim et al., 2006; Korinek et al., 2013]. However, this work did not take into account the interaction between the heated connection and potential receptacle materials and wire insulation. Studies by Aronstein [1977 and 1983] characterized the ignitability of some common materials by overheating connections. However, these connections were predominately in receptacles with aluminum wiring. With all of the research into overheating connections in receptacles, the lack of information in NFPA 921 [2011] regarding the topic is surprising. Additional research is necessary to provide a statistically significant data set for and comprehensive analysis of the progression in a receptacle from a loose connection to a competent ignition source.

A common task of the fire investigator is to determine whether the metallic components exhibit signs of electrical activity (i.e., arcing) or whether the damage is due to fire attack (i.e., melting).The majority of research related to arcing has been conducted with copper wiring. Some work has been conducted with brass and aluminum; however, there has been no systematic study of characteristics of arcing in receptacles or plugs either from fire exposure or due to overheating connections. The recent proposals regarding changes to the arcing characteristics presented in NFPA 921 [2011] are a step in the right direction in terms of moving towards characteristics with a sound scientific basis. However, these characteristics are very qualitative and still generally geared towards arcing in copper wiring. Additional research into arcing in receptacles and plugs is necessary to provide a scientific basis for arcing in components other than copper wiring.

Perhaps the most critical and most difficult aspect of fire investigation involving electrical devices is determining whether the evidence at hand is the cause of the fire or a result of the fire. This topic has been especially investigated for arc beads on electrical wiring without any widely accepted theories. However, this specific type of analysis has not been investigated for overheating and glowing connections in plugs or receptacles. Only anecdotal work [Babrauskas, 2003] has postulated a method of visual analysis for differentiating between receptacles damaged by overheating connections and those damaged by fire attack. However, this analysis is only valid if a good portion of the receptacle is intact; the likelihood of this limits its applicability. Some research has been conducted with respect to the oxide development and glow development in wires, but there is no research which has examined the metallurgical evidence left by overheating and glowing connections in receptacles. While many have focused on examination of arc beads and wiring, the lack of published research on forensic examination of receptacle connections necessitates some exploration of this topic in detail.

1.3 Objectives

The two global objectives of this work were to improve the forensic examination of electrical receptacles and their components and to better understand the potential causes of electrical fires in receptacles. Three primary areas of interest were explored: the development of overheating connections in receptacles (i.e., terminals and at the plug/receptacle interface), electrical and thermal damage to receptacles from fires, and forensic examination of electrically damaged and fire damaged receptacles.

Specifically, this work evaluated the conditions associated with the development of overheating and ignition of a receptacle and the subsequent forensic signatures that can be used to differentiate whether the electrical component was a potential cause of a fire or a victim of a fire. The metallic components from receptacles exhibiting different failure modes as well as receptacles damaged from fire were examined using state of the art techniques to establish the physical and chemical characteristics of the evidence.

1.4 Experimental Approach

Two series of tests were used to accomplish the objectives of this research: (1) laboratory testing of plugs and receptacles and (2) plug and receptacle configurations exposed to two different types of fires. Large quantities of receptacles were evaluated in each test series in order to provide adequate data for evaluating the effects of multiple variables as well as providing a substantial database to establish a quantitative understanding of the accuracy and reliability of forensic tools. The two test series systematically studied a wide range of variables. These variables included the type of electrical device, device materials, device grade/design, device manufacturer, device age, fire parameters; and installation, use, and abuse conditions. Table 1-5 lists the number of tests for each series and the number of receptacles evaluated.

The laboratory testing was designed to expose various receptacle configurations to operating conditions resembling a wide range of what can be found in residential and commercial applications in order to determine the conditions necessary to cause overheating and glowing connections that lead to failures. The testing allowed for overheating connections to develop naturally over extended periods of time such that the failures encountered would be representative of what could happen in real scenarios. Testing was conducted for periods up to 511 days.

Table 1-5. Summary of Test Series.

Test Series		Number of Tests	Receptacles Per Test	Total Number of Receptacles Tested
Laboratory Testing		7	51–78	490
Fire Exposures	Compartment Fire	8	36	288
	Intermediate Scale Furnace	5	36	180

The two types of fire exposures included various single-room compartment fires and a set of intermediate scale furnace fires. The fire exposure testing of receptacles had two purposes. Both the compartment and furnace exposures were used to assess the impact of certain variables relative to thermal damage and electrical arcing in receptacles. The furnace fire exposures were also used to determine whether evidence of parameters required for ignition (determined in laboratory tests) would persist after different levels of fire exposure. Some of the devices which produced glowing connections in the laboratory testing were subsequently exposed to the intermediate scale furnace exposures. The inclusion of these devices along with undamaged energized and non-energized devices provided comparative fire evidence which was evaluated for forensic indicators to differentiate between cause and victim of the fire. Compared to the compartment fires, the use of the intermediate scale furnace had additional benefits. The temperature of intermediate scale furnace was able to be controlled and the receptacles were able to be exposed to much higher temperatures (i.e., above the melting point of some of the metal components) than were reached in the compartment fires.

1.4.1 Experimental Variables

Table 1-6 provides a simplified overview of the test variables evaluated for the laboratory testing of receptacle and plug connections and the fire exposure testing. Complete summaries of all of the receptacles tested and their variables are presented in Appendix G (Laboratory Testing) and Appendix H (Fire Exposure Testing). The goal of variable selection was to assure that the work performed was as relevant and practical as possible so that fire investigators could immediately use the findings of this program to improve their determination of fire cause and to have a technical basis for their opinions and the analysis techniques being employed. Therefore, the aim was that the variables selected were not just reflective of components and conditions existing in the field, but also those that are more highly correlated to fire incidents. The variables were selected to provide bounding limits to be able to distinguish when certain conditions or components can be used as evidence for when ignition is possible and, just as importantly, when it is not possible.

Table 1-6. Summary of Test Variables.

Variable	Laboratory Testing	Fire Exposure Testing
Wiring Method	Back Wire Push-in Side Wired (Screw)	Side Wired (Screw)
Screw Terminal Torque	¼ Turn Loose 1 in-lb (0.113 N-m) 3 in-lb (0.339 N-m) 5 in-lb (0.565 N-m) 7 in-lb (0.791 N-m) 15 in-lb (1.69 N-m)	¼ Turn Loose 1 in-lb (0.113 N-m) 3 in-lb (0.339 N-m) 7 in-lb (0.791 N-m) 12 in-lb (1.35 N-m)
Nominal Plug Connection Retention Force	Non-Modified (0.6–2.5 kg [1.3–5.5 lb]) 0.1 kg (0.22 lb) 0.01 kg (0.022 lb)	Non-Modified (0.6–2.5 kg [1.3–5.5 lb])
Number of Back Wire Removal and Insertions	0 cycles 1 cycle 2 cycles	N/A
Plug Type	Various materials, configurations, & styles (see Section 1.4.2.4)	Various materials, configurations, & styles (see Section 1.4.2.4)
Receptacle Material	PVC Polypropylene Thermosets	PVC Polypropylene Thermosets
Outlet Box Material	None – Open Air PVC	PVC Galvanized Steel
Faceplate Material	None – Open Air Nylon	Painted Steel Nylon
Use Conditions	Vibration Cyclic Loading High Startup Current	N/A
Electrical State	Energized w/ Load (15A, 6A, 3A)	Non-Energized Energized Energized w/ Load (6 to 7A)

1.4.2 Key Test Variables

1.4.2.1 Screw Terminal Torque

The initial laboratory testing consisted of systematically varying screw terminal connections from just below the maximum torque tested in UL 498 [2008] (i.e., 16 in-lb tightening torque test) to progressively looser connections to determine the limit of what ultimately can lead to overheating and ignition. Prior testing had indicated that heating at receptacle contacts can occur with torques greater than 6 in-lb [Burns et al., 1978], and less than 1 in-lb [Ferrino-McAllister et al., 2006; Meese and Beausoliel, 1977]. Receptacles with screw terminals tightened to 15, 7, 5, 3, and 1 in-lb as well as ones with ¼ turn loose configurations were evaluated in the laboratory testing. The ¼ turn loose configuration was an attempt at creating a very loose connection that could be systematically reproduced since the torque equipment could not accurately be used to set torque at a small fraction of 1 in-lb. This configuration was created by first tightening the terminal to 5 in-lb in order to remove any bends in the wire and then loosening the connection by ¼ turn (i.e., 90º).

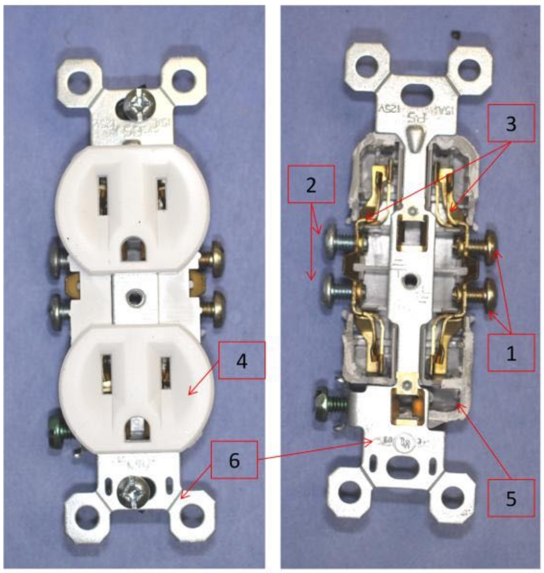
Receptacles used in the fire exposure testing were tightened to 12, 7, 3, and 1 in-lb as well as the ¼ turn loose configuration. The purpose of terminal torque in the fire exposure tests was twofold: first, to evaluate the impact of torque on potential for arcing to occur and second, to determine whether a meaningful post-fire torque measurement could be made.

1.4.2.2 Receptacle Material

This research was aimed at conducting tests with components that are representative of what is most typically found in residences within the United States. Receptacles and plugs, although adhering to certain production and testing standards, can vary widely between different manufacturers in terms of materials, construction, and manufacturing methods. There is little market data which gives insight into which receptacle and plug manufacturers dominate the market. Four of the largest manufacturers of receptacles and other wiring devices in the U.S. over past decades are Pass & Seymour (owned by Legrand), Hubbell, Cooper Wiring Devices, and Leviton. All of these companies have, for decades, produced a wide variety of electrical devices, varying in color, grade, style, and arrangement. Some discussion with electrical contractors and industry representatives revealed that the brands of receptacles that are bought by electrical contractors depend on a variety of factors, including the electrical distributor used (some only carry certain brands), geographical region, pricing of receptacles, the type of project (e.g., residential or commercial), and the size of the project (e.g., single receptacle replacement or new house construction).

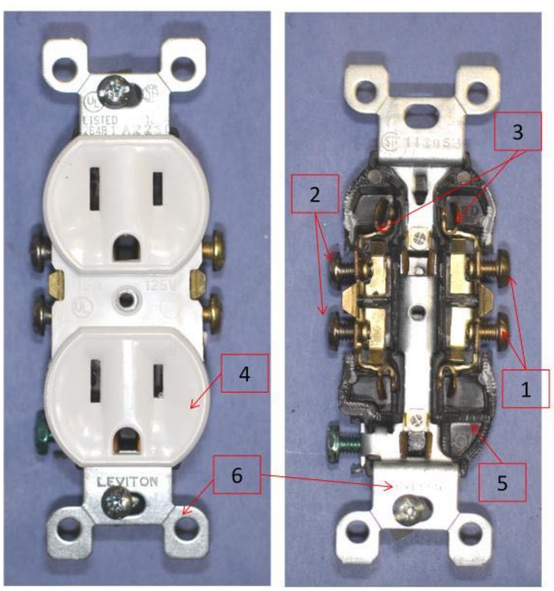
The two basic components of receptacles and plugs are the insulators and conductors. The insulators (i.e., wire insulation and receptacle/plug bodies) are usually plastics such as Nylon, polyvinylchloride (PVC), polypropylene, and thermosets (e.g., phenolics, urea formaldehyde). The conductors (i.e., screws, wires, plug blades, and receptacle internal plug contacts) are typically metals such as steel, brass, and copper and are sometimes plated with other metals such as zinc, brass, or nickel. Plastics are generally one of two types, either thermoplastic or thermosetting. Both types of plastics are combustible to some extent. Normally, when thermoplastics are heated, they will melt and drip [Hirschler, 2008]. On the other hand, as thermosetting plastics are heated, they tend to crack, char, and become brittle. Nylon, PVC, and polypropylene are all thermoplastic materials, but PVC tends to behave both as a thermoplastic and a thermosetting plastic when exposed to elevated temperatures. When heated, PVC materials will often sag and deform before charring rather than becoming liquid and dripping. Over the past few decades, there has been a shift away from using thermosetting plastics in receptacle and plug construction due to increased cost efficiency in the manufacturing process associated with using thermoplastics. The modern processes of injection molding and ultrasonic welding of receptacles streamline the manufacturing of components made of thermoplastics.

The majority of receptacles selected for use in laboratory testing and fire exposure testing were standard grade, new receptacles. These were chosen because they are the most common grade of receptacles found in residential applications. Two thermoplastic receptacles, one PVC and one polypropylene, as well as a variety of aged (thermosets) receptacles were selected for testing. The specific thermoplastic receptacles selected were the Pass & Seymour model 3232-I and 3232-W, constructed of PVC, and the Leviton 5320-W, constructed of polypropylene. These two receptacles are shown in Figure 1-3 and Figure 1-4, respectively. The -I and -W in the model numbers designate the color of the receptacle: -I for ivory and -W for white. Due to limited quantities of certain colors, both white and ivory Pass & Seymour receptacles were purchased.



Pass & Seymour 3232-W or 3232-I		
Part		Material
1	Hot Terminal Screws	Plated Steel
2	Neutral Terminal Screws	Plated Steel
3	Internal Plug Contacts	Brass
4	Receptacle Body – Front	PVC (white)
5	Receptacle Body – Back	PVC (grey)
6	Grounding Strap	Zinc Plated Steel

Figure 1-3. Schematic of new PVC receptacle materials and construction.



Leviton 5320-W		
Part		Material
1	Hot Terminal Screws	Plated Steel
2	Neutral Terminal Screws	Plated Steel
3	Internal Plug Contacts	Brass
4	Receptacle Body – Front	Polypropylene, Isotactic (white)
5	Receptacle Body – Back	Polypropylene, Isotactic (black)
6	Grounding Strap	Zinc Plated Steel

Figure 1-4. Schematic of new polypropylene receptacle materials and construction.

In order to test receptacles that are relevant for both existing construction as well as new construction, a variety of aged receptacles were purchased for testing. The manufacturers of the aged receptacles were not chosen in a systematic way; aged receptacles were purchased from local vendors of used construction materials. The vendors would periodically receive receptacles from houses, apartment buildings, or commercial buildings that had been torn down or had their electrical systems refurbished. All receptacles were collected from vendors located in the Baltimore, MD and Washington, DC metro areas. However, the location of the buildings from which the receptacles came was not known to the authors. The aged receptacle manufacturers procured were: Leviton, Slater, General Electric (GE), H&H, Pass & Seymour, Circle F, Hubbell, Paulding, Arrow, Bryant, National Tool & Mfg. Co. (NTM). Of these manufacturers, only Leviton, Pass & Seymour, Slater – absorbed by Pass & Seymour, Hubbell, Arrow (now Arrow Hart – a subsidiary of Cooper Wiring Devices), and Bryant (a subsidiary of Hubbell) continue to manufacture receptacles. The aged receptacles purchased were a variety of types (e.g., polarized or grounded), grades (e.g., standard or heavy duty), ages, and had a variety of previous use and abuse (e.g., paint, cracks, scratches, and other damage).

These receptacles were separated into five categories based on their approximate age. The approximate age range was determined by the authors based on the materials used, manufacturers, markings, configuration, and construction of the receptacles. It was estimated that the receptacles were between 10 and 60 years old. Table 1-7 lists the categories and corresponding date ranges of the aged receptacles. Some of the Category A and B receptacles were non-grounding type receptacles, meaning they did not have the slot for a grounding pin. The rest of the aged receptacles were grounding type receptacles. Some of the aged receptacles had brass terminal screws and some had steel terminal screws. Screw material was dependent on the specific model.

Table 1-7. Aged Receptacle Categories.

Category	Approximate Date of Manufacture
A	1940's–1950's
B	1950's–1960's
C	1970's
D	Late 1970's–Early 1980's
E	Late 1980's–1990's

1.4.2.3 Outlet Box and Faceplate Materials

All of the receptacles exposed to fire were installed in an outlet box with a faceplate to represent a typical installation. Only a small portion of the laboratory tested receptacles were installed in outlet boxes with faceplates. The use of outlet boxes and faceplates in the two test series served different purposes. For the fire exposure testing, receptacles were installed in outlet boxes and with faceplates because this method was practical for receptacle installation in a mockup wall and because it is typical of receptacle installation in the field. In the laboratory testing, the purpose of installing receptacles in outlet boxes and with faceplates was to determine the effect of the material contribution to overheating and any subsequent ignition. The majority of receptacles in the laboratory testing were tested without outlet boxes and faceplates because of the increased fire load from these materials. The lack of outlet boxes and faceplates allowed the overheating connections developing in receptacles and plugs to be closely observed without having to remove the faceplate.

In the fire exposure tests, both plastic and metal were used for outlet boxes and faceplates. The use of different materials aimed to address the impact of the materials on electrical damage and thermal damage to the receptacles. For example, arcing can occur when energized conductors come into contact with properly grounded metal components. This cannot occur with the plastic outlet boxes and faceplates. Also, the plastic outlet boxes and faceplates will melt and deform when heated in a fire, while the metal components (i.e., steel) will not. This may cause different thermal damage to those items and potentially affect the thermal damage to the receptacle. Only plastic outlet boxes and faceplates were used in laboratory testing. The plastic faceplates used were Leviton model PJ9-W faceplates made of white Nylon. The plastic outlet boxes were Carlon model B118A (18 cubic inch) and B114RB (20 cubic inch) outlet boxes constructed of blue PVC. Both boxes are marketed as being UL classified for use in 2-hour fire walls. The B118A boxes were for new-construction and had two nails for attachment to wood studs. These boxes were used for the fire exposure testing. The B114RB boxes were for old work and had four holes which were used for mounting in the laboratory testing. The metal faceplates used were Mullberry model 79701 constructed of steel and finished with almond color paint. The steel outlet boxes were Steel City model A257-25R, nominally 13.5 cubic inch outlet boxes constructed of galvanized steel. The steel city boxes were for new-construction and had two nails for attachment to wood studs.

1.4.2.4 Plug Type

Plugs are unique compared to receptacles in that they come in two types: those attached to some kind of cord and do-it-yourself plugs that are manufactured for the user to attach to a cord. Both types of plugs can come in a variety of styles, shapes, materials, blade configurations, and blade materials. The plugs used in this test series were systematically selected to examine the effects of plug blade material and configuration on the development of overheating connections. However, the different plug blades and configurations selected were only available on a limited number of plugs. This led to more variation in the style, shape, blade configuration, and plug materials than was originally intended. Three different plugs were selected for testing: plugs with solid brass blades, plugs with folded brass blades, and plugs with nickel plated brass blades (solid). Do-it yourself plugs manufactured by Leviton (Model 48646) were selected for their solid brass blades. These plugs were constructed of vinyl. Plugs with folded brass blades (2-prong) and nickel plated brass blades (2-prong and 3-prong) were from generic, UL listed extension cords manufactured in the Philippines for distribution by Home Depot. Due to limited availability of extension cords with the nickel plated brass blades, three varieties of plugs with nickel plated blades were used: black 3-prong, white 3-prong, and white 2-prong. Photographs showing the different types of plugs can be seen in Figure 1-5 and Figure 1-6. The specific material used for the construction of the extension cord plugs and wiring was not known. However, according to NEC article 400, Stranded Parallel Thermoplastic (SPT) cords such as those purchased (i.e., SPT-2) are constructed entirely of thermoplastic materials [NFPA 70, 2011]. The most common thermoplastic used for SPT-2 cords is PVC.

Figure 1-5. Solid brass (left), folded brass (right) plug blades.

Figure 1-6. Plated plug blades: 2-prong (left) and 3-prong (right).

1.4.3 Receptacle Serial Number

Each receptacle used in the laboratory testing and fire exposure testing was given a unique serial number used for identification and data reporting. Each serial number consisted of a combination of 1 or 3 letters and 3 numbers. The new receptacles began with either PSE (PVC) or LEV (polypropylene). The aged receptacles began with the letter of their category (e.g., A, B, C, D, or E) based on Table 1-7. The three numbers completing the serial number were assigned sequentially beginning with 001 as the receptacles were identified. For example, new polypropylene receptacles were identified as LEV001, LEV002, etc. Refer to Appendices G and H for the specific test variables associated with laboratory tested receptacles and fire exposure receptacles, respectively.

2.0 LABORATORY TESTING OF RECEPTACLES

2.1 Experimental Design

The purpose of the laboratory receptacle testing was to evaluate the potential for residential duplex receptacle and plug connections to form high resistance connections (i.e., overheating or glowing). Seven test racks of up to 78 receptacles per rack were constructed. Testing was conducted in the Hughes Associates, Inc. (HAI) laboratory in Baltimore, Maryland. A summary of the laboratory test racks is shown in Table 2-1, with details for each rack presented in Appendix A. A total of 528 test trials were conducted on 490 receptacles. A portion of the receptacles from Test Rack 1 were modified during the test period such that two trials were conducted for the same receptacles. Test racks were located in two different rooms, with racks 1 and 2 in one room and racks 3 to 7 in the second room. Tests were run for up to 511 days.

Table 2-1. Summary of Laboratory Test Racks.

Test Rack	# of Devices	Devices Tested	Current (amps)	High Startup Current?	Vibration	Power Cycling	Wiring Method	Aged Receptacles
1	68	Receptacles	15	No	No	Yes (Partial)	BW, SW	No
2	52	Receptacles, Plugs	15	No	No	Yes (Partial)	SW	No
3	58	Receptacles	15	No	Yes	No	BW, SW	No
4	78	Receptacles	15	No	No	Yes	SW	No
5	78	Receptacles	3, 6, & 9	No	No	Yes	BW, SW	No
6	78	Receptacles	15	No	No	Yes	SW	Yes
7	78	Plugs	15	Yes	No	Yes	SW	No

Note: BW – Back Wire Push-in, SW – Side Wired

2.1.1 Test Rack Construction

Seven test racks, having between 52 and 78 receptacles each, were constructed for the laboratory testing. Receptacles were mounted in a vertical orientation, spaced 10 cm (4 in.) apart horizontally with the grounding pins at the bottom of each outlet. The receptacles were mounted with approximately 5 cm (2 in.) of separation vertically. The test racks were constructed of steel angle iron and bar stock welded together. Each test rack had up to eight 1.2 m (4 ft) wide horizontal steel mounting bars and two 2.5 cm (1 in.) angle iron vertical support and leg pieces. The top and bottom horizontal steel mounting bars were 2.5 cm (1 in.) wide and the other horizontal mounting bars were 5 cm (2 in.) wide. The horizontal mounting bars had holes drilled such that the manufacturer provided receptacle mounting screws could be used to secure and ground the receptacles to the test rack. In some test racks, ten receptacles were installed in PVC outlet boxes with nylon faceplates. The outlet boxes were attached to the test rack along the top row. A separate wire was used to ground these receptacles. The test racks were placed either on a sheet of 1.2 cm (0.5 in.) thick gypsum wall board, placed on top of a wooden table or they were placed on the concrete floor. A photograph of a typical test rack can be seen in Figure 2-1.

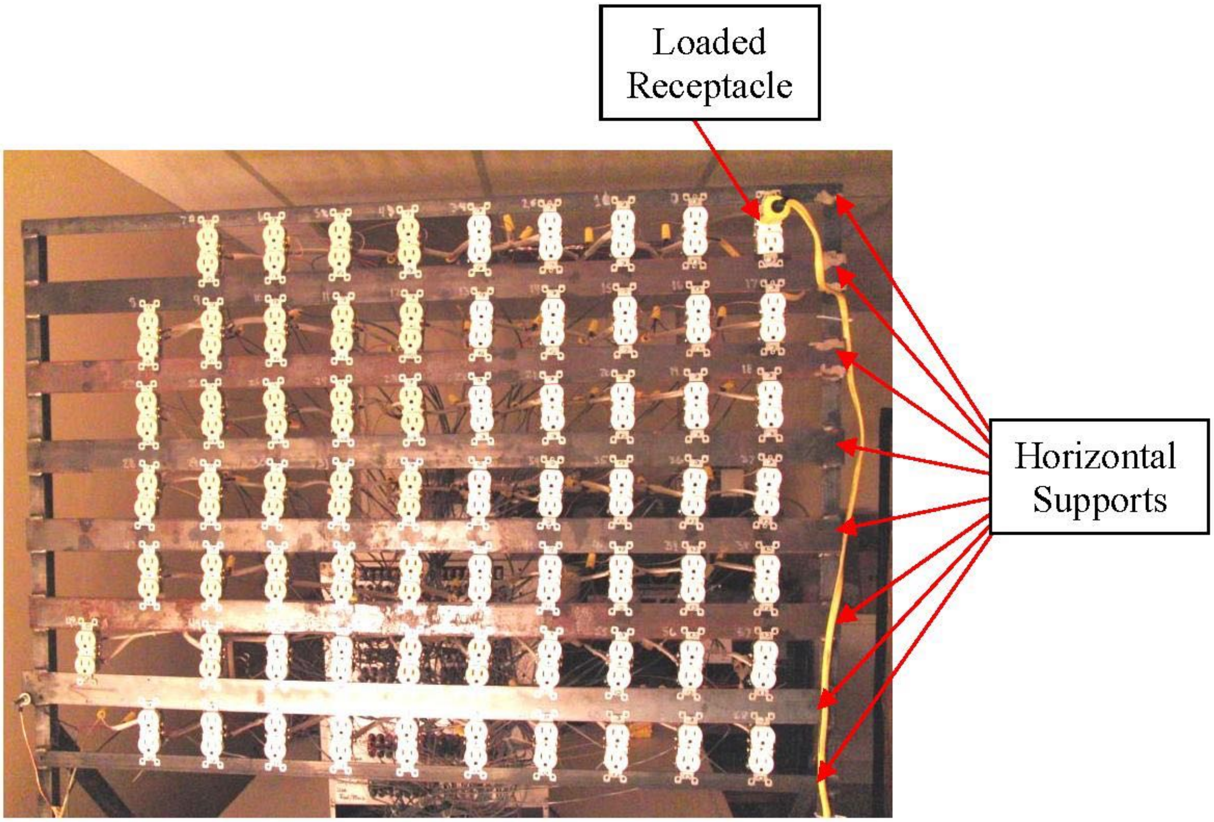


Figure 2-1. Photograph of typical test rack construction.

Receptacles were mounted in the test racks and wired using one of two methods: one for receptacle terminal connections and one for receptacle and plug connections. Romex SIMpull non-metallic sheathed (NM) 3-conductor cable was used to wire the receptacles. This cable had a multi-part construction which consisted of a PVC outer jacket, and paper inner wrap. The hot and neutral conductors were insulated with PVC and have a thin nylon sheath, while the ground wire was bare. Each of the conductors in the NM cable was solid 14 AWG copper. For assessing receptacle terminal connections, the receptacles were wired using a feed through method such that the applied current was passed through both the hot and neutral terminals of every receptacle. Each receptacle was wired with two lengths of approximately 25.4 cm (10 in.) of NM cable. One length was connected, using wire nuts, to the NM cable from the upstream receptacle and the other length was connected, using wire nuts, to the NM cable from the downstream receptacle. A schematic of this wiring method is shown in Figure 2-2.

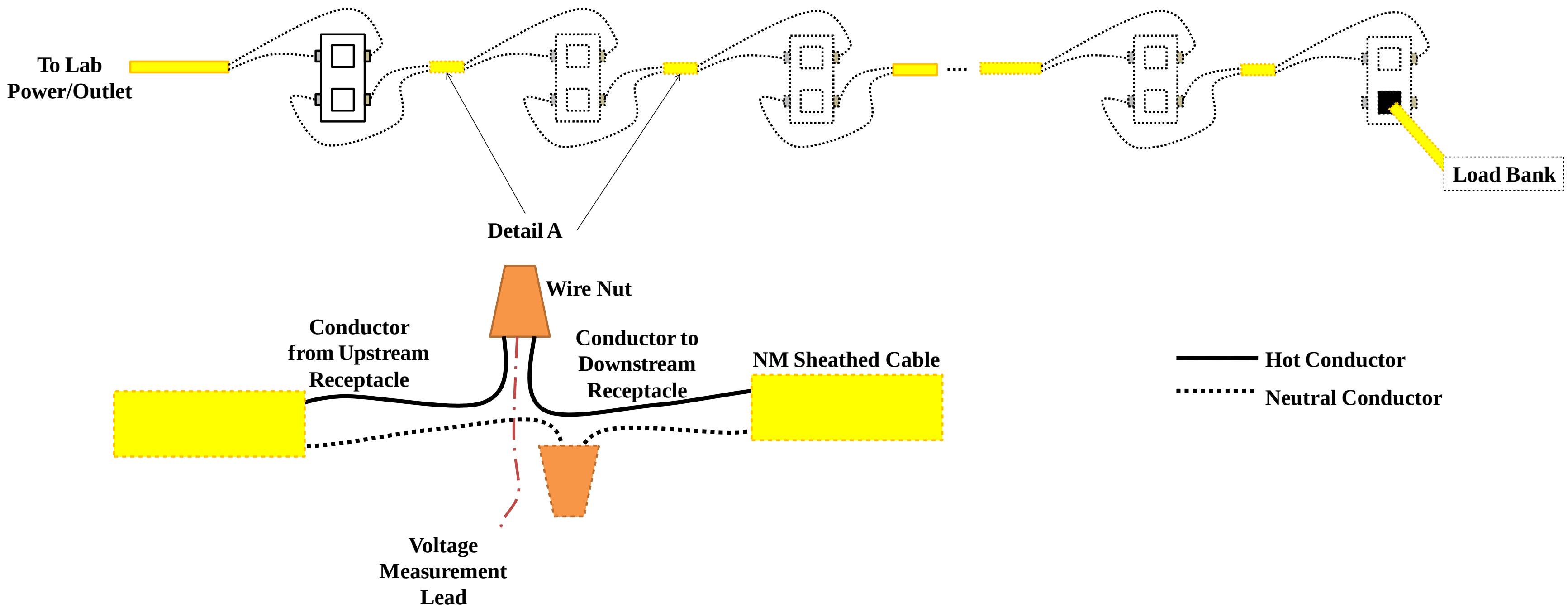


Figure 2-2. Test wiring schematic (receptacle connections).

For assessing receptacles and plug connections, a hot-neutral shunted plug was plugged in to the top outlet. Shunted plugs were created in one of two ways. For the plugs from extension cords, a length of approximately 20 cm (8 in.) of wire was left attached to the plug. The wire was stripped approximately 2 cm (0.75 in.) and the hot and neutral conductors were twisted and soldered together. Either a wire nut or electrical tape was placed on the soldered conductors as insulation. The do-it yourself plugs had two screw terminals for the attachment of wiring. A short length (approximately 2.5 cm (1 in.)) of 12 AWG wire was placed between these terminals and the screws tightened to manufacturer specified tightness. The receptacles were then wired in series using only the hot conductor to ensure that the applied load flowed through both plug blades as well as the hot and neutral terminals of each receptacle. Each receptacle was wired with two lengths of approximately 25.4 cm (10 in.) of single 14 AWG conductor. One length was connected, using wire nuts, to the 14 AWG wire from the upstream receptacle. And the other length was connected, using wire nuts, to the 14 AWG wire from the downstream receptacle. The screw terminals for receptacles with plugs were tightened to the manufacturer's specified tightness. A separate neutral wire, not connected to the receptacles, bypassed the receptacles with plugs. A schematic of this wiring method is shown in Figure 2-3. While the wiring method for plug connections is not suitable for installing receptacles in actual practice, it is the only practical way to draw current through large numbers of receptacle and plug connections. Both of these methods were experimentally convenient from the standpoint that an electrical load could be applied to large numbers of receptacles using a single load.

2.1.1.1 Vibration

Receptacles are typically installed in outlet boxes attached to the structure of a building. Intermittent or continuous movement of a building or the individual receptacle can come from many sources. Vibrations and movement can come from earthquakes, outside construction, weather, natural expansion/contraction, or appliances containing motors. Sources in the literature [Ferrino-McAllister et al., 2006; Ettling, 1982; Shea, 2006] have shown that repetitive manipulation of loose copper connections can lead to the formation of overheating connections quicker than natural development. Therefore, a portion of the laboratory tested receptacles were vibrated to evaluate whether vibration would exacerbate the potential for forming overheating or glowing connections. Plugs were not vibrated because the low nominal retention forces would cause power to cut out as the connection would make and break.

Vibration of one test rack, laboratory Test Rack 3, was accomplished using a vibration motor (Precision Microdrives Model 345-800 45 mm) located approximately at the center of the bottom row of the test rack as shown in Figure 2-4. This vibration motor was capable of providing a maximum vibration amplitude of up to 12G at 77Hz (G is the magnitude of acceleration produced by gravity) (see Figure 2-5). A DC power supply (Elenco Precision model XP-581) was used to power the vibration motor. For the majority of the test, the power supply provided 17 VDC to the vibration motor, producing vibration amplitude of approximately 6.5G at 40Hz based on the motor's curve. Because the test rack was only secured at the floor, movement of the test rack in a horizontal plane parallel to the floor was not prohibited.

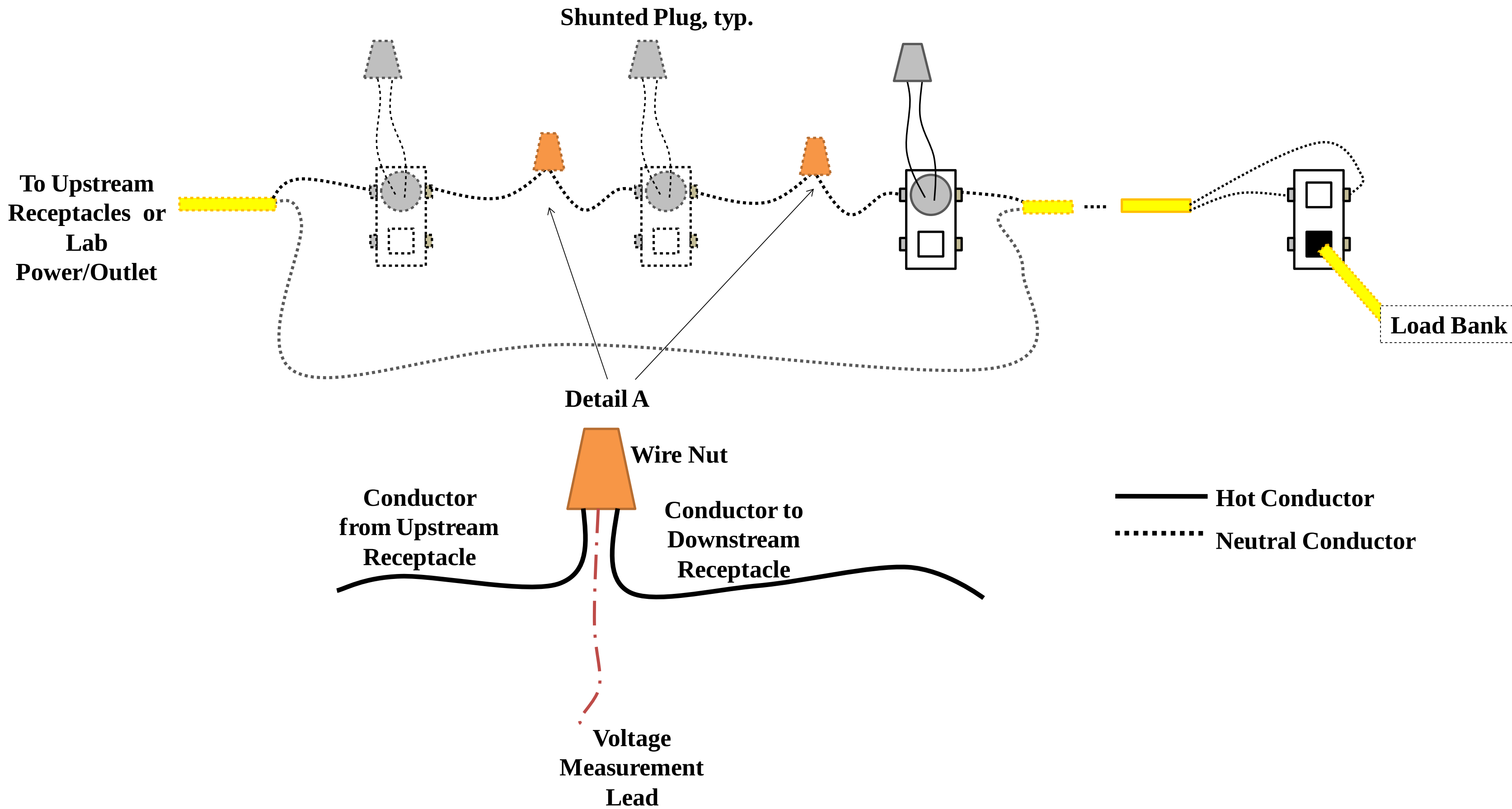


Figure 2-3. Test wiring schematic (Receptacle/Plug Connections).

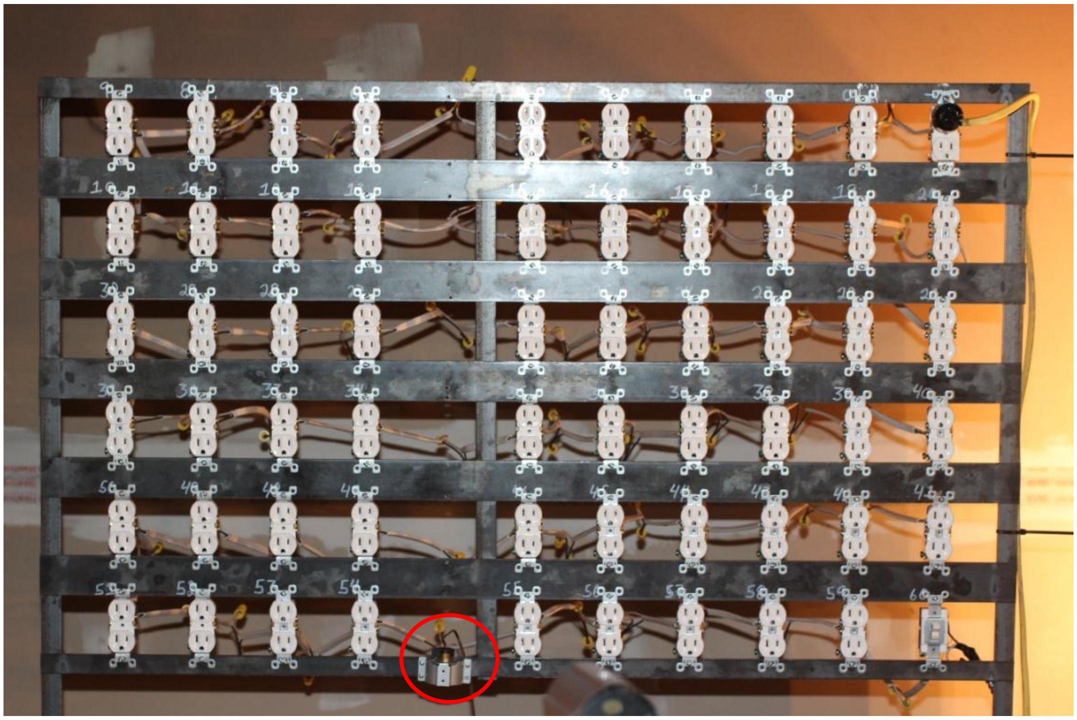


Figure 2-4. Photograph of Test Rack 3 and vibration motor (circled in red).

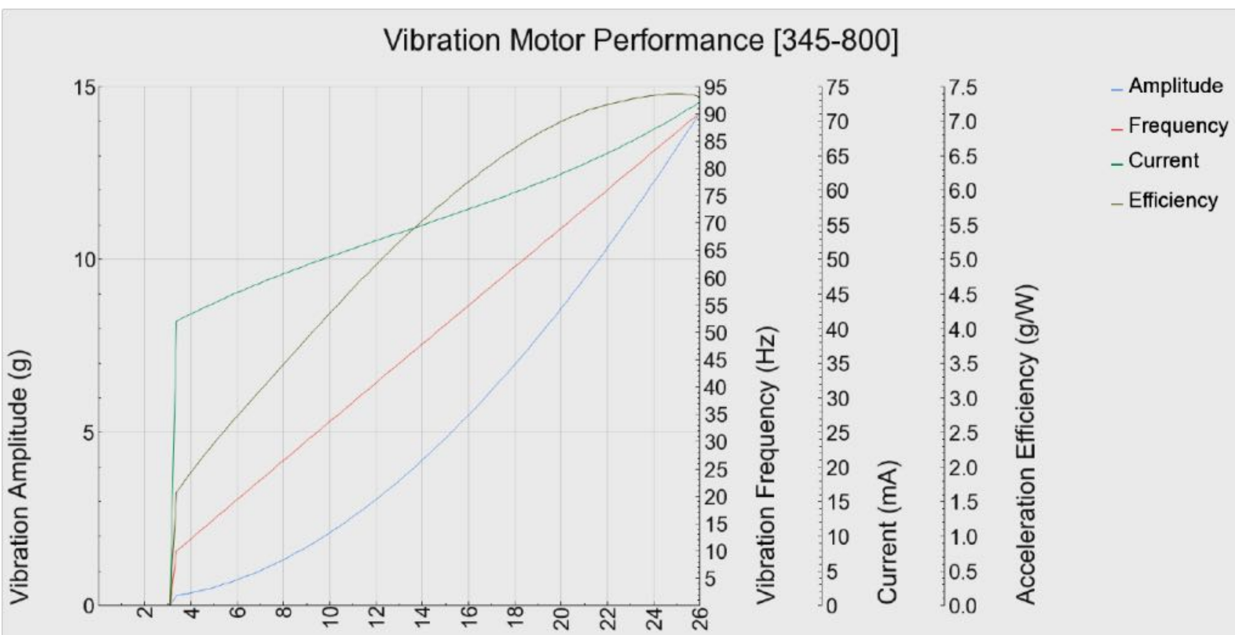


Figure 2-5. Vibration motor performance from manufacturer's datasheet; x-axis in Volts.

2.1.2 Receptacle Installation

2.1.2.1 Screw Terminal Tightening

Screw terminals were tightened using a CDI model 151SP adjustable cam-over type torque screw driver. The CDI torque screw driver would allow the terminal screws to be tightened to a preset torque without over tightening. The cam-over type torque screw driver was set using a calibrated Cedar model DID-4 digital torque screw driver (35 in-lb max; +/- 0.5% F.S.). A hex bit was used to connect the shafts of the two torque screw drivers. The Cedar was held stationary while the CDI was rotated slowly and smoothly in a clockwise direction. The preset torque for the CDI was the maximum measured value displayed by the Cedar torque screw driver. The CDI torque screw driver was increased and decreased by tightening or loosening its set-screw. The process of checking and adjusting the CDI was repeated until the appropriate torque was reached. To tighten the screw terminals, the CDI torque screw driver was firmly placed in the screw head slot perpendicular to the plane of the screw head. The CDI was then slowly and smoothly rotated in a clockwise direction until a clicking sound was heard. The clicking sound indicated the cam slipped and that the preset threshold torque had been reached. In the case of the "¼ Turn Loose" configuration, the screw terminals were tightened to a torque of 5 in-lb and then rotated a ¼ turn (i.e., 90º) in the counter-clockwise direction. All four screw connections on a receptacle were tightened to the same torque. Receptacles with modified plug connections had screw terminals torqued to 15 in-lb.

2.1.2.2 Back Wired Push-in Connections

Back wired push-in receptacle connections rely on the spring force of the internal plug contact to retain the conductor in the receptacle (see Figure 1-2, center). This spring force can be reduced over time by the insertion of a conductor that is larger than intended or by repeated insertion and removal of a conductor [Aronstein, 1993].

Selection of the method for loosening back wired push-in connections was based on what was deemed to be a reasonable level of abuse to the connection. To evaluate back wired push-in connections for the laboratory tested receptacles, each conductor was inserted with 0, 1, or 2 removal and re-insertion cycles (i.e., one, two, and three total insertions, respectively). In this work, the wire connecting the receptacle to the circuit was the same wire that all insertions were conducted with. It should be noted that for these test series, the abuse of the back wired push-in connections is less severe than what is imposed for UL 498 [2008], while for side wired screw connections, the conditions are more severe than what is tested for UL 498 [2008]. The conditions imposed were intended to cover a range of plausible scenarios and not necessarily extreme cases of abuse.

Push-in connections were exercised in the following manner. First, the stripped wire was fully inserted into the hole at the back of the receptacle. If additional removal and re-insertion cycles were required, the wire was removed using a small screwdriver, which was inserted into a slot on the back of the receptacle, to depress the release tab. The wire was then fully re-inserted into the hole at the back of the receptacle. This process was repeated as necessary. All four push-in connections on a receptacle were exercised with the same number of removal and re-insertion cycles.

2.1.2.3 Nominal Plug Connection Retention Force

A practical method for measuring the looseness of the connection between a plug blade and a receptacle internal plug contact is to measure the amount of force it takes to remove the plug blade from the receptacle. This is called the retention force. Studies by Japanese researchers [Hagimoto et al., 2001; Okamoto et al., 2003] have indicated that a reduction of a single plug blade retention force to below 0.1 kg (0.22 lb) can cause overheating. In order to evaluate the potential for overheating connections to develop at the plug and receptacle connection, the retention forces of selected receptacle connections were manually altered using various thicknesses of brass strips of known thickness. Only one plug/receptacle connection (i.e., one of the hot connections) was modified in each receptacle tested. During the preliminary investigation, both the hot and neutral connections were modified and plugs had a tendency to fall out of the receptacle. In laboratory testing, single blade nominal retention forces of 0.01 kg (0.02 lb) and 0.1 kg (0.22 lb) were evaluated as well as receptacles without modification to the retention force. The non-modified retention forces were between 1.5 kg (3.3 lb) and 3.2 kg (7.05 lb). Nominal retention force was measured on individual terminals using a Shimpo model FGV-100x force gauge and a standard solid plug blade.

Plug connections were loosened by repeatedly inserting brass strips into the top-hot receptacle connection. The brass strips ranged in thickness from 1.62 mm (0.064 in.) to 2.38 mm (0.093 in.). The strips were manually manipulated inside of the outlet until the desired nominal retention force was reached. The nominal retention force of the top-hot connection was measured periodically using the Shimpo force gauge with a single plug blade. The plug blade was a brass plated blade approximately 0.52 mm (0.06 in.) thick. The receptacle was held in a vertical orientation and the force gauge was manually inserted and removed from the receptacle in a slow, smooth motion. The nominal retention force of the connection was the maximum force measured by the force gauge. There was some variability in the nominal retention force based on how quickly the movement was performed or how straight the pull force was. In addition, the plug blade used to measure the nominal retention force was not the specific plug that was used in the testing of the receptacles. This plug blade was nominally the same dimensions as the plug blades used in testing.

2.1.3 Electrical Power and Load

The electrical power for the laboratory test racks was provided by two dedicated circuit breaker panels; one was for Test Racks 1 and 2; the second was for Test Racks 3 through 7. Each circuit breaker panel was outfitted with a 200A main circuit breaker and individual 20A circuit breakers for each circuit. Each test rack was connected to a separate 20A circuit breaker. The 20A circuit breakers were used for 15A rated wiring and receptacles to allow for moderate overcurrents (i.e., >15A) to be used for prolonged periods of time. A length of 14 AWG, two conductor wire, either Romex NM cable or armored cable, ran from the circuit breaker panel to the test rack. For Test Racks 3 through 7, a switch was installed in the test rack in order to control the electricity to each test rack. For Test Racks 1 and 2, the electricity was controlled by the individual circuit breakers. The laboratory test power was nominally 120 VAC at 60 Hz.

The electrical load for the test racks was provided by up to 18 tungsten-filament light bulbs, ranging in power from 25 W to 300 W. The light bulbs were arranged in a load bank (see Figure 2-6);

a separate load bank was used for each test rack. The loading circuit consisted of up to 18 light sockets connected in parallel. Up to four switches and one dimmer switch controlled the flow of electricity to groups of light bulbs. This allowed the total current draw to be varied from 0 to 20A. The electrical load was plugged into the “loaded receptacle” placed at one end of the daisy chain of receptacles (see Figure 2-1, Figure 2-2, and Figure 2-3). The loaded receptacles were 20A rated, heavy duty Leviton receptacles wired with the screw connections tightened to manufacturer’s specifications. A section of the neutral wire from the load bank to the loaded receptacle was routed outside of the load bank enclosure to facilitate current measurement (see Figure 2-6).

Figure 2-6. Photograph of light bulb load bank. Note: neutral wire circled.

The electrical load on the laboratory tested receptacles was varied in a number of ways. Different electrical loads (i.e., currents) were applied, power was cycled at regular intervals, and a high startup current load was used for limited cases. Nominal current loads of 3, 6, and 15A were selected to evaluate the receptacles. These are within the range of currents that have been found to produce glowing connections. Glowing connections have been established in copper connections with currents as low as 1A [Sletbak, 1992] and up to 15A [Aronstein, 1983]. Current loads of 3, 6 and 9A were applied to a limited number of receptacles to determine the lower limit of when an overheating connection in a receptacle can develop. The 15A current load was the most common load that was used for the laboratory testing. This current was selected because it represented a maximum normal load that would be expected in a branch circuit. Typical 120V branch circuits are usually protected by 15A or 20A circuit breakers and most 120V duplex receptacles are either 15A or 20A rated. Also, at 15A it was anticipated that the relatively high current load would increase the likelihood of overheating events.

Initially, receptacles were subjected to a continuous current draw which was only turned off when a receptacle needed to be removed from the circuit because of some overheating or arcing event. The impact of cyclical loading on the formation of overheating and glowing connections was studied by Newbury and Greenwald [1980] and Meese and Beausoliel [1977]. But, the decision to cycle each circuit’s power at regular intervals stemmed from observations made during initial testing. It was observed that arcing at the screw terminals would occur for certain receptacles as the power to the circuit was turned on. This generated the question of whether or not the cycling of power had an effect on the formation of overheating connections. The majority of subsequent receptacles had the power cycled off for 1 hour every weekday morning. This is a duty cycle of 97% (i.e., 5 hours off out of every week). While this may seem high, there are many devices including appliances, lighting, and computers which draw current 24 hours a day. The 1 hour off period was selected because it provided ample time for the conductors to cool to near ambient conditions. Towards the end of the laboratory test series, the receptacles were left energized for 24 hours each day. A detailed chronology of each test is presented in Appendix A.

Circuit protection is usually in the form of fuses and various types of circuit breakers. These devices are rated for a certain current; above this current they will trip, cutting power to the circuit. However, there is a lag time associated with the tripping mechanisms. This means that if a load in a circuit is much higher than the rating of the circuit protection but is sufficiently brief (on the order of a few cycles), the circuit will not trip. Typically, when an electrical device containing a motor (e.g., refrigerator, A/C unit, or power tools) is first energized, the rotor is not moving and there is a transient startup current that is several times higher than the normal current. This high startup current comes from the high torque required for the motor to begin moving. For 120V appliances, such as the ones listed previously, the startup current can be as high as 40–50A on a circuit protected by a 15 or 20A circuit breaker. This plausible scenario was explored for a portion of the receptacles tested in order to assess whether the high startup current applied to a circuit would yield a higher probability of an electrical event. This type of load has not been evaluated by other researchers. A Ridgid Model CM14500, 14 inch chop saw was used to provide the high startup current. The chop saw in addition to the normal load provided a peak current of nominally 32 amps which lasted for approximately 1 second.

2.1.4 Instrumentation

Only receptacles in Test Racks 1 and 2 were instrumented during testing. For the majority of receptacles in these test racks, temperature at one terminal and voltage drop across the hot terminals was measured. For all receptacles in these test racks, temperatures were measured using 30 gauge type K thermocouples with the beads placed on one of the hot terminals. For side wired connections, thermocouples were placed with the bead under the terminal screw head where the wire met the screw (see Figure 2-7, left). For back wired push-in connections, the thermocouple was placed with the bead on the section of exposed conductor protruding from the receptacle (see Figure 2-7, center). For the loose plug connection receptacles, thermocouples were placed with the bead at the base of the hot plug blade (see Figure 2-7, right). For all setups, the thermocouples were bonded in place using Omega OB-600 high temperature, electrically conductive cement.

The voltage drop across the hot terminals was calculated for a portion of the receptacles in Test Racks 1 and 2. Voltage leads were connected in parallel with the hot conductors upstream and downstream of the receptacle using wire nuts (see Figure 2-2 and Figure 2-3). Voltage drop across the receptacle terminals was calculated by subtracting the approximate voltage drop across the wiring from the measured voltage drop of the wiring and terminals (i.e., between the upstream voltage lead and the downstream voltage lead; see Figure 2-2 and Figure 2-3). The approximate voltage drop for 20 inches of 14 AWG wire at a current of 15 A is 0.064 V. The line voltage (i.e., between hot and ground) for Test Racks 1 and 2 was also measured. Current for each test rack was measured using an Eaton model EACP1420120SP (range: 0–20A, +/- 0.05A) clamp-on current transducer placed around the neutral conductor running from the load bank to the loaded receptacle. The current draw for Test Racks 3 through 7 was periodically monitored using a Commercial Electric model MS2002 handheld clamp-on ammeter.

Ambient temperature and relative humidity measurements in the room with Test Racks 1 and 2 were collected using an Omega model HX93DAC-C temperature and relative humidity sensor. Ambient temperature and relative humidity measurements in the room with Test Racks 3 through 7 were collected using an Omega OM-DVTH temperature and relative humidity self-contained data logger. Digital photographs were taken before, during, and after testing as needed.

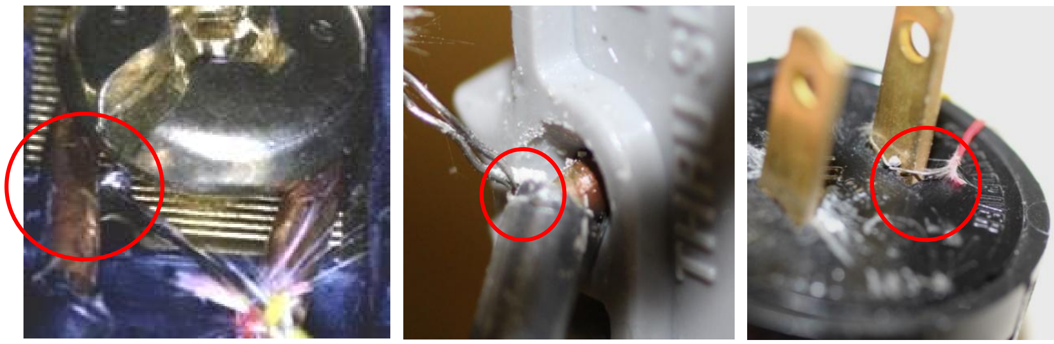


Figure 2-7. Photo of placement of thermocouple beads on side wired connection (left), back wired push-in connection (center), and plug blade (right). Note: Cement not added for visibility of bead.

2.1.5 Data Acquisition

Test Racks 3 through 7 did not have any instrumentation other than the ambient temperature and relative humidity data collected for the test room. An Omega OM-DVTH data logger collected the ambient temperature and relative humidity for Room 2 (i.e., Test Racks 3–7) at a rate of one sample every 2.5 minutes. The data logger collected data until its memory was full at which point the data would be overwritten. The OM-DVTH was capable of storing approximately 1 month of data. Consequently, data was transferred from the data logger to a permanent source approximately once per month. Data from instrumentation for Test Racks 1 and 2 was collected using a combination of National Instruments (NI) data acquisition hardware and software. The NI hardware used to measure voltages, current, ambient temperature, and ambient relative humidity consisted of a SCXI-1001 twelve slot chassis which contained nine SCXI-1125 modules. Each of the SCXI-1125 modules had a SCXI-1327 or SCXI-1313 terminal block attached and measured 8 channels. These terminal blocks allowed for measurements up to 300 Vrms on each channel. The NI hardware used to measure receptacle terminal temperatures consisted of a cDAQ-9178 eight slot chassis containing eight NI 9214 modules. The NI 9214 modules were able to measure 16 temperatures and had 250 Vrms channel to ground bank-type isolation. Each NI 9214 module had several cold-junction compensation (CJC) sensors for increased accuracy.

LabView data acquisition software, by National Instruments, was used to collect and record the data for Test Racks 1 and 2. In order to obtain useful measurements of current and voltage over the long duration tests without having an unmanageable amount of data, root mean square (RMS) calculations were done for each voltage and current measurement. In addition, a low pass filter cutoff frequency of 10 kHz was used for the voltage and current measurement channels to reduce noise. A total of 1500 samples were collected at a frequency of 2000 Hz for each channel's RMS calculation. Ambient relative humidity and temperature were sampled at the same rate, but no RMS calculation was necessary for these measurements. Although data was sampled at a high rate, due to the large computing requirements associated with the RMS calculations, the frequency of data recording for Test Racks 1 and 2 was limited to approximately once per 200 seconds (3.26 minutes). Receptacle terminal temperature measurements for Test Racks 1 and 2 were also recorded at this frequency. In some cases, screen shots of the temperature measurements outputs in LabView were taken in order to collect approximate temperature data for events which were shorter in duration than the sampling rate (3.26 minutes). Some of these screen shots are presented in Section 2.3.3.2.

Two digital video recorders (DVR), with a combined 24 available video channels, were used to record the test racks for the majority of the test duration. The DVRs were manufactured by Zmodo (model DVR-H9108V and DVR-H9116UVDH) and had the capacity for up to 7 days of continuous recording on all channels. Nineteen cameras (CCD and digital camcorders) were used to record any events occurring in the receptacles. In general, every receptacle was covered by at least one camera. Some cameras were kept mobile such that they could be moved to record close-ups of events associated with individual receptacles for better image resolution.

2.2 Experimental Procedures

2.2.1 Receptacle Installation Procedures

Seven test racks were built to test various receptacle configurations and subject the receptacles to a range of use conditions for extended periods of time. The installation of receptacles in the test rack was, in general, a four step process. First, wiring was cut to the appropriate length and the ends were stripped of approximately 1.9 cm (0.75 in.) of insulation in accordance with the strip gauges located on the back of the receptacles. Receptacles with loose screw terminal connections and plug connections had one end of each wire bent into a crook shape with the end of the wire wrapping around the screw in the clockwise direction. Wiring for receptacles with push-in connections was left unbent. Second, the receptacle connections were modified; plug connections were loosened; screw connections were set; and push-in connections were exercised. Then receptacles were mounted to the test rack. Each receptacle was grounded through its connection to the test rack. Lastly, receptacle wiring was connected in the manner shown in Figure 2-2 and Figure 2-3; any required instrumentation was installed; and where required, shunted plugs (see Section 2.1.1) were installed.

2.2.2 Test Procedures

Prior to beginning Tests 1 and 2, all instrumentation was checked for operability using the data acquisition system. Data acquisition was initiated prior to energizing the circuits. After the circuits were energized, the load bank was plugged in and the appropriate load was established. The electrical current was periodically monitored to ensure that the load was correct. If the load was too high or too low, the load bank was adjusted using the switches or by changing out light bulbs for those of a different wattage. Load cycling, vibration, and application of the high startup current were conducted on weekdays (excluding holidays) at approximately the same time each day. From time to time throughout each weekday, the receptacles were observed to note any changes. Changes included overheating, arcing, melting, glowing, discoloration, flaming, etc.

A detailed log book was kept for each test rack. The log book consisted of recordings of every load cycling, vibration, application of the high startup current, and any changes observed for individual receptacles. Both the dates and times were recorded for all instances in the log book. Because the tests were conducted over long periods of time, there were some instances of power outages in the building. When it was possible, the power outages were noted in the log books. The next weekday after a power outage occurred, the test data acquisition system was required to be restarted. Photographs were taken every so often to document the progression of overheating connections in the receptacles. In addition, plugs were removed from their receptacles twice over the course of testing to photograph any damage to either component and then re-inserted.

Throughout the testing, receptacles were removed from the test circuits as a result of various events, including:

- A severed conductor due to melting from a glowing connection;
- Short between hot internal plug contacts and ground;
- Short between neutral internal plug contacts and ground;
- Flaming ignition of receptacle;
- Series arcing at screw terminals; and,
- Removal for SEM examination or use in other testing.

Except for SEM examination or use in other testing, removal of receptacles from the test circuit was necessary because the aforementioned events either caused loss of power (i.e., from shorting) or loss of current to the circuit (i.e., from a severed conductor). However, when a short occurred between the neutral internal plug contact and ground, there was no loss of power or current to the circuit. This fault allowed some or all of the current to flow through the ground for an extended period of time, while also bypassing some of the receptacles in the circuit. For this reason and because the situation presented a safety hazard (i.e., current flow through an unintended path), these receptacles were also removed. In order to remove a receptacle from the circuit, the test rack was first de-energized. Then the wire nuts connecting the receptacle wiring to the upstream and downstream receptacles were removed. Subsequently, the receptacle was removed from the test rack and documented. The wires from the upstream and downstream receptacles were then connected together with wire nuts. If the distance between the receptacles was large enough, a new length of wiring was added to bridge the distance between the two receptacles. Because the authors were not present for the majority of events, part of the documentation process involved a review of the surveillance video. The review of the video revealed the time of the event and whether any flaming, arcing, or smoking occurred. This information, in addition to the activation of the circuit breaker and any observations of loss of current were recorded in the log book for the specific receptacle. A permanent copy of the surveillance video showing the event was then saved.

2.3 Experimental Results and Analysis

Over the seven test racks, there were 528 test trials conducted with 490 receptacles. Receptacles were tested for up to 511 days; all receptacles were tested for a minimum of 192 days. Appendix A lists the specific test durations for each test rack. Receptacles which failed were only tested up to the time of failure. Over the test duration, receptacles experienced effects of overheating ranging from discoloration of plastics to failures of the receptacle including flaming ignition of receptacles and surrounding materials. The current draw for all receptacles discussed in this section was 15A, unless otherwise noted.

Failure rates were computed for a number of scenarios in subsequent sections. The failure rate in units of number of failures per year was computed using the following formula:

$$Failure\ Rate = \frac{Number\ of\ Failures\ in\ a\ Population}{Total\ Time\ Tested\ for\ the\ Population}$$

A population is defined as any subset of the entire set of receptacles tested. The total time tested for the population, in years, is defined as the sum of the times to failure for each receptacle that failed plus the sum of the total time tested for each receptacle that did not fail. For simplicity, the times tested and times to failure were rounded up to whole days. These times also do not account for the time each day when the test racks were not energized (see Section 2.1.3). The failure rates were useful for comparing the failures observed for two variables since they normalized the number of failures by the number of receptacles tested and the times tested.

2.3.1 Formation of Overheating Connections at Receptacle Terminals

In the context of this report, overheating of receptacles and plugs was determined by visual indicators. These visual indicators included: discoloration of metal conductors; discoloration of plastic materials (wiring insulation, plug, receptacle body); deposits of oxidation or corrosion products on metal conductors; charring or melting of plastic materials; glowing connections; loss of plating on receptacle screws; and dezincification of brass components.

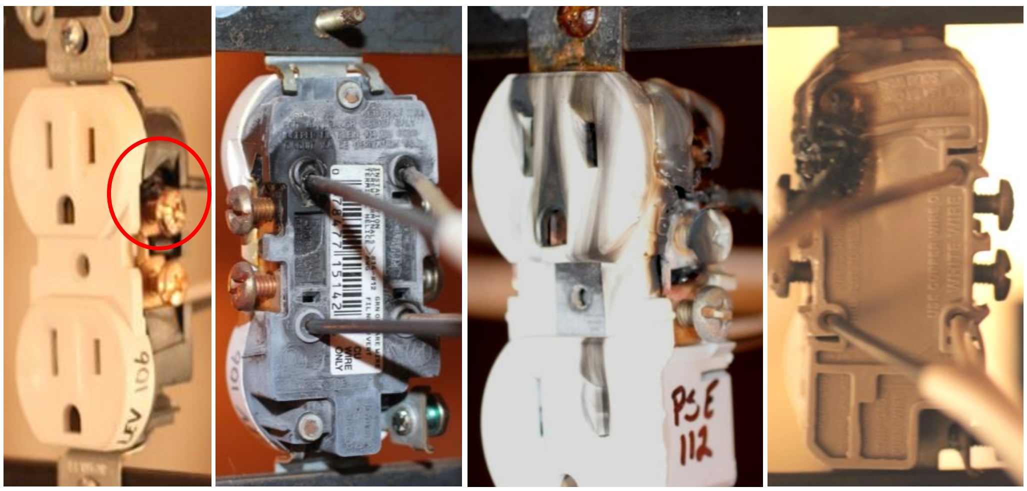
2.3.1.1 Screw Terminal Torque

None of the receptacles with screw terminal connections having torques of 3 in-lb (51 receptacles), 5 in-lb (10), 7 in-lb (10), and 15 in-lb (8) experienced any visual indicators of overheating throughout the test periods. Other researchers have observed heating in receptacles (i.e., a rise in temperature with or without other visual indicators of overheating) with screw terminal torques greater than 6 in-lb [Burns et al., 1978]. However, in this study, receptacles with elevated temperatures alone without any visual indication of overheating were not identified as overheating receptacles. Receptacles having torques of 5, 7, and 15 in-lb were energized for a period of 204 days. Receptacles having torques of 3 in-lb were energized for between 204 and 397 days. Receptacles having torques of 1 in-lb or the ¼ turn loose configuration were energized for between 192 and 511 days. The eight receptacles having torques of 3 in-lb and which were subjected to daily vibrations did not exhibit any signs of overheating. The majority of receptacles having torques of 1 in-lb or the ¼ turn loose configuration did exhibit signs of overheating at one or more of the screw terminals.

2.3.1.2 Back-Wired Push-In Connections

Only three of the 42 back-wired push-in connected receptacles showed indicators of overheating, with one ultimately failing (0.02 failures/year). All of these receptacles were subjected to daily vibrations and were installed with one prior insertion and removal cycle for each wire; two are shown in Figure 2-8. The third receptacle overheated to the point where flaming ignition occurred and the receptacle failed (PSE111); see Section 2.3.4.1 for discussion of this receptacle.

A PVC receptacle (PSE 112; Figure 2-8, right) exhibited charring of the receptacle plastic body in the vicinity of the top-hot push-in connection. This overheating connection also produced dark black smoke which emanated from the area around the overheating connection as well as out the front plug holes of the receptacle as evidenced by soot deposits on the receptacle and those above. A polypropylene receptacle (LEV106; Figure 2-8, left) had a minimal amount of melting in the vicinity of the top-hot push-in connection. This did not appear to produce any significant deposits from smoke. PSE112 and LEV106 remained energized and in the test circuit for an additional 237 and 310 days (i.e., until the end of the test), respectively, without any noticeable changes. These results are not very surprising considering the vigorous testing that receptacles with back wired push-in connections undergo as part of the UL 498 [2008] listing (see Section 2.1.2.2). It is unclear whether receptacles manufactured prior to the changes instituted in UL 498, 1986 edition would have had a larger propensity for overheating under the same conditions as those in this test series.



LEV106 PSE112

Figure 2-8. Photographs showing melting (LEV106, left) and charring (PSE112, right) of receptacles with back-wired push-in connections.

2.3.1.3 Plug Connections

Only five (0.04 failures/year) of the 120 receptacles with plug connections overheated to the point of failure (see Section 2.3.4). Much like the receptacle connections, the majority of loose plug connections that did not fail did show some signs of overheating. The exception to this was for the do-it-yourself plugs that had the solid brass blades. None of these plugs exhibited any signs of overheating. One plug in particular did show some signs of arcing (see Figure 2-9), however this arcing was likely due to make-break arcs that occurred when the plug was manually manipulated to establish current flow. Because of the very loose nature of the receptacle and plug connections (i.e., very reduced nominal retention force), some required manual manipulation in order to complete the circuit so current flow could be established. Once current flow was established, the make-break serial arcs were eliminated. It is possible that the shunting method used for the do-it-yourself plugs (i.e., a section of 12AWG wire connected tightly under two screws) helped reduce the tendency for these plugs to overheat. This connection was very tight and robust compared to the crimp on connections used for the 16AWG stranded wire found within the other plugs. Photos of the shunting method for DIY plugs and the other plugs are shown in Figure 2-10.

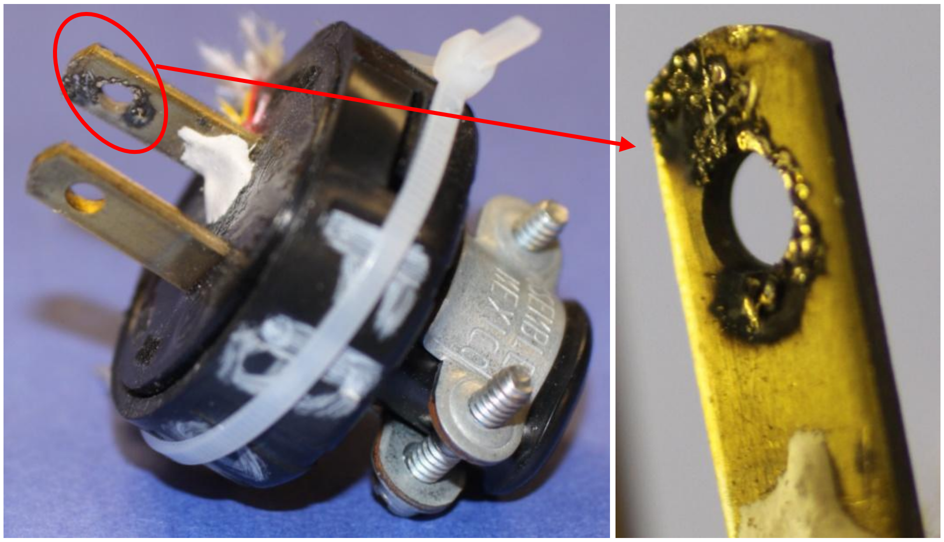


Figure 2-9. Do-it-yourself plug showing arcing damage (PSE044).

Figure 2-10. Shunting method for DIY plugs (left) and for other plugs (right).

The majority of the other two types of plugs, those with folded blades and those with solid plated blades, did show signs of overheating. This even included three out of the four receptacles (1 nickel plated blade plug; 2 folded blade plugs) with unmodified plug retention forces. It is likely that the continuous heat from the current flowing through the plug was enough to cause some minor overheating to begin. As the plugs overheated, the wiring for these plugs tended to get rather hot and often the insulation became rigid. This wiring was PVC, and it is likely that as the wiring became hot, some of the plasticizers were driven off, reducing the flexibility of the wiring. Figure 2-11 shows overheating for a folded blade plug in a PVC receptacle with a nominal retention force of 0.01 kg. With the plug in place, the damage to it and the receptacle appear minimal. This damage would be even less evident had a faceplate been installed. The plug itself shows some overheating in the form of discoloration and charring primarily around the hot blade but with some at the neutral blade as well. The damage to the receptacle matches that of the plug with most of the damage around the hot terminal and some at the neutral terminal. The receptacle also exhibits some sagging on the hot side. Some small brown dots of discoloration of the receptacle face can be seen in Figure 2-11. It is possible that these are a result of ejected particulates from arcing.

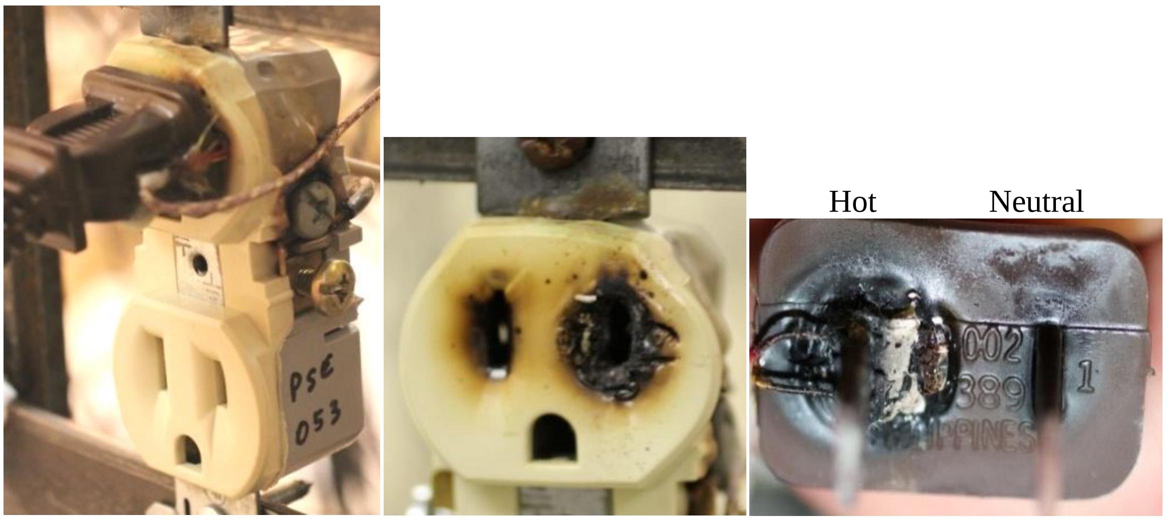


Figure 2-11 Overheating at folded plug blade connection (0.01 kg) on Receptacle PSE053.

The low profile plugs with plated brass blades typically exhibited signs of overheating similar to the receptacle pictured in Figure 2-12. With the plug inserted in the receptacle, overheating was visible for the low profile plugs via areas of discoloration on the back of the plug near the hot plug blade (see left photo in Figure 2-12). The damage to black colored plug blades is similar, but less evident in most cases. The discoloration appears as a white area near the hot terminal as shown in Figure 2-13. Damage to the polypropylene receptacle in Figure 2-12 is limited in this case to melting around the hot terminal. The plastic did not appear to melt and run very much, which indicates that the overheating plug blade was probably not in contact with the plastic (i.e., conducting heat to the plastic). There is some discoloration of the plastic and apparent surface cracking near the top neutral plug blade entrance that has also occurred in this instance. In general, the overheating damage to the low profile plugs appeared to be greater than the other two types of plugs. Figure 2-14 shows X-rays of connections within the low profile plugs and plugs with folded brass blades. Both plugs appear to have crimp connections between the wires and plug blades, made at an angle to the blade. The connections within the low profile plugs are close to the back surface of the plug (i.e., the surface not in contact with the receptacle). This would explain the location and appearance of discoloration on this type of plug.

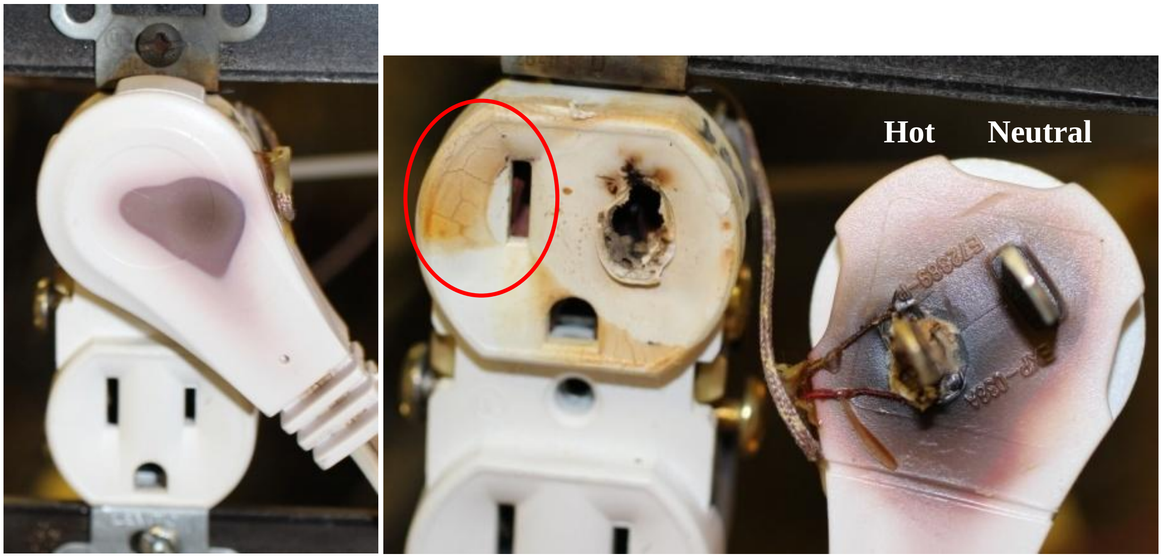


Figure 2-12. Overheating at low-profile plated plug connection on Receptacle LEV053 (0.01 kg).


Figure 2-13. Overheating and discoloration of black plug with plated blade (PSE285; 0.01 kg).

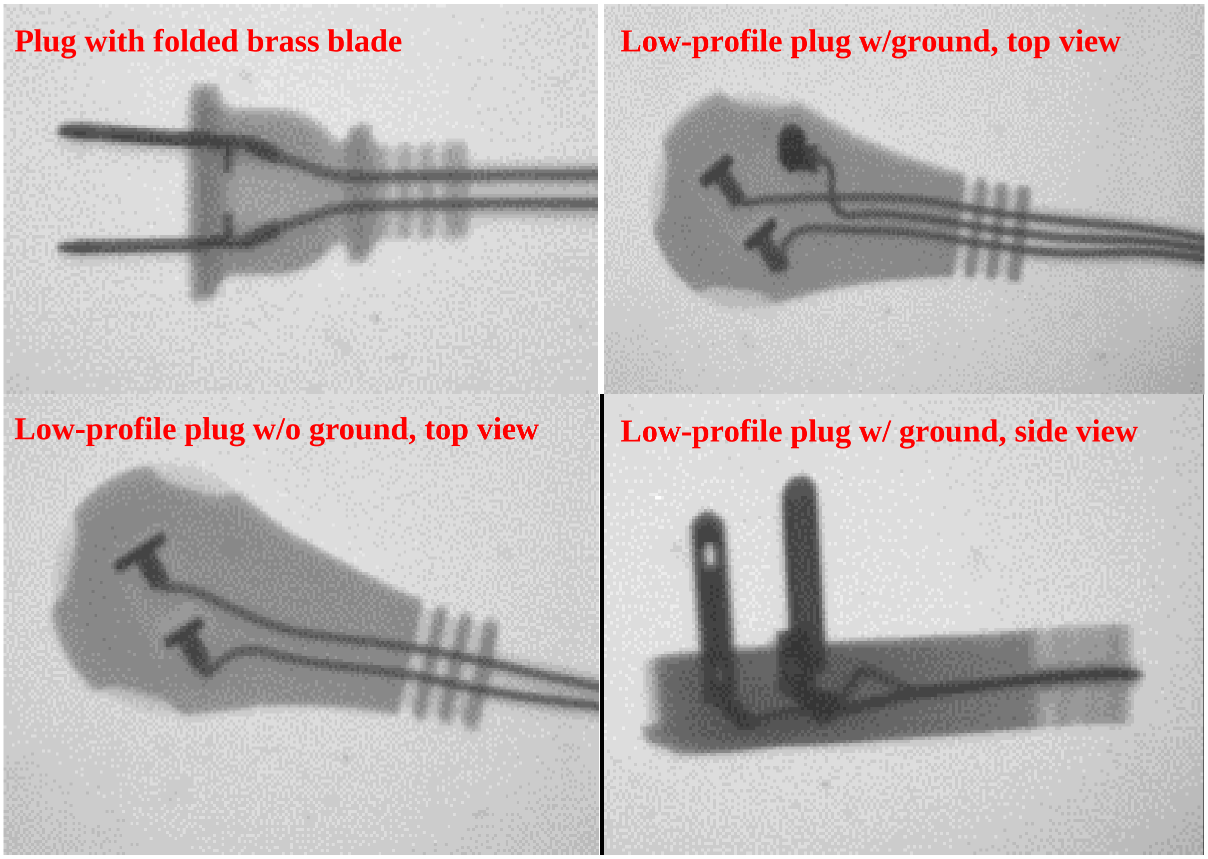


Figure 2-14. X-rays showing connections within the low-profile plugs and plugs with folded brass blade.

2.3.2 Mechanisms for Overheating

2.3.2.1 Oxidation

The development of an overheating connection in a loose terminal connection is a rather straight-forward process. The process begins with a loose terminal connection having a reduced contact area between the wire and the terminal, and thus larger contact resistance, than a well tightened connection. The increased contact resistance will lead to resistive heating as the current flow is limited to the smaller contact area. Cupric oxide (CuO) will then be formed as the copper reacts with oxygen in the air at the elevated temperatures. Copper oxides, being semi-conductive, will further increase the resistance between the wire and terminal [Shea, 2006]. The increased resistance will cause additional heating and production of CuO and the cycle (heating>oxide formation>increased resistance>heating…) will continue until enough of an oxide layer is produced that a glowing connection is formed or the receptacle fails. Cuprous oxide (Cu_2O) may also form on the copper wire at elevated temperatures [Ferrino-McAllister et al., 2006] (see Figure 2-15).

Glowing connections and receptacle failures are discussed in detail in subsequent sections. In general, whether or not a connection overheated was relatively consistent based on the looseness of the connection (i.e., loose connections overheat more often than tight connections). However, what was not very consistent is what causes some receptacles to overheat to the point of failure, while others with the exact same configuration do not. A possible explanation for these differences is that there are certain variables that were not stringently controlled as part of this research program. Because the receptacles were installed in a test rack without an outlet box, the wiring for the receptacles projected from the terminals and was not supported. This could cause physical forces to be applied to the receptacle terminals in different ways than wires pushed into a box. For instance, the tight confines of a box may restrict motion of the wires. Whereas the wires on the rack mounted receptacles extended straight out and were unrestricted in creeping downward while applying a moment arm on the screw terminal (see Figure 2-16). The wiring around screw terminals was intended to be installed uniformly using general guidelines and procedures. However, this does not exclude variation in the stripped length of wire, curve radius, or other bending of the wire.

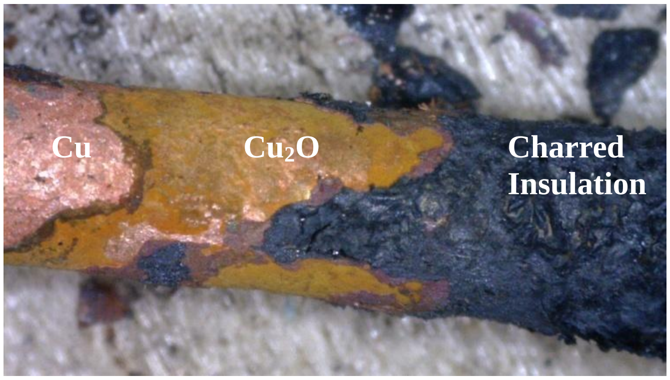


Figure 2-15. Oxidation of wire, showing layer of Cu_2O in center and underlying copper (PSE170).

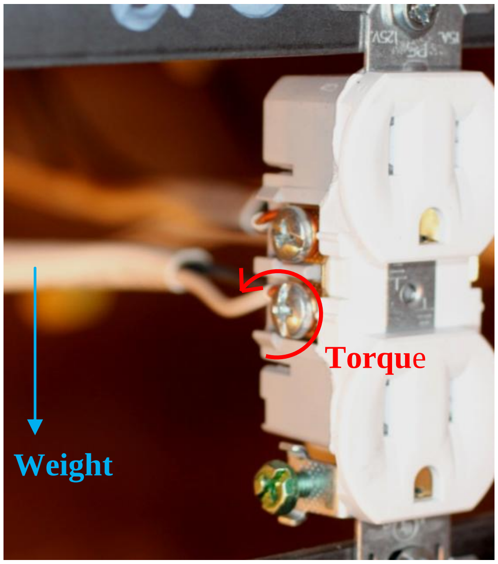


Figure 2-16. Photograph of receptacle from laboratory testing illustrating torque from weight of wires.

It was quite common for receptacles to show multiple signs of overheating at multiple terminals. Figure 2-17 shows a PVC receptacle exhibiting multiple signatures of overheating. This photograph also shows a receptacle having discoloration of the PVC body material around the neutral connections and on the PVC sheathed wiring projecting from the back of the receptacle. In these cases, the plastics progressively transition from their original color (i.e., white, grey, or almond) to a dark brown color. Discoloration of this sort spreads radially outward from the overheating screw connections. This receptacle also shows some dark oxidation products (likely CuO) deposited on the wire around the screw terminal as well as loss of the nickel plating on the neutral screw terminals. Copper oxides CuO and Cu_2O can be differentiated based on color; Cu_2O is typically a red-orange color, while CuO is typically black [Shea, 2006]. Typically, the Cu_2O was observed as a surface coating on the conductor. The CuO observed began as a surface coating, but in some cases built up to thick friable layers (see Figure 2-20). The thick layers of CuO could be easily broken off using one's fingers, but the surface coatings of both oxides (CuO and Cu_2O) required more effort such as a brush to remove.

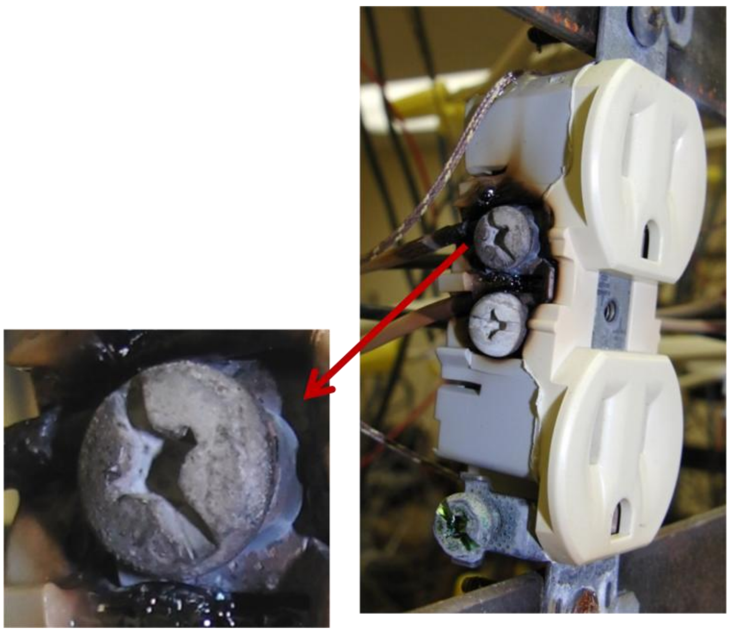


Figure 2-17. Photograph showing oxide layer on wire and loss of plating on receptacle screw on PSE016 (¼ turn loose).

Some severe cases of oxidation of copper wiring as a result of glowing connections resulted in drastic thinning and tapering of the conductor. Figure 2-18, Figure 2-19, and Figure 2-20 are three instances where severe oxidation on the receptacle wiring near the screw connection was observed. In these cases, the wiring was severely pitted and the diameter of the wire was reduced by up to ½ of the original size. The wire insulation, in most of these cases, was charred and friable, which allowed more of the wire to be exposed to air. As the diameter of the wire was reduced, so was the current carrying capacity of the conductor. This further contributed to overheating of the connection. This thinning of the conductor is unique compared to necking of the conductor at a glow spot (see Section 2.3.3.3). The main difference is that the conductor thinning occurs gradually over a longer length whereas necking occurs suddenly at the glow spot.

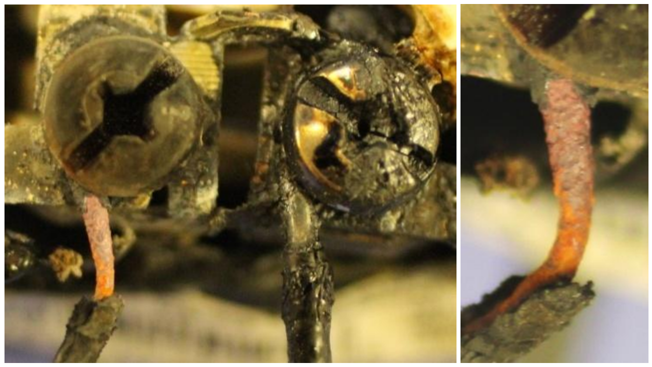


Figure 2-18. Thinned and pitted wire from oxidation (LEV009).

Figure 2-19. Thinned and pitted wire from oxidation (PSE263).

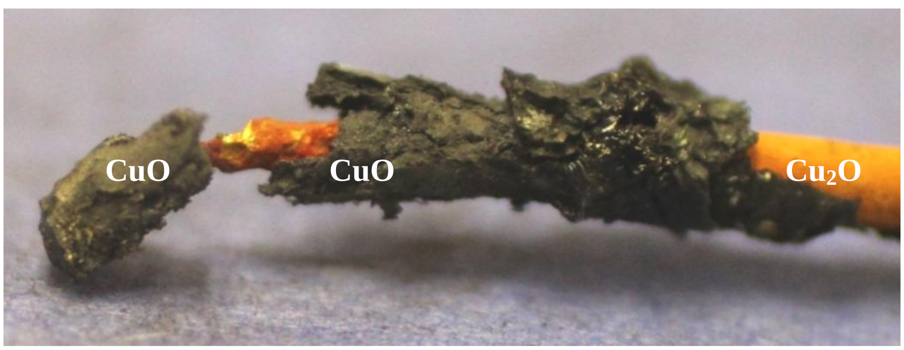


Figure 2-20. Thinned and pitted wire from oxidation (PSE133).

2.3.2.2 Corrosion

Copper and copper alloys are resistant to corrosion by dry gasses at ambient temperatures or lower [Craig and Anderson, 1995]. However, copper alloys are more vulnerable to corrosion in liquid/vapor chlorine environments and at elevated temperatures. Figure 2-21 shows a receptacle that has a white colored deposit on the surface of the wire. The white colored deposits were only observed on the PVC receptacles, while the dark copper oxide deposits were found on PVC, polypropylene, and thermoset receptacles. The white corrosion deposits were surface coatings and, like the copper oxides, required a brush to remove. EDS analysis of the white deposit revealed that it was primarily chlorine (see Figure 2-22 and Figure 2-23). The chlorine is likely a result of corrosive attack by PVC vapors from the receptacle. When PVC is heated to approximately 270ºC, hydrogen chloride gas is evolved [Hirschler, 2008]; the exact temperature at which hydrogen chloride gas evolves is highly dependent on the specific stabilizers and fillers used in a specific PVC formulation. Hydrogen chloride gasses combine with atmospheric moisture to form hydrochloric acid which then corrodes the copper. Copper has a fair resistance to corrosion by hydrochloric acid according to the ASM Handbook of Corrosion Data [Craig and Anderson, 1995]. The chlorine corrosion layer was present along the length of the exposed section of wire. The SEM images in Figure 2-24 show the characteristic white corrosion layer atop a receptacle wire. The images show that the corrosion is a distinct layer atop the copper wire and that the corrosion stops at the boundary between the exposed wire and the intact wire insulation (boundary of corrosion noted as blue lines). A portion of the bare copper is shown in the 2000x magnified image between the boundary of the corrosion layer and the wire insulation. White corrosion products were also found on the brass contacts where dezincification was present (see Section 2.3.2.2.1). Even though dezincification created a copper rich layer at the surface of the brass contacts, the dark copper oxides were not observed on the dezincified brass. Although the resistance of the corrosion products were not measured, it is likely that they increased the electrical resistance at the connections, much like the copper oxides.

Further visual examination of the conductor in Figure 2-22 revealed dendritic deposits on the surface of the conductor, appearing to extend outward from underneath the screw head (see Figure 2-25). These types of deposits were found on the wiring of three receptacles near the screw terminals. SEM Examination of the dendrites shown in Figure 2-25 appeared to indicate that the dendrites were forming over top of the chlorine corrosion layer (see Figure 2-25). The dendrites were found to be primarily copper (see EDS spectra in Figure 2-26). Presence of the dendrite formations suggests that some form of vaporous copper existed at a point during the overheating/corrosion process which was then re-deposited on the wire. The copper dendrite formations were only observed to exist in two cases where the whitish corrosion was identified. It is unclear if the dendrites were present in other cases where overheating and/or corrosion occurred, but it is likely that these dendrites would be obscured or removed as a result of severe overheating.

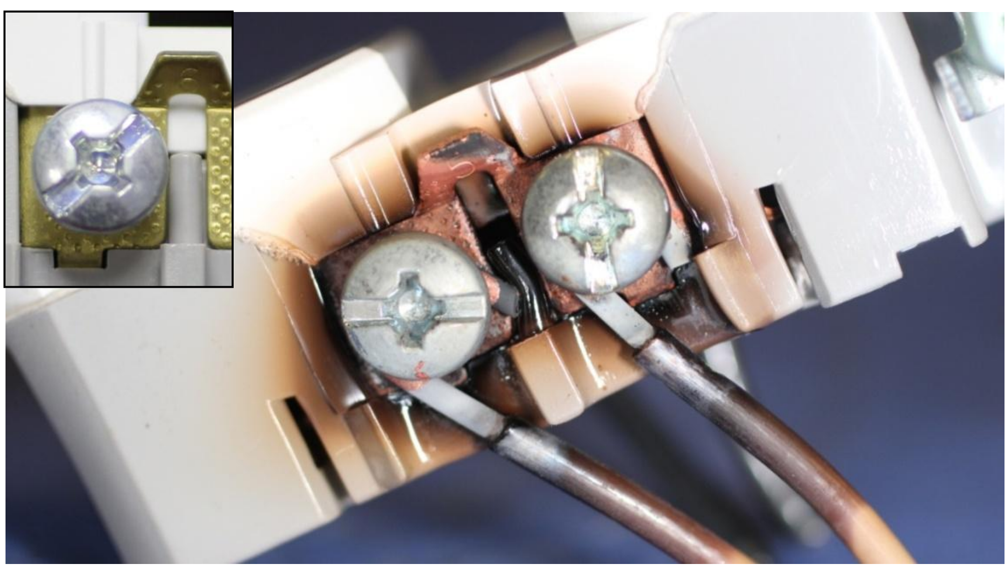


Figure 2-21. Photograph showing corrosion of wire, discoloration of plastic, and dezincification of brass components on PSE171 (exemplar photo of brass contacts shown in upper left).

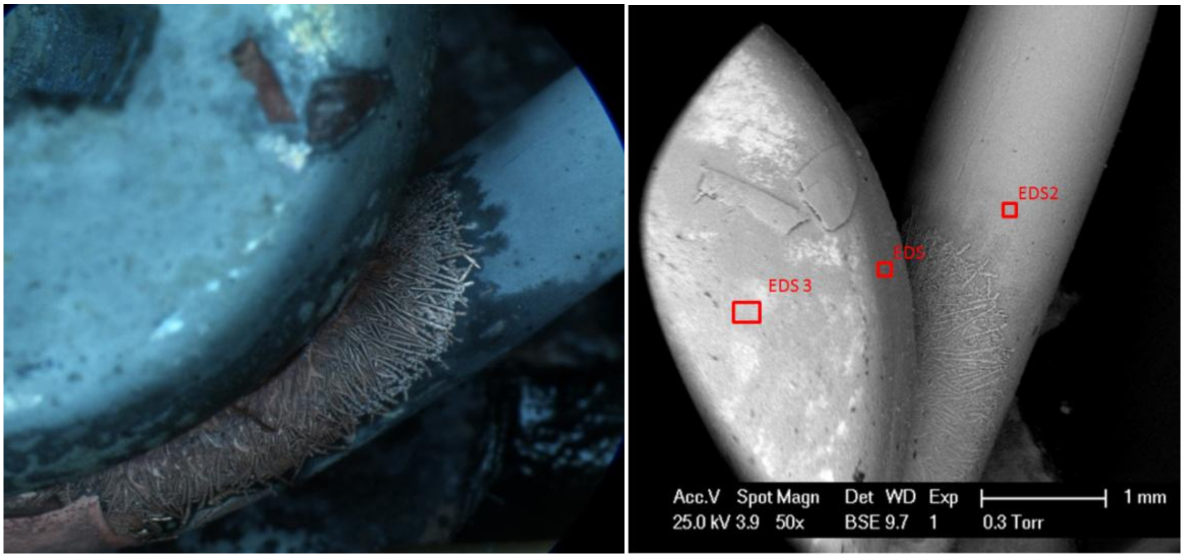


Figure 2-22. Microscopic image (left) and SEM image with EDS locations (right) of top-neutral conductor/screw from PSE171.

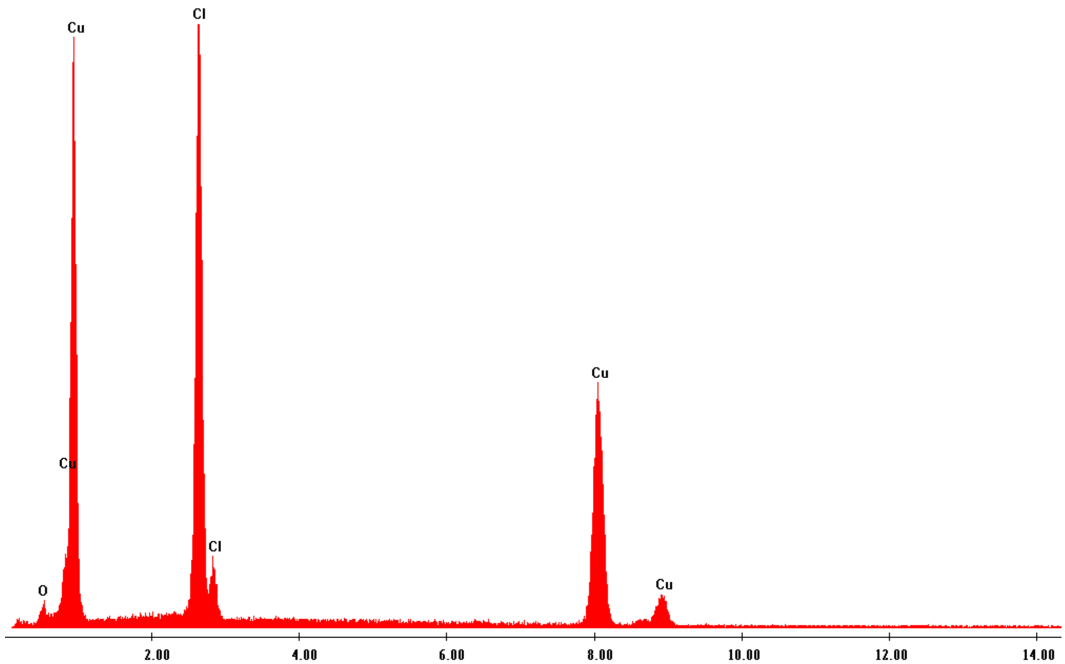


Figure 2-23. EDS Spectra for corrosion layer, “EDS2” in Figure 2-20 (right).

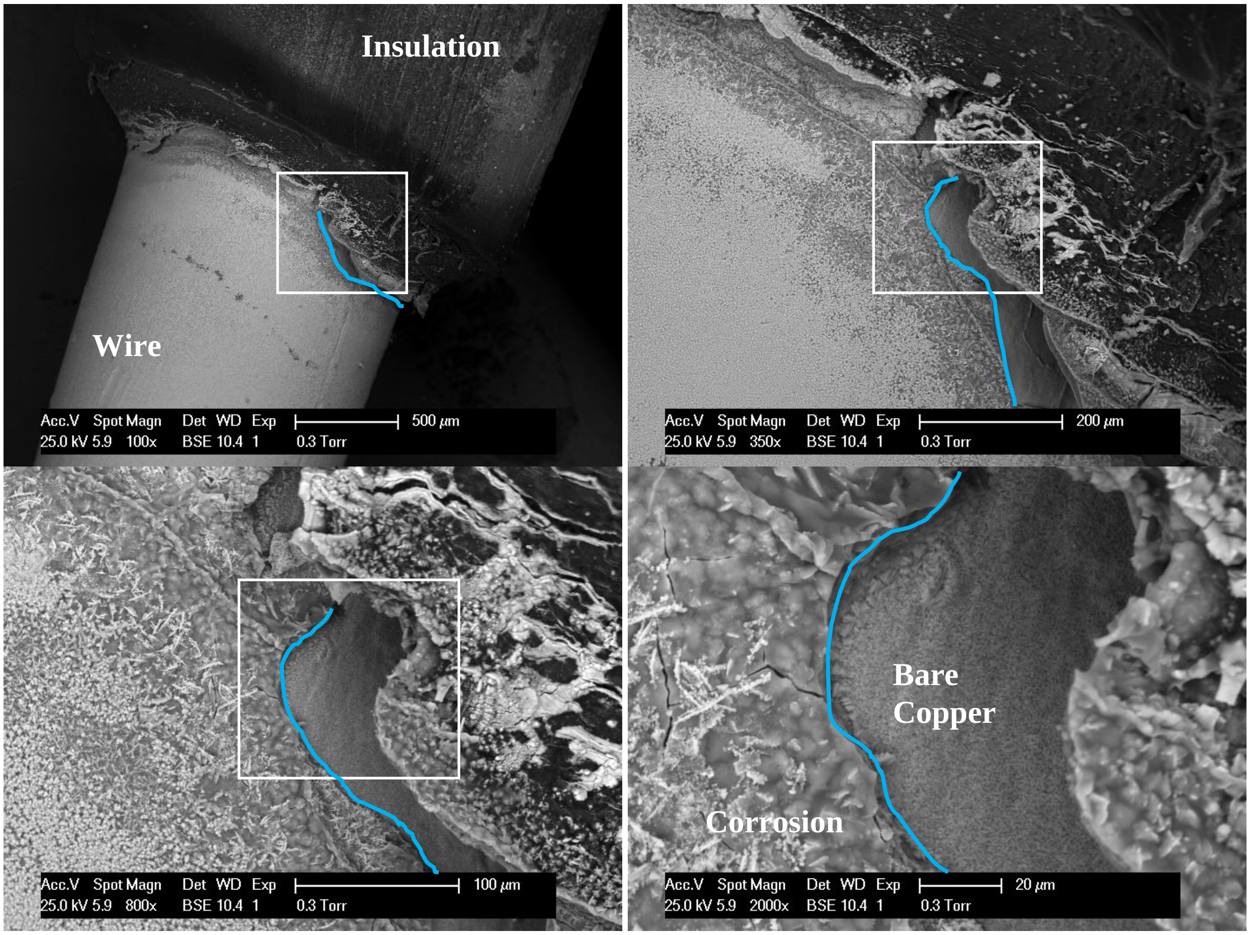


Figure 2-24. SEM images (100x–2000x) of white corrosion deposit at interface of wire and insulation for PSE 171.

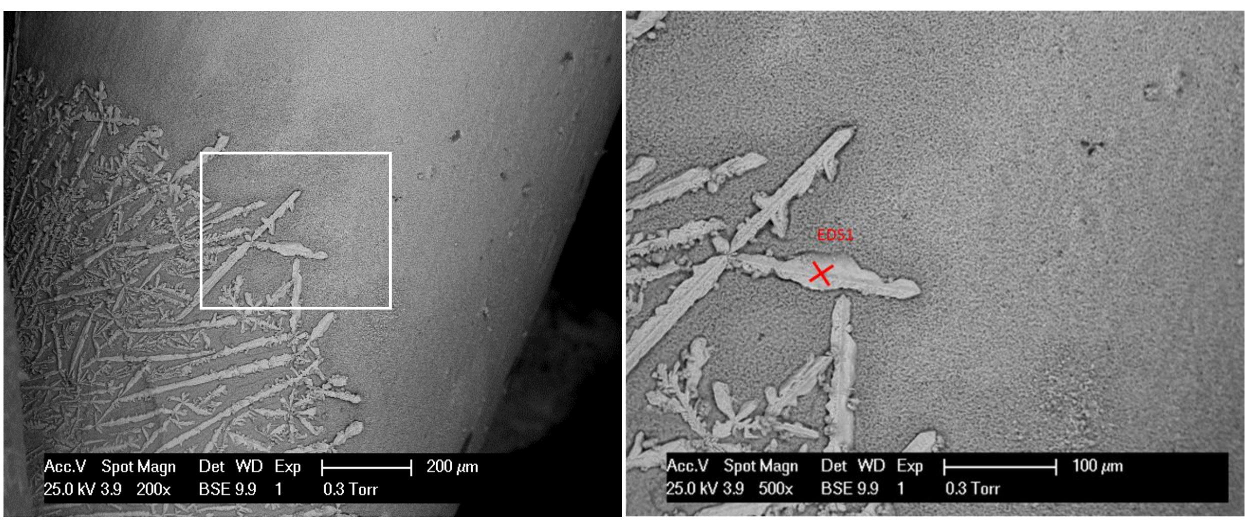


Figure 2-25. SEM images at 200x and 500x magnification of dendritic structure on PSE171; EDS location noted by an 'X'.

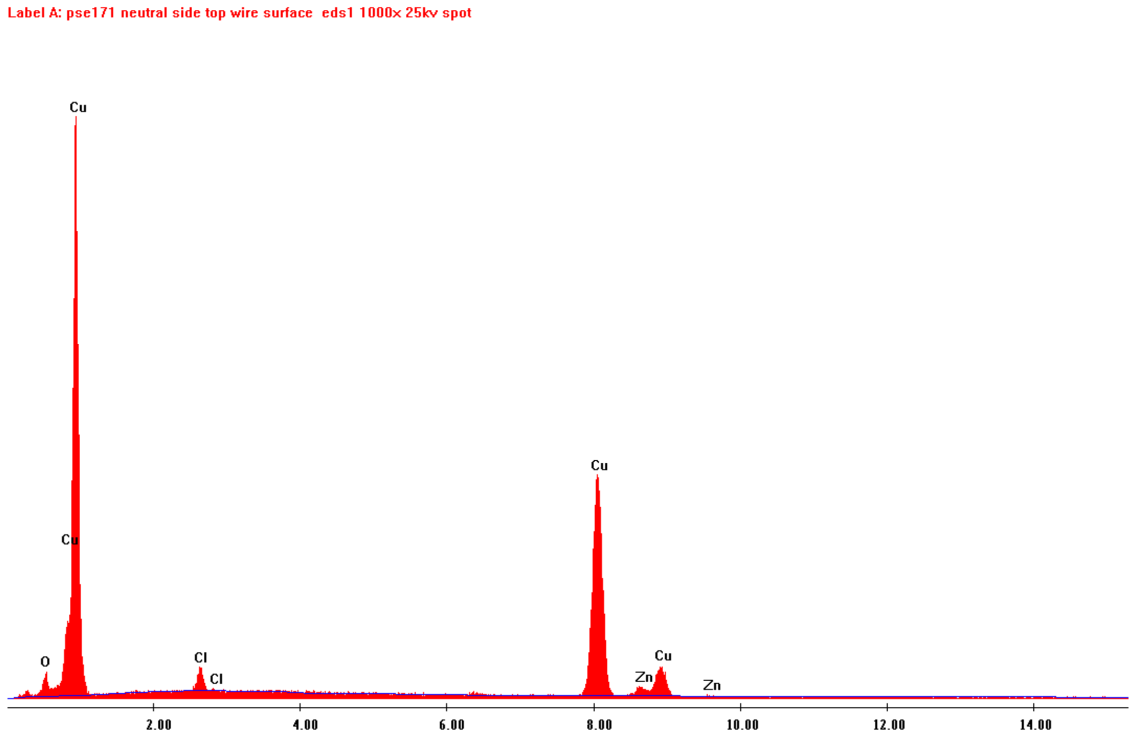


Figure 2-26. EDS Spectra for dendrite, “EDS1” in Figure 2-23 (right).

2.3.2.2.1 Dezincification

Another visual indicator of overheating and corrosion in receptacles is the change in appearance of the brass receptacle contacts. Figure 2-27 illustrates the change in color of brass from yellow to a coppery color. This is an indication that the zinc from the brass has been selectively leeched from the surface due to the corrosion [Fontana, 1986]. Selective leeching of zinc from brass due to corrosion is referred to as dezincification. Common yellow brass (e.g., cartridge brass) is made up of approximately 70% copper and 30% zinc. Dezincification can only occur in brasses with 15% or more zinc. Additives such as tin, arsenic, or antimony reduce the possibility of dezincification [Fontana, 1986]. Dezincification can either occur in a localized area, known as plug-type, or uniformly across a surface, known as layer-type. Typically dezincification occurs in brass pipe and fittings exposed to corrosive liquids. Layer-type dezincification favors brasses with high zinc content and acidic environments [Fontana, 1986]. Increases in temperature and oxygen concentration will increase the rate of dezincification [Fontana, 1986]. In the case of an overheating receptacle, both a relatively high oxygen concentration (i.e., from air) and elevated temperatures are present, hence the appearance is that the dezincification is layer-type. The hydrogen chloride vapors from PVC provide the corrosive atmosphere and the brass contacts are approximately 30% zinc (see Table 2-2) and thus are susceptible to dezincification.

While the overall dimensions of the dezincified item do not change dramatically, the copper that remains after dezincification is porous and mechanically weak [Fontana, 1986]. It is unclear to what effect dezincification has on the electrical conductivity of the brass contacts. Dezincification is a rather slow process, occurring over periods of weeks or more in this test series. The visual indicators of dezincification (i.e., copper colored surface of brass) will not be present for melted brass as the zinc usually will not vaporize during the melting process unless the brass is molten for an extended period of time. Also, the relatively short duration of fires (i.e., hours versus weeks) will not provide enough time for significant dezincification to occur even if corrosive vapors are present.

In order to illustrate the effects of dezincification, a terminal screw and attached internal brass receptacle contacts having experienced overheating and corrosion were sectioned and polished (see Section 3.2.3.3). A microscopic image of the cross-sectioned brass contact reveals layer-type dezincification (see Figure 2-27) occurring on the contact. This image is a close-up of the area from a sectioned screw circled in blue in Figure 2-64. There is a visible line of demarcation between the bulk brass (yellow) and the dezincified brass (copper colored). The dezincified brass is a relatively porous layer approximately 5 microns (1.9×10^{-4} inches) in thickness compared to the 0.76 mm (0.03 inch) thick brass contact. It is unlikely that this small amount of dezincification would have an effect on the structural or electrical properties of the brass contact. EDS measurements were taken to determine the chemical makeup of the bulk brass compared to the dezincified brass (see Table 2-2). The results confirm what is observed visually; the bulk brass has a higher relative concentration of zinc than the dezincified brass. Carbon, oxygen, iron, and chlorine are impurities likely resulting from the corrosive atmosphere, char, and surface preparation techniques. The EDS measurements are meant to be a qualitative comparison showing the relative change of the zinc between the two areas; the error of these measurements was not quantified.

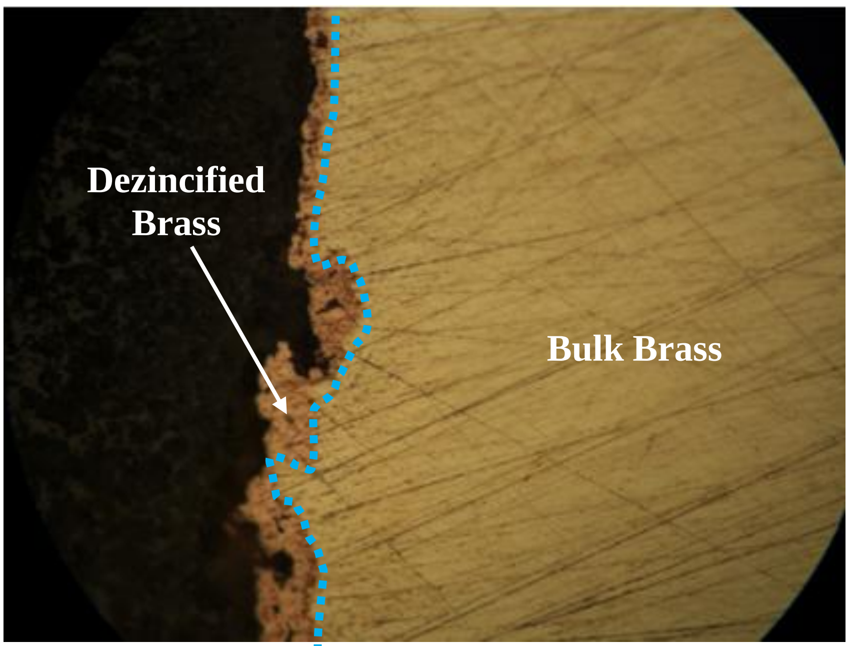


Figure 2-27. Section of brass contact from PSE170 (500x) showing dezincification (from circled area in Figure 2-64).

Table 2-2. EDS Measurements of % Mass of Chemical Components of for Bulk Brass and Dezincified Brass from Brass Receptacle Contact (PSE170, Figure 2-27).

Element	Bulk Brass	Dezincified Brass
Copper (Cu)	60	66
Zinc (Zn)	27	17
C, O, Cl, Fe	13	17

Dezincification was also observed for nickel plated brass plug blades. The process of dezincification for plug blades, especially those plated with nickel is likely more complicated than that of the bare brass contacts. This is because the nickel plating provides a physical barrier that prevents dezincification of the underlying brass. Before dezincification of the underlying brass can occur, the nickel plating would need to be removed. A combination of corrosion from the plug material vapors and heating from the overheating connection is expected to cause the loss of nickel plating. Also, any nickel remaining would likely prevent dezincification on the underlying brass, creating less uniform dezincification across the area. Figure 2-28 shows loss of plating and dezincification for a low profile plug blade. The dezincification appears to be more localized as the nickel plating still remained over portions of the plug blade, but there was noticeable pitting on the plating and dezincified brass. This dezincification occurred in a polypropylene receptacle, but the plug material was likely PVC.

Figure 2-28. Loss of plating and dezincification of low profile plug blade; nominal retention force of 0.01 kg (LEV286).

2.3.3 Effects of Overheating

2.3.3.1 Receptacle Material Behavior

Three different primary receptacle materials (see Section 1.4.2.2) were used in the test series. Each of these three materials is quite distinct with respect to the physical response to overheating. Polypropylene is a thermoplastic material which, when heated, will melt, run, pool, and drip as shown in Figure 2-29. Reported melting temperatures for Polypropylene are around 160–165ºC [Hirschler, 2008]. Melting of the polypropylene would allow the internal plug contacts some freedom of movement. PVC is also a thermoplastic material, but because of the addition of plasticizers, it behaves slightly different than other thermoplastic materials. When heated, the PVC receptacles would deform, sag, and eventually char as shown in Figure 2-30. Even when the PVC receptacles had been severely deformed by an overheating connection at the screw terminal, the internal and external structure of the receptacle remained largely intact preventing the movement of the internal contacts. It is impossible for thermosetting plastics to change their physical state below their degradation temperature, which can be rather high (approximately 300ºC [Hirschler, 2008]). When heated, the thermoset receptacles became brittle, cracked, charred, and bits of material were dislodged (see Figure 2-31). The material internal to the receptacle, however, usually remained in place, retaining the separation between hot/neutral conductors and the ground strap. As the receptacles overheated, the smell of the plastics was quite prominent within the test rooms, even if smoke was not observed. The smells of the three different plastics were unique compared to each other.

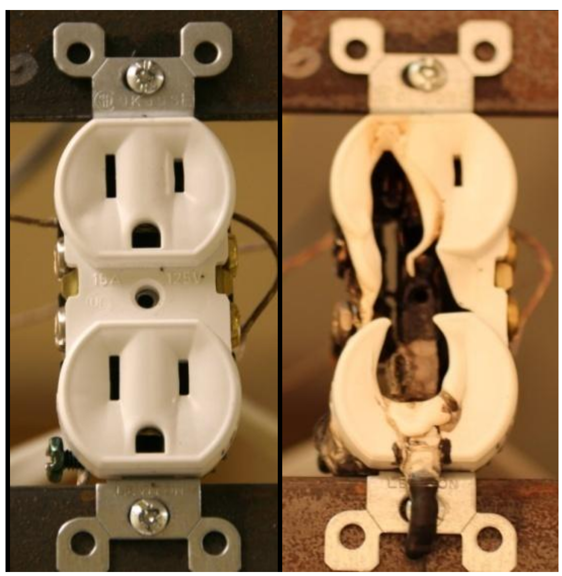


Figure 2-29. Photographs showing melting and pooling/dripping of polypropylene receptacle (LEV008).

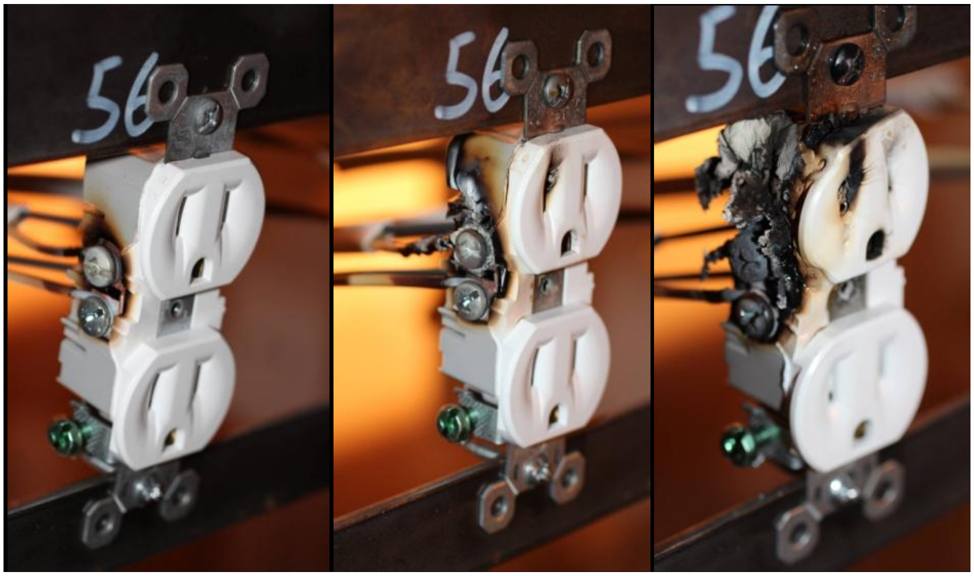


Figure 2-30. Photographs showing melting, sagging, and charring of PVC receptacle (PSE132).

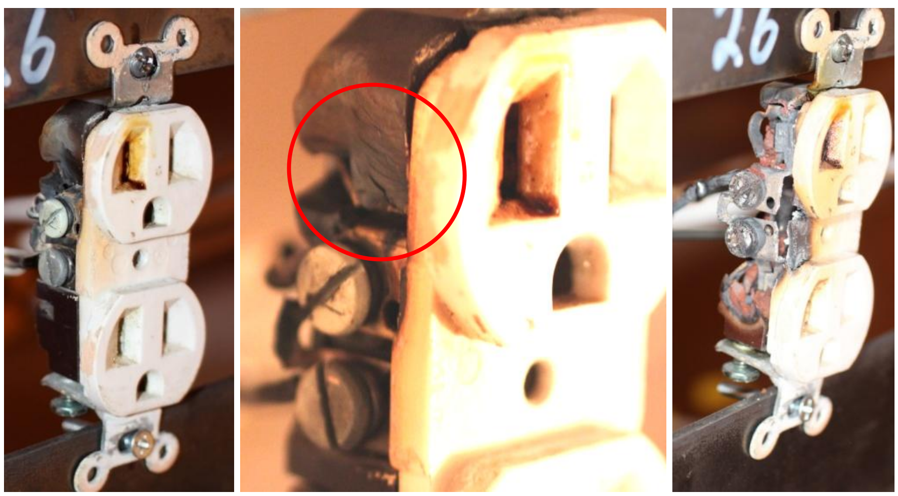


Figure 2-31. Photographs showing cracking and loss of material for a thermoset receptacle (C009).

2.3.3.2 Temperature Rise and Voltage Drop

A portion of receptacles in Test Racks 1 and 2 were instrumented to measure the temperature at the top hot terminal and the voltage drop across the hot terminals. The temperature and voltage measurements and calculation techniques are described in Section 2.1.4. The ambient temperatures in the laboratory test rooms were rather high compared to typical ambient conditions due to the heat generated by the light bulb load banks in the test rooms. The average, maximum, minimum, and standard deviation of the ambient temperatures and relative humidity are shown in Table 2-3 over the majority of the test duration. The ambient temperature and relative humidity fluctuated daily based on a variety of factors including: HVAC operation, AC voltage changes, weather, season, heat from load banks, etc. All temperatures reported herein are as measured (i.e., not temperature rise above ambient).

Table 2-3. Ambient Temperature Data for Laboratory Test Rooms.

Room	Measurement (units)	Minimum	Maximum	Average	Std. Deviation
Room with racks 1 and 2	Temperature (ºC)	22	36	31	2.8
	Humidity (%RH)	0.5	60	24	13.7
Room with racks 3, 4, 5, 6, and 7	Temperature (ºC)	18	40	32	3.6
	Humidity (%RH)	9	53	23	6.3

The maximum temperature, voltage drop, power dissipation are presented in Table 2-4 for selected receptacles having failure events due to overheating. Power dissipation calculations are described in Section 2.1.4. Descriptions of the specific failure events are located in Section 2.3.4. Voltage drop measurements were not taken for three of the receptacles. The temperatures, voltage drops, and power dissipation values in Table 2-4 are taken from the time period just prior to the failure event, usually within a day or two depending on the event. Figure 2-32, Figure 2-33, Figure 2-34, and Figure 2-35 show plots of the voltage drop and temperature measured for the receptacles. For these four receptacles, the temperature measurements were located at the screw terminal that was overheating. It is unlikely that the temperature measurements impacted or contributed to the overheating. In general, the voltage drop and temperature track rather well together: if the temperature rises, so will the voltage drop and vice-versa. This behavior was expected as the overheating connections arise from increases in resistance due to oxidation and corrosion (see Sections 2.3.2.1and 2.3.2.2) and voltage drop is proportional to the resistance (V=IR).

Table 2-4. Maximum Temperature, Voltage Drop, Power Dissipation for Selected Receptacles.

Receptacle S/N	Temp/Voltage Figure	Failure Event	Temperature (ºC)	Voltage Drop (V)	Power Dissipation (W)
PSE024	Figure 36	Conductor Severed, Arc Unknown	769	2.4	36
LEV062*	Figure 37	Flaming Ignition	624	2.1	32
LEV037	Figure 38	Shorted, Hot to Ground	307	0.8	12
LEV035	Figure 44	Conductor Severed, With Arc	510	4.1	62**
LEV010	-	Shorted, Hot to Ground	200	-	-
LEV014	-	Shorted, Hot to Ground	250	-	-
LEV015	-	Shorted, Hot to Ground	120	-	-

*Glowing plug/receptacle connection.
** Impulse in voltage drop when power was cycled on, actual maximum without instantaneous peak was 47W.

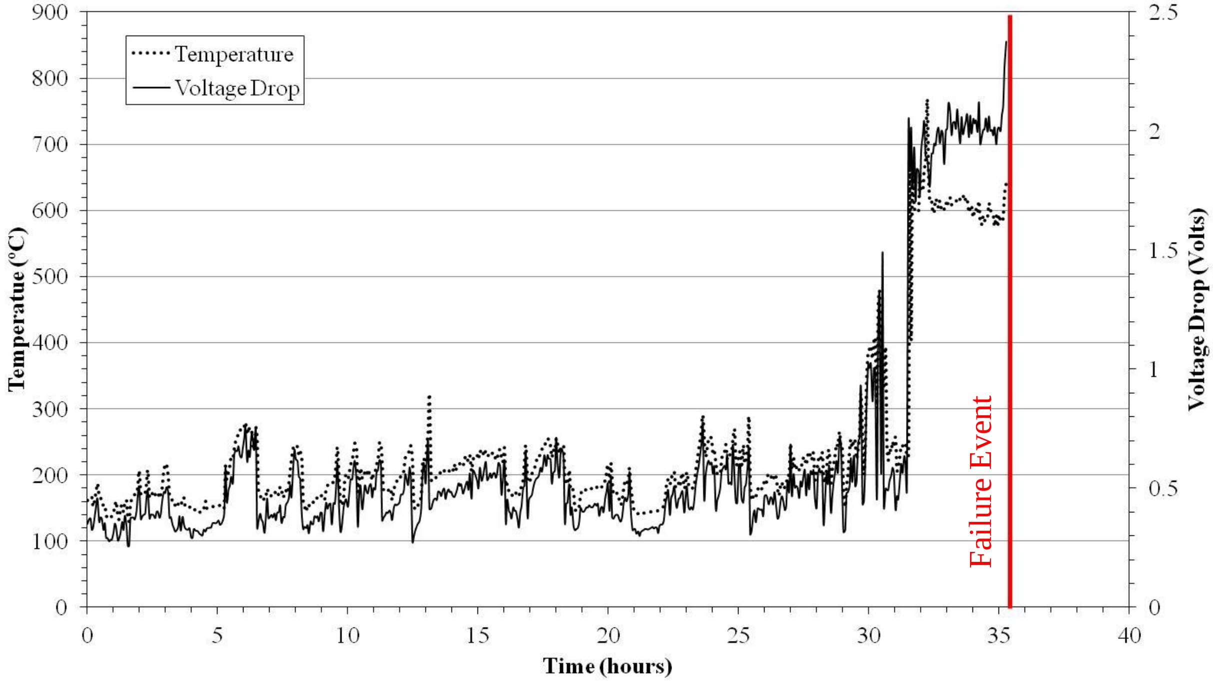


Figure 2-32. Temperature and voltage drop for PSE024 leading to failure event.

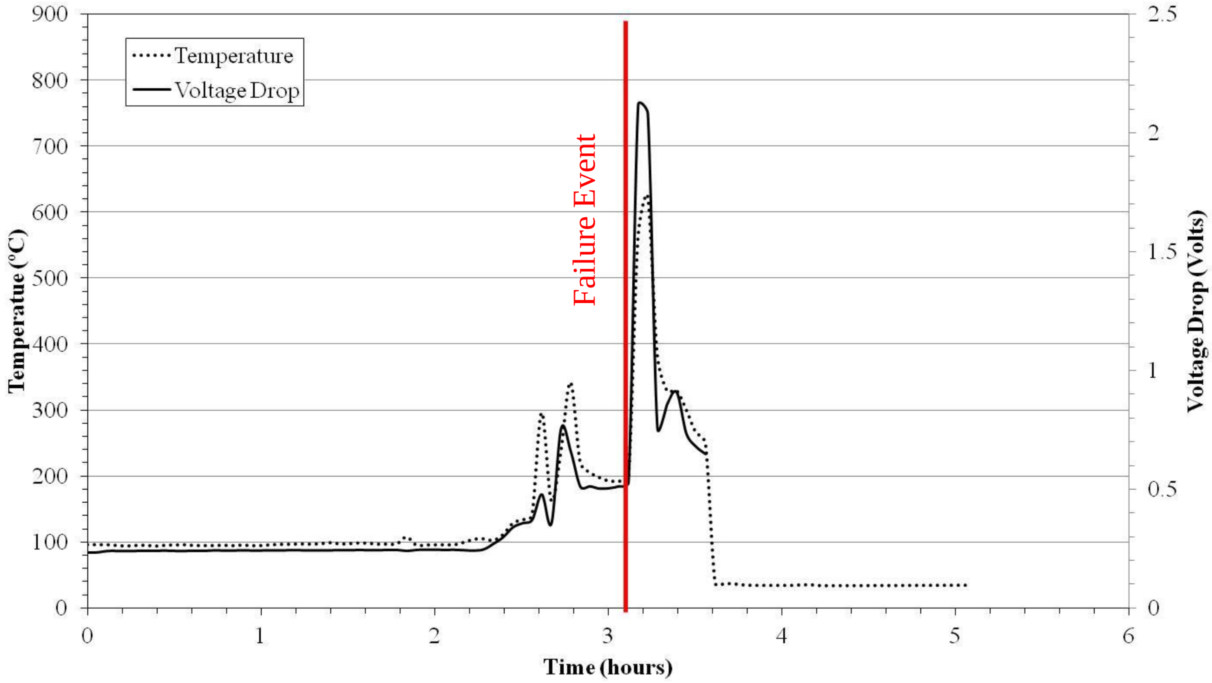


Figure 2-33. Temperature and voltage drop for LEV062 leading to failure event.

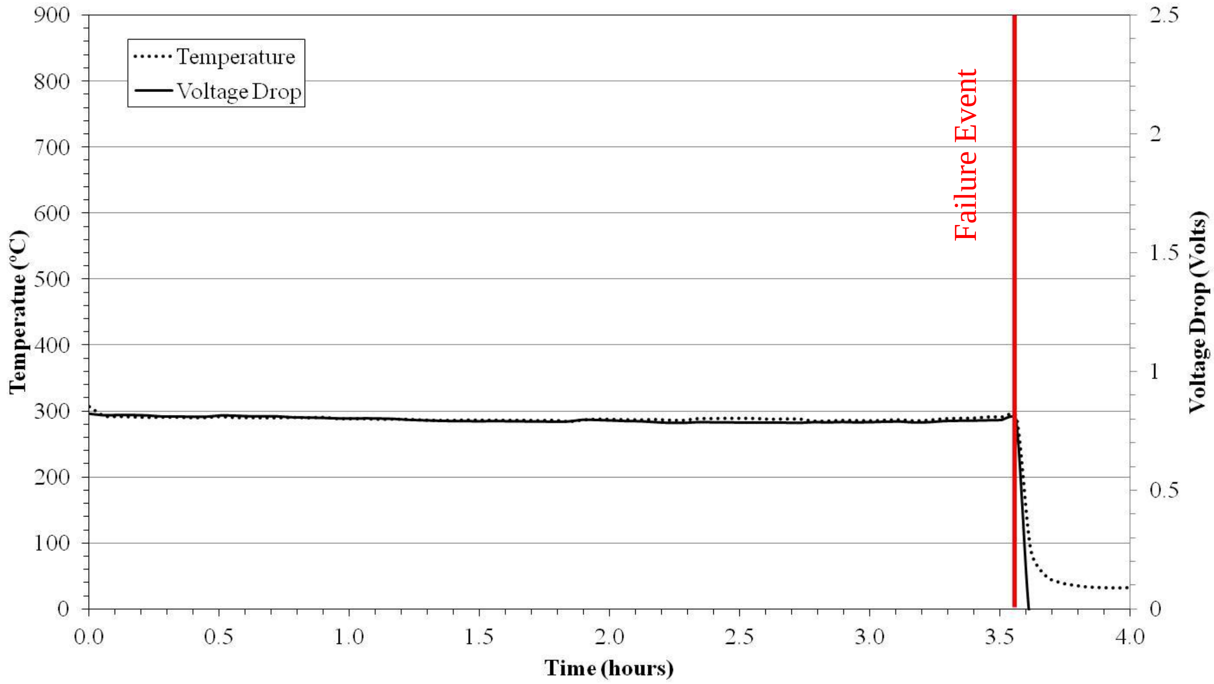


Figure 2-34. Temperature and voltage drop for LEV037 leading to failure event.

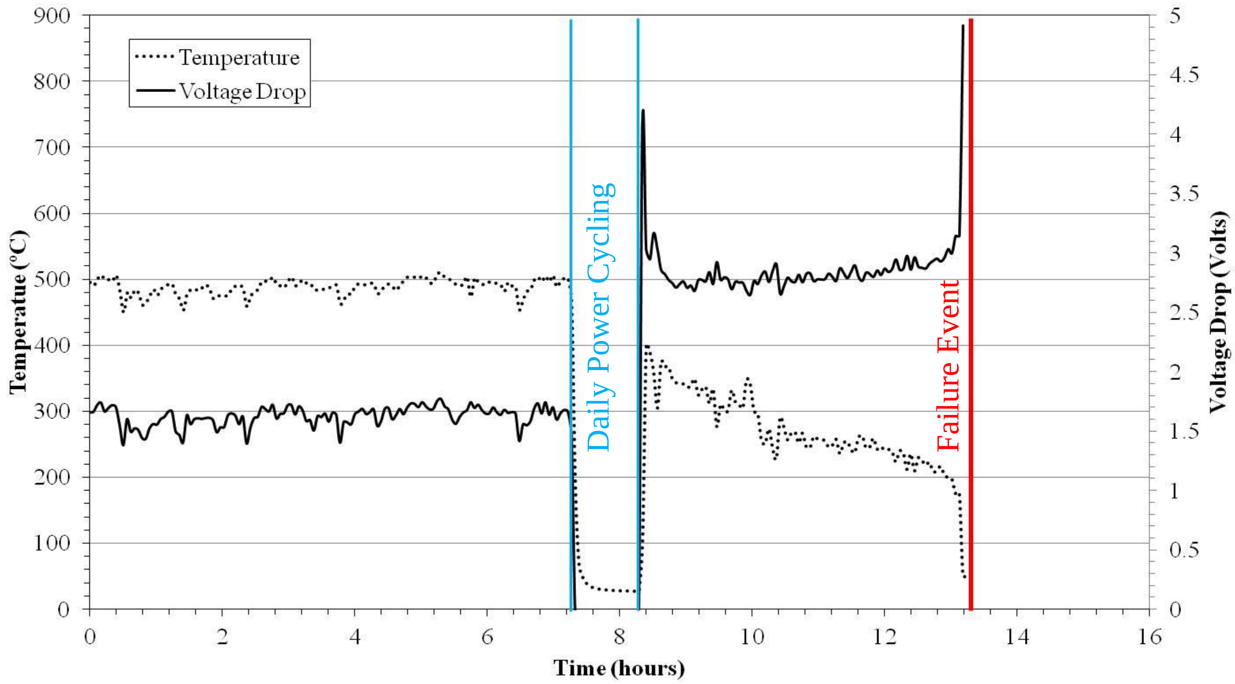


Figure 2-35. Temperature and voltage drop for LEV035 leading to severed conductor failure event.

In the event of a loss of power to the circuit, either from a short circuit activating the circuit breaker (Figure 2-34) or from the daily power cycling (Figure 2-35), temperatures at the terminal connections would return to ambient within a few minutes. This was true for measured terminal temperatures over 500ºC. The receptacle components (i.e., brass, steel, copper) are too thermally conductive to retain any notable heat for an extended duration after current flow (i.e., the source of heat) ceased. However, when the current flow was re-established, the temperature and voltage drop typically returned to the original values (Figure 2-35) within a matter of minutes. In the case of LEV035, the glowing connection re-established after the power was cycled on; and approximately 5 hours later, the conductor severed (i.e., the voltage drop increased). In this case, the decrease in temperature after power cycling is probably indicative of the glow spot moving away from the temperature measurement location. For PSE024, the receptacle failure event occurred over the weekend and there was no evident outside stimulus. The receptacle had been fluctuating between approximately 100ºC and 300ºC for about 30 hours or more and then suddenly experienced a large increase in temperature and voltage drop about 5 hours before the receptacle failure (Figure 2-32). Similar, relatively rapid heating behavior can be seen for two other receptacles (Figure 2-33 and Figure 2-34). The rapid heating of receptacles before the failure events typically took on the order of minutes, while the time spent at the elevated temperature before the failure event was on the order of tens of minutes or hours.

Receptacles PSE024, LEV062, and LEV035 all experienced a glowing connection at the time of their failure. The maximum temperatures (510 to 769°C) are within the range of expected values in the vicinity of a glowing connection. The location of thermocouples did not allow for the direct measurement of the glow spot, especially when the glow spot moved along the conductor. In the case of the plug connection for LEV062, the glow spot was located at the interface of the plug blade and receptacle contacts, while the thermocouple was located at the base of the plug blade, somewhat removed from the glowing area. However, it is important to note that overall, the receptacles having failure events including a glowing connection reached significantly higher temperatures than those just experiencing a hot-to-ground shorting event. At the time of severing of the conductor, the voltage drop would drastically increase because of the open circuit and the temperature would drastically decrease due to the loss of current.

The power dissipations of the three glowing connections in the time period before the failure event were 32, 36 and 47W. This includes two glowing connections at a screw terminal and one for a plug connection. The maximum power dissipation for LEV035 was 62W. However, this value was a momentary increase in the voltage drop at the exact time that the power was cycled on. Often as the power was cycled on, receptacles experiencing overheating would arc at the overheated connections (see Section 2.3.7.3.3). This instantaneous peak is likely related to the arcing phenomena rather than the heat dissipation at the glowing connection, which is why two values are reported.

For a few cases, it was noted that the temperature and voltage drop would oscillate at a rather rapid frequency (see Figure 2-36 and Figure 2-37, respectively). In these cases, the oscillations would take place quicker than data was recorded (i.e., less than 3 minutes) and thus the fluctuations would not be typically captured in detail. However, for a few instances, the temperature data was able to be gathered and analyzed at a quicker rate (about 1 sample per 15 seconds) so the oscillations could be recorded; this data is presented for receptacle LEV038. Receptacle LEV038 did not overheat to a point of failure, but only experienced mild oxidation and very minimal melting at the screw terminal over the entire test. The average peak to peak times for the temperature and voltage measurements over the time period shown in Figure 2-36 and Figure 2-37 were 114 and 121 seconds, respectively. Over this period, the temperature fluctuated between 70 and 110ºC, while voltage drops fluctuated between 0.02 and 0.5 volts.

While the temperatures and voltage drops are not significant compared to those reported for the failure events, the oscillating behavior may lend some insight into the formation and behavior of certain overheating connections. In the case where frequent oscillation of temperatures and voltage drops occur, it is possible that the cyclical heating and cooling is due to thermal expansion and contraction of the wiring combined with oxidation. A flow chart showing this cycle is shown in Figure 2-38.

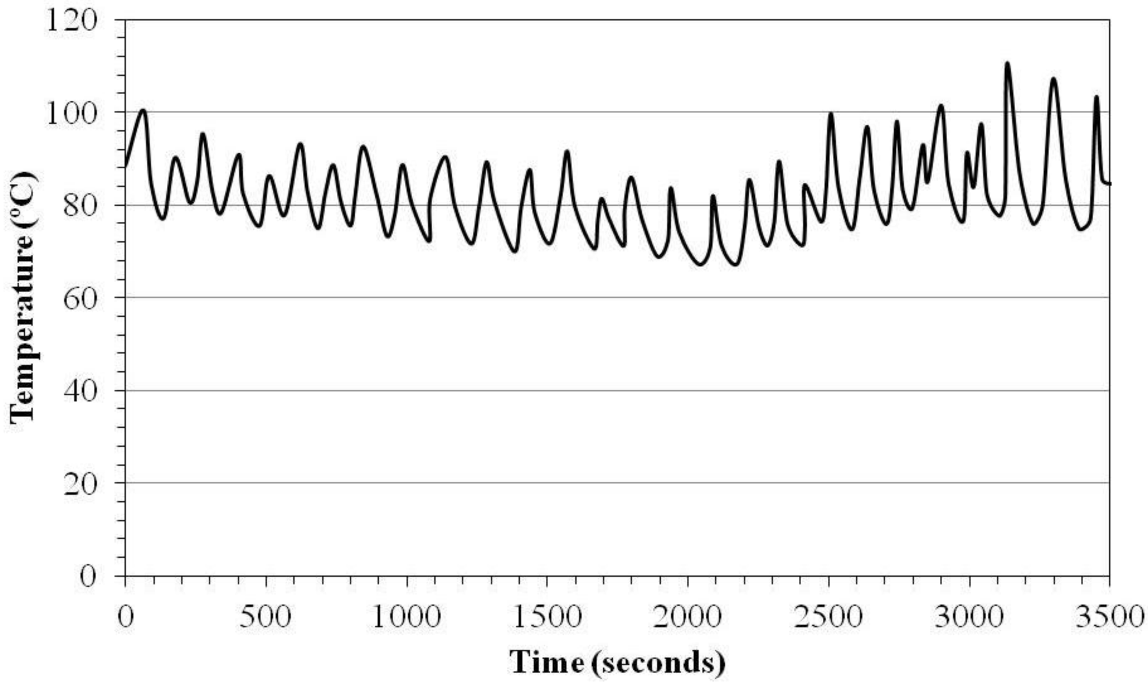


Figure 2-36. Temperature oscillations in receptacle LEV038.

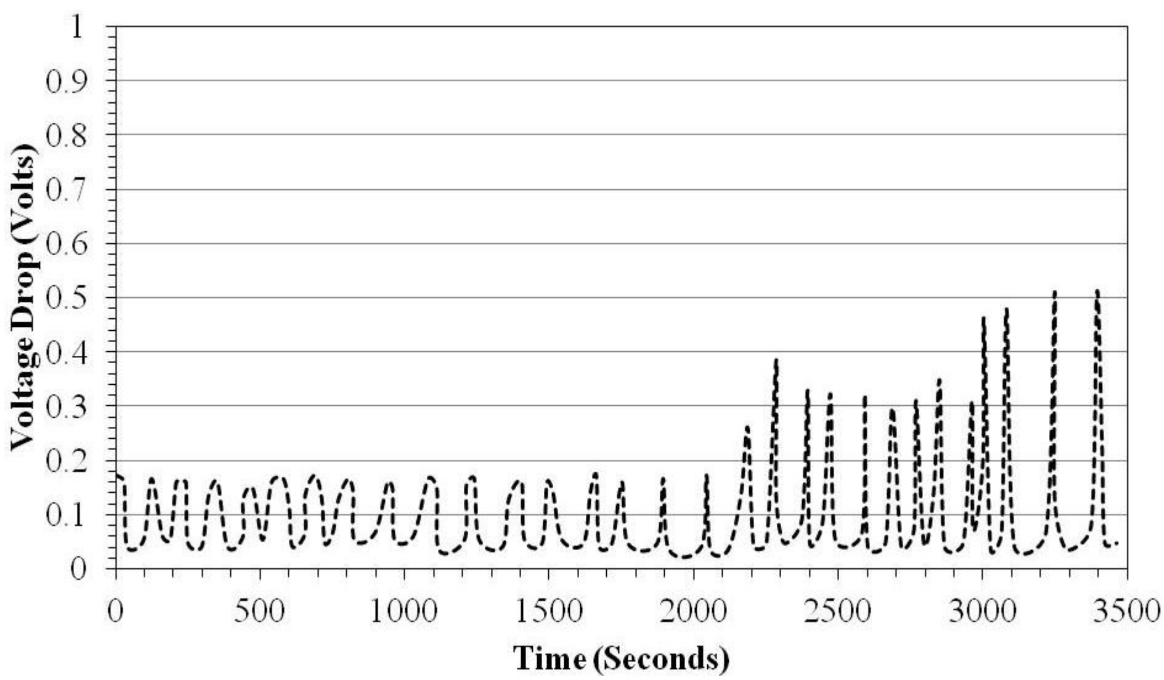


Figure 2-37. Voltage drop oscillations in receptacle LEV038.

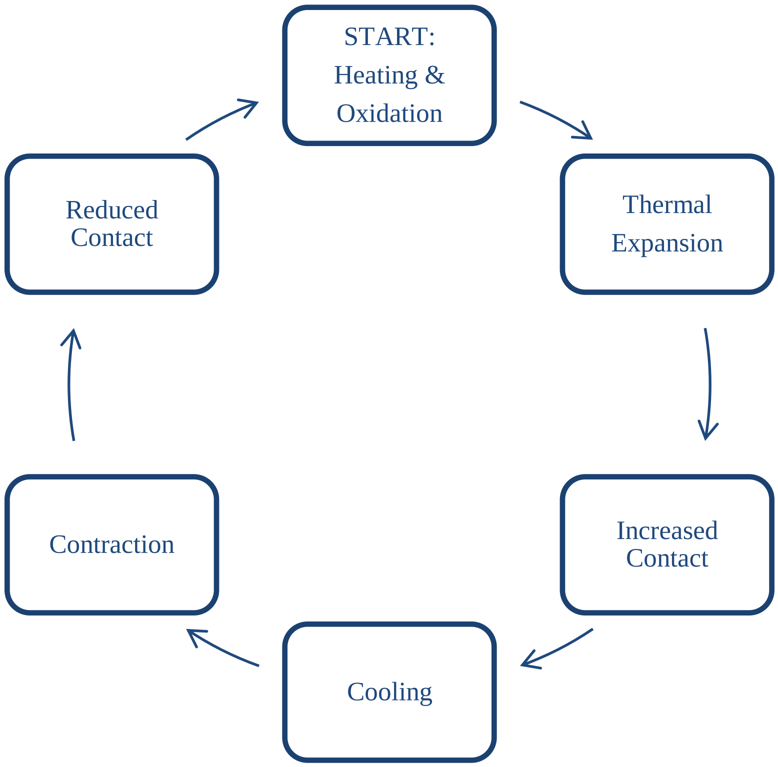


Figure 2-38. Potential heating and cooling cycle for a connection showing frequent oscillations in temperature.

2.3.3.3 Glowing Connections

It is well accepted that oxidation of copper conductors at a loose connection can lead to overheating and potentially glowing at that connection. This oxidation is typically dark grey or black in color. Dark oxidation was observed to have formed on a large portion of receptacles in conjunction with the development of the overheating connections (see Section 2.3.2.1). Discoloration, charring, and melting of the receptacle materials also occurred because of overheating. For cases where glowing was developed at the screw terminal, it took one of two forms. Either a reddish-orange glow of the entire screw terminal and conductor developed (see Figure 2-39) or a bright glow spot at some point along the conductor at the screw terminal developed. In some cases, the glowing transitioned from a localized spot to an overall glow at the terminal or vice-versa. Temperature measurements were taken for some glowing connections using a handheld thermocouple reader and a 1.6 mm (0.0625 inch) diameter Type-K, inconel sheathed exposed bead thermocouple. Temperatures of up to 600ºC and 1100ºC were measured at overall glow and localized glow spots, respectively. Measured temperatures were slightly higher than the melting point of copper (1085ºC) and significantly above that of the brass receptacle contacts (930ºC). Despite local temperatures well above the melting point of brass, none of the cases where the copper conductor melted due to overheating did the brass receptacle contacts show signs of melting. It is expected that the size and arrangement of the internal brass contacts allowed the heat from the glowing conductor to dissipate and remain below the melting temperature.

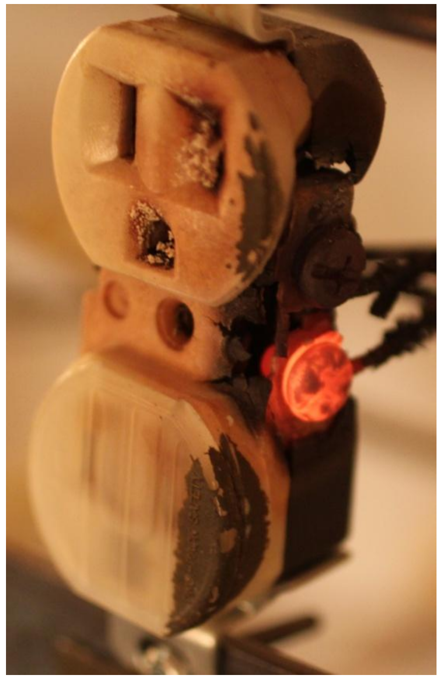


Figure 2-39. Thermoset receptacle with overall glow at ¼ turn loose connection (E010).

Development of the bright glow spots was quite fickle and usually began without any apparent stimulus. In some cases, the bright glow spots would appear with several small arcs as power was cycled for the receptacles, and in other cases, the glow spot would appear seemingly at a random time when the receptacle was energized. Glowing could last for days and often reappeared after an hour or more without power applied to the circuit. In addition, the glow spots sometimes disappeared and re-appeared days later for no apparent reason. When the glow spots remained for extended periods (i.e., hours), the glow spot would tend to migrate in a counterclockwise direction around the screw head, following the conductor. As the glow spot moved, the copper conductor would melt at the spot location and re-solidify (i.e., weld) where the spot was previously (see Figure 2-40). This was very similar to the behavior observed by Korinek et al. [2013]. In almost all cases, this motion (i.e., melting and re-solidifying) created curved striations in the welded copper (see Figure 2-39). The curved striations in the welded conductor, which formed for 26 instances of receptacle failure events (see Table 2-9), are a clear indication that a glowing connection was present. The electrical conductivity of metals is dependent on their temperature; at elevated temperatures, the conductivity decreases. This compounds the increased resistance at a glowing connection due to oxidation.

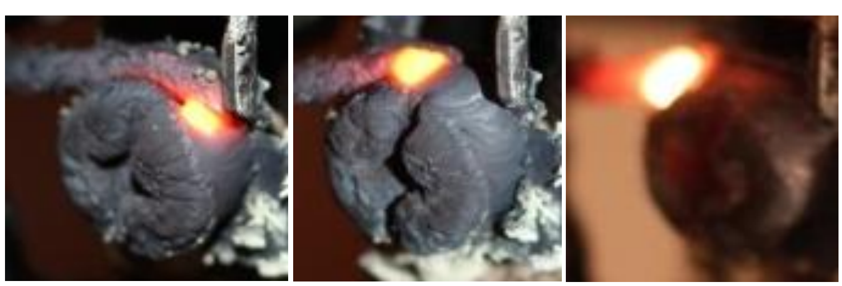


Figure 2-40. Movement of glow spot on receptacle LEV275 at 0 min (left), 164 min (center), and 329 min (right).

Figure 2-41. Curved striations from glow movement on receptacles, receptacle LEV275 (left) and E003 (right).

For all failure events where the conductors severed, a bright glow spot developed at some point along the copper conductor at the loose connection. Once the glow spot had moved to the part of the conductor not underneath the screw head, the conductor would begin to neck (see Figure 2-42) as mechanical forces (weight and tension on the wire) stretched the wire at the glow spot (i.e., where the copper was molten). Korinek et al. [2013] also observed necking, but attributed it to surface tension forces in the molten material. As a result of the necking, the conductors typically severed, sometimes accompanied by a series parting arc. In no cases did the series arcing cause a circuit breaker to trip. The severing of the conductor at the glow spot produced various characteristic ends on the severed conductors (see Section 2.3.5.4).

Figure 2-42. Necking of conductor at glow spot on receptacle LEV277.

Glowing of receptacle connections was not restricted to those at screw terminal connections. In limited cases, glowing was observed at the connection between the internal plug contacts and the plug blade. In Figure 2-43, part of the receptacle had melted, revealing the glowing connection at the interface of the plug blade and receptacle internal contact. The glowing observed at these connections was an overall glow, which did not appear to be focused in one particular spot. It is possible that the materials of the plug blades and internal contacts (i.e., brass) prohibited the formation of significant amounts of semi conductive copper oxides at the contacts. It is principally the copper oxides which cause the bright glow spots to form.

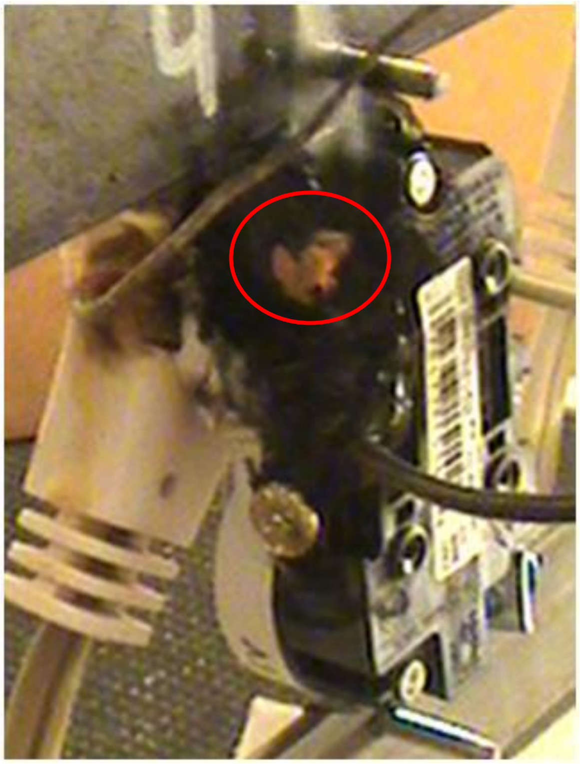


Figure 2-43. Glowing at plug blade and internal plug contact (LEV062).

2.3.3.4 Enlarged Screw Heads

Twenty-eight cases were observed where a heavy layer of corrosion was developed on the screw terminals of receptacles with failure events (see Table 2-10). This was termed an enlarged screw head (see Figure 2-44, right). The enlarged screw heads are characterized by a swollen appearance with narrowed screw slots due to the buildup of corrosion products. The enlarged screw heads had a black, grey, or reddish color, and fine surface porosity though the surface was relatively smooth. In these cases, rather than a dark oxidation of the copper conductor causing the overheating at the terminal, a layer of white corrosion was deposited on the conductor at some point during the testing (see Figure 2-44, left). This was quite common for the PVC receptacles, and twenty-eight cases were observed where the white corrosion developed into the enlarged screw head condition. Examination with a Scanning Electron Microscope (SEM) equipped with Energy-dispersive X-ray Spectroscopy (EDS) revealed that this corrosion was primarily chlorine, likely coming from the PVC. In one case where the enlarged screw head developed, after approximately 145 days of testing, it was observed that a crystalline deposit was formed on the conductor (see Figure 2-44, center). Over the course of approximately 29 hours, the initial chlorine corrosion developed into a crystalline deposit and then corroded the screw head ultimately leading to an overheating event and failure of the receptacle. Unfortunately, it was not possible to determine whether this specific series of events occurred for the other cases where an enlarged screw head was found. However, the enlarged screw heads appeared to be similar (see Section 2.3.5.3) and are a clear indication that a glowing connection and chlorine corrosion were present.

Figure 2-44. Development of enlarged screw head on receptacle PSE170 at T = 0 hours (left), T = 21.6 hours (center) and T = 29.2 hours (right).

2.3.4 Receptacle and Plug Failures

Some of the overheating connections led to a failure event in the plug and/or receptacle. A failure event is defined as an overheating connection accompanied by the evolution of smoke, flame, electrical arcing, and/or a glowing connection resulting in an electrical failure of the receptacle or plug. These events were allowed to progress without interference from test personnel. Often, the events occurred at times of the day when no event personnel were present. Examination of surveillance video footage of the failure events revealed their progression. After the events, the receptacles were removed from the test circuit and forensically documented. The various overheating events included:

- Conductor severed with accompanying arc
- Conductor severed without accompanying arc
- Conductor severed; arc unknown
- Shorting – hot to ground
- Shorting – neutral to ground
- Shorting – hot to neutral
- Flaming ignition
- Series arcing at screw terminal

There was some overlap in the failure events. For instance, some, such as flaming ignition, could also have had a shorting event or a severed conductor. In cases where multiple failure events were present, the precedence in terms of classification for analysis purposes was as follows flaming ignition > severed conductors > shorting. Each receptacle failure was classified as a single event. As was documented in Section 2.3.3.3, glowing connections could move around the screw connection to a point where necking of the conductor began. Eventually, the necking would progress to a point whereby the wire was severed. Severing of the wire was sometimes accompanied by an arc as the two sides of the wire separated. As the conductor severed, current flow generally ceased, but in only one case was a circuit breaker tripped. For this case (LEV013), the bottom hot conductor was severed and the physical forces on the remaining wire caused the internal brass conductor to come into contact with and short to the receptacle grounding strap. In the arc unknown cases, surveillance video was not available at the time of failure. Shorting of a hot conductor to ground conductor was always accompanied by circuit breaker activation in this test series. Shorting of the neutral conductor to the ground was not. A neutral to ground short does not usually present a significant hazard provided the ground conductor is appropriately sized, installed, and maintained. However, in the daisy-chain configuration tested, a neutral to ground short would cause an unintentional flow of electricity through the ground such that some of the receptacles were bypassed.

A summary of the failure events and the minimum, maximum, average, and standard deviations of the time to the event are shown in Table 2-5. The time to an event was calculated as the number of days between when the receptacles were initially energized until the day when they were removed from the test rack.

Table 2-5. Summary of Time to Receptacle/Plug Failure Events.

Failure Event	Number of Failure Events	Min. Time to Event (days)	Max. Time to Event (days)	Avg. Time to Event (days)	Std. Dev. of Time to Event (days)
Conductor Severed, w/ Arc	12	62	225	142	56
Conductor Severed, w/o Arc	16[A]	19	311	131	90
Conductor Severed, Arc Unknown	16[B]	21	326	239	83
Shorted, Hot to Ground	15	5	365	135	97
Shorted, Neutral to Ground	12	14	324	113	125
Shorted, Hot to Neutral	1	342	342	342	-
Flaming Ignition	17	18	341	186	108
Series Arcing-Open Circuit	1	56	56	56	-
All	**90**	**5**	**365**	**161**	**104**

A – One receptacle failed with current of 9A.
B – Time to failure unknown for one receptacle (PSE164).

The time to the failure events covered a large range, from 5 days to 365 days with an average time to failure of 161 days. At first glance, it appears that the neutral to ground shorting events occurred quicker, on average, than the other failure events. However, the mechanics of the neutral to ground and hot to ground shorting events are very similar, if not exactly the same (i.e., heat causes plastic to melt, causing contacts to move and short to the grounding strap). Therefore, one would assume that their time to failures would be similar. There do not seem to be any other obvious trends in the data which would suggest that any one failure event was more likely to occur quicker or slower than another. It should be noted, though, that the data presented in Table 2-5 encompasses all test variables including terminal tightness, plug and receptacle connections, etc. Analysis of the impact of individual variables will be discussed in subsequent sections. The large range of times to failures has two significant results. First, the quickest time to failure (5 days) is a rather short span of time in the expected life of a receptacle, which is about a few decades. This implies that a specific receptacle failure could be tied to a certain event (i.e., receptacle modification, installation, load addition, etc.). On the other hand, the longest time to failure of 365 days is noteworthy in that it suggests that failure events can be quite removed from the initial installation or modification, especially considering the receptacle and/or plug may have duty cycles well below the test specimens.

2.3.4.1 Flaming Ignition

Flaming ignition of receptacles and plugs has occurred in seventeen instances (see Table 2-6); that is, approximately 0.04 failures/year. These events are the most significant in that they demonstrate the ability of overheating receptacles to develop into potentially competent ignition sources. Flaming ignition occurred for ten receptacles constructed of polypropylene; four with plugs and six without plugs; four installed with PVC outlet boxes and nylon faceplates and six not installed with outlet boxes and faceplates. Flaming ignition occurred for seven receptacles constructed of PVC; one with a plug and six without plugs; two installed with a PVC outlet box and nylon faceplate and five not installed with outlet boxes and faceplates. Flaming ignition occurred for one PVC receptacle with a back-wired connection. Flaming ignition did not occur for receptacles constructed of thermosets. However, thermoset receptacles were not tested with outlet boxes and faceplates nor were they tested with plug connections. These numbers point out that the plastic receptacle body material appears to play a role in the likelihood of flaming ignition. The polypropylene receptacles were slightly more likely to have flaming ignition events during testing (0.05 failures/year) than the PVC receptacles (0.03 failures/year). In addition, it should be noted that the only failure events for receptacles with plug connections were flaming ignition events.

Table 2-6. Summary of Flaming Ignition Events. Note: All Receptacles at 15A.

Receptacle S/N	Receptacle Material	Terminal Torque (in-lb)	Number of Removal and Re-Insertion Cycles	Type of Plug	Plug Nominal Retention Force (kg)	Days to Failure	Duration of Flaming (sec)	Max. Flame Height (inches)	Flaming Location
LEV275	Polypropylene	¼ Turn Loose	N/A	N/A	N/A	18	15	3	Back
LEV173[A]	Polypropylene	¼ Turn Loose	N/A	N/A	N/A	39	[D]	[D]	[D]
LEV269[A]	Polypropylene	¼ Turn Loose	N/A	N/A	N/A	48	234[B]	8	Front/Back
PSE166[A]	PVC	¼ Turn Loose	N/A	N/A	N/A	193	100[B]	10	Front/Back
LEV265[A]	Polypropylene	¼ Turn loose	N/A	N/A	N/A	213	154	6	Front
PSE165[A]	PVC	¼ Turn Loose	N/A	N/A	N/A	227	4	4	Front/Back
LEV023	Polypropylene	1	N/A	N/A	N/A	240	30	4	Back
PSE175	PVC	¼ Turn Loose	N/A	N/A	N/A	255	28	8	Front/Back
LEV266[A]	Polypropylene	¼ Turn Loose	N/A	N/A	N/A	279	376	4	Front
PSE174	PVC	¼ Turn Loose	N/A	N/A	N/A	305	5	4	Back
PSE176	PVC	¼ Turn Loose	N/A	N/A	N/A	318	[D]	[D]	[D]
PSE111	PVC	N/A	1	N/A	N/A	341	[D]	[D]	[D]
LEV062[C]	Polypropylene	N/A	N/A	Solid-Plated	0.01	62	[D]	[D]	[D]
PSE285[C]	PVC	N/A	N/A	Solid-Plated	0.01	110	62[B]	12	Front/Back
LEV286[C]	Polypropylene	N/A	N/A	Solid-Plated	0.01	183	120[B]	24	Front/Back
LEV063[C]	Polypropylene	N/A	N/A	Solid-Plated	0.01	268	8	2	Back
LEV060[C]	Polypropylene	N/A	N/A	Solid-Plated	0.1	62	150	4	Front/Back

[A]- Installed in outlet box with faceplate.
[B]- Maximum flame height during approximately the first 10% of the total event duration.
[C]- Plug connections.
[D]- Flaming ignition event not captured on video.

A Consumer Product Safety Commission (CPSC) meeting in 1995 discussed the increasing use of thermoplastics (e.g., PVC, polypropylene) over ceramics and thermosets (e.g., phenolics and urea formaldehyde) in electrical devices such as receptacles [Edwards, 1995]. Mr. Krawiec, of CPSC, indicated that thermoplastic materials are much more likely to lose their structural integrity at elevated temperatures than thermosetting materials used before. Mr. Krawiec also stated that the effect of this behavior would lead to low-level failures that may result in catastrophic failure. The predictions of Mr. Krawiec at this meeting are very close to what was observed in this test program, where the overheating (i.e., low-level failure) leads to flaming ignition (i.e., catastrophic failure) in receptacles constructed of thermoplastics but not for receptacles constructed of thermosets. Even though flaming ignition events were rare in this test series, there is no doubt that receptacles constructed of thermosets are inherently safer from an ignition perspective.

Although the loosest connections (i.e., ¼ turn loose and 0.01 kg) formed the majority of flaming ignition events (14 out of 17), other factors, such as material properties and configuration (i.e., outlet box, faceplate, etc.), may have influenced the development of a heated connection to a flaming event more than the difference between torque conditions. Developing an overheated connection is dependent on the looseness of the connection; however, once it is established, the transition to flaming is likely governed by other variables.

The flaming ignition events were very diverse in terms of the duration, size, and location of the flames. Table 2-6 and Table 2-7 summarize the key data for the flaming ignition events. In four cases, the video surveillance system did not capture the flaming ignition event. Flaming ignition was determined based on visual indicators of flaming (i.e., soot, charring of the receptacle and/or adjacent receptacles) or in-person observation of flaming. The duration of flaming ignition events ranged from as little as 4 seconds to over 6 minutes. In all cases, the receptacles and plugs self-extinguished and did not spread to adjacent receptacles. Maximum flame heights ranged from 2 inches to 24 inches. Often, for the larger flame heights (i.e., greater than or equal to 8 inches), the flames were largest during 10% or so of the total event duration, and diminished quite drastically for the rest of the event. In the case of the smaller flaming events, flame heights were more consistent throughout the duration of the event. Figure 2-45 and Figure 2-46 show two examples of flaming ignition events.

Table 2-7. Summary of Evidence of Overheating and Glowing in Receptacles with Flaming Ignition Events.

Receptacle S/N	Tripped Circuit Breaker?	Arc Location?	Welded Conductor? Curved Striations?	Enlarged Screw Head?	Severed Conductor End (Wire)	Severed Conductor End (Screw)	Notes
LEV275	No	None apparent.	Yes/Yes	No	Round	Irregular	Flaming droplets.
LEV173	No	Between top and bottom hot wires.	Yes (2)/Yes (2)	No	2 x Round	2 x Round	No video.
LEV269	Yes	Arcing in wiring – multiple locations.	Yes (2)/Yes (2)	No	Various Beads From Arcing	N/A	Flaming droplets.
PSE166	No	Large arcing location. Multiple arcs likely between ground strap and hot plug contacts.	No	No	N/A	N/A	Flaming faceplate fell off. Ejected copper.
LEV265	No	Between hot plug contact and ground strap.	Yes/Yes	No	N/A	N/A	Flaming droplets.
PSE165	No	Between hot plug contact and ground strap.	Yes (2)/No (2)	Yes (3)	2 x Irregular	2 x Irregular	-
LEV023	No	None apparent.	No	No	N/A	N/A	-
PSE175	No	Between hot plug contact and ground strap.	Yes (2)/No (2)	Yes	2 x Irregular; 1 round from arcing	2 x Irregular; 1 round from arcing	Flaming droplets.
LEV266	No	Between hot plug contact and ground strap.	No	No	Irregular	Irregular	Flaming droplets.
PSE174	No	None apparent.	Yes/No	Yes	Irregular	Irregular	-
PSE176	No	None apparent.	Yes/No	Yes	Irregular	Irregular	No video.
PSE111	No	Series arcing at neutral wire-terminal interface.	N/A	N/A	N/A	N/A	No video.
LEV062	No	Between hot plug blade and hot internal plug contact.	N/A	N/A	N/A	N/A	No video. Flaming observed in-person.
PSE285	Yes	Between hot plug blade and ground strap.	N/A	N/A	N/A	N/A	Paper tag from plug above burned.
LEV286	No	At base of ground pin.	N/A	N/A	N/A	N/A	Initiated by high startup current activation. Ejected material that charred paper.
LEV063	Yes	Between hot plug contact and ground strap.	N/A	N/A	N/A	N/A	-
LEV060	No	Between hot plug blade and hot internal plug contact.	N/A	N/A	N/A	N/A	-

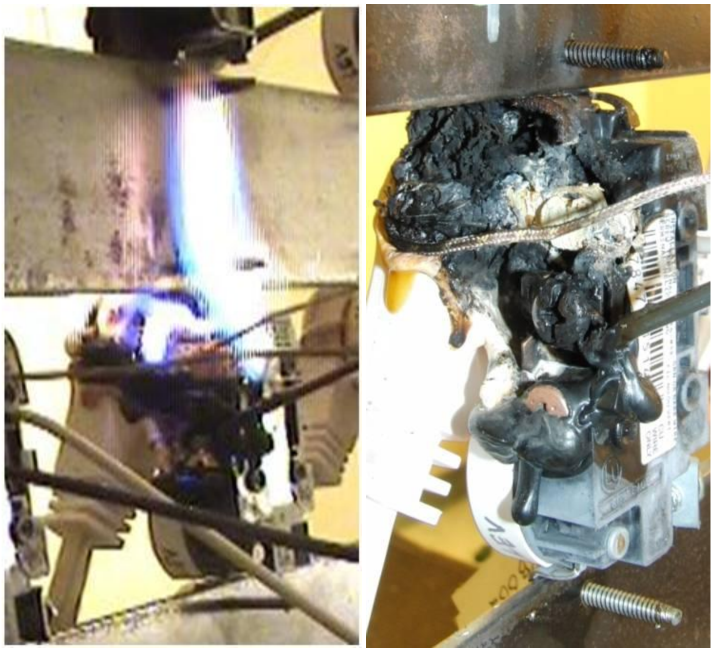


Figure 2-45. Flaming ignition in a receptacle with plug (left) and resulting damage (right).

Figure 2-46. Flaming ignition of receptacle in box (before ignition (left) and 21 seconds after ignition (right)).

Evidence of arcing was observed in 13 out of the 17 receptacles with flaming ignition failure events. Four receptacles did not show signs of arcing upon inspection. From video examination, the polypropylene receptacle LEV275 had a glowing connection which severed with an accompanying arc that caused ignition. This would explain why, aside from the severed conductor, no parallel arcing or series arcing evidence was found. There is some discussion of the severed conductor ends in Section 2.3.5.4. LEV023 did not have a severed conductor, but limited arcing was observed from the video examination. It is likely that this arcing was series arcing between the wire and the screw terminal. Two receptacles (PSE174 and PSE176) had evidence of melting of the brass plug contacts which may have destroyed evidence of arcing. Arcing and sparks were observed in the video for PSE174; there was no video captured for PSE176, but the melting observed was on the neutral plug contacts so any arcing which may have occurred would have been series arcing between the receptacle contact and the grounding strap. Series arcing between two hot conductors was observed in 3 of 13 receptacles having arcing evidence. Two receptacles were with plug connections (LEV060 and LEV062) and one with loose screw terminal connections (LEV173). Series arcing will not trip circuit breakers (see Section 1.1.2).

Ten of the 13 receptacles exhibiting arcing evidence had parallel arcs occur between the hot conductor and the ground conductor (see Table 2-7). Of these ten, only three tripped the circuit breaker during the course of the flaming ignition event. Parallel arcing that occurred in receptacles experiencing flaming ignition failures tended to occur for extended periods (i.e., more than a momentary, single arc) whether or not they ended up tripping the circuit breaker. The extended arcing tended to create arcing damage that was over a larger area than a single arc (see Figure 2-47). A possible explanation for this is that the flames from the fire produce relatively rapid melting of the receptacle from multiple sides, whereas melting from overheating is localized to the overheating connection. The rapid rate of melting (i.e., seconds for flaming vs. minutes/hours for overheating) would cause more freedom of movement in the internal plug contacts, allowing them to arc and potentially clear the arc before circuit protection activates. The slower melting rate and localized melting from overheating connections, on the other hand, would not allow the contacts to move as freely and quickly, thus creating a firmer contact when shorting occurs.

Some of the receptacles had evidence of glowing connections in addition to arcing. Eight out of 11 receptacles with loose side-wired connections had 11 welded conductors; six welded conductors had curved striations; and four receptacles had multiple welded conductors. It is unclear whether the severing of the conductors at the glow spots occurred as a result of the flaming ignition or contributed to the ignition itself. Four of the five side-wired PVC receptacles with loose connections having flaming ignition were observed with enlarged screw heads; one had three enlarged screw heads.

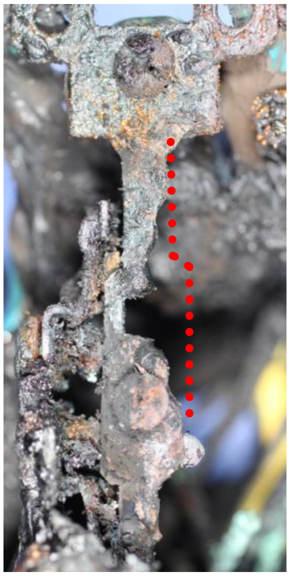


Figure 2-47. Arcing to grounding strap from internal hot brass contact (not pictured) during flaming ignition event (PSE166).

Six receptacles had melting plastic drip while flaming. PSE166 had most of the faceplate fall to the ground burning (see Figure 2-48), but it is unclear whether the faceplate continued to burn while on the floor as this is out of the video frame. Because the faceplate is constructed of Nylon, it is unlikely that it burned for very long while on the ground as these faceplates tend to self-extinguish without the application of an external flame. LEV269 had a flaming droplet, likely plastic from the faceplate, fall about 6 inches to the receptacle below and sustain flaming for about 5 seconds before it self-extinguished (see Figure 2-49). The receptacle below LEV269 did not ignite as a result of the flaming droplet. The other receptacles with flaming droplets behaved similar to LEV269. The PVC outlet boxes did appear to contribute to the size and duration of the flaming events.

Figure 2-48. Flaming faceplate drops to ground (PSE166).

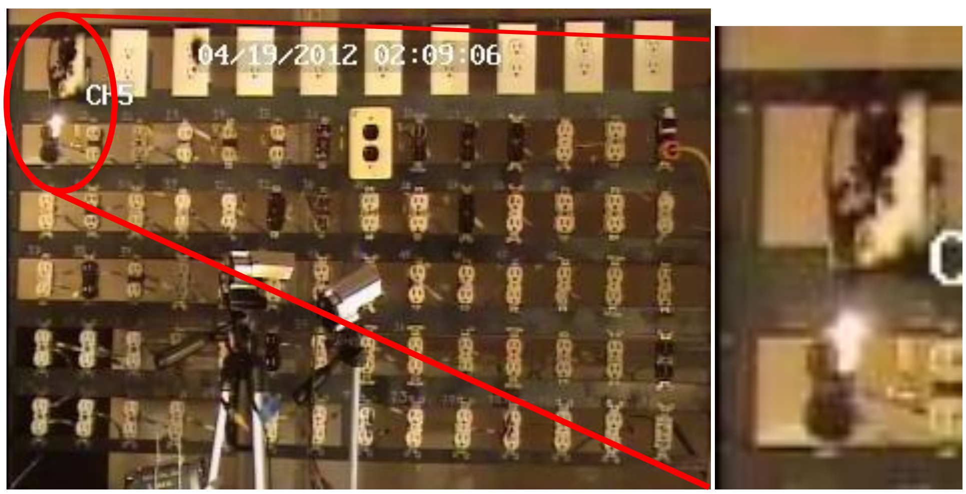


Figure 2-49. Flaming droplet falls to receptacle below (LEV269).

Ejected copper material was observed for two cases of flaming ignition. Flaming ignition of receptacle LEV286 with a solid blade, nickel plated grounding plug was initiated as the high startup current source was energized (see Section 2.3.7.3.3). This caused a large amount of flaming, smoke, and ejected material as shown in Figure 2-50 for a period of a few seconds before subsiding to a steadier, smaller flame. A globule of ejected copper from this receptacle and plug traveled about 3 feet to a horizontal piece of paper on a table where it flattened and charred, but did not ignite the paper (see Figure 2-51). The approximate diameter of the flattened globule was 1.22 mm (0.048 inches). The flaming ignition of receptacle PSE166 produced some molten copper which ejected and landed on a vertical piece of the steel support structure (see Figure 2-52). The ejected copper was in the shape of a bead (diameter = 2.2 mm (0.085 inches)) with a flat, tail-like spatter structure extending about 3.8 cm (1.5 inches).

Figure 2-50. Flaming ignition of plug/receptacle with ejected material (LEV286).

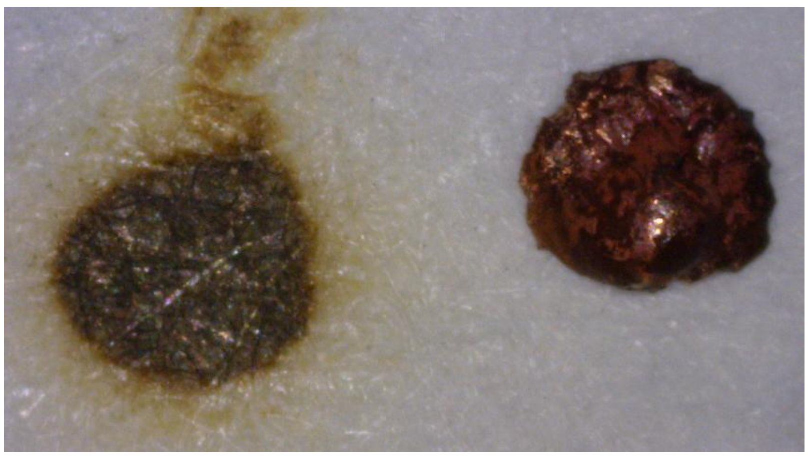


Figure 2-51. Ejected copper and charred paper (LEV286).

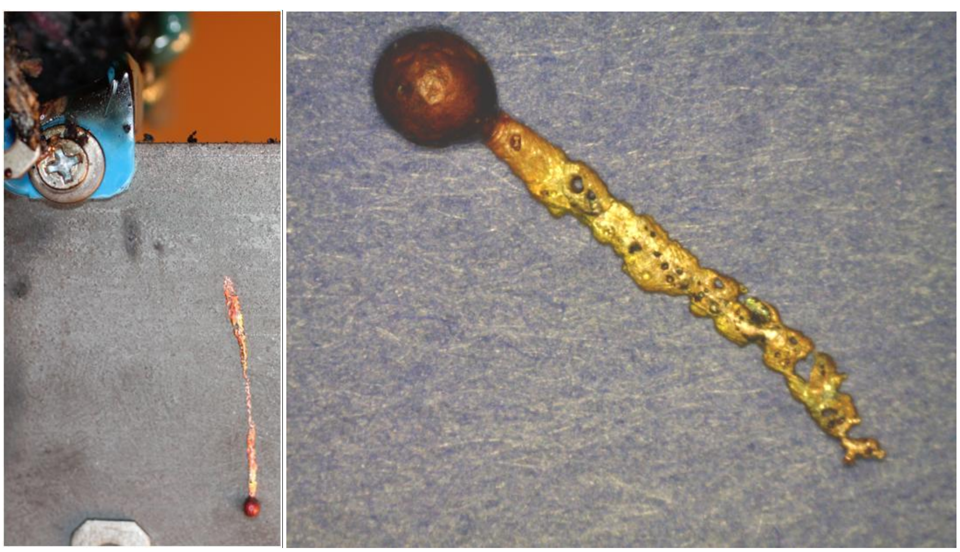


Figure 2-52. Ejected particle landed on steel support structure (PSE166).

Even though the receptacles were installed approximately 7.5 cm (3.0 inches) vertically from each other, in no cases did adjacent receptacles become involved due to the flaming ignition events. This is attributed to both the relative brevity of the events and the self-extinguishing nature of the plastic materials. In addition, most of the longer duration, larger fires were at the top row of the test racks with nothing above them. However, it is likely that most of the cases where flaming ignition occurred could have led to ignition of a range of proximate materials. For receptacles that were not installed in outlet boxes with faceplates, it is unclear what affects the additional items would have had on the flaming ignition event. Presumably, the confinement of heat by the enclosure would have exacerbated the flaming ignition.

2.3.5 Evidence of Failure Events at Screw Connections

The subsequent sections will discuss the physical (visual) evidence produced as a result of receptacle failure events. The physical evidence produced as a result of plug failure events will be discussed in Section 2.3.6. After each receptacle failure event, the receptacle was visually inspected to determine the presence of arcing, welded conductors (from glowing), enlarged screw heads, parting of conductors, thinned wiring, and pitted wiring. In addition, a portable X-ray machine was used to examine selected receptacles.

2.3.5.1 Arcing

Arcing was determined by visual inspection of the receptacle contacts, grounding strap, and wiring. Arcing was identified in cases where one or more of the following characteristics were observed:

- Localized damage with a sharp line of demarcation around the damaged area;
- Corresponding damage on the opposing conductor;
- Resolidification waves;
- Copper drawing lines or metal edges and lettering visible outside the damaged area;
- Spatter deposits;
- Small beads or globules near arc area;
- Notches in metal components;
- Multiple divots, arc spots; and
- Transfer of metal between conductors.

The arcing damage from receptacle failures was examined for the presence of the proposed NFPA 921 [2014] characteristics of arcing and melting; see Section 4.0 for results and discussion. In the cases where visual observation was not possible, a portable X-ray machine was used to first check for arcing in the internal contacts. This was conducted for receptacles where the internal contacts were blocked from view by the intact plastic receptacle body. The X-rays were able to show, in some cases, where notches from arcing were created (see Figure 2-53). In other cases, the X-ray showed apparent contact between the internal plug contacts and the grounding strap, but no indication of a notch or bead (see Figure 2-54). After X-rays and additional photographs were taken, the receptacles were cut apart using hand tools to inspect the internal contacts and grounding strap for evidence of arcing. Though destructive, cutting apart the receptacles allowed visual inspection of the conductors to determine whether arcing was present for receptacles where apparent contact in the x-ray did not show an obvious notch. After disassembly, the receptacle in Figure 2-54 (LEV129) did not visually show evidence of arcing between the neutral contacts and the grounding strap. Table 2-8 contains a summary of the arcing evidence observed on receptacles and the quantity of receptacle failure events that tripped a circuit breaker. It should be noted that the severed conductors were sometimes accompanied by an arc at the time the conductor severed. The arcing evidence presented in Table 2-8 is related to the arcing between two conductors that occurred in receptacles and not the arcs that occurred at the time the conductors were severed. Arcing in failure events for plug connections are not included in Table 2-8, but can be found in Table 2-15.

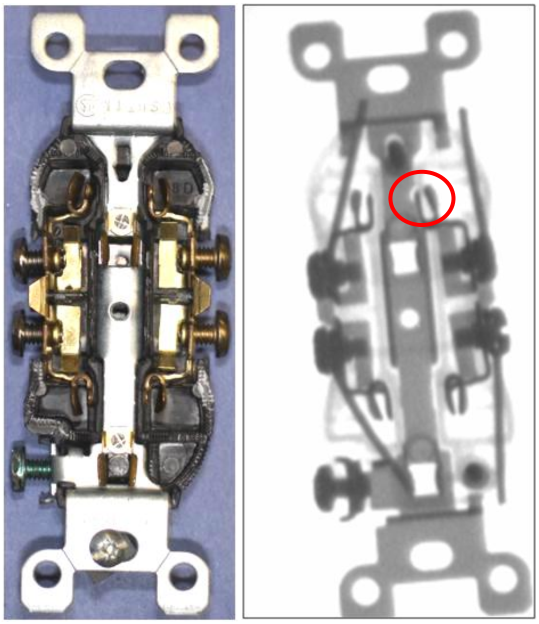


Figure 2-53. Exemplar receptacle and X-ray of arcing between hot contact and grounding strap, notch in grounding strap (LEV126).

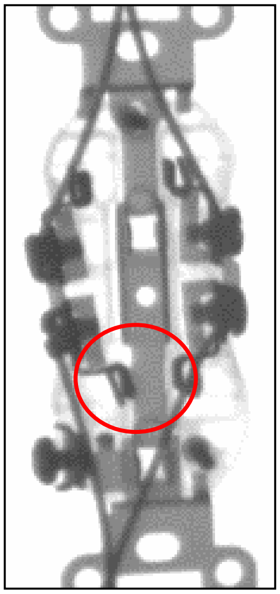


Figure 2-54. X-ray showing apparent contact between neutral terminal and grounding strap (LEV129).

Table 2-8. Summary of Arcing Evidence Found in Receptacle Failures (Plug Failure Events Not Included).

Failure Event	Number of Failure Events	Qty. That Tripped Breaker	Qty. with Arcing
Conductor Severed, w/ Arc	12	1	1
Conductor Severed, w/o Arc	16	0	2
Conductor Severed, Arc Unknown	16	0	1
Shorted, Hot to Ground	15	15	15
Shorted, Neutral to Ground	12	0	5
Shorted, Hot to Neutral	1	0	1
Flaming Ignition[A]	12	3	8
Series Arcing-Open Circuit	1	0	1
All	**85**	**19**	**34**

A – See Table 2-7 for description of arc locations

In only four of the 44 failure events where the conductors were severed at the glow spot did a receptacle exhibit arcing evidence; only one of four tripped the circuit breaker. In one instance, video surveillance of receptacle LEV013 revealed that while the connection was glowing, two arcs occurred within 1 second of each other. Immediately after the arcs, the glow appeared to diminish. It was unclear which event, arcing or conductor severing, occurred first or whether they occurred at the same time. For LEV013, a photograph of the internal hot contacts is shown in Figure 2-55, and the grounding strap is shown in Figure 2-56. All of the shorting events where the hot and ground conductors came into contact tripped the circuit breaker and produced identifiable arcing evidence.

Parallel arcing events (i.e., hot to ground or hot to neutral) tend to produce very large fault currents and the magnetic mechanisms in circuit breakers are designed to interrupt these currents very rapidly. On the other hand, shorting of the neutral conductor to the ground conductor does not produce an increased current because both of the conductors are nominally at the same potential (i.e., 0V). The current only changes path; part goes through the ground conductor and part through the neutral. Only five of the 12 neutral-to-ground shorts produced evidence of arcing whereas all 15 of the hot-to-ground and hot-to-neutral shorts produced evidence of arcing. Neutral to ground shorting was not evident in any of the flaming ignition events. However, when left undisturbed for an extended period of time, series arcing between neutral and ground conductors did cause some characteristic arcing damage to the conductors. Figure 2-57 shows a photograph of arcing between the neutral plug contact and the receptacle grounding strap that developed into a glowing connection which persisted for an extended time. After a few days of arcing/glowing between the neutral and ground strap, the receptacle was removed from the test circuit. A shallow notch (see Figure 2-57) was formed in the grounding strap as a result of the extended arcing and glowing.

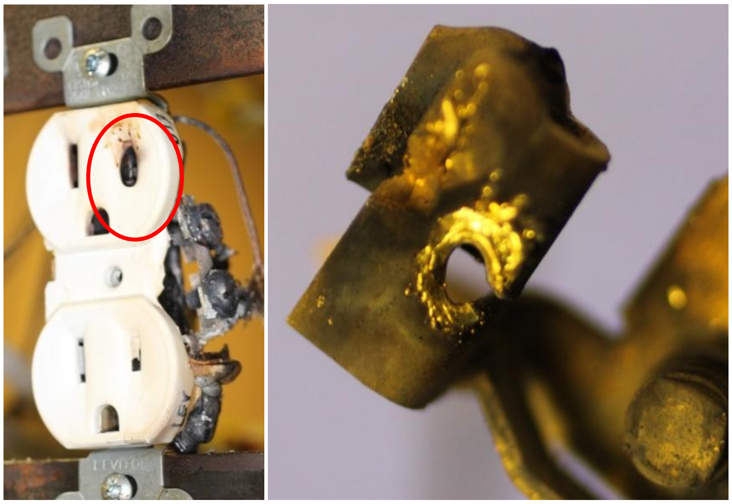


Figure 2-55. Arcing in receptacle LEV013 (left) between hot contact (right) and grounding strap (Figure 2-56).

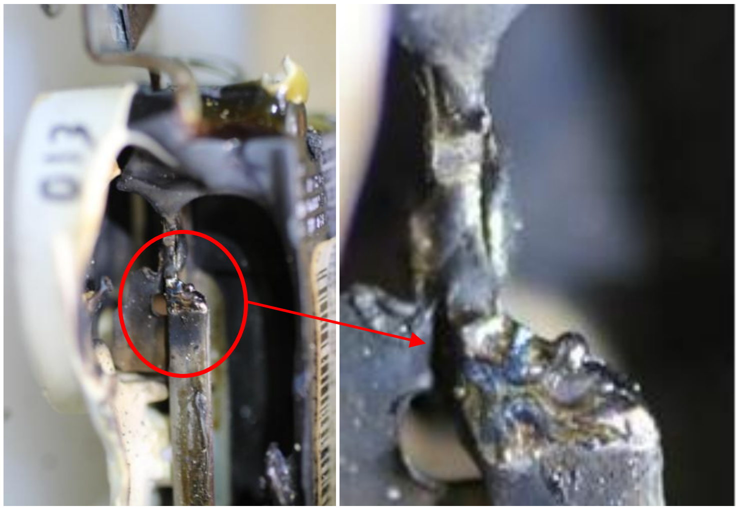


Figure 2-56. Arcing in receptacle LEV013 at grounding strap.

Figure 2-57. Arcing and glowing between neutral to ground during test (left), with resulting shallow notch in grounding strap (right) (LEV008).

2.3.5.2 Welded Conductors from Glowing Connection

Welded conductors were observed on a number of receptacles across the majority of failure events. Table 2-9 lists a summary of the receptacle failures, welded conductors, and welded conductors with curved striations observed for each type of failure; this table does not include the plug failure events. Welded conductors were divided into two types: those with curved striations and those without curved striations. As described in Section 2.3.3.3, curved striations are an indication that the glow spot moved along the conductor around the screw terminal. The curved striations could appear in a variety of ways. Both deep grooves and very shallow striations were observed. A typical example of curved striations is shown in Figure 2-58; the welded conductor fills the gap between the edge of the screw head and the brass internal contact plate. It is possible that the adhesion forces between the molten copper and the solid steel screw caused the molten copper to fill the gap. In the cases where distinct curved striations were not observed, it was for one of two reasons; the wire was only partially melted or there was an enlarged screw head (see discussion in Section 2.3.5.3). Partially welded conductors are a result of a failure event occurring before the glow spot could completely move around the screw.
A photograph of a partially welded conductor with no distinct curved striations is shown in Figure 2-59.

Table 2-9. Summary of Welded Conductors from Glowing Found in Receptacle Failures.

Failure Event	Number of Failure Events	One Welded Conductor	Two Welded Conductors	Welded Conductors with Curved Striations (Total)
Conductor Severed, w/ Arc	12	7	2	7
Conductor Severed, w/o Arc	16	13	2	13
Conductor Severed, Arc Unknown	16	13	2	9
Shorted, Hot to Ground	15	2	0	1
Shorted, Neutral to Ground	12	2	0	1
Shorted, Hot to Neutral	1	0	0	0
Flaming Ignition	12	4	4	6
Series Arcing-Open Circuit	1	0	0	0
All	**85**	**41**	**10**	**37**

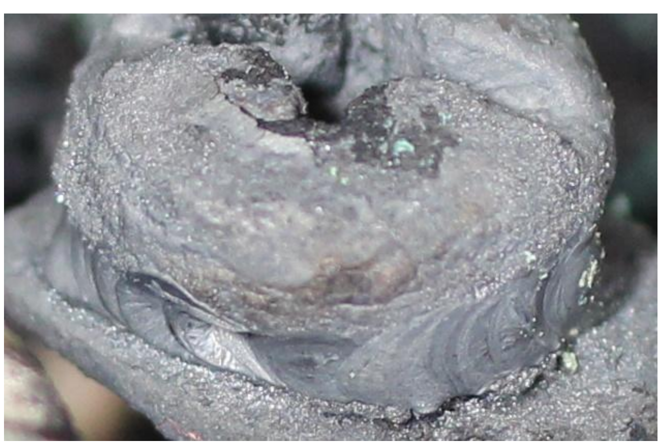


Figure 2-58. Welded conductor showing curved striations (PSE023).

Figure 2-59. Partially welded conductor; no curved striations (LEV127).

The majority (80%) of receptacles having welded conductors had only one welded conductor at the time of receptacle failure. In only ten receptacles; six polypropylene, two PVC, and two thermoset; two welded conductors were observed on the same receptacle. In all cases where two welded conductors were observed, both were on the same side of the receptacle, where the heat was conducted through the common brass receptacle contacts. Figure 2-60 shows two welded conductors with curved striations from the same receptacle (LEV277, ¼ turn loose).

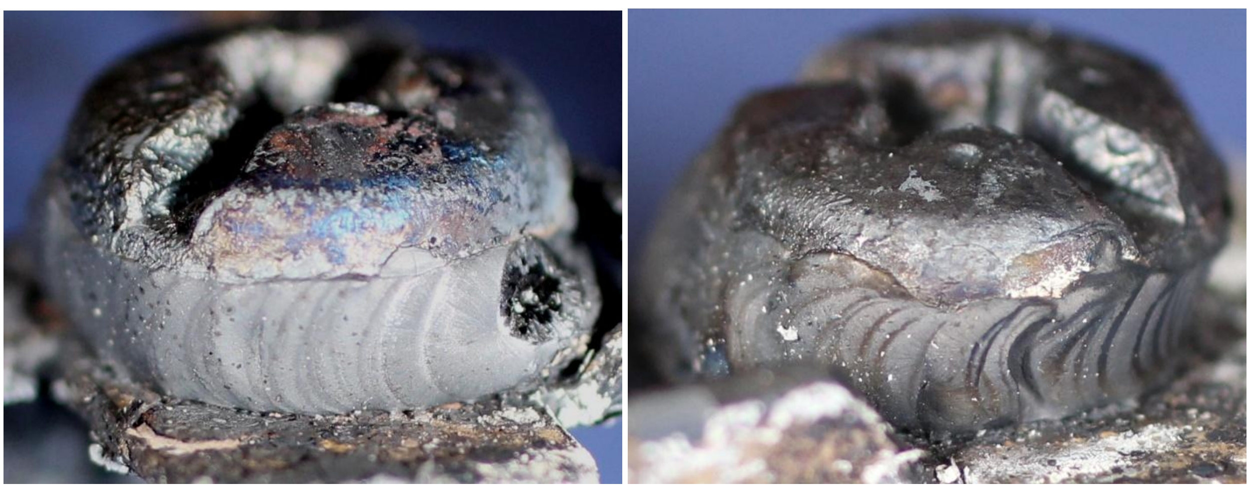


Figure 2-60. Two welded conductors showing curved striations from the same receptacle (LEV277).

2.3.5.3 Enlarged Screw Head

The enlarged screw head is a phenomenon arising from the corrosion of the copper wire and steel screw on a receptacle by HCl gasses evolved from the thermal degradation of PVC receptacle materials (see Section 2.3.2.2). Table 2-10 provides a summary of the enlarged screw heads observed for each failure event, whether the conductor was melted, and whether curved striations appeared. The enlarged screw heads are characterized by a swollen appearance with narrowed screw slots due to the buildup of corrosion products. The corrosion deposits on the screw heads appear to be rather porous and grey, black, or dark red in color (see Figure 2-61, Figure 2-62 and Figure 2-63). All of the enlarged screw heads observed in the laboratory testing were on PVC receptacles. In no case was anything similar seen for the polypropylene or thermoset receptacles. Even when a polypropylene or thermoset receptacle was located above a receptacle with an enlarged screw head (i.e., in the pathway of buoyant HCl), enlarged screw heads did not develop. This may suggest that the high concentrations of HCl in the vicinity of the degrading PVC are required to form the enlarged screw head. Research by Bertelo et.al [1985] on the generation of hydrogen chloride in large and small systems suggested that 20–30% of the generated HCl is deposited within a few inches of the decomposition site. In only one receptacle (PSE165) was more than one enlarged screw head observed. This receptacle had three enlarged screw heads; it is plausible that the overheating of the two terminals on the same side of the receptacle exacerbated the development of each other and the degradation of the PVC causing both to become enlarged.

Table 2-10. Summary of Enlarged Screw Heads Found in Receptacle Failures.

Failure Event	Number of Failure Events	With Enlarged Screw Head		
		Total	With Welded Conductor	With Welded Conductors and Curved Striations
Conductor Severed, w/ Arc	12	6	5	1
Conductor Severed, w/o Arc	16	6	5	1
Conductor Severed, Arc Unknown	16	8	7	2
Shorted, Hot to Ground	15	1	0	0
Shorted, Neutral to Ground	12	1	1	0
Shorted, Hot to Neutral	1	0	0	0
Flaming Ignition	12	6[A]	4[B]	0
Series Arcing-Open Circuit	1	0	0	0
All	**85**	**28**	**22**	**4**

A – Four receptacles with enlarged screw heads; one receptacle had three.
B – Two receptacles each had two welded conductors.

Figure 2-61. Enlarged screw head on receptacle PSE134.

Figure 2-62. Enlarged screw head from receptacle PSE129.

Figure 2-63. Enlarged screw head from receptacle PSE170.

A total of twenty-six receptacles formed twenty-eight enlarged screw heads as a result of corrosion. Enlarged screw heads were formed for receptacles which had a variety of failure events including flaming ignition. The majority of enlarged screw heads did exhibit melting of the copper wire, but only 4 of 28 had a welded conductor with curved striations.

One of the enlarged screw heads was cross-sectioned and polished to examine the extent of the corrosion buildup, its chemical makeup, and its microstructure (see Section 3.2.3.3 for sectioning and polishing methodology). A photograph of the cross-sectioned screw in the brass receptacle contact is shown in Figure 2-64. The thickness of the corrosion layer atop the screw was approximately 1.2 mm (0.047 inches) at the thickest point. The corrosion covered almost the whole surface of the screw and threads but was not a constant thickness over the entire surface. It can be seen that the corrosion byproducts are primarily surface growth with some loss of volume of base steel. An exemplar cross-sectioned screw is shown for reference in Figure 2-65. A SEM image shows the plating overtop the steel which was approximately 4-5 μm thick.

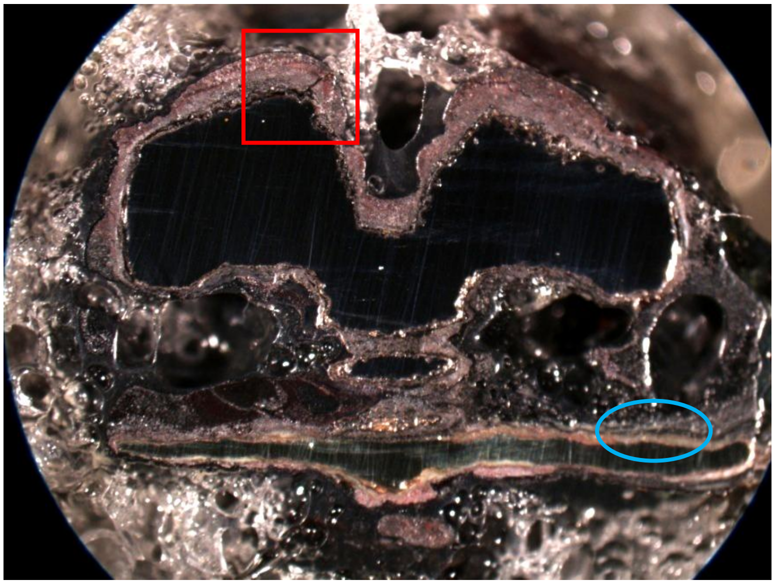


Figure 2-64. Sectioned and polished enlarged screw head from PSE170.
Note: Square indicates area of EDS mapping; section of brass terminal with dezincification circled.

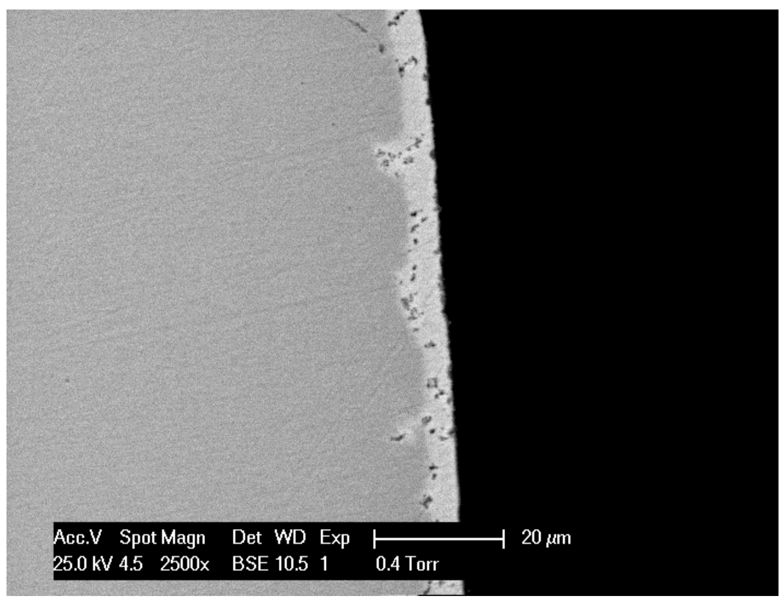


Figure 2-65. Sectioned exemplar PSE screw (hot).
Note: Plating thickness approx 4-5 microns.

A SEM examination was conducted of the cross-sectioned screw. Figure 2-66 shows a back-scatter image of the corrosion layer atop the steel (a red square in Figure 2-64 indicates the location of the SEM image). There appears to be a boundary (indicated by a dotted red line) between two layers of the corroded material indicated by the difference in color. It appears that the corrosion material nearest to the screw head is more dense. This is observed in Figure 2-67 where the grain structure of the corrosion products are shown. The material appears to be very porous in the outer layer. In order to determine the chemical makeup of the different layers of corrosion, an EDS mapping of the area shown in Figure 2-66 was conducted. Carbon, chlorine, copper, iron, manganese, oxygen and silicone were mapped, with the results shown in Figure 2-68. Each element is plotted as a relative concentration.

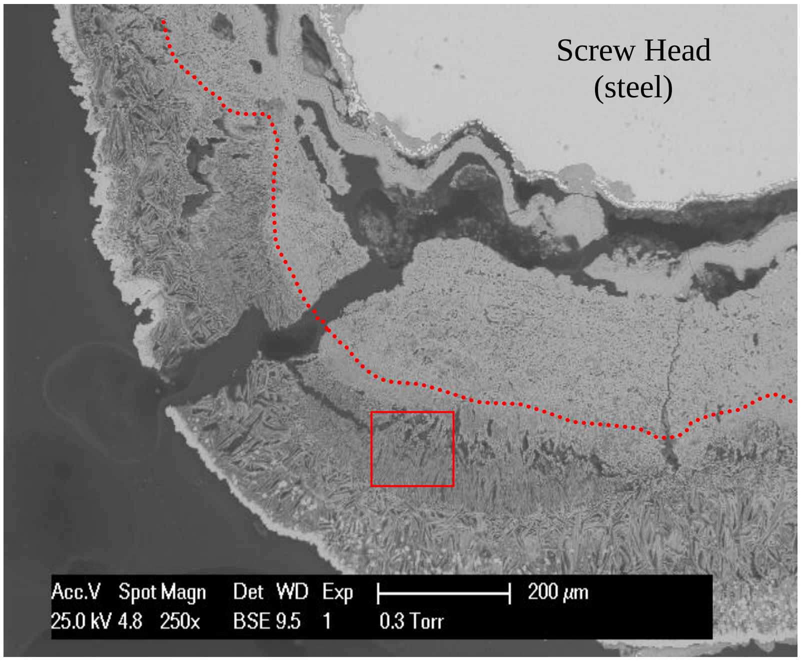


Figure 2-66. SEM image (250x) showing different layers of corrosion for sectioned PSE170 enlarged screw.

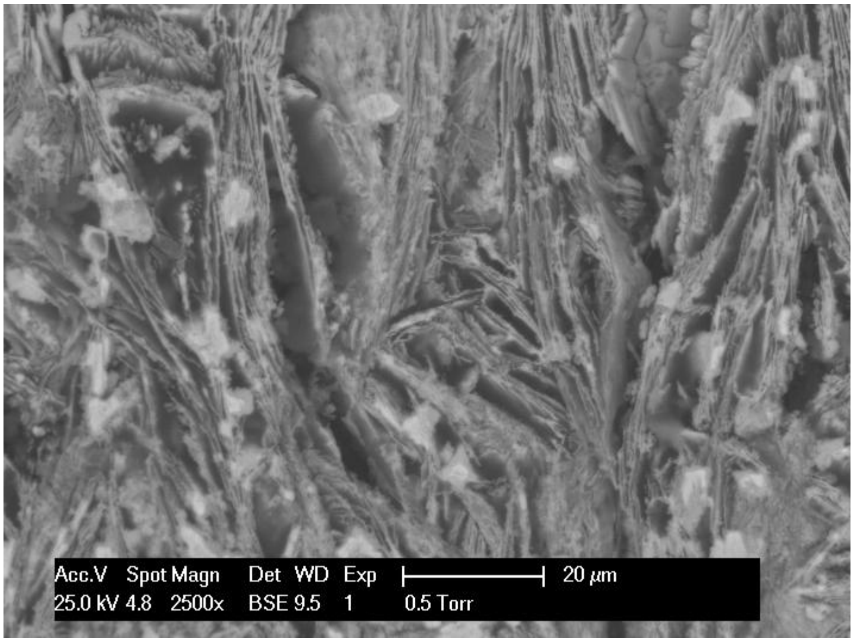


Figure 2-67. SEM image (2500x) showing grain structure of corrosion layer for sectioned PSE170 enlarged screw. Note: Image location noted as red box in Figure 2-66.

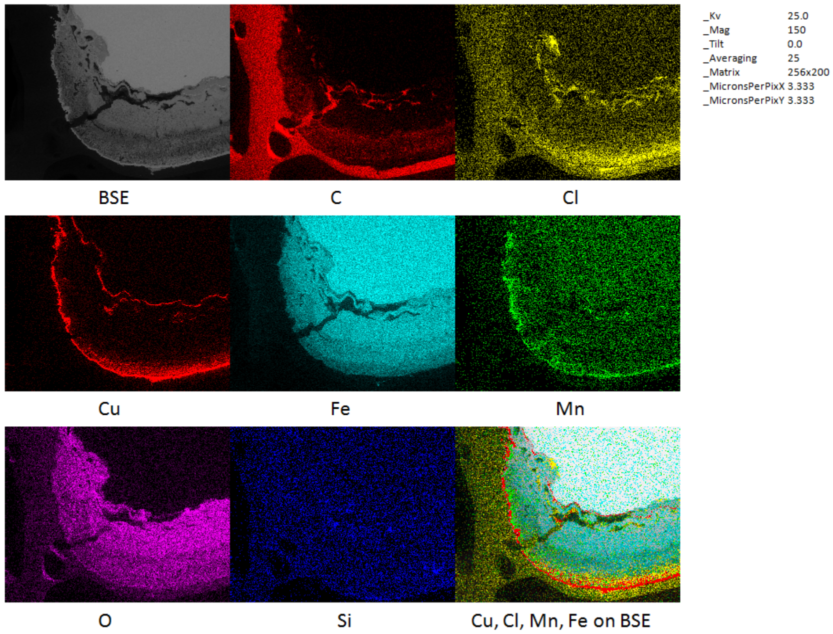


Figure 2-68. EDS Mapping of Oxide Layer for sectioned screw from PSE170.

The EDS mapping of the corrosion layers revealed a wealth of information. It should be noted that carbon and some of the Cl, O, and Si show up from the resin that the sample was mounted in and background measurements. It appears that the corrosion layer is largely iron and oxygen, most likely in the form of iron oxide. Both the dot maps for iron and oxygen show a slight change in concentration at the boundary between the different corrosion layers. Chlorine does not seem to be present in large quantities except at the interface of the corrosion and the screw head and part of the outer boundary of the corrosion. Though what is perhaps the most interesting is the dot map for copper which shows copper concentrated at the boundary between the corrosion layer and steel as well as the outer boundary of the enlarged screw head. In fact, the layer of copper is also quite distinct under a light microscope as well (see Figure 2-69).

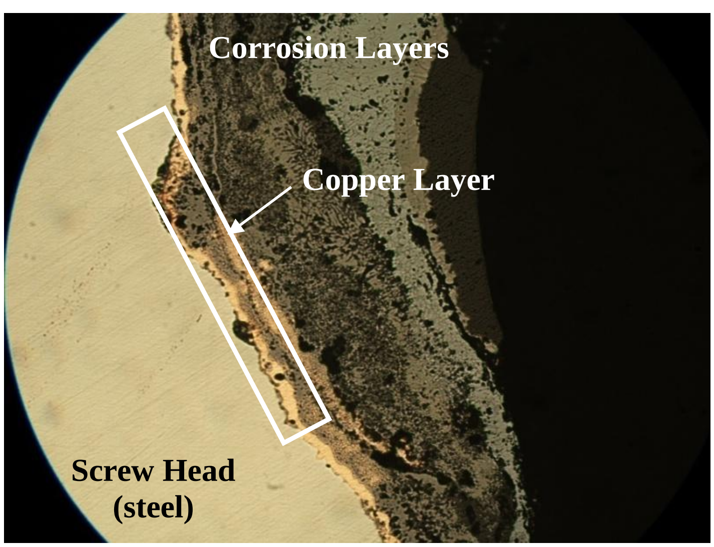


Figure 2-69. Microscope image (200x) of PSE170 showing copper at surface of screw beneath corrosion layer.

2.3.5.4 Severed Conductor Ends

As a result of the glowing connections, some receptacles experienced severing of the wire conductor at or near the screw terminal. The severing produced unique evidence on the end of the wire and at the screw terminal. Table 2-11 lists a summary of the type of end on the wire side of the severed conductor for each failure event. Table 2-12 lists a summary of the type of end on the screw terminal side of the severed conductor for each failure event. The severed conductor ends on the wire side were round and sometimes dimpled globules, flat ends with no globule, or irregular shaped ends. Table 2-13 shows photographs of the various wire ends that were observed for the receptacle failures. The round and sometimes dimpled ends appear to be similar to arc beads, however their color was typically shiny grey rather than a copper color. The dark grey color was possibly due to the heavy oxidation located at the glow spots. Further examination of a round/shiny conductor end from LEV173 revealed that the round/shiny part was in fact a cap located atop a flat end (see Figure 2-70). Secondary examinations of the round and shiny conductor ends observed for receptacle failures revealed that they were all comprised of a flat end with a round/shiny cap. Both types of ends are characteristic of a conductor severed due to a glowing connection; in Table 2-11, the severed ends are classified by their as-found state.

The majority of severed conductor ends were round/shiny or flat with the remainder having an irregular shape as shown in Table 2-13. The severed conductor ends from glowing connections can be distinguished from arcing based on an evaluation of their color (i.e., black/grey for severed conductors versus coppery color for arc beads), the absence of characteristic arcing traits (see Section 4.0) and the presence of indicators of overheating in the severed conductor. The round shape of arc beads is more pronounced than the round severed conductors, and arc beads typically lack significant oxidation, thinning, or pitting which is commonly present in the conductors severed from glowing connections. In addition, the round severed conductor ends were actually a cap of copper oxides atop a flat wire end; see discussion below. Severed conductors were not present for any of the shorting failure or series arcing failure events.

Twenty-eight of the 32 round and/or shiny severed conductor ends on the wire side were paired up with round and/or shiny severed conductor ends on the screw side. Three were paired up with irregular severed conductor ends on the screw side. The remaining round and/or shiny severed conductor ends on the wire side did not have a pairing severed conductor end on the screw side; part of the brass contact was missing. Eighteen of the 22 irregular severed conductor ends (not including those from arcing) on the wire side were paired up with irregular severed conductor ends on the screw side. Three irregular severed conductor ends on the wire side were paired up with a round and/or shiny severed conductor end on the screw side. The two flat severed conductor ends were split, with one having an irregular severed conductor end and the other having a round and/or shiny severed conductor end on the screw side.

Table 2-11. Summary of Severed Conductor Evidence on Wire Found in Receptacle Failures.

Failure Event	Number of Failure Events	Round and/or Shiny	Flat	Irregular
Conductor Severed, w/ Arc	12	7	1	4
Conductor Severed, w/o Arc	16[A]	13	1	1
Conductor Severed, Arc Unknown	16[A]	9	0	6
Shorted, Hot to Ground	15	0	0	0
Shorted, Neutral to Ground	12	1	0	0
Shorted, Hot to Neutral	1	0	0	2[B]
Flaming Ignition	12	2[C]	0	9[D]
Series Arcing-Open Circuit	1	0	0	0
All	**85**	**32**	**2**	**22[B,D]**

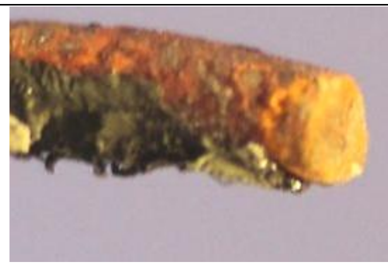
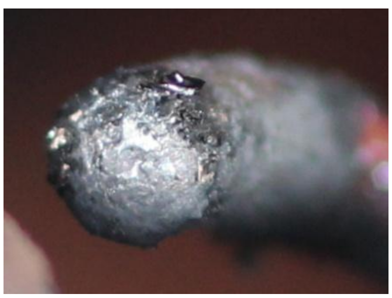
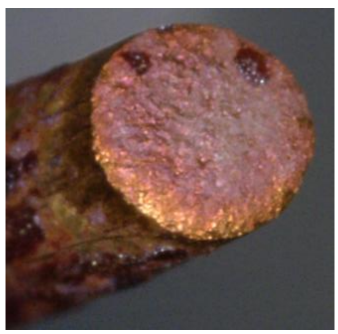
A – One severed conductor lost during disassembly and transportation.
B –Two irregular/round beads are from arcing.
C – One receptacle had two parting connections.
D – Three irregular/round beads are from arcing.

Table 2-12. Summary of Severed Conductor Evidence on Screw Side Found in Receptacle Failures.

Failure Event	Number of Failure Events	Round and/or Shiny	Irregular
Conductor Severed, w/ Arc	12	5	7[A]
Conductor Severed, w/o Arc	16	15	1
Conductor Severed, Arc Unknown	16	13	3
Shorted, Hot to Ground	15	0	0
Shorted, Neutral to Ground	12	0	1
Shorted, Hot to Neutral	1	0	2[B]
Flaming Ignition	12	2[C]	9[D]
Series Arcing-Open Circuit	1	0	0
All	**85**	**35**	**23**

A – None; part of brass conductor missing.
B – Two irregular/round beads from arcing.
C – One receptacle had two parting connections
D – Three receptacles had two parting connections; one receptacle had a round/irregular bead from arcing.

Table 2-13. Photographs of Wire Ends from Failure Events Severed by Glowing.

Round Ends	Flat	Irregular
 E003 –with dimple *Conductor Severed w/o Arc*	 LEV018 *Conductor Severed w/o Arc*	 PSE170 *Conductor Severed w/ Arc*
 LEV035 – shiny *Conductor Severed w/o Arc*	 LEV013 *Conductor Severed w/ Arc*	 PSE134 *Conductor Severed w/ Arc*
 LEV267 *Conductor Severed w/o Arc*	 LEV173 (initially observed as round) *Flaming Ignition*	

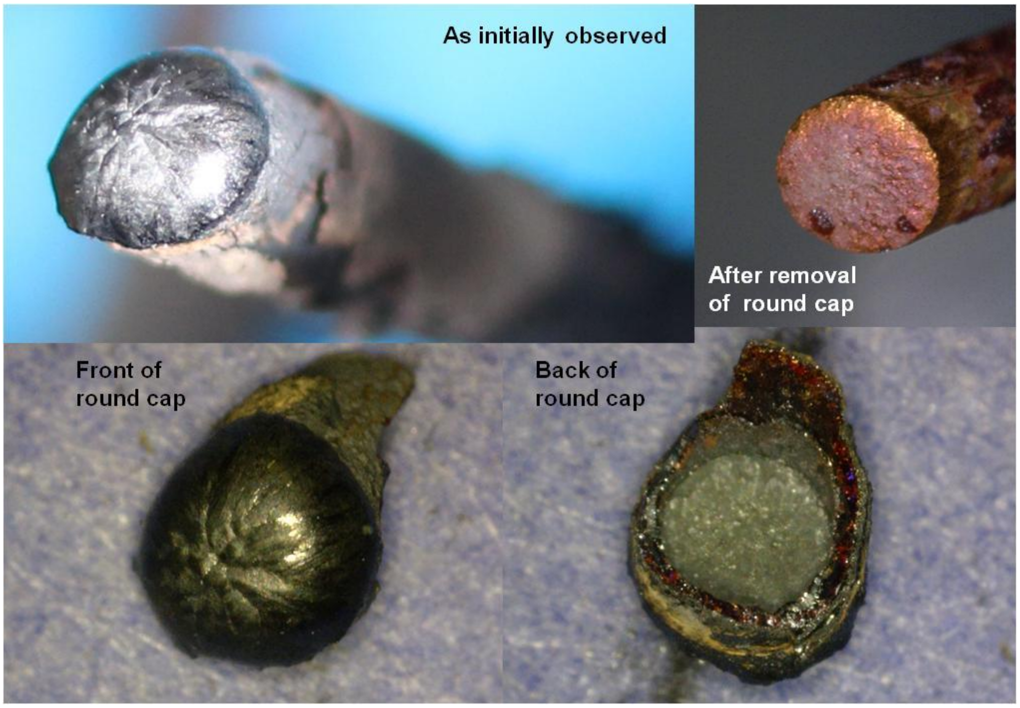
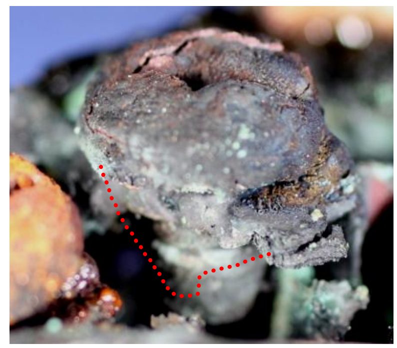
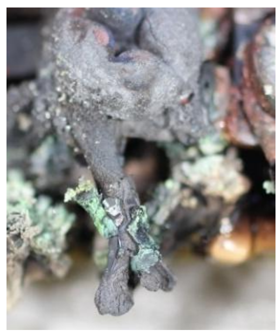


Figure 2-70. Round, shiny severed conductor end showing round cap and flat underneath (LEV173).

The severed conductor ends on the screw side of the severed conductor were similar in form to the wire ends. Round and/or shiny and irregular shaped evidence was observed. Table 2-14 shows some examples of the various types of severed conductor ends observed on the screw side of the conductor. In most cases, the location of severing was directly adjacent to the screw head, but in some cases it occurred up to 1.2 cm (0.5 in.) from the screw head on the wire. In addition, for one receptacle (PSE263), it was found that part of the brass terminal was missing in the location of the severed conductor, possibly due to the arcing that occurred when the conductor was severed. The irregular shaped conductor from PSE134 was also quite interesting (see Table 2-14); it appeared that the wire split and splayed open into four pieces approximately 1.2 cm (0.5 in.) from the screw head. In most cases, the irregular shaped ends appeared for receptacle failure events having arcing. But, round and shiny ends were also observed for severed conductor failure events having arcing.

An interesting severed conductor end was observed on the screw of LEV275, resulting from severing with an accompanying arc. There were three fingerlike projections coming from the welded conductor (see Figure 2-71); these fingerlike projections were not observed on any other receptacles. A closer examination of this area using the SEM revealed what appears to be a spatter on the surface of the welded conductor emanating from the point where the conductor severed (see Figure 2-72). EDS measurements of the chemical composition of the spatter (Figure 2-73) and the surface of the welded conductor (Figure 2-74) revealed that the surface spatter is primarily copper, iron, and oxygen while the underlying material is copper and oxygen. It is possible that the iron in the spatter came from either the bulk steel of the screw or iron oxide that was involved in the arcing event.

Table 2-14. Photographs of Severed Conductor Evidence on Screw Side Found in Receptacle Failures.

Round/Shiny Ends	Irregular	None
 E003 *Conductor Severed w/o Arc*	 PSE170 *Conductor Severed w/o Arc*	 PSE263 *Conductor Severed w/ Arc (approximate area of missing material outlined)*
 LEV035 *Conductor Severed w/o Arc*	 PSE134 – split *Conductor Severed w/ Arc*	
 PSE133 *Conductor Severed w/o Arc*		

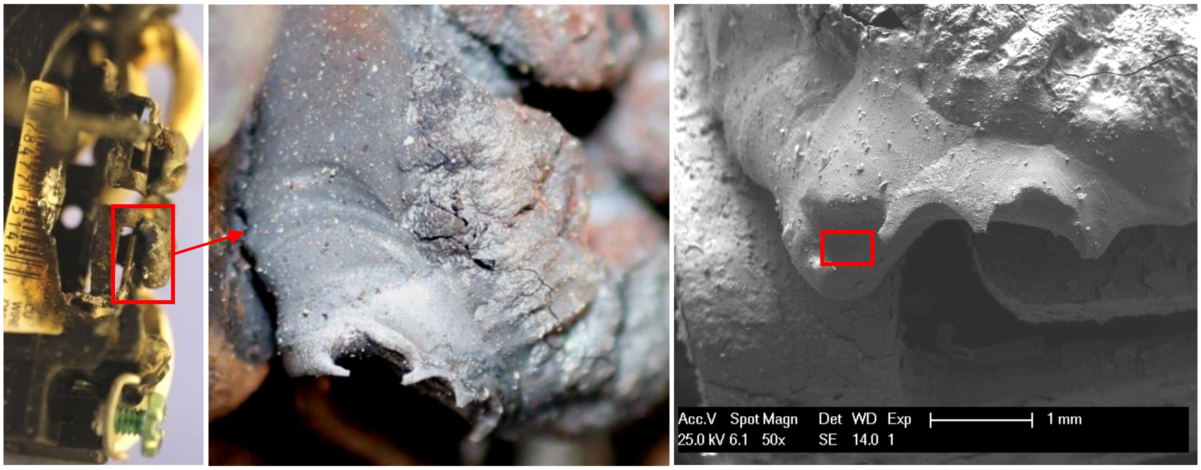


Figure 2-71. Severed conductor end near screw terminal (SEM, right, 50x); square indicates approximate location of image in Figure 2-72 (LEV275).

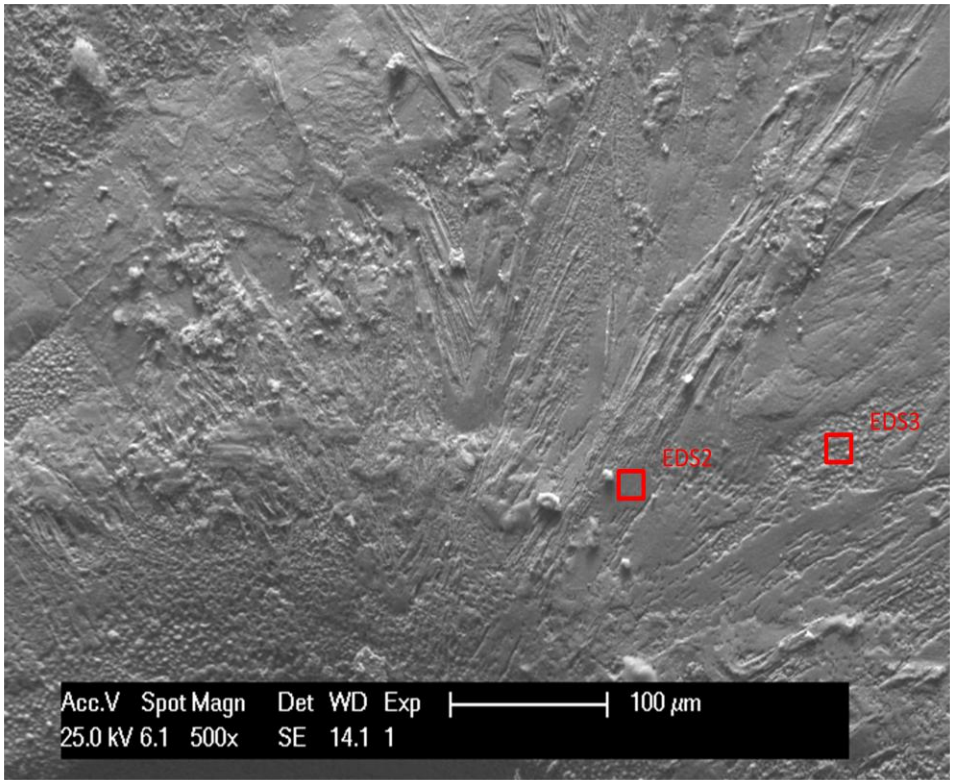


Figure 2-72. Image of area on severed conductor end near screw terminal (500x); EDS locations indicated (LEV275).

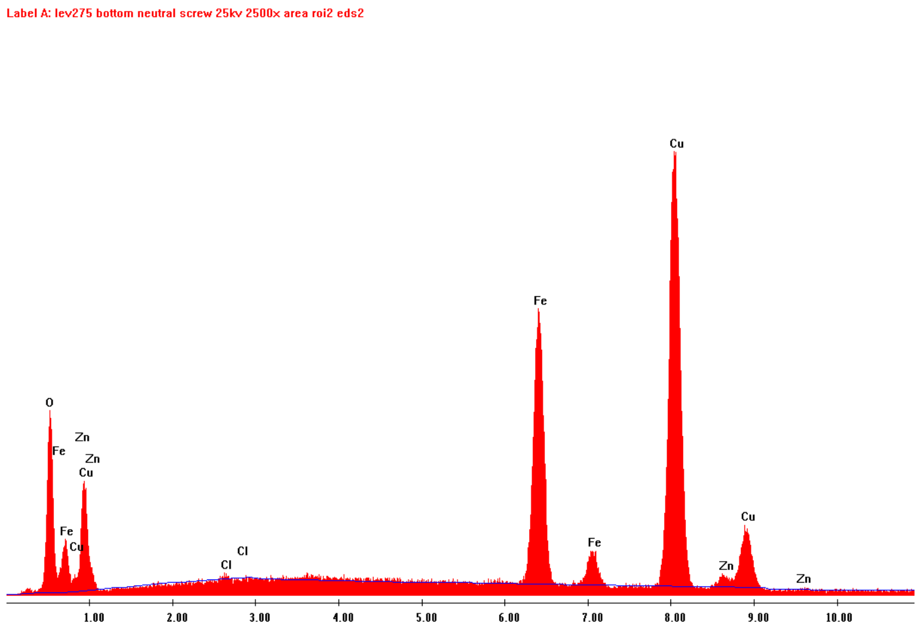


Figure 2-73. EDS spectra for spatter on surface of welded conductor (LEV275).

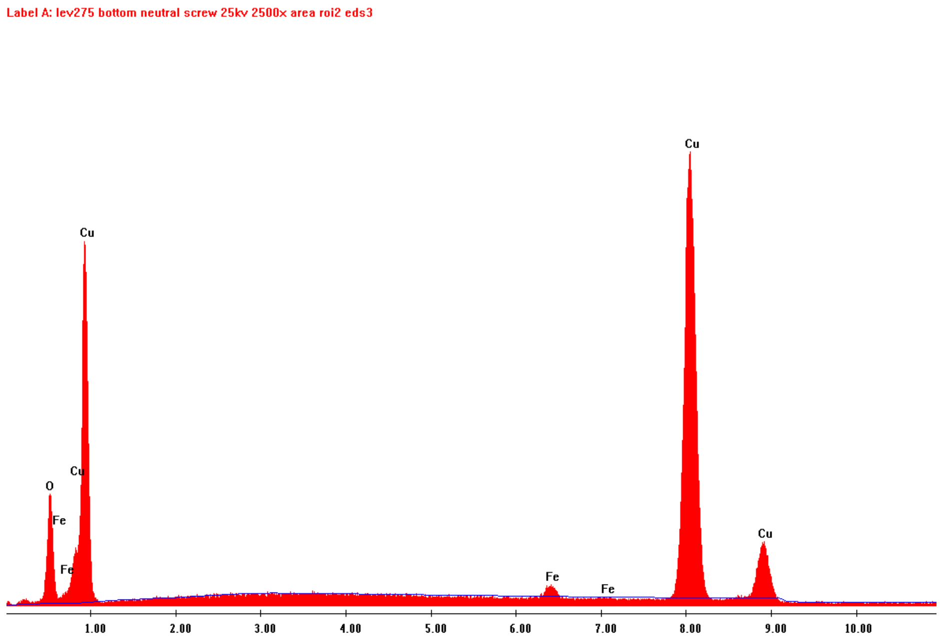


Figure 2-74. EDS spectra for surface of welded conductor (LEV275).

2.3.6 Evidence of Failure Events for Plug Connections

The evidence of overheating for failure events involving plug connections was not as distinct as the evidence for failures involving receptacle terminal connections. There were no obvious indicators that glowing had occurred in any of the receptacles/plugs (i.e., analogous to melted conductors or enlarged screw heads). But, there were a few different types of evidence of overheating found at the plug connection failure events including arcing, dezincification, and corrosion products. Table 2-15 lists the observed evidence of overheating for all of the failure events for plug connections. All of the failure events for plug connections were flaming ignition events involving the low-profile plugs with plated brass blades.

In all cases of flaming ignition in plug connections, evidence of arcing was found. Those receptacles (2 out of 5) that tripped circuit breakers (PSE285 and LEV063) showed signs of parallel arcing between a hot conductor and the ground strap. Those receptacles that did not trip circuit breakers showed evidence of series arcing between two hot conductors. Arcing evidence was determined using the characteristics presented in Section 2.3.5.1. Figure 2-75 shows the arcing damage between the hot plug blade and the grounding strap for PSE285. The green square in Figure 2-75 indicates the approximate area of contact between the internal plug contacts and the plug blade. The arcing damage is located on the plug blade behind this contact area (i.e., towards the interface between the receptacle and plug surfaces). Because the arcing damage is not located at the area of contact between the blade and internal plug contacts, it is likely that this occurred during the flaming ignition event and not during the overheating process. For receptacle LEV060, arcing occurred between the hot plug blade and internal plug contact. Some transfer of material is evident on both the plug blade and the receptacle contact (see Figure 2-76). It is unclear whether this arcing occurred during the failure event or prior to it. Arcing also occurred in the plug, away from the receptacle contacts for LEV286. In this case, arcing occurred at the base of the ground pin within the plug (see Figure 2-77). It is likely that the arcing occurred between the ground pin and the hot wire or base of the hot plug blade (see Figure 2-77). However, additional examination of the hot plug blade and hot plug wire did not yield any conclusive evidence to determine the corresponding arc location.

Table 2-15. Summary of Observed Evidence for Plug Connection Failure Events.

Receptacle S/N	Plug Nominal Retention Force (kg)	Trip Circuit Breaker?	Arcing?	Dezincification?	Corrosion?
LEV060	0.1	No	Between hot plug blade and hot internal plug contact.	Yes	Yes
LEV062	0.01	No	Between hot plug blade and hot internal plug contact.	Yes	No
PSE285	0.01	Yes	Between hot plug blade and ground strap.	No	No
LEV286	0.01	No	At base of ground pin.	Yes	No
LEV063	0.01	Yes	Between hot receptacle contact and ground strap.	Yes	No

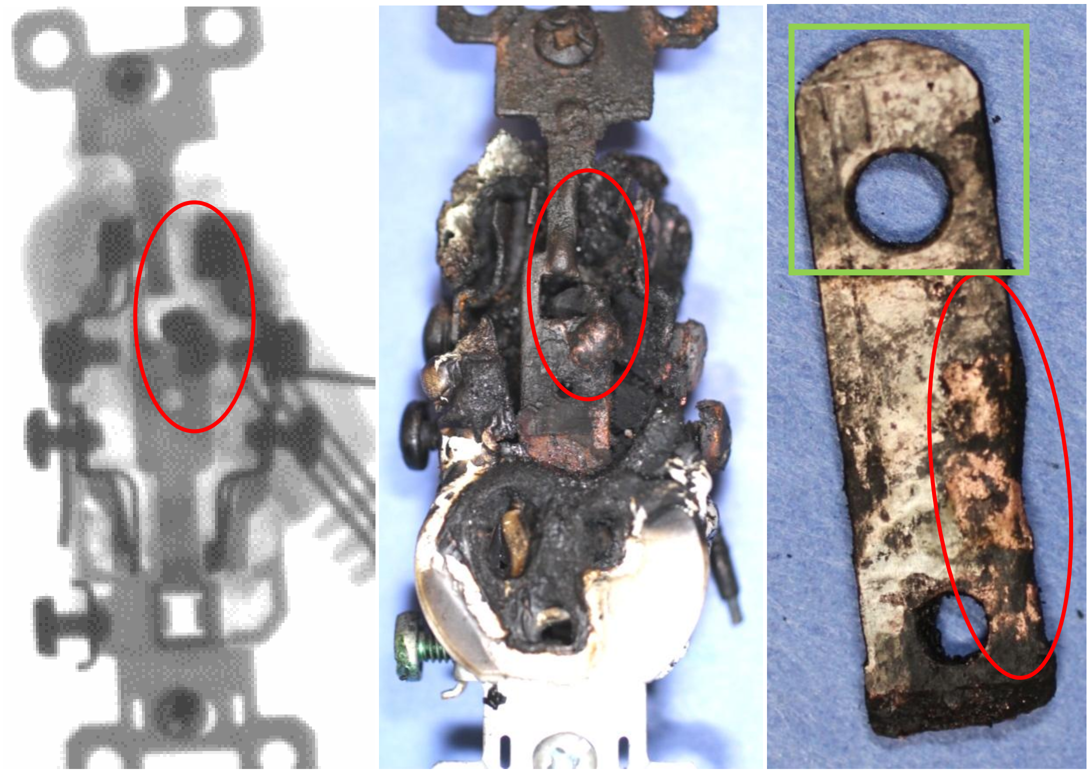


Figure 2-75. Arcing between grounding strap (left, center) and hot plug blade (right) from PSE285.

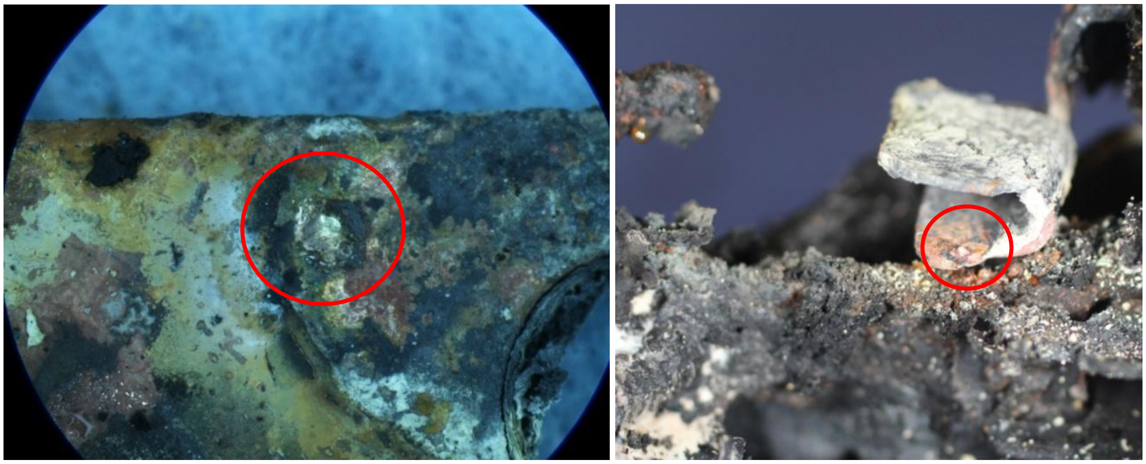


Figure 2-76. Arcing between hot plug blade (left) and hot receptacle terminal (right) for LEV060.

Figure 2-77. Arcing damage at back of ground pin (bottom); hot blade (top) from plug in receptacle LEV286.

Corrosion was evident for the majority of the receptacles and plugs involved in flaming ignition failure events. Corrosion was observed in the form of a whitish deposit (see Figure 2-78) or dezincification (see Figure 2-79). The whitish deposit on the plug blade and internal plug contacts is likely due to the degradation of the PVC plug during overheating. This process would be similar to that described in Section 2.3.2.2. Dezincification was observed for 80% of the receptacle and plug failure events. Dezincification on both the brass plug blades (after loss of plating) and the brass internal plug contacts was found.

Figure 2-78. White residue (corrosion) at plug/receptacle connection (LEV060).

Figure 2-79. Loss of plating and dezincification on hot plug blade (LEV060).

2.3.7 Test Variable Effects on Receptacle Failures

2.3.7.1 Primary Receptacle Material

Three types of receptacle materials were evaluated in the laboratory testing: PVC, polypropylene, and thermosets. Numerous manufacturers of the thermoset receptacles (aged) were tested and single manufacturers of the PVC and polypropylene receptacles (new) were tested. A summary of the receptacle events as a function of the primary receptacle body material is presented in Table 2-16; this table does not include plug failure events. This data indicates that the receptacle body material has a rather large impact on the types of failure events. This is especially evident for the cases where the internal contacts short and where flaming ignition occurs. There were a total of 23 polypropylene receptacles where the internal contacts shorted compared to four PVC and zero thermosets. This suggests that the propensity for a receptacle to short is proportional to its inclination to melt. Polypropylene receptacles melt rather easily, while PVC receptacles tend to sag and thermoset receptacles retain their structure at higher temperatures. The greater ability to melt allows the internal contacts freedom of motion to contact the grounding strap of the receptacle. The increased hazard associated with this behavior for thermoplastics (e.g., PVC and polypropylene) compared to thermosets (e.g., phenolics and urea formaldehyde) was also mentioned in a CPSC technical meeting [Edwards, 1995].

For the PVC and polypropylene receptacles, there was approximately 1.2 mm (0.05 in.) of insulation (i.e., barrier) between the internal contacts and the ground strap. A sample of the thermoset receptacles was measured and it was found that the insulation between the internal contacts and the ground strap was on the order of 2.0 mm (0.078 in.). It is possible that the amount of physical separation between the internal contacts and the grounding strap and the rigidity of that insulation with respect to heat also played a part in the likelihood of receptacles to fail due to shorting. However, based on visual examination, the retention of spatial structure as the receptacle thermally degrades is believed to be the driving factor of whether components short. There were no instances where arcing through char was observed to have occurred.

Table 2-16. Summary of Receptacle Failure Events as a Function of Receptacle Material.

Failure Event	**Number of Failure Events**	**Polypropylene**	**PVC**	**Thermosets**
Conductor Severed w/ Arc	12	2	7[A]	3
Conductor Severed w/o Arc	16	5[A]	6[A]	5
Conductor Severed Arc Unknown	16	3[A]	9[B]	4
Shorted, Hot to Ground	15	12[B]	3	0
Shorted, Neutral to Ground	12	11[A]	1	0
Shorted, Hot to Neutral	1	0	0	1
Flaming Ignition	12	6[C]	6[D]	0
Series Arcing-Open Circuit	1	0	0	1
Total – Side Wired [Failure rate of receptacles tested at ¼ turn loose or 1 in-lb (failures/year)]	**84 [0.41]**	**39 [0.49]**	**31 [0.34]**	**14 [0.40]**
Total – Back Wired [Failure rate of receptacles tested with 1 or 2 insertion & removal cycles (failures/year)]	**1 [0.03]**	**0 [0]**	**1 [0.05]**	**None Tested [N/A]**

A – 1 in box
B – 2 in box
C – 4 in box
D – 2 in box; one back-wired push-in connection (w/ 1 insertion and removal cycle)

For flaming ignition of receptacles with loose terminal connections, there were six polypropylene receptacles, six PVC receptacles, and zero thermoset receptacles. The tendency for flaming ignition to occur appears to be related to the way in which the receptacles degrade. Polypropylene receptacles melt and pool, while PVC and thermoset receptacles tend to char, leaving a large portion of the mass retained in a less combustible, less dense solid matrix. The char yield for thermoset plastics are between 60 and 70% and PVC is approximately 11% [Hirschler, 2008]. The char layer also acts as a barrier between the heat source (i.e., overheating connection) and the virgin material.

Where the conductors were severed due to a glowing connection at 15A, the failure rates were more prevalent in thermoset receptacles than polypropylene or PVC receptacles. Failure rates were calculated from the total number of receptacles for each material that had either 1 in-lb connections or the ¼ turn loose configuration (<<1 in-lb). The failure rates for receptacles with conductors that severed due to a glowing connection were 0.34 failures/year (12 total) for thermosets, 0.31 failures/year (22) for PVC, and 0.17 failures/year (10) for polypropylene. This ranking is inversely proportional to the degree of degradation that these material types experienced. Consequently, the most structurally sound thermoset receptacles did not allow movement of the conductors and contacts, which may have decreased the likelihood of other failure events, such as shorting which requires movement of the components.

2.3.7.2 Surrounding Materials

In total, 40 receptacles were placed in outlet boxes and had faceplates installed. Ten of these were in the test rack with an applied current of 3A (later 6A and 9A) and ten of these were used with the plug arrangement. All of the receptacles installed in an outlet box were set to the loosest screw terminal configuration (¼ turn loose) or plug nominal retention force (0.01 kg); no thermoset receptacles were installed in outlet boxes. None of the twenty receptacles installed in outlet boxes with faceplates with currents of 9A and less or plugs overheated to the point of failure. Table 2-17 lists the receptacle failure events based on whether the receptacles were installed in outlet boxes with faceplates or in open air. In this section, only PVC and polypropylene receptacles with ¼ turn loose configurations (<<1 in-lb) at 15A are considered; receptacle failure rates were calculated only for receptacles with these variables.

Table 2-17. Summary of Receptacle Failure Events as a Function of Being within an Outlet Box with Faceplate or in the Open Air (All With ¼ Turn Loose Connections at 15A; No Thermoset Receptacles; No Plug Connections; No Back-Wired Push-in Receptacles).

Failure Event	Number of Failure Events	In Box	In Open Air
Conductor Severed w/ Arc	8	1	7
Conductor Severed w/o Arc	9	2	7
Conductor Severed Arc Unknown	8	3	5
Shorted, Hot to Ground	15	2	13
Shorted, Neutral to Ground	12	1	11
Shorted, Hot to Neutral	0	0	0
Flaming Ignition	10	6	4
Series Arcing-Open Circuit	0	0	0
Total [Failure rate of PVC and polypropylene receptacles tested at ¼ turn loose (failures/year)]	**63 [0.89]**	**15 [1.17]**	**48 [0.82]**

It appears that the outlet boxes and faceplates have some affect on the propensity for a receptacle to overheat to the point of failure. Receptacles installed in outlet boxes were more prone to having failure events (1.17 failures/year) compared to receptacles in open air (0.82 failures/year). But there is an even greater disparity between receptacles installed in outlet boxes compared to those in open air when it comes to the flaming ignition failure events. Six out of 20 receptacles installed in outlet boxes with faceplates (0.47 failures/year) with loose screw connections (i.e., ¼ turn loose) had flaming ignition compared to four out of 87 (0.07 failures/year) in open air. It would intuitively make sense that installation of a receptacle in an outlet box with faceplate would increase the likelihood of flaming ignition. The outlet boxes and faceplates provide both additional flammable material and confinement of heat from the overheating connections.

The only five receptacles with loose plug connections that had failure events were in the open air. All five were flaming ignition failure events. Only ten plug connections were tested with the receptacles installed in outlet boxes with faceplates. With the limited number of receptacles with plug connections installed in outlet boxes with faceplates, there is not enough failure data to indicate any trends for this combination of variables.

2.3.7.3 Installation, Use, and Abuse

2.3.7.3.1 Screw Terminal Torque

Screw terminal torques from below 1 (i.e., ¼ turn loose) to 15 in-lb were used in this testing. The looseness of the screw terminal connection appears to be one of the main driving factors in the likelihood of a receptacle failing due to overheating. Table 2-18 lists the minimum, maximum, average, and standard deviation for the time to failure as a function of terminal torque. Table 2-19 lists the specific failure events as a function of terminal torque. Screw connections having a torque of 3 in-lb or higher did not have any failure events due to overheating. The receptacles with the ¼ turn loose configuration (<<1 in-lb) had a much higher failure rate (0.87 failures/year) than those with the 1 in-lb torque (0.10 failures/year). Despite the large standard deviations in the times to failure event, the ¼ turn loose connections, on average, failed quicker than those at the 1 in-lb torque. Also, the¼ turn loose configuration produced the quickest time to failure (5 days). This failure event was the shorting of a hot conductor to ground (LEV014). And 34 (75%) of the ¼ turn loose receptacles had the failure events occur quicker or equal to the fastest time to failure for a 1 in-lb receptacle (115 days). Due to the limited number of failure events for receptacles with 1 in-lb connections, trends with respect to the tendency for each of the two low torque terminal configurations to exhibit certain failure modes cannot be commented on.

Table 2-18. Summary of Receptacle Failure Event Times with Respect to Screw Terminal Torque (@ 15A).

Terminal Configuration	Number of Failure Events	Failure Rate (failures/year)	Min. Time to Event (days)	Max. Time to Event (days)	Avg. Time to Event (days)	Std. Dev. of Time to Event (days)
¼ Turn Loose	75[A]	0.87	5	365	157	107
1 in-lb	8	0.10	115	255	189	48
≥3 in-lb	0	0.00	-	-	-	-
Total	**83**	**-**	**5**	**365**	**160**	**104**

A – Time to failure for 1 receptacle (PSE164) unknown.

Table 2-19. Summary of Receptacle Failure Events with Respect to Screw Terminal Torque (@ 15A).

Failure Event	Number of Failure Events	¼ Turn Loose (<<1 in-lb)	1 in-lb
Conductor Severed w/ Arc	12	11	1
Conductor Severed w/o Arc	15	14	1
Conductor Severed Arc Unknown	16	11	5
Shorted, Hot to Ground	15	15	0
Shorted, Neutral to Ground	11	11	0
Shorted, Hot to Neutral	1	1	0
Flaming Ignition	12	11	1
Series Arcing-Open Circuit	1	1	0
Total	**83**	**75**	**8**

2.3.7.3.2 Nominal Plug Connection Retention Force

At 15A, there were far fewer failure events in receptacles with plugs (5) than the loose screw terminal connections (83). However, all of the failure events in plugs were flaming ignition while only 13% of the 83 failure events for loose screw terminal connections were flaming ignition. Table 2-20 lists the minimum, maximum, average, and standard deviation for the time to failure for the different plug blade nominal retention forces. The majority of failure events (4 of 5) occurred in receptacles having the lowest nominal retention force and none occurred in the receptacles having the non-modified retention force. The limited data indicates that the looser the plug connection, the more likely for a failure event to occur.

Table 2-20. Summary of Receptacle Events with Respect to Nominal Plug Retention Force (@ 15A).

Terminal Configuration	Number of Failure Events	Failure Rate (failures/year)	Min. Time to Event (days)	Max. Time to Event (days)	Avg. Time to Event (days)	Std. Dev. of Time to Event (days)
0.01 Kg	4	0.05	62	268	156	78
0.1 kg	1	0.02	62	62	62	-
Non-Modified	0	-	-	-	-	-
All	5	0.04	62	268	137	79

2.3.7.3.3 Electrical Load

The majority (450) of receptacles were tested at a current of 15A. The remaining 78 receptacles were tested at a current of 3A for 90 days, 6A for 114 days, and 9A for 192 days. None of the receptacles at a current of 6A or lower had any failure events due to overheating. In fact, only one receptacle showed signs of oxide formation at a current of 6A or less. This polypropylene receptacle (LEV212), with ¼ turn loose terminals, was installed in a box with a faceplate. After the current was increased to 9A, approximately half of the receptacles having torques of 1 in-lb and the ¼ turn loose configuration began to exhibit signs of overheating. Receptacles tested at 9A and lower included PVC and polypropylene receptacles, with 1 in-lb and ¼ turn loose connections. One receptacle (PSE216), after 190 days at 9A current, had a severed conductor failure event. This was the only failure event to occur at 9A or less.

Not only does the magnitude of the electrical load appear to have an effect on the development of overheating connections, but the application of that load also had an effect. Three different load applications were used in this test series: continuous load, load with cycling (1 hour off each morning), and a high startup current load. These loads are described in detail in Section 2.1.3. With the exception of the vibrating test rack, the power cycling load was applied for a portion of the test durations for Test Racks 2 and 4 through 7 (see Appendix A). The continuous load was applied to Test Rack 1 for a period of 204 days before the power cycle load was applied. In this 204 day time period, only four receptacles (all at 1 in-lb) overheated to the point of failure. The receptacles on this test rack were modified, in part, after the continuous loading period; receptacles with terminal torques of 3 in-lb and higher were changed to either 1 in-lb or the ¼ turn loose configuration. Of the non-modified receptacles (LEV023, 1 in-lb), only one more overheated to the point of failure approximately 36 days after power cycling was initiated.

The power cycling appeared to have an effect on the formation of overheating connections leading to failure events. Series arcing at overheating terminal connections was often heard and/or seen as the power was cycled on. In some cases, the arcing was accompanied by glowing. It is likely that the current surge that occurs when the power is turned on thermally shocks the cool connections such that arcing occurs. There is limited directly comparable data to support the assertion of the impact of power cycling. The only failure events that occurred prior to the power cycling were for 1 in-lb connections. There was failure of one receptacle (LEV023) with 1 in-lb connections that occurred in the test rack that had both periods with power cycling and periods without power cycling. And there were only two other receptacles (E004 and C008) that were never subjected to continuous load (i.e., only subjected to power cycling) and had terminal torques of 1 in-lb that overheated to the point of failure.

The high startup current load was only used on Test Rack 7; this test rack only contained receptacles with loose plug connections. The high startup current load application began after 112 days of normal testing (i.e., 15A current with power cycling) and continued for an additional 78 days. Only one of the receptacles exposed to the high startup current load overheated to the point of failure. This failure event occurred after 71 days of the high startup current application. Receptacle LEV286 experienced a flaming ignition event as the high startup current was applied. A description of this event is located in Section 2.3.4.1. Within the limited testing, the high startup current did not have a distinct measurable effect on the formation of overheating connections. However, in the case of LEV286 it does appear that the application of the high startup current load at the time when this receptacle was overheating was the cause for the receptacle transitioning to flaming ignition.

2.3.7.3.4 Vibration

A limited number of receptacles were subjected to daily vibration. For these receptacles, the electrical load was left on continuously. No plug connections were tested with vibration, nor were any receptacles installed in outlet boxes with faceplates. Table 2-21 lists the minimum, maximum, average, and standard deviation of the time to failure for receptacles as a function of both the terminal configuration and the use of vibration. For the receptacles not subjected to vibration, only those that were not installed in outlet boxes with faceplates and not plug connections are reported in Table 2-21. Only one of the failure events actually occurred as the test rack was vibrating; this receptacle shorted between the hot receptacle contacts and the grounding strap. The remainder of failure events occurred during periods without vibration. Vibration did not affect connections with torques of 3 in-lb. The only instances of overheating and failure of back-wired push-in connections were observed when vibration was applied (see Section 2.3.1.2). Twenty-two receptacles with back-wired push-in connections were installed on the test rack with vibration. Twenty back-wired receptacles were evaluated on racks without vibration.

The results indicate that vibration of the receptacles had a significant effect on the likelihood of failure occurring, but not the time to failure. Receptacles with the ¼ turn loose configuration (<< 1 in-lb) overheated to the point of failure at a much higher rate of 2.5 failures/year when subjected to vibration compared to only 0.69 failures/year for those not subjected to vibration. The receptacles not subjected to vibration had failures occur both for much shorter and much longer time periods than the entire range of failure events for receptacles subjected to vibration. The average time to failure event was not significantly different between receptacles with vibration and those without.

None of the 14 receptacles with 1 in-lb connections subjected to vibration had overheating leading to receptacle failure events compared to eight failure events for 1 in-lb receptacles not subjected to vibration (these values do not include events occurring for receptacles in boxes or receptacles with plug connections). The occurrence of less receptacle failures with vibration than without is notable in that it is the opposite of what occurred for the ¼ turn loose receptacles. The duration of vibration (223 days) was comparable to the longest time to failure for a 1 in-lb connection (255 days). Due to the limited number of failure events for receptacles with 1 in-lb connections, the lack of observable impacts of vibration on 1 in-lb connections should not take away from the impact observed for ¼ turn loose connections.

Table 2-21. Summary of Receptacle Events with Respect to Vibration (@ 15A).

Vibration Condition	Terminal Configuration	Number of Failure Events*	Failure Rate (failures/year)	Min. Time to Event (days)	Max. Time to Event (days)	Avg. Time to Event (days)	Std. Dev. of Time to Event (days)
With Vibration	¼ Turn Loose	13	2.5	59	243	117	58
	1 in-lb	0	0	-	-	-	-
	3 in-lb	0	0	-	-	-	-
	Back-wired (1 insertion & removal cycle)	1	0.07	341	341	341	-
	All	13	-	59	243	117	58
Without Vibration	¼ Turn Loose	47	0.69	5	365	162	118
	1 in-lb	8	0.13	115	255	189	48
	≥3 in-lb	0	0	-	-	-	-
	Back-wired	0	0	-	-	-	-
	All	55	-	5	365	166	111

* These values do not include events occurring for receptacles in boxes or receptacles with plug connections.

3.0 FIRE EXPOSURE TESTING

Two different fire exposures were used to subject receptacles to various levels of heating, including various compartment fires and an intermediate scale furnace. The purpose of the fire exposure testing was to assess the damage and potential forensic signatures of a wide range of electrical receptacle configurations when exposed to fire. Eight wall assemblies containing 36 receptacles each were constructed for the compartment fire testing. Five wall assemblies containing 36 receptacles each were constructed for the furnace fire testing. A summary of the compartment and furnace fire exposure tests are shown in Appendix B and C, respectively. A total of 468 test trials were conducted with 468 receptacles. A complete summary of each receptacle tested in the fire exposure tests can be found in Appendix H.

All of the furnace fire testing was conducted at the Hughes Associates, Inc. laboratory in Baltimore, MD. The compartment fire exposure testing was conducted at the Bureau of Alcohol, Tobacco, and Firearms and Explosives (ATF) Fire Research Laboratory (FRL) located at the National Laboratory Center in Beltsville, Maryland. Forensic examinations of receptacles and plugs were conducted in the HAI examination laboratory. SEM examinations and Fourier Transform Infrared Spectroscopy (FTIR) analysis were conducted at the Travelers Insurance Engineering Laboratory in Windsor, Connecticut.

3.1 Experimental Design

3.1.1 Compartment Fire Tests

The compartment fires were conducted in conjunction with a separate project [Mealy and Gottuk, 2013]. The fuel packages and ventilation conditions were selected based on the other project's needs, but yielded a wide range of exposures. The furnace fire exposures were conducted as stand-alone tests for this project. As such, the exposure duration and imposed temperature curve (i.e., fire exposure) were selected based on their impact on this project. The parameters governing the compartment fires and furnace fire exposures will be discussed in the following sections. A summary of each compartment fire test can be found in Appendix B.

3.1.1.1 Compartment Fire Configuration

The construction and layout of the compartment used in this testing can be found in Section 2.2 with additional details by Mealy and Gottuk [2013]. The compartment fires consisted of three fuels: the flooring material, Class A furnishings, and flammable liquid accelerants. The fuels used in the compartment fires were typical of what is found in a residential setting. The Class A fuels evaluated included an upholstered sofa, an upholstered chair, a coffee table, and plastic baby car seats. The materials used in the Class A fuels included polyurethane foams, polyester wadding, cotton upholstery, particle board, oriented strand board (OSB), and other plastics. The substrates used for the compartment fire testing included vinyl flooring over plywood and carpet/padding over plywood. The compartment had two ventilation configurations: full door and slit vent. The full vent was 0.9 m (36 in.) wide and 2.0 m (80 in.) tall, while the slit vent was 0.2 m (8 in.) wide and 2.0 m (80 in.) tall. These vents were selected because they represent typical ventilation schemes in residential compartment fire scenarios. In order to vary the thermal exposure within each test, receptacles were placed at nominal heights of 0.45 m (1.5 ft), 1.2 m (4.0 ft), and 2.0 m (6.5 ft) within the compartment. Some receptacles used in the compartment fires had extension cords plugged in to the top outlet. The flammable liquid used to initiate the compartment fires was gasoline. Table 3.1 is a summary of the relevant test parameters and heat release rate (HRR) from the compartment fire testing [Mealy and Gottuk, 2013]. In the compartment fire testing, the receptacles were not placed near the Class A combustibles in the room such that direct flame impingement on the receptacles was reduced. This was done to eliminate any interference of the receptacles with the other project and also because it was expected that further from the fire source, the temperatures would be relatively constant at any one elevation. This would ensure that all receptacles at the same elevation would nominally receive the same thermal exposure.

Table 3-1. Summary of Compartment Fire Tests [Mealy and Gottuk, 2013].

Test ID	Ventilation Configuration	Primary Spill Location	Flooring Material	Peak HRR (MW)	Time to Peak HRR (s)	Test Duration (s)
6-1	Full Door	Floor	Carpet	6.3	218	260
6-2	Slit Vent	Floor	Carpet	0.9	272	480
6-3	Full Door	Upholstered Chair	Carpet	7.2	158	264
6-4	Slit Vent	Upholstered Chair	Carpet	1.8	723	713
6-5	Full Door	Floor	Vinyl	5.0	64	186
6-6	Slit Vent	Floor	Vinyl	1.1	221	506
6-7	Full Door	Upholstered Chair	Vinyl	3.7	121	190
6-8	Slit Vent	Upholstered Chair	Vinyl	0.9	139	566

3.1.1.2 Wall Assembly Construction

Receptacles in the compartment fire tests were located in a partial wall assembly placed in the test compartment as shown in Figure 3-1. The general arrangement of the combustible loading in the compartment is also shown in Figure 3-1. Each wall assembly was located in the second and third stud-bays from the front right corner of the room. The wall assembly was constructed of 2 by 4 inch dimensional lumber (i.e., studs) with the majority of receptacles enclosed with lumber on four sides as shown in Figure 3-2. Receptacles on the outside of the wall assembly were enclosed on three sides (i.e., top, bottom, and inner boundaries) with lumber and the outer boundaries were covered with 12.7 mm (0.5 in.) thick gypsum wall board. The wall assembly was enclosed on the front and back surfaces with 12.7 mm (0.5 in) thick gypsum wall board effectively isolating each receptacle. No insulation was used within the wall cavity. Seams between the wall assembly and the compartment were sealed using 3M intumescent fire barrier sealant (IC 15WB+).

Sets of twelve receptacles were installed at nominal heights of 2.0 m (6.5 ft), 1.2 m (4.0 ft), and 0.45 m (1.5 ft) as shown in Figure 3-3. For convenience, a numbering scheme was used to identify the location of receptacles within the wall assembly. Groups of three receptacles were given a letter designation from A to L. Within these groups, receptacles were numbered 1 through 3 as noted in Figure 3-3. Outlet boxes were attached to the vertical studs using two built-in nails. The receptacles were mounted to the outlet boxes using two machine screws and oriented such that the grounding slot was at the bottom of each outlet. Receptacles were spaced approximately 12.7 cm (5.0 in.) on center horizontally and approximately 15.2 cm (6.0 in.) on center vertically. Vertical pairs of receptacles (e.g., B3 and D3, F3 and H3, etc.) were centered at 2.0 m (6.5 ft), 1.2 m (4.0 ft), and 0.45 m (1.5 ft) heights. Wiring for each of the receptacles exited the back of the wall assembly through individual 1.2 cm (0.5 in.) unsealed holes.

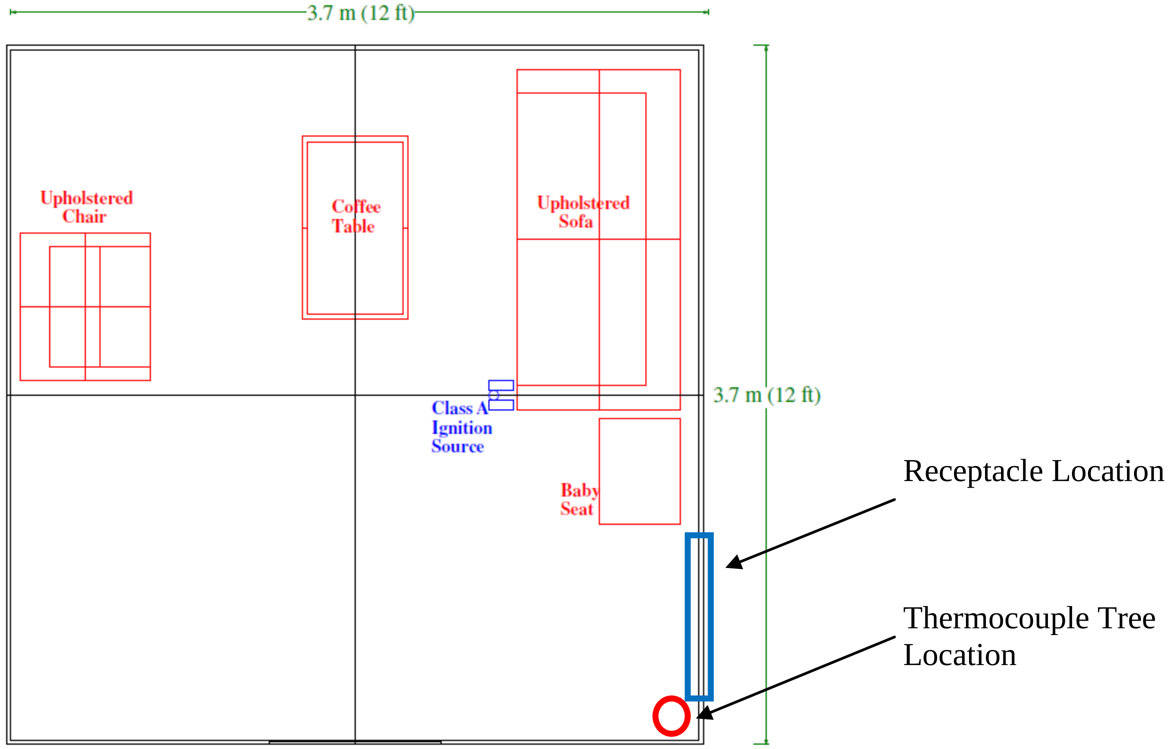


Figure 3-1. Test compartment and location of receptacles.

Figure 3-2. Typical outlet box installation for Test 1 (left) and Tests 2 through 8 (right).

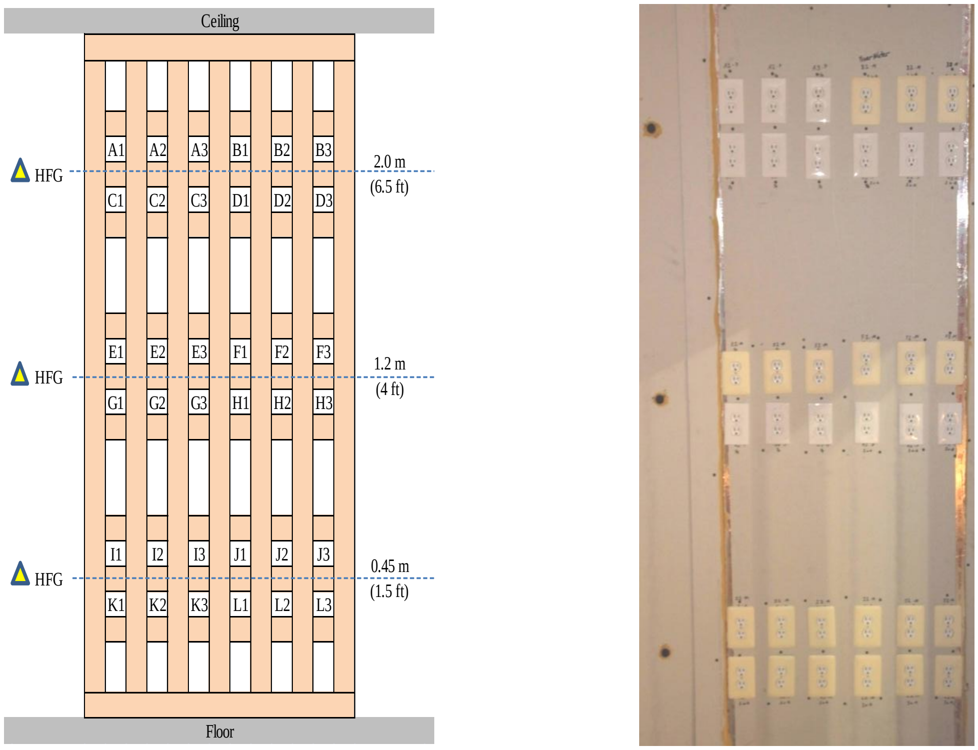


Figure 3-3. Diagram and photograph of receptacles in wall assembly (inside view).

The construction of the wall assemblies for Tests 1, 2, and 3 differed slightly from that noted above. Changes in the construction were intended to make the construction process more efficient and to increase uniformity. For Test 1, there were four notable differences. First, each receptacle was enclosed on only three sides by 2 by 4 dimensional lumber (see Figure 3-2). Second, there was no separation between vertical pairs of receptacles (i.e., between A1 and C1, E1 and G1, etc.). Third, all electrical wiring for the receptacles in Test 1 was run down a 12.7 mm (0.5 inch) channel between the outside sheet of gypsum wall board and 2 by 4 lumber construction. And finally, receptacles in Test 1 were installed at heights of 1.8 m (6.0 ft), 1.2 m (4.0 ft), and 0.6 m (2.0 ft). For Test 2, every receptacle was enclosed on all four sides using 2 by 4 dimensional lumber. Also, the inner and outer gypsum wall board panels used for Test 2 were 15.9 mm (0.625 in.) thick rather than 12.7 mm (0.5 in.) panels which were used for the other tests. In addition, a portion of the receptacles in Test 2 were installed upside down such that the grounding slot was located at the top of each outlet. Some of the outlet boxes in Test 3 were installed such that their front edge projected approximately 3 mm (0.125 in.) past the surface of the inside panel of gypsum wall board. This created gaps between the faceplates and the gypsum wall board which were sealed using 3M intumescent fire barrier sealant (IC 15WB+).

3.1.1.3 Receptacle Power

A stand-alone 40 slot, 200A load center (circuit breaker panel) manufactured by Square-D was assembled to provide power to the energized receptacles for both the compartment fire testing and furnace testing. Each energized receptacle was connected to a separate 15A circuit breaker (Square-D model HOM115). Each circuit breaker was wired with a 0.6 m (2.0 ft) section of 12/2 NM sheathed cable routed outside of the load center and terminating in a female plug. Extension cords were used to connect the receptacles to the load center. Each energized receptacle with a load had two 14/2 NM sheathed cables wired to the screw terminals which exited the back of the wall assembly. One cable terminated with a male plug for connection to the load center and the other terminated with a female plug for connection to the heater used for the electrical load. A maximum of 12 heaters were used for a single test. Each energized receptacle had two 14/2 NM sheathed cables wired to the screw terminals which exited the back of the wall assembly. One cable terminated with a male plug for connection to the load center and the other terminated with a wire nut used on each conductor such that both cables were energized. Each non-energized receptacle had two 14/2 NM sheathed cables wired to the screw terminals which exited the back of the wall assembly. Both cables terminated after a short length outside of the wall assembly with no connections.

In the fire exposure tests, each receptacle was in one of three electrical states: non-energized, energized without a load, or energized with a load. These are the three possible states that a receptacle could be in at the time of a fire. Non-energized receptacles were used as a control to determine whether thermal effects could produce damage that resembled electrical damage (i.e., false positive indicators). Energized receptacles both with and without loads were used to evaluate the potential for arcing due to the fire exposures and whether arcing in these states produced different evidence. The electrical loads used in the fire exposure testing were Warmwave 1500W portable electric heaters (models HFQ15A and HPG15B-M). The nominal current draw from the heaters was between 6 and 7A.

3.1.1.4 Extension Cord Installation

In Tests 6, 7, and 8 the bottom row of six receptacles was outfitted with extension cords plugged in to the bottom outlet of each receptacle. The extension cords were located inside of the compartment and arranged such that adjacent cords were not touching. The extension cords were placed on the floor of the compartment with a single loop in the wiring approximately 0.46 m (1.5 ft) down the length of the cord from the receptacle (see Figure 3-4). The loop was used to reduce the floor space taken up by the cords as well as to create a potential arcing location (i.e., where the cord overlaps itself).

Figure 3-4. Location and arrangement of extension cords in compartment.

3.1.1.5 Instrumentation

A comprehensive description of the instrumentation used in the compartment fire tests can be found in the test report from Mealy and Gottuk [2013]. A subset of this instrumentation is described herein. A temperature tree, comprised of nine thermocouples spaced at 0.3 m (1 ft) intervals, was installed at the location within the test enclosure noted in Figure 3-1. The points of measurement (i.e., beads) were located 0.15 m (6 in.) from both walls of the test enclosure to minimize the effect of the wall boundary. The bottom and top thermocouples in the tree were located 2.5 cm (1 in.) from the floor and ceiling, respectively. The temperature tree was located approximately 0.76 m (30 in.) from the centerline of the receptacle wall assembly.

Heat flux measurements were taken at various locations throughout the compartment. Three of these measurements were collected from the center of the rear wall directly opposite the ventilation opening. Measurements in the rear wall were at elevations of 0.6, 1.2, and 1.8 m (2.0, 4.0, and 6.0 ft). For Tests 2 through 8, three wall heat flux measurements were collected on the right wall of the test enclosure near the receptacle wall assembly. These measurements were located 1.4 m (4.5 ft) from the front wall of the test enclosure at elevations of 0.45, 1.2, and 2.0 m (2.5, 4.0, and 6.5 ft). All heat flux measurements were collected using water-cooled, Schmidt-Boelter type, heat flux transducers. Rear wall transducers had a range of 0 to 200 kW/m^2 (Medtherm model 64-20SB-19) and right wall transducers had a range of 0 to 150 kW/m^2 (Medtherm model 64-15SB-19). Digital photographs were taken before, during, and after testing as needed.

3.1.1.6 Data Acquisition

Data for compartment fire tests was recorded using the existing ATF FRL data acquisition system. Control of test equipment and acquisition systems was achieved using iFix Intellution, a Supervisory Control and Data Acquisition system (SCADA). The data collection and cataloging was performed through FireTOSS, a software package unique to the ATF FRL. Instrumentation was connected to the SCADA using Yokogawa DA 100 and DS 600 data acquisition units. A sampling frequency of 1 Hz was used for all tests. A standard camcorder captured video of the load center to determine when the individual circuit breakers tripped.

For Tests 5, 6, and 8, a Hioki Power Quality Analyzer (Model PW3196) was used to measure and record the current and voltage waveforms for four receptacles. Table 3-2 lists the specific receptacles for Tests 5, 6, and 8 which were monitored by the PW3196. Clamp-on current transducers and wired voltage probes were used on the hot conductors between the load center and the receptacle. The PW3196 operates by continuously monitoring the 8 channels at a rate of approximately 200 kHz and recording a waveform of 16 cycles (approximately 0.267 seconds) for each channel at the time of an event. Only events indicative of arcing were selected in order to minimize erroneous data. Events included current spikes (parallel arcing), voltage drops (circuit breakers operating), and current drops (circuit breakers operating).

Table 3-2. Summary of Receptacles That Were Monitored by the Hioki PW3196.

Test	Receptacle S/N	Receptacle Location	Hioki Channel
5	PSE248	E-1	1
	PSE249	E-2	2
	LEV253	F-1	3
	LEV254	F-2	4
6	B010	B-1	1
	B011	B-2	2
	B012	B-3	3
	C019	D-1	4
8	PSE318	A-1	1
	PSE319	A-2	2
	LEV323	B-1	3
	LEV324	B-2	4

3.1.2 Intermediate Scale Furnace Testing

The purpose of the furnace testing was to assess the damage and potential forensic signatures of a wide range of electrical receptacle configurations in a fire condition that may lead to melting of metal components. Five wall assemblies containing 36 receptacles each were constructed for the furnace testing. A total of 180 test trials were conducted with 180 receptacles. A summary of each furnace test can be found in Appendix C.

The furnace allowed for the exposure of the receptacles, in a controllable manner, to higher temperatures than those obtained in the compartment fire testing. In addition to the goals of the compartment fire testing, the purpose of the furnace testing was to create false-positive indication of arcing and to mask evidence of arcing by causing the copper and brass conductors to melt. The melted components were then forensically analyzed and compared to incidents of electrical arcing and overheating connections in receptacles. The primary metal components in receptacles and plugs are brass, copper, and steel with melting temperatures of 930ºC, 1080ºC, and 1500ºC, respectively. These temperatures are at the higher end of the range of temperatures expected in a compartment fire. Time-averaged gas temperatures in a compartment fire rarely exceed 1300ºC [Walton and Thomas, 2008]. Maximum furnace temperatures of 1000ºC and 1250ºC were selected to provide exposures that were projected to melt the brass and copper components, respectively. The furnace was controlled such that the average furnace temperature reached 1000ºC within 6 minutes, with durations between 13 and 15 minutes.

3.1.2.1 Furnace Description/Construction

The HAI intermediate scale furnace is a premixed, natural gas fed, forced air furnace. Typically this furnace is used for standard fire exposures of structural elements. The outside of the furnace is constructed of 0.6 cm (0.25 in.) thick steel plate and angle iron pieces. The overall exterior dimensions are 1.2 m (4.0 ft) wide, by 1.5 m (5.0 ft) tall, by 1.06 m (3.5 ft) deep. The interior of the furnace is lined with 15.2 cm (6.0 in.) thick rigid ceramic fiber insulation. The overall interior dimensions are 0.9 m (3.0 ft) wide, by 1.2 m (4.0 ft) tall, by 0.9 m (3.0 ft) deep.

Two burners are used to create a nearly uniform temperature within the furnace. One burner is located at the bottom front of the right side of the furnace; the second burner is located at the bottom rear of the left side of the furnace. The furnace exhaust is located nominally in the center of the rear side of the furnace, opposite the vertical sample location. A negative pressure was generally maintained throughout operation of the furnace in order to limit the smoke emitting from the test sample into the laboratory space. A photograph of the furnace used in this test series is shown in Figure 3-5. The negative pressure within the furnace was kept low in order to minimize effects on combustion of the wall assembly.

Figure 3-5. Photograph of intermediate scale furnace.

3.1.2.2 Wall Assembly Construction

The frame wall assemblies used for furnace testing were constructed in a similar manner as those used for the compartment fire testing. The wall assembly was constructed of 2 by 4 inch dimensional lumber (i.e., studs) with each receptacle enclosed with lumber on four sides, except as shown in Figure 3-2. The wall assembly was enclosed on the front and back surfaces with 15.9 mm (0.625 in.) thick gypsum wall board effectively isolating each receptacle. The wall assembly had overall dimensions of 1.2 m (4.0 ft) wide by 1.5 m (5.0 ft) tall. Holes in the non-exposed side of the wall assembly were the minimal size necessary for the passage of wiring and instrumentation. The receptacles were centered in the exposed portion of the wall assembly as shown in Figure 3-6. Bracing consisting of 2 by 4 nominal lumber was screwed to the top, middle, and bottom of the back of the wall assembly to facilitate securing the wall assembly to the furnace. No insulation inside of the wall cavity was used. A layer of 2.5 cm (1.0 inch) thick Fiberfrax ceramic fiber insulation was placed between the furnace and the wall assembly. The Fiberfrax was used to prevent smoke or flames from exiting at the interface of the furnace and wall assembly. The same load center that was used for the compartment fire testing (see Section 3.1.1.3) was used for the furnace fire testing.

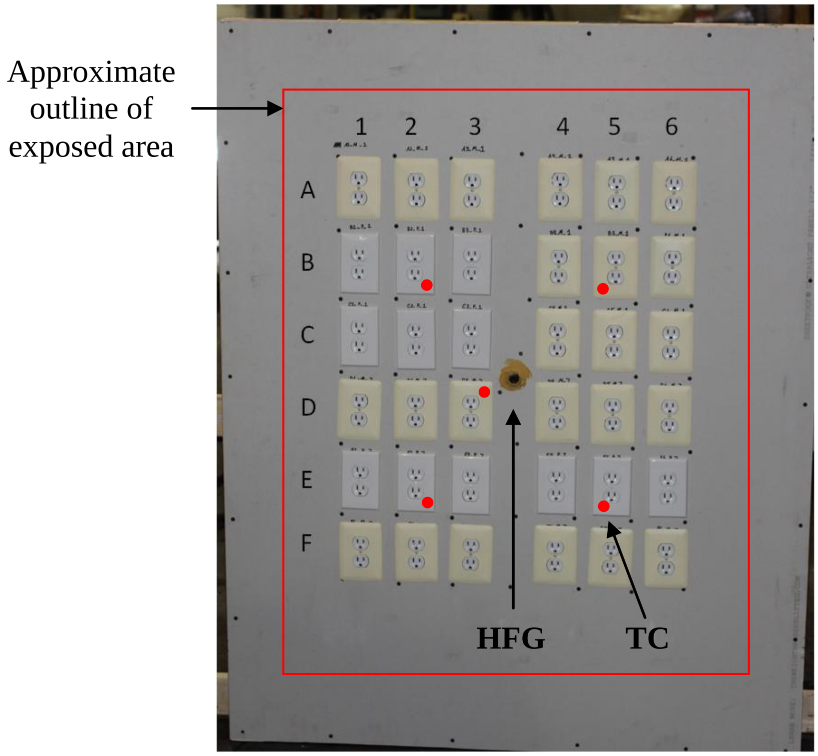


Figure 3-6. Photograph of wall assembly, elevation view, showing location of instrumentation and approximate outline of the exposed area.

Receptacles were placed in a grid such that they were spaced approximately 12.7 cm (5.0 in.) on center horizontally and approximately 15.2 cm (6.0 in.) on center vertically. Outlet boxes were attached to the vertical studs using two built-in nails. The receptacles were mounted to the outlet boxes using two machine screws supplied with the receptacle and oriented such that the grounding slot was at the bottom of each outlet. For the furnace fire testing, all of the receptacles were installed in metal boxes. Only metal boxes were used because at the elevated temperatures in these tests, it was assumed that using plastic boxes would make identification of the receptacle remains very difficult and possibly allow the receptacles to fall out of the wall assembly and into the furnace; the steel outlet boxes provided more robust mounting method for the receptacles. For convenience, a numbering scheme was used to identify the location of receptacles within the wall assembly. Rows were identified by letters and columns by numbers. Receptacles were referred to using a row-column ID (e.g., A1, A2… F5, and F6).

A limited set of receptacles which had previously experienced overheating connections (i.e., potential fire cause receptacles) were exposed to the furnace fire test. This testing allowed the examination of whether actual evidence of overheating connections would persist after a severe fire exposure. Receptacles with various levels of previous damage were evaluated including: oxidized connections, welded conductors, enlarged screw heads, receptacles with glowing connections, receptacles which shorted, and receptacles having flaming ignition. These receptacles were installed in the wall assembly in the same manner as exemplar receptacles. However, there were some cases where prior melting of the receptacle prevented the installation of a faceplate. In these limited cases, some plastic had to be removed around the faceplate mounting screw in order to install the faceplate. The amount of plastic removed was minimized and was not likely to have affected the test in any way. Wire sections with arc beads from prior fire exposure testing were installed in a 5.0 cm (2.0 in.) layer of ceramic fiber board (Duraboard) fastened inside of the box and secured with a high temperature cement (Omega OB-600). A photograph of the wire sections is shown in Figure 3-7. The arc bead was approximately flush with the front edge of the outlet box (approximately 1.1 cm (0.5 in.) from the surface of the ceramic insulation).

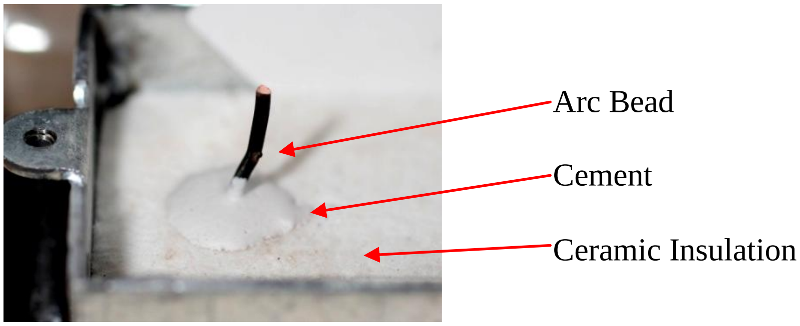


Figure 3-7. Photograph of typical installation of wire sections with arc bead.

3.1.2.3 Instrumentation

Instrumentation for the furnace testing included thermowells to measure furnace gas temperature, furnace pressure at one elevation, a heat flux (HFG) at one elevation, and thermocouples (TCs) to measure the temperature inside the wall assembly adjacent to five of the receptacle boxes. Furnace gas temperatures were measured at five locations 15.2 cm (6.0 in.) in front of the vertical wall assembly using closed thermocouple probes described in ASTM E119. The furnace thermocouples were located with one in the center of the exposed area and one in the center of each quadrant of the exposed area. Furnace pressure was measured 0.3 m (1.0 ft) below the top of the sample using pressure probes as specified in ASTM E119. Furnace pressure was measured using Setra model 264 bi-directional pressure transducers with a ±62 Pa range and accuracy of 0.33% full-scale. A water-cooled, Schmidt-Boelter type, heat flux transducer was placed nominally in the center of the receptacles with the face flush with the gypsum wall board (see Figure 3-6). For thermal protection of the data lines, the heat flux transducer was placed inside of a 15.2 cm (6.0 in.) long, 1 inch nominal diameter pipe and sealed with 3M intumescent fire barrier sealant (IC 15WB+). The heat flux transducer had a range of 0–200 kW/m^2 (Medtherm model 64-20SB-19). Temperatures adjacent to receptacle boxes were measured using closed bead, Type K, ungrounded, inconel sheathed thermocouples. Five thermocouples were positioned inside of the wall cavity near receptacles B2, B5, D3, E2, and E5 as shown in Figure 3-6. The location of these thermocouples roughly corresponded to the locations of furnace thermocouples. Wall cavity thermocouples were located such that the risk of contact with energized wiring and receptacle boxes was minimized. Digital photographs were taken before, during, and after testing as needed.

3.1.2.4 Plug Installation

In furnace fire Tests 4 and 5, the bottom row of 6 receptacles was outfitted with extension cords plugged in to the bottom outlet of each receptacle. The extension cords were located inside of the furnace and arranged such that adjacent cords were not touching. A layer of ceramic fiber insulation was placed over top of the cords inside of the furnace (see Figure 3-8). Because the furnace temperatures were expected to be above the melting point of copper for an extended period, the insulation was used to preserve a section of the wiring such that there would be something left to examine. Beneath the insulation, the cords were coiled and separated such that they were not touching. Approximately 0.6 m (2.0 ft) of the extension cord was left exposed.

Figure 3-8. Location and arrangement of extension cords in furnace (left) and insulation placement (right).

3.1.2.5 Data Acquisition

All test data was recorded using a National Instruments SCXI data acquisition chassis and LabView data acquisition software. All data channels were sampled and recorded at a rate of 1 Hz. Ambient temperature and relative humidity were recorded prior to the test commencing.
A standard digital camcorder captured video of the load center to determine when the individual circuit breakers tripped. The video recording was synced with the data acquisition system at the time of ignition.

3.2 Experimental Procedures

A complete description of the procedures and calibration methods for the compartment fire tests, excluding the receptacle wall assemblies, can be found in Mealy and Gottuk [2013]. Section 3.2.1.1 outlines the relevant test procedures for the compartment fire tests with respect to the receptacle wall assemblies. Section 3.2.2.1 outlines the relevant test procedures for the furnace fire tests.

3.2.1 Compartment Fire Testing

3.2.1.1 Test Procedures

A series of eight compartment fire tests were conducted with 36 receptacles installed in a wall assembly. The wall assembly was constructed independent of the compartment as described in Section 3.1. After its construction, the wall assembly was secured to the compartment wall vertical wood studs and seams between the wall assembly and the compartment walls were sealed. Receptacle screw connections were then tightened to the specified torque using the method outlined in Section 2.1.2.1. For receptacles in the compartment fire testing, the ground wire was attached to the grounding screw and securely tightened. It should be noted that the screw terminals for receptacles in the wall assembly used for compartment fire Test 1 were tightened prior to transportation of the wall assembly to the test facility. For compartment fire Tests 6, 7, and 8, some pre-test measurements of nominal retention force and terminal loosening torque were taken for each receptacle. The nominal retention force for each terminal (Tests 6 and 8) was measured using the method described in Section 2.1.2.3. In order to assess the effect of installing the receptacle in the outlet box on the terminal torque, the loosening torque for each terminal was measured before installation in the box (Tests 7 and 8) and after the receptacle was installed and removed from the box (Tests 6, 7, and 8) using the method described in Section 3.2.3.1. After the first torque measurement, each screw terminal was retightened to the specified torque using the method outlined in Section 2.1.2.1. Once the terminals were properly tightened, the specified faceplates were installed on the receptacles and the wall assembly was photographed.

Prior to each test, all instrumentation was checked for operability using the data acquisition system. The main breaker for the test panel and the individual circuit breakers were first confirmed to be in the "OFF" position before plugging in any receptacle wiring. The wiring for each receptacle was then plugged in to the appropriate circuit breaker. Heaters, where required, were then plugged in to the appropriate receptacle wiring. At this point, the circuit breaker and heater numbers were recorded for each receptacle. All circuits were energized (i.e., main breaker and individual breakers set to the "ON" position) approximately 10 minutes prior to ignition to allow the heaters time to warm up. Heaters were set as shown in Figure 3-9 and the current draw for each heater was recorded. After the fuel for a given test was measured, all video cameras were activated. Once the recording of all video cameras was verified, the data acquisition system was initiated and the fuel was poured and ignited. The video recording and data acquisition systems at ATF FRL were synced to a common time source. In addition, the time of ignition with respect to start time for the data acquisition system was recorded.

Figure 3-9. Heater setting for compartment fire tests.

The compartment fire was permitted to grow and burn naturally. The video camera covering the circuit breaker panel recorded individual activation of the circuit breakers (i.e., tripping) as the fire progressed. The ventilation scheme remained fixed during all tests. Test duration varied based on a variety of parameters. With the exception of the first test, tests involving full-door ventilation were permitted to burn for an additional 60 to 120 seconds after the doorway plume was ignited. The first test was allowed to burn for 300 seconds (5 min.) after ignition of the doorway plume. For tests involving the slit ventilation scenario, the fires were permitted to burn for between 8 and 12 minutes. The compartment fire test durations are listed in Table 3.1. At the end of the tests, the main circuit breaker was turned to the “OFF” position de-energizing all circuits and manual suppression was achieved using a 2.5 inch manual water hose line. During manual suppression, care was exercised to limit the amount of water sprayed in the direction of the receptacle wall assembly.

3.2.1.2 Sample Recovery Procedures

After the manual suppression was complete and the compartment was secured, sample recovery procedures were begun. First, all heaters were unplugged from the receptacles and all receptacles were unplugged from the circuit breaker panel. A photograph of the circuit breaker panel was taken to document which breakers had tripped at the end of the test. Additional photographs of the interior and exterior of the wall assembly were taken to document the conditions at the end of the test. Each cord exiting the exterior of the wall assembly was cut as close to the exterior surface of the wall assembly as possible to facilitate easier transport from the test facility to the examination facility. The entire wall assembly was then removed from the compartment wall in one piece and transported to the examination facility where it was again photographed.

At the examination facility (i.e., the Hughes Associates office in Baltimore, MD), the wall assembly was disassembled such that each individual receptacle was separated from the rest. First, the drywall was removed from the front and rear faces of the wall assembly. Then, the wood stud frame was disassembled. At this point, groups of several receptacles were still attached to the same studs. A band saw was used to cut the wood studs and separate the receptacles. Each receptacle remained attached to approximately 15.2 cm to 20.3 cm (6.0 to 8.0 in.) of the wood stud. The disassembly process was conducted in a careful manner to ensure the receptacles were not damaged during the process. The receptacles attached to the wood studs were placed in individual, labeled plastic bags and stored for later examination and documentation. Examination and documentation were conducted in accordance with Section 3.2.3.1.

3.2.2 Intermediate Scale Furnace Testing

3.2.2.1 Test Procedures

A series of five intermediate scale furnace fire tests were conducted with 36 receptacles installed in a wall assembly. The wall assembly was constructed as described in Section 3.1.2.2. After its construction, receptacle screw connections were then tightened to the specified torque using the method outlined in Section 2.2.1. For receptacles in the furnace fire testing, the ground wire was attached to the grounding screw and securely tightened. For furnace Test 1, some pre-test measurements of nominal retention force and terminal loosening torque were taken for each receptacle. The nominal retention force for each terminal was measured using the method described in Section 2.1.2.3 In order to assess the effect of installing the receptacle in the outlet box on the terminal torque, the loosening torque for each terminal was measured before installation in the box and after the receptacle was installed and removed from the box using the method described in Section 3.2.3.1. After the first torque measurement, each screw terminal was retightened to the specified torque using the method outlined in Section 2.2.1. Once the terminals were properly tightened, the specified faceplates were installed on the receptacles and the wall assembly was photographed. The wall assembly was then secured and sealed to the furnace.

Prior to each test, all instrumentation was checked for operability using the data acquisition system, the gas line to the furnace was purged with nitrogen, the furnace was confirmed to be grounded. The main breaker for the test panel and the individual circuit breakers were first confirmed to be in the "OFF" position before plugging in any receptacle wiring. The wiring for each receptacle was then plugged in to the appropriate circuit breaker. Next, all individual circuit breakers were turned to the "ON" position. The exhaust systems for the test space and the furnace were initiated and the natural gas valves were confirmed to be closed. Before ignition, video recording was started, the furnace spark igniters were turned on, and the main circuit breaker was turned to the "ON" position. At this point, the receptacles were energized. At the time of ignition, data acquisition started and the video was synchronized using a camera flash. The video camera covering the circuit breaker panel recorded individual activation of the circuit breakers (i.e., tripping) during the test. The spark igniters were de-energized after ignition was visually confirmed through the viewports in the furnace burners. During the test, the furnace temperature was manually adjusted in accordance with the prescribed time-temperature curve by regulating the natural gas pressure. A negative pressure inside of the furnace was maintained throughout the test by manipulating the furnace exhaust damper. Tests were run for between 12 and 15 minutes before the gas flow was terminated. After gas flow was terminated, the main circuit breaker was turned to the "OFF" position de-energizing all circuits and video recording was stopped. In furnace Test 2, nitrogen was pumped into the furnace for two minutes after the test ended in an attempt to inert and cool the environment. This had minimal effect and was not repeated in later tests.

3.2.2.2 Removal and Sample Recovery Procedures

After test power was de-energized, wall assembly instrumentation was disconnected and the wall assembly was removed from the furnace. In general, the removal process took between 2 and 3 minutes to complete. At this time, a sheet of 1.6 cm (0.625 in.) drywall was placed over the furnace opening to block heat from the furnace onto the wall assembly. Residual burning of the wall assembly was extinguished using targeted application of water from a handheld hose line. In general, extinguishment of flames took about one minute with smoldering wood studs extinguished in an additional 4 to 5 minutes. The panel remained underneath the exhaust hood for a minimum of 3 hours in order to cool. Once the panel had cooled enough to handle, it was disassembled in the same manner as described in Section 3.2.1.2.

3.2.3 Forensic Examination

Forensic examination and documentation was conducted for receptacles in the compartment fire tests, furnace fire tests, and those removed from the laboratory test racks. The majority of forensic examinations were conducted at the Hughes Associates examination facility. In general, the examination and documentation method was a multi-step process in which the receptacles, outlet boxes, faceplates, wiring, and plugs were systematically documented, disassembled, and evaluated for thermal damage and evidence of electrical activity (i.e., arcing) and overheating. A limited number of receptacles were further examined using the Scanning Electron Microscope at the Traveler's Insurance Engineering Lab in Windsor, CT. Detailed lists of procedures for forensic examinations, both at the Hughes Associates examination facility and at the Traveler's Engineering Laboratory, are included in Sections 3.2.3.1 and 3.2.3.2.

Various examination and evidence processing techniques were used to document and assess the plug and receptacle debris generated by the laboratory and fire exposure testing. To assess the validity of these techniques, the results were then compared to other studies and established guidelines on fire debris analysis [NFPA 921, 2011]. Visual analysis of thermal damage and electrical activity (i.e., arcing) from overheating connections and fire exposures was conducted using a digital camera and various digital microscopes. The post-fire loosening torque of screw terminals and nominal retention forces of some receptacles were examined using a digital torque screwdriver and force gauge, respectively. In some cases, an ultrasonic cleaner was used to remove debris from metal components to allow better examination. A Scanning Electron Microscope (SEM) was also used to examine some receptacles at high magnification. The SEM had Energy-dispersive X-ray Spectroscopy (EDS) capabilities which allowed the chemical characterization of the samples. To facilitate the examination of receptacles internal components in a non-destructive manner, some samples were imaged using a portable X-ray machine.

3.2.3.1 Receptacle Examination

Documentation of individual receptacles began with photographs of all sides of the receptacle, outlet box, and faceplate (where present). A Cannon T3i, 16MP DSLR camera was used for photography. Faceplates were unscrewed from the receptacles and observations of any welding or melting between the faceplate and receptacle were noted. Next, the thermal damage to the receptacle, outlet box, and faceplate were documented in accordance with the definitions listed in Appendix D. X-ray images of the receptacle in the outlet box or the receptacle removed from the outlet box were taken in some cases. The X-ray used was an RTR-4 portable digital X-ray system manufactured by SAIC.

After the faceplate was removed, visual signs of arcing and melting were searched for on the metal components of the receptacle, on wiring, outlet boxes, and faceplates. The visual signs of arcing and melting are described in Section 4.0. During examinations, an exemplar receptacle was generally kept on hand for comparison with the receptacle components from testing. Arcing damage was documented with photographs from the digital camera as well as using a Dino-Lite model AD413TL digital microscope.

During the inspection for arcing damage, the receptacle mounting screws were removed and examined. Then the receptacle itself was removed from the outlet box by gently pulling it until the sides of the receptacle were visible outside of the box. Photographs of the screw terminals were taken and the condition of each receptacle screw was recorded. The receptacle screws were noted as clean, sooty, covered with melted plastic, or covered with char. For all of the receptacles in the compartment fire tests, the torque to loosen each screw terminal was measured using the Cedar digital torque screwdriver. When the receptacle was mostly intact, the body was held firmly, the torque screwdriver was rotated in a smooth, counterclockwise motion and the peak torque was recorded. When only the metal receptacle components remained, the individual components were firmly held with a pair of needle nose pliers, the torque screwdriver was rotated in a smooth, counterclockwise motion and the peak torque was recorded. The pliers were located such that they would not be placed on locations where arcing occurred. In some cases, where the receptacles were largely intact, post-fire nominal retention force measurements were conducted for individual terminals in the manner described in Section 2.1.2.3.

In general, receptacles from the laboratory testing were examined in the same manner as those from compartment fire tests and furnace fire tests. However, for these receptacles more attention was given to the documentation of items related to overheating. These included the description of oxidation layers and buildup, discoloration of conductors, evidence of glowing connections, and melting of wire insulation. Also, the damage to the receptacle itself was described in more detail. Rather than an overall description of the damage, for laboratory tested receptacles, the damage on specific areas of the receptacle were described separately.

3.2.3.2 Scanning Electron Microscopy (SEM)

A number of receptacles of interest were transported to the Traveler's Insurance laboratory for additional inspection and documentation using a Scanning Electron Microscope (SEM). The SEM enabled the inspection of items at magnifications over 5000x and had the ability to analyze the chemical constituents of a specific area of interest. Prior to examination with the SEM, the areas of interest were examined using a high power microscope fitted with a digital camera in order to study the features that were going to be looked at using the SEM. The sample was then mounted on an aluminum SEM mount with a carbon tape base and copper tape securing the sample. The carbon and copper tapes were used to help ground the sample and prevent charging of the sample by the electron beam. Charging is where non-conductive surfaces, or surfaces that are not properly grounded, build up a charge which obscures the SEM image collection. In most cases, the entire receptacle was mounted for inspection, but, if necessary smaller components were removed from the complete item for separate inspection. When a component was removed from the receptacle, both the receptacle and the component were photographed.

The SEM used for the examination was a Phillips Excel 30 Environmental SEM (ESEM). The SEM was equipped with a Genesis system Electron-dispersive X-ray Spectroscopy (EDS) sensor manufactured by EDAX. The SEM could operate at a high vacuum or at a low vacuum using the ESEM feature. When the ESEM feature was activated, a minute amount of water vapor was pumped into the chamber under a low vacuum. This feature allowed for the examination of non-conductive items while eliminating surface charging. During the SEM examination, the item would be oriented such that optimal images and elemental analysis could occur. Successive images at increasing magnifications were recorded such that the region of interest could be shown with respect to the entire item. Each region of interest (ROI) was marked on a printout of the overall image. In a specific area of interest, features were identified for elemental analysis. The EDS sensor was used to analyze the elemental makeup of a spot or area in the ROI. Each location where an EDS measurement was taken was recorded on an image of the specific ROI. In addition, the EDS sensor had the capability to create an elemental map showing the specific location of individual elements over an area. Collection of EDS data for a given area or spot was conducted for a minimum of 50 seconds. EDS mapping took upwards of an hour depending on the area being analyzed. The technician operating the SEM analyzed the output of the EDS sensor (i.e., an EDS spectra) in order to identify elemental peaks. EDS spectra were used to calculate the percentages of each element present. However, these percentages should only be used as a qualitative measurement. There are many variables that affect the accuracy of the EDS results including the working distance of the sample to the sensor, the angle between the sample and the sensor, the count rate, smoothness of the surface, spot size, electron beam voltage, and penetration depth. In addition, if one is describing a rather large item such as a screw or an arc bead, even accurate elemental percentages may widely vary over the rather large surface. After all analysis with the SEM and EDS was finished, the SEM was vented and the item being examined was removed. If necessary, the item was cleaned using a Branson ultrasonic cleaner with a mild detergent and then re-examined. Selected EDS spectra from SEM examinations are contained in Appendix F; others are presented in the main body of this report.

3.2.3.3 Polishing and Sectioning

In order to examine subsurface characteristics, some specimens were cross-sectioned. Specifically, some receptacle screw terminals were sectioned to examine the oxide layers and interface of the screw and conductor. First, the specimens were placed in a mounting cup such that the plane of interest was parallel with the bottom of the cup. In most cases, this required a spring clip to hold the item. Once the item was in the proper place, a resin was carefully poured into the mounting cup such that the entire specimen was covered. The resin used to mount the specimen was Struers SpeciFix-40 resin. A ratio of 25 grams of resin to 10 grams of curing agent was used. The samples were then placed in an oven to cure for a minimum of 4 hours at 43.3ºC (110ºF). Once completely cured, the samples were placed in a Struers grinding and polishing machine. The samples were ground down until the proper depth was achieved. Water was used to remove the ground material from the grinding disc during grinding. The surface was then polished with progressively finer grain diamond polishing cloths until a mirror finish was achieved. A polishing lubricant was used and compressed air was used to dry the samples. Periodically during the polishing process, the samples were examined under a microscope to determine whether more polishing was necessary. After polishing was complete, some photographs were taken with the microscope to document the sample before placing it in the SEM. SEM examination of the cross-sectioned samples was conducted in the same manner as described in Section 3.2.3.2.

3.2.3.4 FTIR Analysis

A Perkin Elmer Fourier transform infrared spectroscopy (FTIR) machine was used to analyze the samples of the plastic materials from the new Leviton and Pass & Seymour receptacles. Several samples were taken from the front and back areas of each receptacle body. First, a razor blade was used to cut a sliver of non-damaged material. A second sliver was then cut from the same location in order to have two virgin (i.e., never before exposed) surfaces. These were then placed in the FTIR machine and analyzed. The FTIR spectra are shown in Appendix E.

3.3 Experimental Results and Analysis

3.3.1 Thermal Damage Characterization

In subsequent sections, the thermal damage to each of the different receptacles, outlet boxes, and faceplates are characterized and correlated to the thermal environment from the fire exposures. A number of categories of thermal damage were created for each type of receptacle, outlet box, and faceplate in order to discretize the thermal damage observed for each item. The damage categories represent the end-state of the item evaluated. For each item, the group of thermal damage categories represents a continuum of damage. This means that each damage category may encompass the characteristics of lesser damage categories.

3.3.1.1 Thermal Insult

Thermal insult is a term used to denote the heat impact from a fire exposure to a certain target. Within a compartment fire, the thermal insult could be the fire exposure to a receptacle or the fire exposure to an entire wall. To be useful for modeling or calculation purposes, the thermal insult should be well characterized in terms of temperature and/or heat flux as a function of both time and space for the particular exposure and target. Even if the thermal insult from a fire exposure is well characterized, using this data for predictions of ignition, fire resistance, or equipment damage is still quite difficult. Consequently, being able to do the reverse, i.e., predict the thermal insult from visual analysis of equipment damage, is equally difficult to do with a high degree of certainty. Fire investigators, however, are often left with fire damaged components (e.g., receptacles) and are tasked with evaluating the thermal environment created by the fire. Thus, predicting the thermal insult to a component (and by extrapolation, predicting the thermal environment) based on the thermal damage to that component would be a valuable forensic tool.

In light of the difficulties in predicting thermal insult from fire damaged equipment, a simpler task was chosen. This task was to correlate measurements of the fire environment to the extent of damage to the receptacles, outlet boxes, and faceplates. Each of the fire exposure tests contained instrumentation that measured the fire environment in terms of the exposure temperature and heat flux at various locations near the wall assembly containing the receptacles (see Sections 3.1.1.5 and 3.1.2.3). Ideally, the thermal exposure is a characterization of the entire time-temperature and/or time-heat flux data for each receptacle. Fully characterizing these temporal parameters in a concise manner is complex. Thus, average, maximum, and integrated values were considered. One particular issue that arises from using and integrated or average value of heat flux and temperature curves is that these values can be achieved by various exposures. Both a short duration fire with a high heat flux (or temperature) and a long duration fire with a low heat flux (or temperature) could produce the same integrated heat flux (or temperature) values, while in reality the thermal damage created by these scenarios (i.e., melting, charring, etc.) can be very different.

Figure 3-10 shows photographs of the thermal damage to two PVC receptacles exposed to two different fire scenarios but which have approximately equal integrated heat flux values. Both receptacles were installed in PVC outlet boxes with steel faceplates. Table 3-3 presents the integrated, maximum, and average heat flux values as well as the average and maximum temperature values measured for both receptacles. Visually, it is quite easy to see that the thermal damage to the two receptacles is different. Each measurement of thermal environment presented herein has its drawbacks. The integrated heat flux values do not illustrate the differences in thermal damage, but the average and maximum temperature and heat flux values do a better job. The differences between the maximum heat flux values and temperature values are more pronounced than for the averages. However, the maximum values do not account for duration of the exposure. Average values, on the other hand account for the exposure duration, but smooth out peak values.

Despite the noted limitations, the pursuit of a metric to correlate fire damage to the fire environment is still warranted. The maximum exposure temperature measurement was chosen for use in characterizing the thermal damage to receptacles, outlet boxes, and faceplates. Using this measurement is a practical metric that would be suitable for field use by fire investigators and has the most familiar quantifiable meaning. Correlations between the damage to receptacles, outlet boxes, and faceplates and the maximum exposure temperature are presented for each material of each type of component in Sections 3.3.2, 3.3.3, and 3.3.4.

Figure 3-10. Thermal damage to PVC receptacles: mostly consumed (PSE101, left) and totally consumed (PSE137, right).

Table 3-3. Summary of heat flux and temperature data for two PVC receptacles.

Test (Location)	Receptacle Serial No.	Receptacle Damage Category	Integrated Heat Flux (kJ/m^2)	Average Heat Flux (kW/m^2)	Maximum Heat Flux (kW/m^2)	Average Temperature (°C)	Maximum Temperature (°C)
2 (G1)	PSE101	Mostly Consumed	8183	17	34	339	515
3 (B1)	PSE137	Totally Consumed	8521	32	84	500	840

The maximum temperatures from the compartment fire tests were computed from the thermocouple trees for each elevation of receptacles. Because the two rows of receptacles at each elevation were centered about the elevation, multiple thermocouples from the thermocouple tree were averaged and the maximums were determined form the averaged temperatures. The maximum temperature at the 0.45 m (1.5 ft) elevation was calculated from the 0.3 m (1.0 ft) and 0.6 m (2.0 ft) thermocouples. The maximum temperature at the 1.2 m (4.0 ft) elevation was calculated from the 0.9 (3.0 ft), 1.2 m (4.0 ft), and 1.5 m (5.0 ft) thermocouples. The maximum temperature at the 2.0 m (6.5 ft) elevation was calculated from the 1.8 m (6.0 ft) and 2.1 m (7.0 ft) thermocouples. Every receptacle at a particular elevation was assigned the maximum temperature for that elevation. The maximum temperatures for the furnace fire exposure testing were computed as described in Section 3.3.1.1.1.

3.3.1.1.1 Furnace Temperature Characterization

Original temperature measurements in the furnace fire exposure testing included five closed probes, measuring the gas temperature approximately 15.2 cm (6.0 inches) away from the exposed face of the wall assembly, and five thermocouples placed adjacent to the outlet boxes inside of the wall assembly. In order to provide a more accurate evaluation of the thermal damage from the furnace fire exposures, the temperature as a function of the location on the wall assembly was further characterized. A wall assembly consisting of a 5.0 cm (2.0 inch) thick layer of high density Duraboard ceramic insulation atop a wood stud frame was constructed. Temperatures at each of the 36 locations where receptacles were installed in prior furnace exposure testing (see Figure 3-6) were measured using 3.1 mm (0.125 inch) diameter, Type K, grounded, Super Omegaclad sheathed thermocouples. The thermocouples were placed such that the bead was approximately 6.3 mm (0.25 inches) from the surface of the ceramic insulation. In addition, five heat flux gauges were placed at the approximate locations of the internal thermocouples from the furnace fire exposure testing (see Section 3.1.2.3).

Three furnace characterization tests were conducted. The intent was to replicate the furnace fire test average thermowell temperatures and compare these to the individual temperatures measured at each of the receptacle locations. The furnace was controlled such that the average furnace temperature over the entire test duration matched one of the furnace fire tests. Furnace fire Tests 2, 4, and 5 were replicated. Furnace fire Test 1 was similar to Test 5 except it was approximately 1.5 minutes shorter. The furnace characterization data from furnace Test 5 was used for furnace Test 1. Furnace fire Test 3 was similar to Test 4 except it was approximately 1 minute shorter. The furnace characterization data from furnace Test 4 was used for furnace Test 3. The target temperature (i.e., original furnace test average thermowell temperature), measured average thermowell temperature, and average wall thermocouple temperature are presented for each of the replicated furnace fire tests in Figure 3-11, Figure 3-12, and Figure 3-13. Also presented in these figures are contour plots of the temperature differences (°C) between individual wall thermocouples and average furnace thermowell temperatures averaged over the final minute of exposure. A positive number indicates that at that location, the temperature is higher than the average furnace thermowell temperature. A negative number indicates that at that location, the temperature is lower than the average furnace thermowell temperature.

In general, the wall temperatures tended to rise much quicker at the beginning of the test than the thermowell temperatures. This was attributed to the thermal lag associated with the large diameter thermowells (2.13 cm (0.84 in.)) in comparison to the small diameter (3.1 mm (0.125 in.)) wall thermocouples used. Also, the average wall temperatures were consistently below the average thermowell temperatures and the difference between the two curves was steady after about four minutes into each test. The bottom right corner of the wall assembly (from inside the furnace) tended to have the hottest temperatures. This hot spot is due to the location of the burner at the front of the furnace (see Figure 3-5). The flames from the front burner would impact the furnace wall opposite the burner, in the vicinity of receptacle locations E6 and F6. A couple of cool spots were also observed near receptacle locations B1 and A3.

The exposure temperature for each receptacle in each furnace exposure test was calculated by adding (for positive values) or subtracting (for negative values) the temperature differences from the average thermowell temperature measured during the actual furnace test. Maximum temperature values were then computed. This data is presented in subsequent sections as the maximum exposure temperature for each receptacle. Because the ceramic insulation used in the furnace characterization testing does not burn, the measured temperatures do not account for combustion of the plastics and wood used in the construction of the wall assemblies.

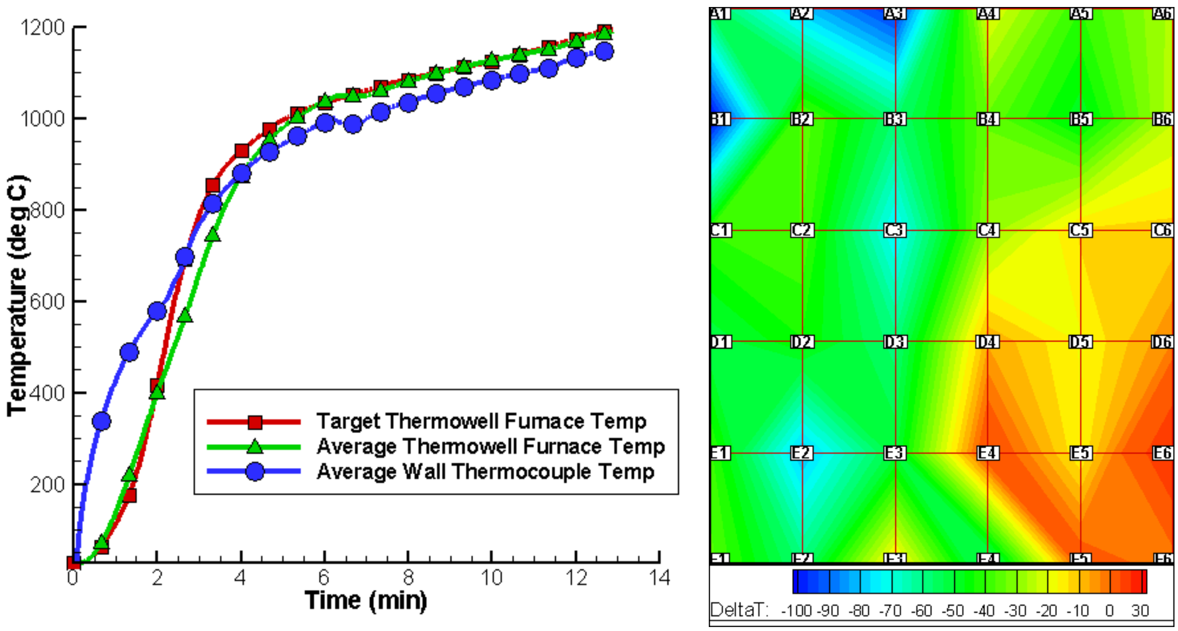


Figure 3-11. Furnace temperature characterization for furnace exposure Test 2: average temperatures (left) and contour plot of temperature differences (right).

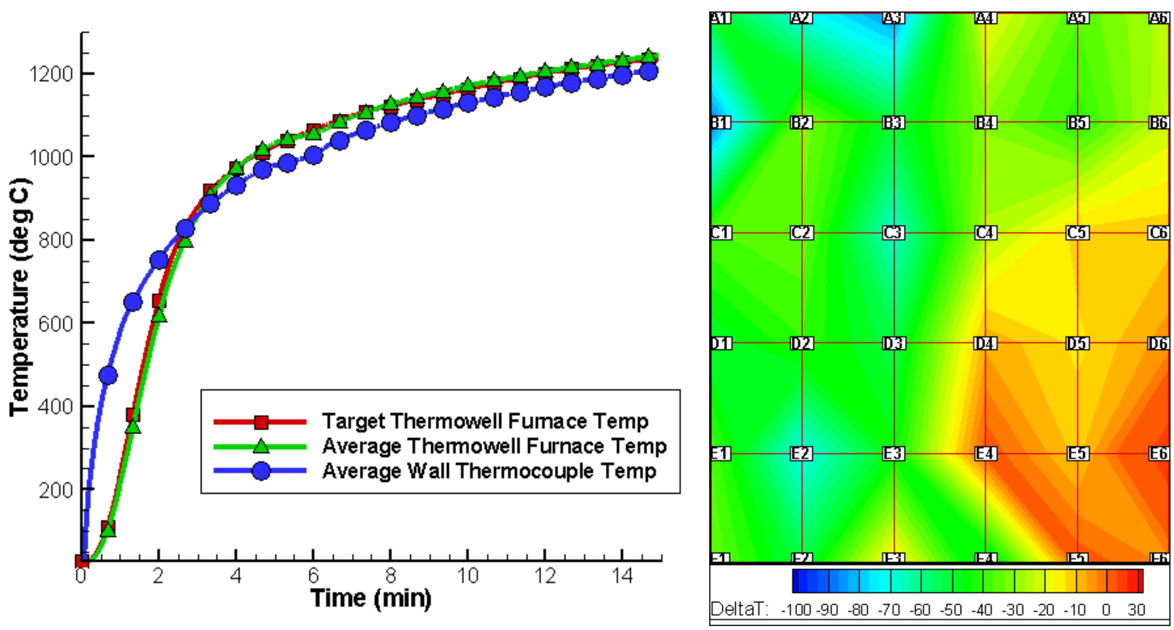


Figure 3-12. Furnace temperature characterization for furnace exposure Tests 3 and 4: average temperatures (left) and contour plot of temperature differences (right).

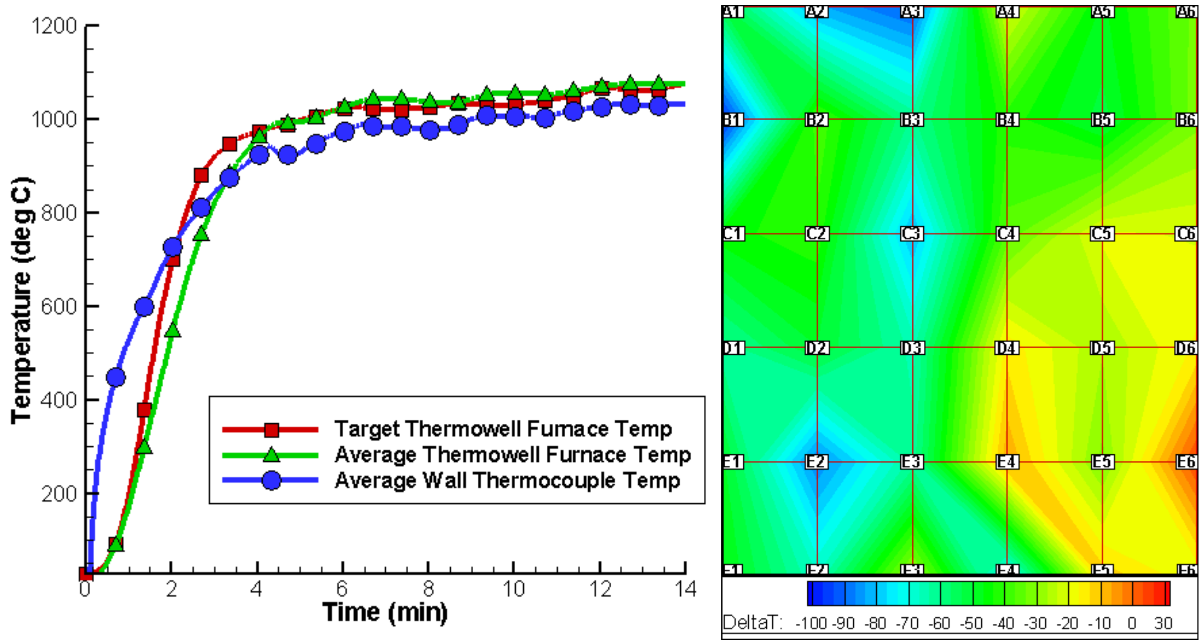


Figure 3-13. Furnace temperature characterization for furnace exposure Tests 1 and 5: average temperatures (left) and contour plot of temperature differences (right).

3.3.2 Receptacle Thermal Damage

Fire damage to the plastic components of the receptacles was characterized during the forensic examination of each receptacle. In general, the progression of damage for each material used for the receptacles was unique. However, for all of the materials, the thermal damage tended to be uniform across the exposed face and advanced from the exposed face towards the rear of the receptacle. The progression of damage from the front of the receptacle to the rear of the receptacle is consistent with observations in the literature [Babruaskas, 2003] and is quite distinguishable from the localized damage that is due to overheating (see Section 2.3.3.1). The individual material behaviors, with respect to heating, observed in the fire exposure testing were similar to those found in the laboratory testing (i.e., melting, charring, cracking). Melting of brass and copper receptacle components and wiring will be discussed in depth in Section 3.3.6. Appendix B and Appendix C give summaries of the durations and other data from the compartment fires and furnace fires, respectively.

3.3.2.1 Polypropylene Receptacles

Similar to what was seen from the laboratory testing, polypropylene receptacles would melt, run, and drip as they were heated by the fire exposures. The five damage categories for polypropylene receptacles are defined in Table 3-4. Figure 3-14 shows the progression of thermal damage for a series of polypropylene receptacles. The damage to the receptacles was relatively uniform across the face of the receptacle and progressed evenly from front to back. In some cases, for example the mostly melted receptacle in Figure 3-14, the tendency of the polypropylene to melt and flow caused the damage to the top of the receptacle to appear to be greater than the bottom (i.e., there was less plastic remaining at the top of the receptacle). In the more severe fire exposures (i.e., higher temperatures or extended duration), the entire polypropylene receptacle would be consumed with no plastic remaining on the metal components or outlet box.

Table 3-4. Damage Category Descriptions and Abbreviations for Polypropylene Receptacles.

	Abbreviation	Damage Category	Description/Definition
Increasing Thermal Damage ↓	PM	Partially Melted	Less than half of the receptacle is melted.
	MM	Mostly Melted	More than half of the receptacle is melted; some of the plastic from the receptacle remains.
	TC	Totally consumed	The receptacle has been completely melted and no plastic remains.
	BM	Brass Melted	Brass components of the receptacle have been all or partially melted; no copper has been melted.
	CM	Copper Melted	Copper wiring has been all or partially melted.

Exemplar | Partially Melted | Mostly Melted | Totally Consumed

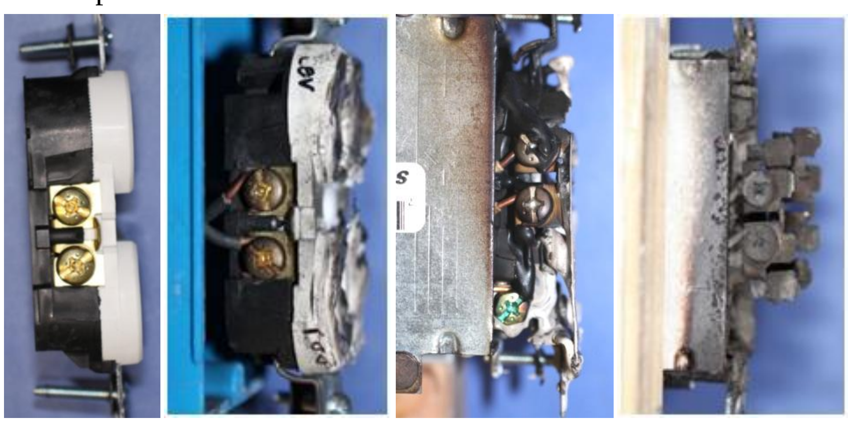


Figure 3-14. Photographs of damage progression in polypropylene receptacles, left most photograph is exemplar receptacle.

Table 3-5 lists the minimums, maximums, averages and standard deviations for the maximum exposure temperatures for each damage category for polypropylene receptacles. Figure 3-15 is a histogram plot of damage category frequency for polypropylene receptacles as a function of the maximum exposure temperature range. This data is presented for all of the polypropylene receptacles over all fire exposure testing, irrespective of the faceplate material, outlet box material, or energized state of the receptacle. In all cases some damage to the receptacle was present after the fire exposure. In general, the average temperatures for each damage category are distinct and increase as the damage gets more severe. However, the large standard deviations, especially for the totally consumed category, illustrate that there is a significant spread to the data as shown in Figure 3-15.

Table 3-5. Summary of Maximum Exposure Temperature Data for Each Damage Category for Polypropylene Receptacles.

Damage Category	Qty.	Min. of Maximum Temperature (ºC)	Max. of Maximum Temperature (ºC)	Avg. Maximum Temperature (ºC)	Std. Dev. of Maximum Temperature (ºC)
Partially Melted	15	454	559	511	50
Mostly Melted	18	515	711	584	73
Totally Consumed	101	546	1119	787	162
Brass Melted	36	964	1231	1121	89
Copper Melted	15	1000	1204	1151	56

Polypropylene receptacles are unique when it comes to the totally consumed damage category compared to the other receptacle materials. When heated to above its melting temperature, polypropylene will melt and flow, leaving no char. PVC and thermosets, on the other hand, leave char behind which forms an insulating layer and will degrade at different temperatures than the original material (see Section 2.3.3.1). The melting behavior of polypropylene means that when even modestly elevated above its melting point, if the exposure duration is long enough, the receptacle will be totally consumed. Such was the case for the polypropylene receptacles in compartment fire Tests 2, 4, and 8 which were limited ventilation, long duration fires (see Appendix B). For these tests, the average maximum temperature for the totally consumed receptacles was 614ºC. For the receptacles exposed to short duration, flashover fires (Tests 1, 3, and 5) and furnace fires in the totally consumed category, the average maximum temperature was 840ºC. A similar trend is observed for the mostly melted damage category. The partially melted receptacles were only observed in the short duration flashover compartment fire tests (Tests 2, 6, and 8).

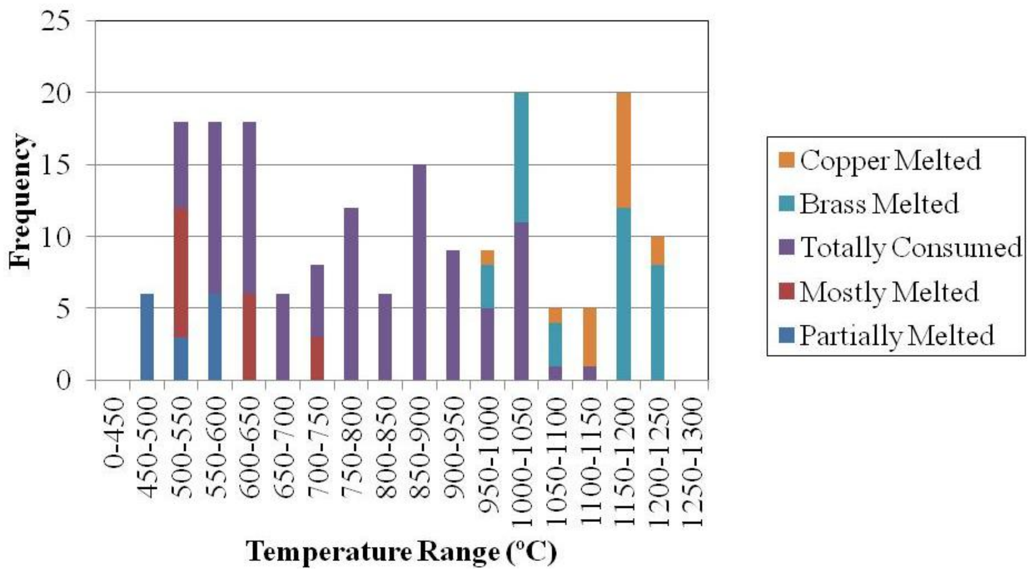


Figure 3-15. Histogram plot of damage category frequency for polypropylene receptacles as a function of the maximum exposure temperature range.

3.3.2.2 PVC Receptacles

As PVC receptacles were heated by the fire exposures, they would brown, bubble, deform, and char. This was somewhat similar to the damage created by overheating (see Section 2.3.3.1). The six damage categories for PVC receptacles are defined in Table 3-6. Figure 3-16 shows the progression of fire damage for a series of PVC receptacles. The damage to the receptacles was relatively uniform across the face of the receptacle and progressed evenly from front to back. PVC receptacles heated by fire did not tend to exhibit sagging of the plastic materials which was seen for the overheating connections (see Figure 2-30, right). The body materials would deform such that straight edges would become wavy (see Figure 3-16, partially consumed), but no effects of gravity were apparent. This is possibly due to the relatively short time scale of the fire exposures (i.e., minutes) versus the longer time scales for overheating (i.e., days). Over shorter time periods, at temperatures above those that cause charring, the PVC does not have enough time to begin sagging because the receptacle will char. The PVC char is more rigid than the softened plastic. In all cases, some of the charred receptacle remained in the outlet box after the fire exposure and tended to retain a rectangular shape. When the receptacle was considered totally consumed or the brass or copper melted, the receptacle tended to be a clump of white char located behind the grounding strap (see Figure 3-17). The char was generally unrecognizable from the original receptacle.

Table 3-6. Damage Category Descriptions and Abbreviations for PVC Receptacles.

	Abbreviation	**Damage Category**	**Description/Definition**
Increasing Thermal Damage ↓	PM	Partially melted	The front of the receptacle has blistering/bubbling and is deformed; the back is intact and may be slightly deformed.
	PC	Partially consumed	The front of the receptacle will be char; the back will be melted or deformed but with the shape still recognizable.
	MC	Mostly consumed	The front of the receptacle will be char; the back will be char but with the shape still recognizable.
	TC	Totally consumed	The entire receptacle will be char, the shape will be unrecognizable, and it will not be attached to the receptacle contacts.
	BM	Brass melted	Brass components of the receptacle have been all or partially melted; no copper has been melted.
	CM	Copper Melted	Copper wiring has been all or partially melted.

Figure 3-16. Photographs of damage progression in PVC receptacles, left most photograph is exemplar receptacle.

Figure 3-17. Photograph of totally consumed PVC receptacle with copper melting (PSE385) showing remaining char.

Table 3-7 lists the minimums, maximums, averages and standard deviations for the maximum exposure temperatures for each damage category for PVC receptacles. Figure 3-18 is a histogram plot of damage category frequency for PVC receptacles as a function of the maximum exposure temperature range. This data is presented for all of the PVC receptacles over all fire exposure testing, irrespective of the faceplate material, outlet box material, or energized state of the receptacle. In all cases some damage to the receptacle was present after the fire exposure. In general, the average temperatures for each damage category increase as the damage gets more severe. However, the large standard deviations for some of the categories, illustrate that there is a significant spread to the data as shown in Figure 3-18.

Because a large portion of the PVC receptacles remained as char after the fire exposure, it made classifying the receptacle damage more arbitrary than for some of the other receptacles, outlet boxes, and faceplates. This could partially explain the close average maximum temperatures and overlap in temperature ranges between the partially and mostly consumed categories and the mostly and totally consumed categories. But the duration of the fire exposure seems to have more of an effect on the maximum temperature ranges. If the mostly consumed damage category is examined separately, one can see the effect of the duration and intensity of the fire on the receptacle damage. For compartment fire Tests 2, 4, and 8, which were limited ventilation and long duration tests, the average maximum temperature was 598ºC. For compartment fire Tests 1, 3, and 5, short duration flashover tests, the average maximum temperature was 810ºC. These values suggest that a low temperature, long duration fire and a high temperature, short duration fire can produce the same amount of damage. The same patterns are also evident in the partially melted, partially consumed, and totally consumed damage categories.

Table 3-7. Summary of Maximum Exposure Temperature Data for Each Damage Category for PVC Receptacles.

Damage Category	Qty.	Min. of Maximum Exposure Temperature (ºC)	Max. of Maximum Exposure Temperature (ºC)	Avg. Maximum Exposure Temperature (ºC)	Std. Dev. of Maximum Exposure Temperature (ºC)
Partially Melted	21	454	656	558	83
Partially Consumed	12	515	859	710	133
Mostly Consumed	51	515	1187	727	184
Totally Consumed	53	546	1180	883	148
Brass Melted	29	982	1238	1143	80
Copper Melted	7	1136	1251	1197	44

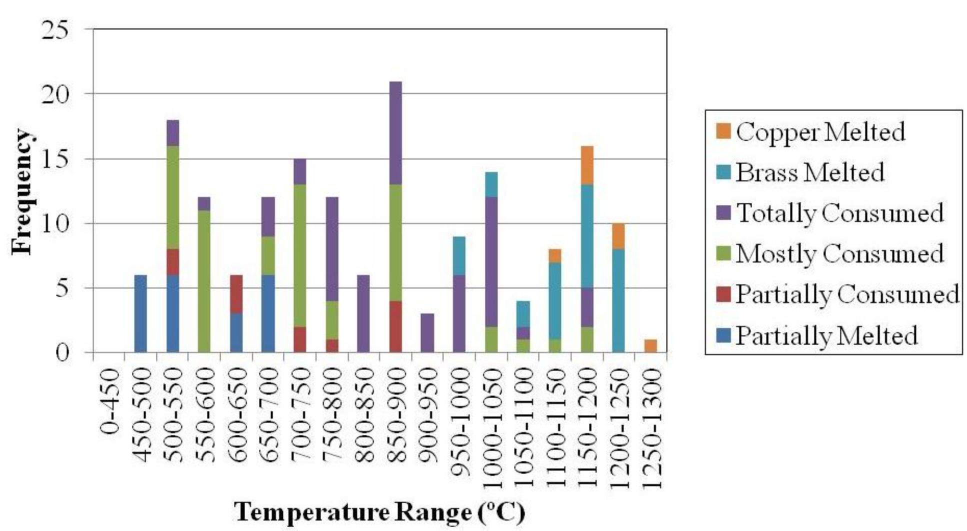


Figure 3-18. Histogram plot of damage category frequency for PVC receptacles as a function of the maximum exposure temperature range.

3.3.2.3 Thermoset Receptacles

A number of different manufacturers of thermoset receptacles were used and these receptacles covered a wide range of ages. Although chemical analyses were not performed for each receptacle, it is likely that the thermoset receptacles were constructed of either phenolics or urea formaldehyde. All of the thermoset receptacles were grouped together in order to evaluate the thermal damage to the receptacles. Receptacle manufacturer and age were not evaluated. It was not expected that either of these variables would greatly affect the thermal damage to the receptacle. The thermoset receptacles were the most resilient of all of the fire receptacles with respect to fire damage. The damage to thermoset receptacles began with discoloration and charring; then cracking and separation of receptacle parts; and finally the receptacles would become brittle and material would fall off. The six damage categories for thermoset receptacles are defined in Table 3-8. Figure 3-19 shows the progression of fire damage for a series of thermoset receptacles. In general, the damage to the receptacles was relatively uniform across the face of the receptacle and progress from front to back. The progression of damage was somewhat similar to the damage created by overheating (see Section 2.3.3.1).

In most cases, the loss of material from the thermoset receptacles would be localized in certain areas (see Figure 3-19, loss of material). It is possible that the receptacle body was thinner in certain areas which caused some pieces to fall off more than others. But, even when some of the material began to fall off, the receptacles still retained their original shape. In the most severe fire exposures, the entire receptacle would break apart and no parts would remain together or attached to the metal plug contacts. When this occurred, the remaining charred material usually still retained its shape, but was very brittle and powdery.

Table 3-8. Damage Category Descriptions and Abbreviations for Thermoset Receptacles.

	Abbreviation	Damage Category	Description/Definition
Increasing Thermal Damage ↓	CH	Charred	The receptacle retains the original form; it may be brittle or charred, but has no cracking.
	CR	Cracking	The receptacle retains the original form; it is brittle and has cracking.
	LM	Loss of material	Parts of the receptacle body have broken loose and are missing.
	TC	Totally consumed	No parts of the receptacle remain intact or attached to the receptacle contacts.
	BM	Brass melted	Brass components of the receptacle have been all or partially melted; no copper has been melted.
	CM	Copper Melted	Copper wiring has been all or partially melted.

Exemplar | Charred | Cracked | Loss of Material | Totally Consumed

Figure 3-19. Photographs of damage progression in thermoset receptacles, left most photograph is exemplar receptacle (E021).

Table 3-9 lists the minimums, maximums, averages and standard deviations for the maximum exposure temperatures for each damage category for thermoset receptacles. Figure 3-20 is a histogram plot of damage category frequency for thermoset receptacles as a function of the maximum exposure temperature range. This data is presented for all of the thermoset receptacles over all fire exposure testing, irrespective of the faceplate material, outlet box material, or energized state of the receptacle. In all cases some damage to the receptacle was present after the fire exposure. Because the thermoset receptacles were only tested in a limited number of compartment fire tests (Tests 6 and 7) and furnace fire tests (furnace Tests 4 and 5), the maximum temperature data is separated into two groups. The lower temperature group was from the compartment fire tested receptacles and the higher group from the furnace fire tested receptacles. In general, the average temperatures for each damage category increase as the damage gets more severe. The relatively small standard deviations for most of the categories, except the loss of material category, illustrate that the data is rather closely grouped as shown in Figure 3-20. There were nine receptacles exhibiting loss of material that have temperatures between 550ºC and 600ºC. These receptacles were all from compartment fire Test 6, a limited ventilation, and long duration fire test. The remaining receptacles were from furnace fire tests, which had significantly higher exposure temperatures.

Table 3-9. Summary of Maximum Exposure Temperature Data for Each Damage Category for Thermoset Receptacles.

Damage Category	Qty.	Min. of Maximum Exposure Temperature (ºC)	Max. of Maximum Exposure Temperature (ºC)	Avg. Maximum Exposure Temperature (ºC)	Std. Dev. of Maximum Exposure Temperature (ºC)
Charred	36	559	696	629	52
Cracked	15	585	696	655	44
Loss of Material	13	585	1201	752	261
Totally Consumed	4	987	1027	1009	14
Brass Melted	25	1026	1238	1166	62
Copper Melted	14	1164	1251	1214	24

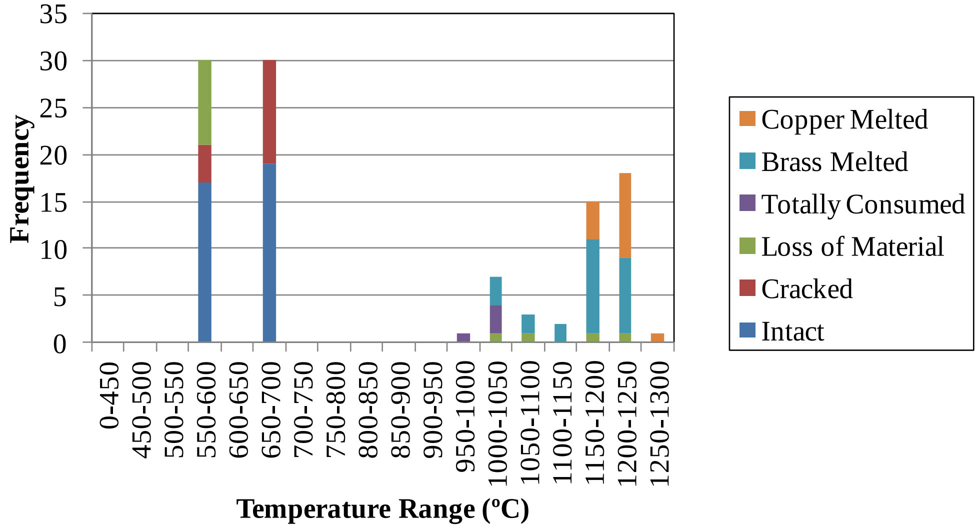


Figure 3-20. Histogram plot of damage category frequency for thermoset receptacles as a function of the maximum exposure temperature range.

3.3.3 Faceplate Thermal Damage

3.3.3.1 Nylon faceplates

The damage to the nylon faceplates was relatively uniform across the face of the faceplate. The damage to the nylon faceplates included the plastic discoloring to brown, blistering on the surface, and curving of the faceplate away from the wall. The two damage categories for Nylon faceplates are defined in Table 3-10. As the thermal damage increased, the faceplates melted off of the receptacle, leaving nothing behind except the attaching screw. This would leave the receptacles directly exposed to the fire environment. None of the fallen faceplates were found in any discernible form from the plastic remains on the floor of the compartment or in the furnace. Even as the faceplate began to blister and discolor on the front surface, the back surface remained undamaged with minor discoloration beginning in the blistering areas on the front. Figure3-21 shows a typical blistered/partially melted and an exemplar nylon faceplate. There were no remnants of the totally consumed faceplates.

Table 3-10. Damage Category Descriptions and Abbreviations for Nylon Faceplates.

Increasing Thermal Damage ↓	Abbreviation	Damage Category	Description/Definition
	BL	Blistered – Partially Melted	Blisters on surface of faceplate, may be distorted or partially melted.
	TC	Totally Consumed	No faceplate remains. Some melted plastic may remain, but is minimal.

Figure 3-21. Photographs of damage progression in nylon faceplates, exemplar (left) and blistered/partially melted front (center) and back (right).

The progression of damage to nylon faceplates from an external fire exposure was not similar to the damage created by overheating. Figure 3-22 shows the receptacle faceplates from two overheating connections, with one having had flaming ignition (right). In the center photo in Figure 3-21, there are some light areas where the faceplate remains somewhat white in color rather than brown. This was observed on all of the blistered/partially melted faceplates; this was the area of the faceplate where the receptacle behind was in contact. It is likely that the receptacle behind provided a heat sink for the faceplate. On the other hand, for faceplates used in the laboratory testing where an overheating connection was present, there was generally a darkened and charred area where the overheating receptacle would have been in contact with the faceplate (see Figure 3-22, left). This discoloration is from the heat produced by the loose connections and is much darker in color than the discoloration from the fire. It is likely that hotter local temperatures present for the overheating connections caused the dark discoloration, but because they were localized, they did not cause the faceplate to fall off.

Figure 3-22. Photographs of typical faceplate damage from overheating connections: LEV171 (left) and LEV269 (right).

Table 3-11 lists the minimums, maximums, averages and standard deviations for the maximum exposure temperatures for each damage category for nylon faceplates. Figure 3-23 is a histogram plot of damage category frequency for nylon faceplates as a function of the maximum exposure temperature range. This data is presented for all of the nylon faceplates over all fire exposure testing, irrespective of the receptacle material, outlet box material, or energized state of the receptacle. There were only six of the nylon faceplates that remained intact and attached to the receptacle after the fire exposures; these exhibited the blistering and partial melting described previously. All of these faceplates were from compartment fire Test 2 (long duration, limited ventilation), were located at the bottom of the test wall assembly, and had the same maximum temperature. This data would suggest that even for long duration fire exposures (i.e., tens of minutes), nylon faceplates will remain intact up to maximum temperatures of about 500ºC. This is likely also dependent on the faceplate material. Only nylon faceplates were evaluated in this test program.

Table 3-11. Summary of Maximum Exposure Temperature Data for Each Damage Category for Nylon Faceplates.

Damage Category	Qty.	Min. of Maximum Exposure Temperature (ºC)	Max. of Maximum Exposure Temperature (ºC)	Avg. Maximum Exposure Temperature (ºC)	Std. Dev. of Maximum Exposure Temperature (ºC)
Blistered – Partially Melted	6	454	454	454	0
Totally Consumed	161	515	1251	832	229

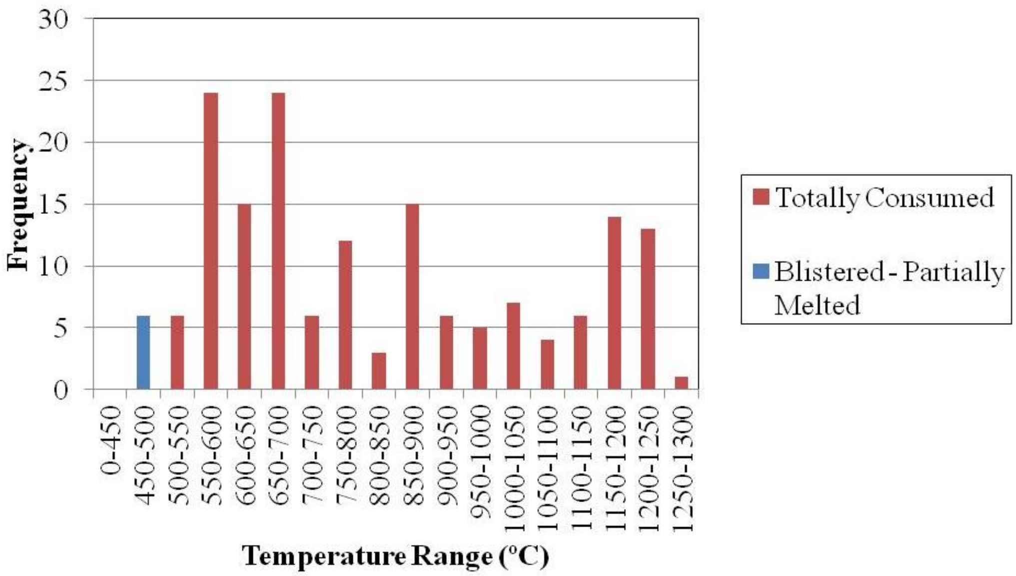


Figure 3-23. Histogram plot of damage category frequency for nylon faceplates as a function of the maximum exposure temperature range.

3.3.3.2 Steel Faceplates

As steel faceplates were heated by the fire exposures, they would become covered with soot, paint decomposed (browned), paint would burn off, develop a blistered appearance and scaling, and melt. The four damage categories for steel faceplates are defined in Table 3-12. Steel faceplates were not evaluated in the laboratory testing. Figure 3-24 shows the progression of fire damage for a series of steel faceplates. The damage to the faceplates was relatively uniform across the front face of the faceplate. The damage to the steel faceplates did not progress from the front to the back in the same manner as the receptacles and outlet boxes. Since the steel faceplates were rather thin (1.06 mm (0.042 in)) compared to the other items (nylon faceplates: 0.25 cm (0.1 in.); receptacles: ~2.5 cm (1.0 in.); outlet boxes: ~7.5 cm (3.0 in.)), the damage on the front of the faceplate was often the same as on the back of the faceplate. Also, the melting of the steel faceplates occurred in localized areas rather than from front to back. The steel faceplates having blistering and scaling damage would often begin to rust after the fire exposure.

Table 3-12. Damage Category Descriptions and Abbreviations for Steel Faceplates.

	Abbreviation	Damage Category	Description/Definition
Increasing Thermal Damage ↓	SO	Sooty/Discolored	Plate appears to have some color (beige) left and some areas with soot. Some of faceplate is discolored brown.
	BP	Paint Burned Off	Paint on the surface of the faceplate has been burned off; some paint may remain as flakes on the faceplate.
	BS	Blistered/Scaling	Faceplate appears to have scaling or blisters over most or all of the front face.
	PM	Partially Melted	Some of the faceplate has melted away; the faceplate does not retain original outline/shape.

Table 3-13 lists the minimums, maximums, averages and standard deviations for the maximum exposure temperatures for each damage category for steel faceplates. Figure 3-25 is a histogram plot of damage category frequency for steel faceplates as a function of the maximum exposure temperature range. This data is presented for all of the steel faceplates over all fire exposure testing, irrespective of the receptacle material, outlet box material, or energized state of the receptacle. In all cases some damage to the faceplate was present after the fire exposure. The average temperatures for each damage category are very distinct and increase as the damage gets more severe. There was minimal overlap between the range of maximum temperatures for the sooty/discolored and burned paint damage categories The blistered/scaling and partially melted damage categories also overlapped somewhat. There was a distinct demarcation between the burned paint and blistered/scaling temperature ranges which corresponds to the differences in temperatures between the furnace fire exposures and the compartment fire exposures.

Figure 3-24. Photographs of damage progression in steel faceplates.

Table 3-13. Summary of Maximum Exposure Temperature Data for Each Damage Category for Steel Faceplates.

Damage Category	Qty.	Min. of Maximum Exposure Temperature (ºC)	Max. of Maximum Exposure Temperature (ºC)	Avg. Maximum Exposure Temperature (ºC)	Std. Dev. of Maximum Exposure Temperature (ºC)
Sooty/Discolored	36	454	615	542	49
Paint Burned Off	134	515	903	703	128
Blistered/Scaling	114	959	1238	1104	88
Partially Melted	14	1150	1251	1206	27

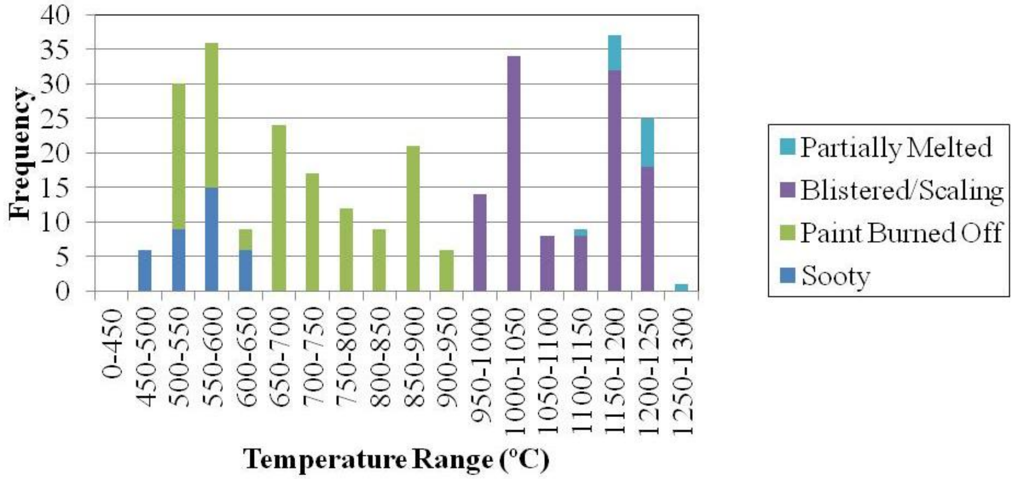


Figure 3-25. Histogram plot of damage category frequency for steel faceplates as a function of the maximum exposure temperature range.

The maximum temperatures for the partially melted faceplates were much lower than the melting temperature of steel. Melting temperatures of steel are upwards of 1400ºC, depending on the composition. The furnace exposure temperatures were characterized at the centers of the receptacle locations (see Section 3.3.1.1.1). It is possible that there were local hot spots not captured by the thermocouples, but this does not explain differences between the exposure temperature and steel melting temperature of between 200ºC and 300ºC. However, the furnace characterization was conducted with an inert wall assembly that did not burn, while the furnace fire tests, on the other hand, were conducted with receptacles, wood studs, and wiring insulation that did burn. It is possible that the contribution of the burning receptacles, wiring, and/or faceplate materials produced higher local temperatures for the steel faceplates causing them to melt. The melting of the steel faceplates was primarily located around the perimeter of the faceplate and not near the underlying receptacle. Alloying would not have caused this melting as there was no evidence that any other molten metal had dripped on these faceplates.

3.3.4 Outlet Box Thermal Damage

3.3.4.1 PVC Outlet Boxes

As the PVC outlet boxes were heated by the fire exposures, they discolored, deformed, sagged, and charred. This behavior is similar to the PVC receptacles observed in this test series (see Section 3.3.2.2). The four damage categories for PVC outlet boxes are defined in Table 3-14. Figure 3-26 shows the progression of fire damage for a series of PVC outlet boxes. Only six of the PVC outlet boxes were undamaged and free of soot deposits on the outside at the end of the fire exposure (compartment fire Test 2). These outlet boxes did have some soot inside, behind the receptacle. Three of these outlet boxes had steel faceplates (sooty) and three had plastic (blistered/partially melted); all of the receptacles were partially melted polypropylene receptacles.

Table 3-14. Damage Category Descriptions and Abbreviations for PVC Outlet Boxes.

Increasing Thermal Damage ↓	Abbreviation	Damage Category	Description/Definition
	CL	Clean	No soot on the box.
	PM	Partially Melted	Less than half of the box is melted, most of blue color remains.
	MM	Mostly Melted	More than half of the box is melted, some blue color remains.
	PC	Partially Consumed	No blue color remains, original shape of the box is not discernible.

Fire exposure to the outlet boxes, both PVC and metal, was slightly different than the receptacles or faceplates. Whereas receptacles and faceplates have an entire face exposed to the fire, the outlet boxes were installed such that their front edge was approximately flush with the exposed surface of the drywall on the wall assembly. Because of this configuration, the exposure of the outlet box would have initially been blocked by the faceplate and receptacle. At some point the damage would have began on the front edge of the outlet box. And as the outlet box deformed and the receptacle and faceplate were damaged, the exposure to the outlet box would have likely changed as different pathways for heat were established. Despite the more complicated exposure mechanisms of the outlet boxes, in general, the damage to the PVC outlet boxes was relatively uniform across the outlet box. In some cases, such as the mostly melted receptacle in Figure 3-26, the damage near the top or bottom was somewhat more. It is difficult to say what caused this preferential damage, but it is possible that this arose from the deformation of the outlet box which caused the box to detach from the mounting nail.

Figure 3-27 shows three PVC outlet boxes damaged by overheating receptacle connections in the laboratory testing. The damage to the PVC outlet boxes from fire exposure is not very different from the damage due to overheating receptacle connections. The charred and blackened areas due to overheating receptacle connections are relatively confined to the area around the screw terminals, even when the entire outlet box has begun to deform and sag (Figure 3-27, right). Some of the fire damaged receptacles exhibited damage that was very similar in appearance and location to the outlet boxes damaged by overheating receptacle connections. It is expected that if additional thermal exposure to the outlet boxes with overheating were to occur, the damage developed would become similar to those outlet boxes only exposed to fire.

Figure 3-26. Photographs of damage progression in PVC outlet boxes (increasing thermal insult from top left to bottom right).

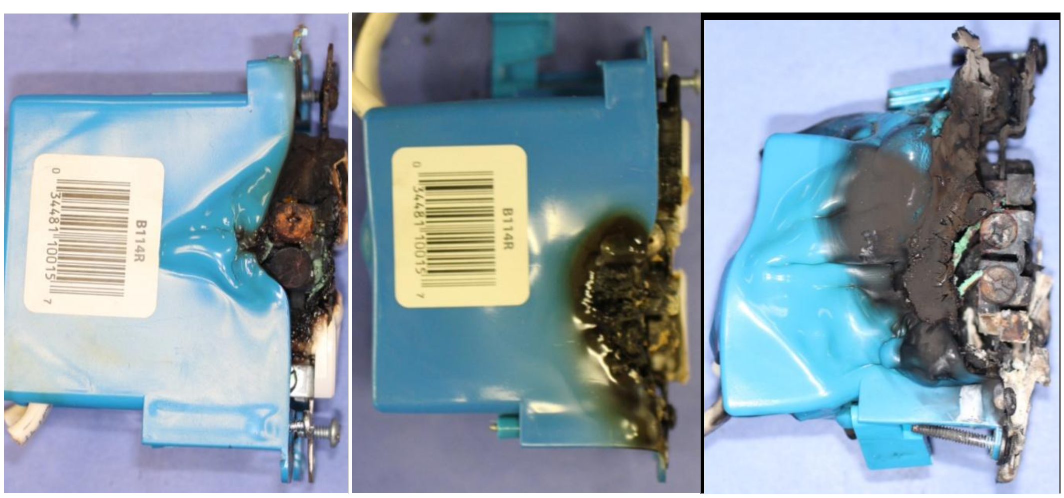


Figure 3-27. Photographs of damaged PVC outlet boxes from selected laboratory tested receptacles: PSE263 (left), LEV267 (center), and LEV269 (right).

Table 3-15 lists the minimums, maximums, averages and standard deviations for the maximum exposure temperatures for each damage category for PVC outlet boxes. Figure 3-28 is a histogram plot of damage category frequency for PVC outlet boxes as a function of the maximum exposure temperature range. This data is presented for all of the PVC outlet boxes over all fire exposure testing, irrespective of the receptacle material, faceplate material, or energized state of the receptacle. PVC receptacle boxes were not used in the furnace fire exposures. The only trend that appears in this data is that below approximately 500ºC, the PVC outlet boxes will not be damaged. This is because at the low temperatures, the faceplates and receptacles remain intact, preventing heat from reaching the outlet box. If the fire exposure durations at these low temperatures were to be much longer, it would be more likely for the PVC outlet boxes to be damaged. The partially melted, mostly melted, and partially consumed damage categories all overlap significantly in terms of the maximum exposure temperature ranges. The faceplate material and receptacle material do not appear to have a significant impact on the partially melted, mostly melted, or partially consumed damage categories. Aged receptacles were not installed in PVC outlet boxes for any of the tests.

Table 3-15. Summary of Maximum Exposure Temperature Data for Each Damage Category for PVC Outlet Boxes.

Damage Category	Qty.	Min. of Maximum Exposure Temperature (ºC)	Max. of Maximum Exposure Temperature (ºC)	Avg. Maximum Exposure Temperature (ºC)	Std. Dev. of Maximum Exposure Temperature (ºC)
Clean	6	454	454	454	0
Partially Melted	28	515	886	727	122
Mostly Melted	43	515	903	750	131
Partially Consumed	13	559	903	755	116

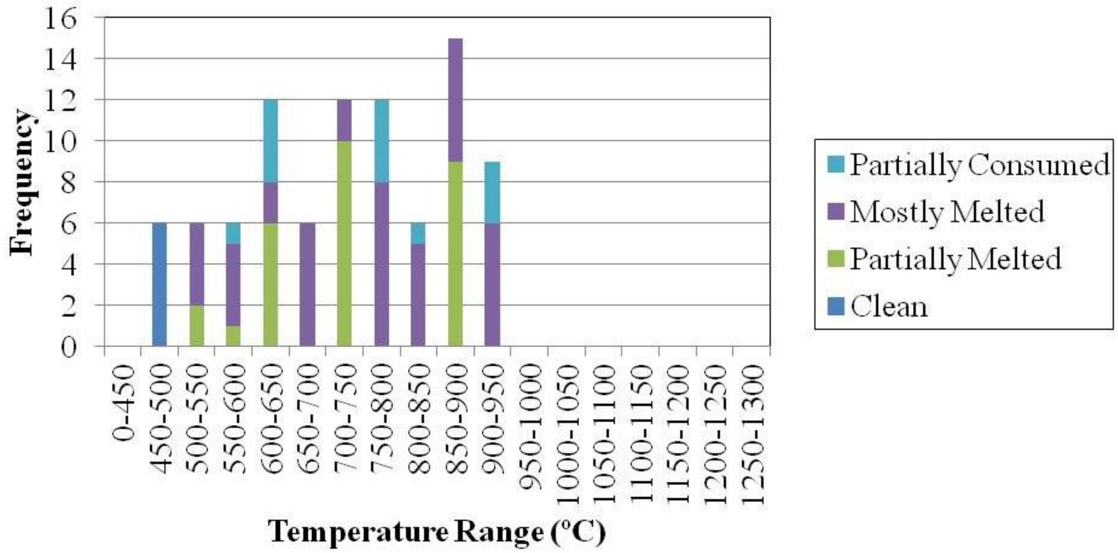


Figure 3-28. Histogram plot of damage category frequency for PVC outlet boxes as a function of the maximum exposure temperature range.

3.3.4.2 Steel Outlet Boxes

As the steel outlet boxes were heated by the fire exposures, smoke deposited on the surfaces and the zinc plating was lost; none of the outlet boxes underwent any physical deformation or melting. The loss of zinc plating was determined visually. In some cases, soot deposits remained on the outlet boxes after the loss of the zinc plating. The four damage categories for steel outlet boxes are defined in Table 3-16. Figure 3-29 shows the progression of fire damage for a series of steel outlet boxes. Thirty-five of the steel outlet boxes had negligible soot (i.e., they were clean) on the outside at the end of the fire exposure. These outlet boxes did have some soot inside, behind the receptacle. Seven of these outlet boxes had nylon faceplates; three were blistered/partially melted and four were totally consumed. Twenty-eight of the clean outlet boxes had steel faceplates; seventeen were sooty and eleven had the paint burned off.

Table 3-16. Damage Category Descriptions and Abbreviations for Steel Outlet Boxes.

	Abbreviation	Damage Category	Description/Definition
Increasing Thermal Damage ↓	CL	Clean	Negligible soot on the box.
	SO	Sooty	Soot deposits located on outlet box; the zinc plating remains underneath soot layer.
	LP	Loss of Plating	Beneath soot deposits, the majority of the zinc plating on the box is gone.
	PM	Partially Melted	Part of the outlet box has melted.

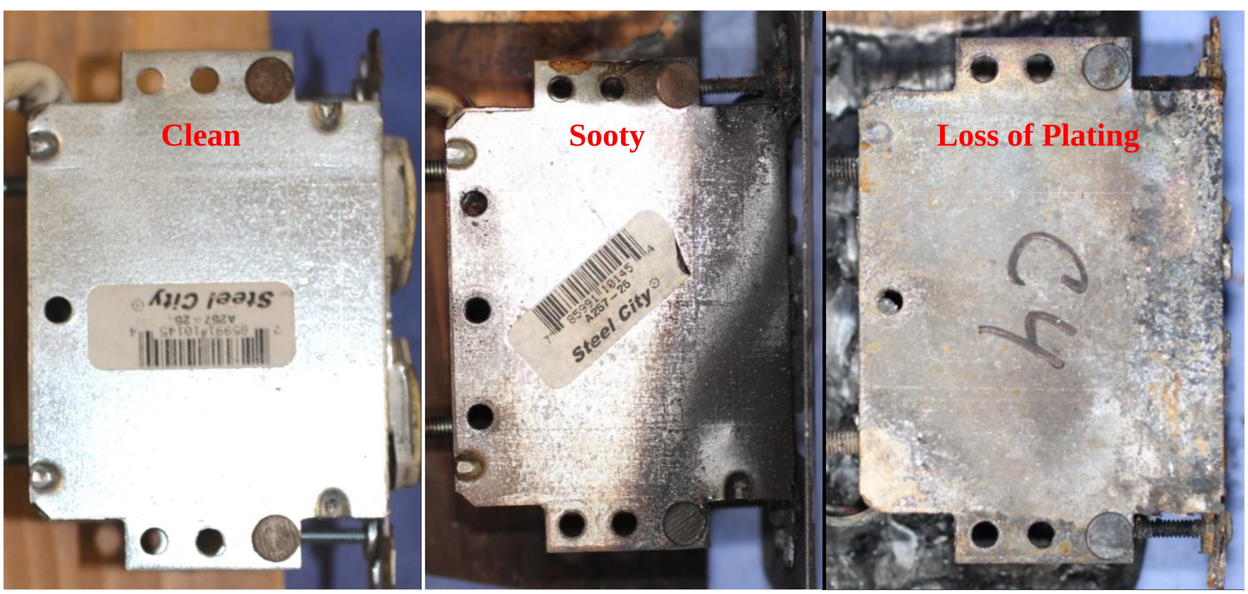


Figure 3-29. Photographs of damage progression in steel outlet boxes (increasing thermal insult from left to right).

Table 3-17 lists the minimums, maximums, averages and standard deviations for the maximum exposure temperatures for each damage category for steel outlet boxes. Figure 3-30 is a histogram plot of damage category frequency for steel outlet boxes as a function of the maximum exposure temperature range. This data is presented for all of the steel outlet boxes over all fire exposure testing, irrespective of the receptacle material, faceplate material, or energized state of the receptacle. In general, the average temperatures for each damage category increase as the damage gets more severe. However, the temperature ranges for the clean and sooty categories are not distinct. Only three of the 181 receptacles exhibiting loss of zinc plating were from the compartment fire tests (Test 3). These three receptacles had the lowest maximum temperatures in this damage category (883ºC); the lowest maximum temperature for the remaining receptacles was 959ºC. There do not appear to be any significant trends with respect to the impact of faceplate material or receptacle material on the outlet box damage.

Table 3-17. Summary of Maximum Exposure Temperature Data for Each Damage Category for Steel Outlet Boxes.

Damage Category	Qty.	Min. of Maximum Exposure Temperature (ºC)	Max. of Maximum Exposure Temperature (ºC)	Avg. Maximum Exposure Temperature (ºC)	Std. Dev. of Maximum Exposure Temperature (ºC)
Clean	35	454	886	588	123
Sooty	159	515	903	663	110
Loss of Plating	181	883	1251	1116	93

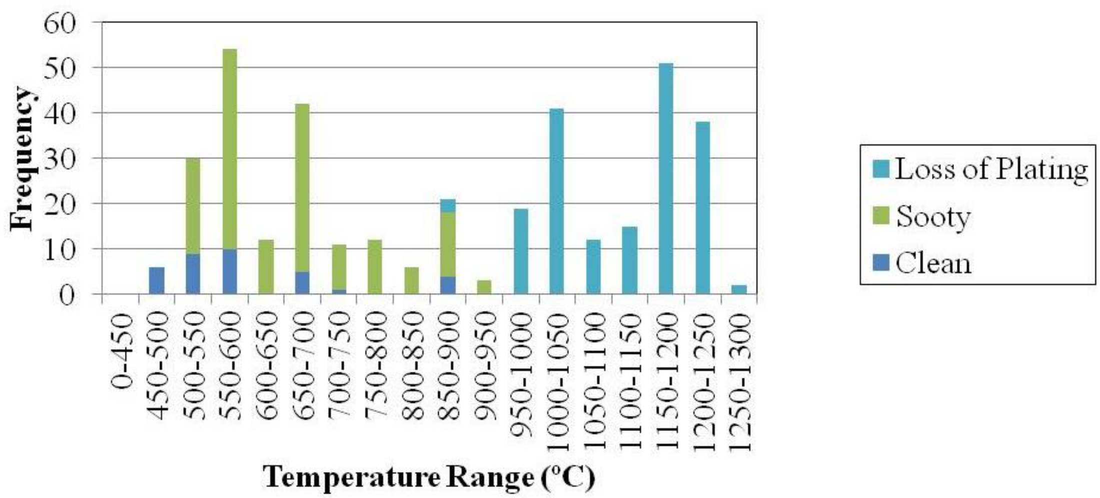


Figure 3-30. Histogram plot of damage category frequency for steel outlet boxes as a function of the maximum exposure temperature range.

3.3.5 Assessing the Fire Environment from Thermal Damage

A general process was developed to use the maximum exposure temperature data presented in the previous sections to assess the thermal environment based on the observed damage to the receptacle, faceplate, and outlet box. To demonstrate this process, a polypropylene receptacle will be evaluated in this section. Figure 3-31 shows the thermal damage to a steel faceplate, PVC outlet box, and polypropylene receptacle from compartment fire Test 4 (LEV160; location E-1).

Figure 3-31. Photographs of steel faceplate (left), PVC outlet box (center) and poly propylene receptacle (LEV160, right).

The first part of this process was to classify the thermal damage to the receptacle, faceplate, and outlet box based on the definitions presented in the previous sections. The steel faceplate had the paint burned off and did not exhibit any blistering, scaling, or melting. The PVC outlet box had considerable melting and deformation, but some of the color was still visible and the box partially retained its shape. This level of damage would be considered mostly melted. The polypropylene receptacle had been totally consumed; no plastic from the receptacle remained attached to the brass contacts; and neither the brass contacts nor the copper wiring exhibited evidence of melting from the fire. The second part of this evaluation was to gather the maximum exposure temperature ranges (i.e., the average ± 1 standard deviation) for the damage categories determined for the receptacle, faceplate, and outlet box. This data is presented in Table 3-18 for the components making up the LEV160 receptacle installation.

Table 3-18. Summary of Maximum Exposure Temperature Data for Components Making Up the LEV160 Receptacle Installation.

Item	**Average Maximum Exposure Temperature (ºC)**	**Std. Dev. of Max. Exposure Temperature (ºC)**	**Avg. - 1 Std. Dev. (ºC)**	**Avg. + 1 Std. Dev. (ºC)**
Steel faceplate: Paint Burned Off (Table 3-13)	703	128	575	831
PVC Outlet Box: Mostly Melted (Table 3-15)	750	131	619	881
Polypropylene Receptacle: Totally Consumed (Table 3-5)	787	162	625	949

The third and final step was to determine an approximate maximum exposure temperature range based on the ranges of temperatures for the damage categories selected. The maximum exposure temperature range for each component making up the LEV160 receptacle installation is plotted with the average temperature for each damage category in Figure 3-32. Each temperature range has been shaded to illustrate the overlap of the temperature ranges. The most likely exposure temperature for the components making up the LEV160 receptacle installation would be where all three temperature ranges overlap. This range of temperatures is between the lowest of the average + 1 standard deviation values (831ºC) and the highest of the average - 1 standard deviation values (625ºC). Although the identified range is rather large (i.e., 206ºC between the upper and lower bounds), the actual maximum temperature for LEV160 was 680ºC, which does fall within the range identified.

The fire exposures used in this test series covered a wide range of fire scenarios. But, within each group of tests, there was not much variation of the fires. All of the non-flashover fires were low temperature and long duration fires; all of the flashover fires were higher temperature and short duration fires; and all of the furnace fire exposures were very high temperatures and long duration fires with respect to the compartment fire tests. Additional analysis of thermal damage to receptacles from other fire scenarios representing different thermal exposures would strengthen this methodology for broader applicability.

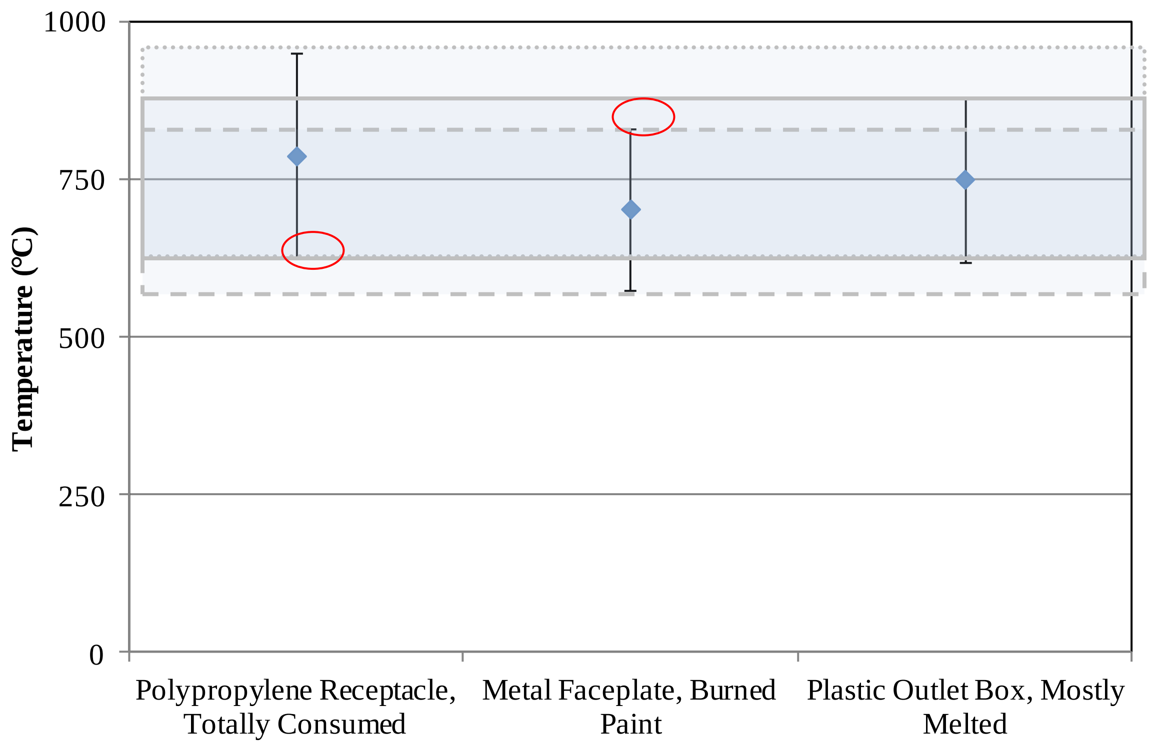


Figure 3-32. Plot of the thermal insult temperature ranges for components making up the LEV160 receptacle installation.

3.3.6 Melting of Metal Receptacle Components and Wiring

Melting of brass and copper receptacle components due to fire exposure was only observed in the furnace fire exposure tests. The maximum exposure temperature in any of the compartment fire tests in the vicinity of the wall assembly was 903ºC. This is less than the melting point of brass which is approximately 930ºC and therefore melting of these components was not expected. The melting evidence that was found in the post-fire examinations for furnace fire tested receptacles was identified using the naked eye or low powered microscopes.

3.3.6.1 Characteristics of Melting for Brass and Copper Receptacle Components

Characteristic traits of melting in brass receptacle components and copper wiring were determined based on the visual evaluation of non-energized receptacles. These characteristics were then used to evaluate potential melting locations in energized receptacles. The characteristics of melting of copper and brass components were unique compared to those for arcing (see Section 4.0). In general, the characteristics of melting in copper and brass were similar, however there were some nuances. These nuances, discussed in Sections 3.3.6.1.1 and 3.3.6.1.2, were attributed to the differences in construction between brass receptacle contacts (i.e., stamped and bent) and copper wiring (i.e., cylindrical; formed by drawing through dies). Some of the steel faceplates were also melted during the fire exposures. A description and photograph of this melting is found in Section 3.3.3.2.

3.3.6.1.1 Melting of Brass

For brass receptacle components, the following traits of melting were frequently observed: effects of gravity, thinning of brass components, holes through brass components, no clear line of demarcation between damaged and undamaged areas, pitting of surface, and round globules. These are in general agreement with the proposed changes to NFPA 921 [2014] as discussed in Section 4.0 of this report. One or more characteristic traits needed to be observed for melting to be confirmed. In most occasions, more than one characteristic was observed for a potentially melted component.

In general, the melting of brass receptacle components occurred uniformly across the exposed area. Figure 3-33 shows the typical progression of melting of brass receptacle components from non-energized polypropylene receptacles. The leftmost photograph is of a totally consumed polypropylene receptacle; no melting was observed for this receptacle. In the left-center photo in Figure 3-33, the plug blade contacts (circled in left most photo) have melted off of the component. The third photo shows holes developed in the brass components near the terminal screws. These types of holes were observed in a number of cases. It may appear quite peculiar that the center of the square shaped part of the brass component would melt out while the outer edge would mostly retain its original shape. Because the receptacle contacts are manufactured by stamping and bending strips of brass, it is possible that the edges of the components have slightly different properties (i.e., thickness, hardness, density, etc.) which cause preferential melting in certain areas. Also, the configuration of the brass components within the receptacle could be a factor in why the components exhibit these unique melting characteristics. For example, PVC receptacles will deform and char, exposing certain areas of the internal brass contacts to the fire while shielding others. Also, contacts can shift after the receptacle body materials have degraded, changing which part of the contacts is exposed.

As melting progressed, the receptacle contacts could eventually break apart when the connecting metal was melted away (see rightmost photograph in Figure 3-33). As the majority of the remaining brass melted away, cases were observed where the terminal screws remained lightly attached to the copper wiring prior to the copper itself melting. The thinner ground pin contacts on the receptacle grounding strap would usually exhibit melting when the plug contacts did also. But in some cases, only one or the other was melted. Figure 3-34 shows pitting and holes formed by melting in the ground pin contacts of an energized polypropylene receptacle. The contacts retained their original shape but exhibited pitting over a large portion of the surface. Evidence of arcing was found between the hot plug contact and the grounding strap in close proximity to the ground pin contacts shown in Figure 3-34. However, it is unlikely that any of the melting damage to the ground pin contacts was from arcing. This is because the pitting is located on both sides of the ground pin contacts (i.e., shielded and not shielded from the arcing) and is observed over an extended area. In addition, the holes formed in the ground pin contact are somewhat round, but the edges are irregular and not smooth.

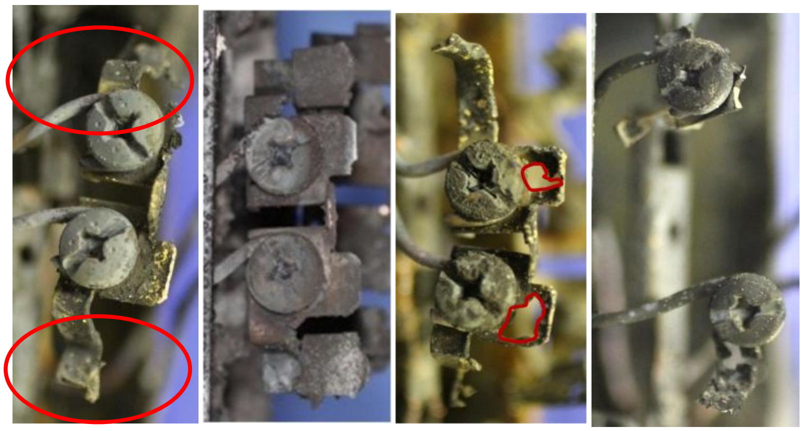


Figure 3-33. Progression of melting of brass receptacle components from non-energized receptacles; no melting observed in left most photo.

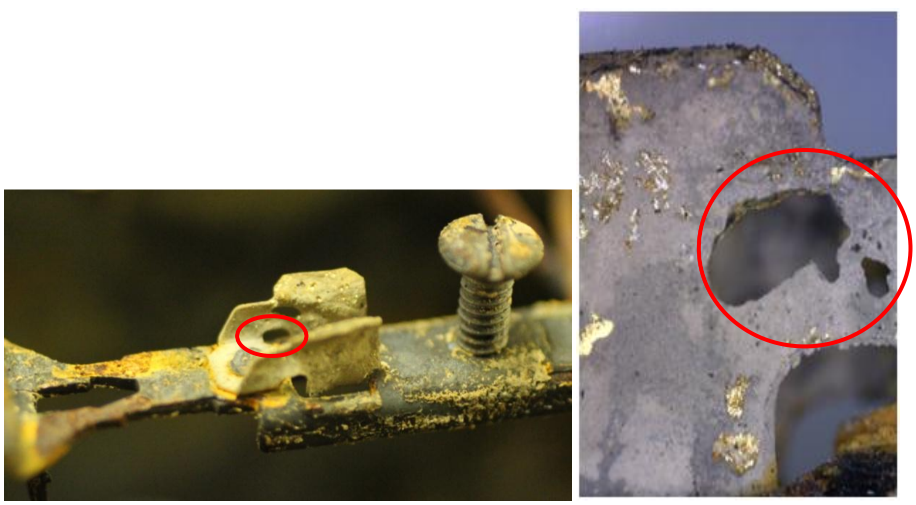


Figure 3-34. Melting of ground pin contacts; pitting and holes shown (LEV347, energized).

A rather unique case of surface pitting was observed for the PVC receptacle PSE346 as shown in Figure 3-35. For this non-energized receptacle, on the neutral side brass receptacle contacts, a number of parallel oblong divots were observed on the inside surface (nearest to the grounding strap). These divots were rather deep for the brass contact, on the order of half of the contact thickness. There were also visible lines surrounding and in between the divots. Overall, however, the brass contact does not show extensive melting damage. It is possible that the char from the PVC receptacle impacted the formation of the divots in this particular pattern, although no other cases were observed with this type of melting. Another unique case of melting was observed in a non-energized PVC receptacle as shown in Figure 3-36. The melting of this receptacle's brass contact was moderate overall, but in the area circled in red on Figure 3-36 there was significant thinning of the contact in a more localized area. This section of melted conductor is a very thin lattice of brass. The brass was too thin and fragile to measure the thickness, but it appears to be on the order of the thickness of a sheet of paper. Alloying was ruled out in this case because there was no proximate melted components that could have impacted this area.

Figure 3-35. Photographs of melted brass receptacle contacts showing surface pitting (PSE364, non-energized).

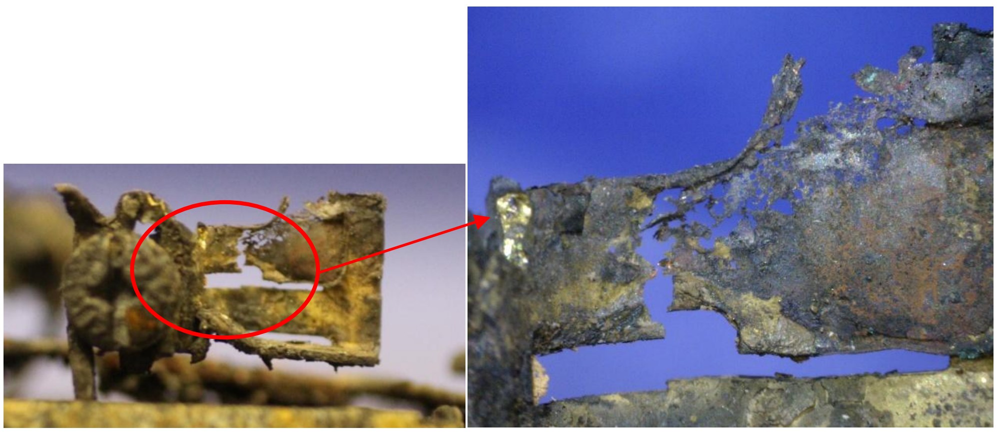


Figure 3-36. Photograph of melted brass receptacle contact showing thinning of contacts and holes (PSE373, non- energized).

Effects of gravity and round globules in melted brass contacts were quite prevalent when melting was extended beyond a single localized area. Effects of gravity in melted brass include formation of round globules and thinning, thickening, dripping and running of the brass contacts. Figure 3-37 shows a round globule that formed on the neutral break off tab of an energized PVC receptacle. Evidence of arcing in this receptacle was found on the hot and ground wiring behind the receptacle and was not in the vicinity of this globule. The globule is rather rough and was probably a result of melted brass running down the contact (see gravity direction in Figure 3-37). This brass contact also shows some thickening to the right of the globule in the direction of gravity. The melting of the brass contacts from PSE337 is not localized and extends from the break off tab to the bottom part that grips the plug blade.

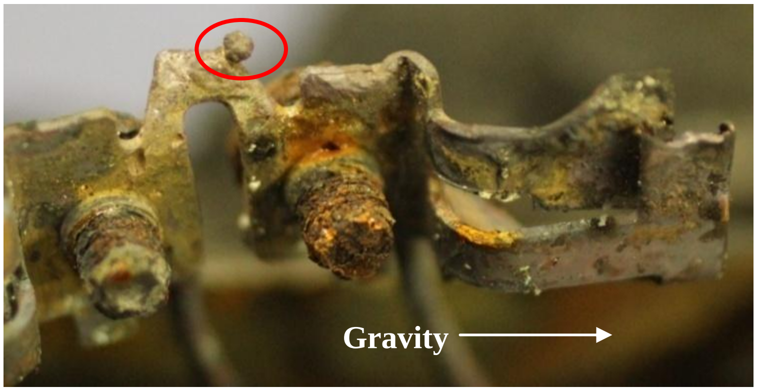


Figure 3-37. Photograph of melted brass receptacle neutral contact showing round globule and effects of gravity (PSE337, energized).

Even when the brass contacts are mostly melted from around the screw terminal, there may still be effects of gravity evident. Figure 3-38 shows the effects of gravity on the melted brass receptacle contacts from a non-energized polypropylene receptacle. The brass that is remaining on the screw terminal is not recognizable from the un-melted contacts; there are only two globules hanging from the screw that remain. Below the original location of the brass contact a pool of solidified brass can be seen at the bottom of the outlet box (solid circle). During the test, it appears that the brass also began to flow and drip through a hole in the bottom of the outlet box. Figure 3-39 shows the flow of melted brass for a non-energized polypropylene receptacle; the brass around the top terminal is thinned, pitted, and has a hole, while the brass around the bottom terminal is thicker and forms a round globule. This globule is very rough in appearance and the melting of the brass extends over the majority brass contact.

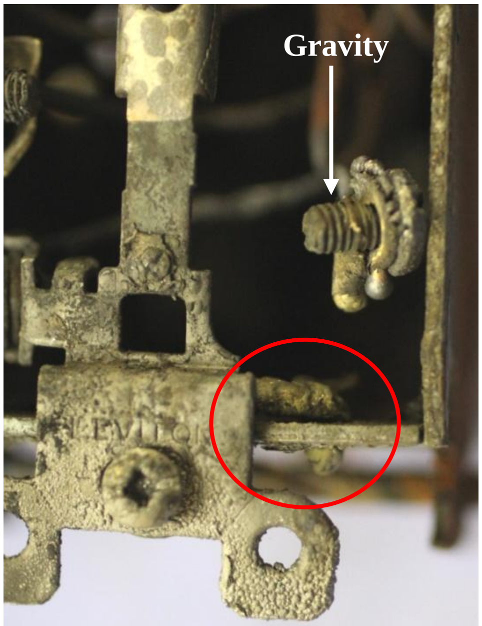


Figure 3-38. Photograph of melted brass receptacle contact showing round globules, effects of gravity and dripping brass (LEV363, non-energized).

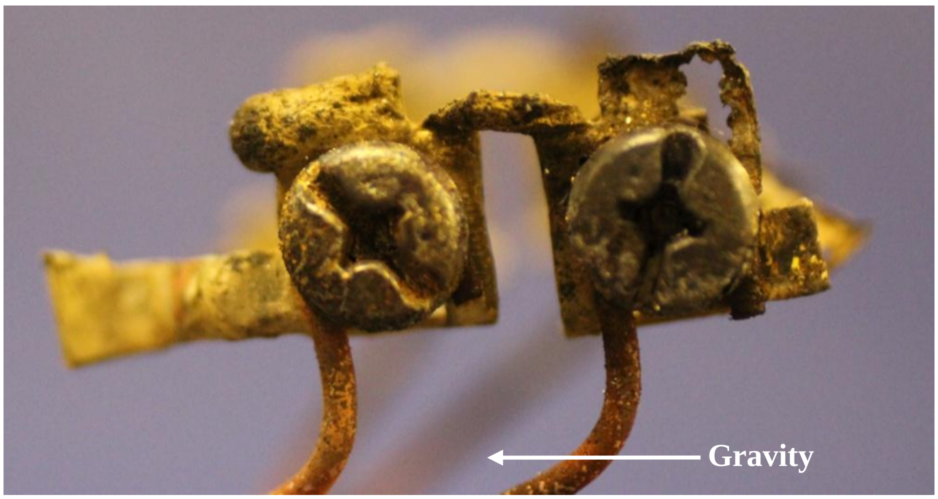


Figure 3-39. Photograph of melted brass receptacle contact showing round globule and effects of gravity (LEV354, non-energized).

3.3.6.1.2 Melting of Copper

Melting of solid copper wiring attached to receptacles and stranded copper wiring from extension cords was observed in some of the furnace fire exposure tests. In general, the melting of solid copper wiring attached to receptacles occurred uniformly across the exposed area. Melting of stranded copper wiring was quite extensive in the furnace fire exposures. This was due to the location of the wiring in the direct pathway of the burner at the front of the furnace near the wall assembly (see Figure 3-8). As a result, the majority of extension cord wiring was completely melted up to the point where it went beneath the ceramic insulation (see Figure 3-40). Melted copper conductors had various appearances including tapered ends, flat ends, pointed ends, irregular ends, and round globules. The following characteristic traits of copper melting were observed for stranded and solid copper wiring: gradual necking of conductor, surface pitting, effects of gravity, terminal screws separated from the conductor, and fusing of wire strands. One or more characteristic traits needed to be observed for melting to be confirmed. In most occasions, more than one characteristic was observed for a potentially melted component. In every case where melting of copper was identified in a receptacle, melting of brass components was also evident.

Figure 3-40. Extension cord wiring covered with insulation prior to test (left), with insulation after test (center) and with insulation removed (right) after furnace Test 4.

A clear line of demarcation between damaged and undamaged areas is an accepted indicator of arc melting. However, in a few cases this characteristic was observed in cases of melted copper. For instance, Figure 3-41 shows a wire from a non-energized polypropylene receptacle that has a round globule at one end. This globule has a rather distinct line of demarcation between it and the un-melted wire (shown as a dashed line). Evaluating this piece of evidence based on the clear line of demarcation alone could lead one to believe that the globule was from arcing. However, there was other clear evidence of copper melting due to fire exposure that was observed for this receptacle. Had the energized state of the receptacle been unknown during the evaluation, this piece of wire would have been a potential arcing location having extensive thermal damage. Figure 3-44 (left) shows another instance of a clear line of demarcation between the damaged site (i.e., the flat end) and the undamaged conductor. Also, faint copper drawing lines can be seen extending from the damaged area. Again, additional evidence (see Figure 3-44 center and right) from the receptacle and knowledge that the receptacle was non-energized, clearly indicates that melting of copper conductors from the fire has occurred and not arcing. These pieces of evidence do not suggest that the characteristics of a clear line of demarcation and copper drawing lines extending from the area of damage are not indicators of arcing. But, they do suggest that potential arcing or fire melting evidence from a receptacle should be examined within the context of the entire receptacle.

Figure 3-41. Melted copper wiring from a non-energized polypropylene receptacle showing line of demarcation (LEV389).

The melting point of brass is approximately 150ºC below that of copper. As such, in a receptacle with brass components and copper wiring, the brass should melt before the copper does. This was the case for the receptacles tested; in all cases where melting of copper was observed, the brass conductors were mostly melted away, if not completely melted. As the brass conductors melted away, this left the copper wiring wrapped around the screw as shown in Figure 3-42 (left). In some cases, the screw fell from the wiring (see Figure 3-42, right). Both of the photographs in Figure 3-42 show the wires beginning to taper. As melting continues, the wire looses the original crook-shape and a straight section of wire is left pointing outward from the outlet box (see Figure 3-43, left), usually exposing just a small section at the end of the wire. This arrangement causes melting to often occur along the longitudinal axis of the wire which creates distinct melting evidence on the conductors as compared to the brass components (i.e., flat ends, pointed ends, and irregular ends).

Figure 3-43 shows an irregular, bumpy, and slightly tapered copper wire with a relatively flat surface at the end. Figure 3-44 shows three different examples of melted copper wiring were found from a single non-energized polypropylene receptacle (LEV371). The left image shows a wire with a flat end. This wire has a rather distinct line of demarcation between the melted area and the un-melted wire, with the copper drawing lines somewhat visible. The flat side of the wire is rough and with many divots; Figure 3-45 shows another example of this. The center photograph in Figure 3-44 shows a wire with a pointed end having a clear line of demarcation between the un-melted wire and the melted area. The surface of the end of the wire is rather smooth and rounded. The third melted copper wire from LEV371 has the more typical appearance of a melted copper wire with the irregular tapered end that has some pitting. The fourth conductor from LEV371 was located at the bottom of the outlet box, partially melted but still attached to the screw with a melted brass globule.

Figure 3-42. Tapering of melted copper wiring on a polypropylene receptacle (energized, LEV365, left) and a thermoset receptacle (non-energized, C023, right).

Figure 3-43. Photographs of melted copper wiring from a PVC receptacle showing tapered shape, irregular surface, and flat end (energized, PSE369).

Figure 3-44. Photographs of three melted copper wire ends from a single non-energized polypropylene receptacle (LEV371): flat (left with blowup of flat face), pointed (center), and tapered (right).

Figure 3-45. Photograph of melted copper wiring showing a flat end with pitting from a non-energized PVC receptacle (PSE384).

Pitting of copper conductors ranged from small divots over the surface of the melted conductor to extensive pitting that left the wiring very porous. Figure 3-46 shows an irregular shaped end of a melted copper wire attached to the terminal screw. The melted conductor has an area of small pits and large overall divots that give the irregular appearance. Severe pitting of the melted copper conductors was observed in only a few cases. In these cases, the majority of copper wiring in the outlet box was melted. Figure 3-47 shows a photograph of an outlet box that with the melted wire contained inside (left) as well as a blown up photograph of the severely pitted copper wiring (right). This outlet box had an energized polypropylene receptacle installed. The photograph of the outlet box also shows the effects of gravity on the melted copper that has been deposited and pooled in the bottom right of the outlet box. The severely pitted wiring retained its original shape, but became very porous. It is unclear exactly what conditions would cause this to happen, but the surface of this wire does appear to have a significant layer of cuprous oxide (rust/orange color). Effects of gravity in copper wiring were observed as round globules extended down the copper wiring and pools of copper deposited in the bottom of outlet boxes. Figure 3-48 and the right photo in Figure 3-53 show two instances of round globules of melted copper on un-melted wire.

An interesting case of copper melting occurred on the ground screw terminal from a non-energized PVC receptacle. This can be seen in Figure 3-49 where the copper has melted and filled in the area between the screw head and the ground strap terminal. This was the only observed instance of copper melting in this fashion. The melted copper appears to have some rather large voids as evidenced by some surface holes. This type of melting is somewhat similar to the welded conductors formed by glowing connections. What sets this evidence apart from the welded conductors formed from glowing connections is that this does not exhibit the curved striations associated with the glowing connections (see Section 2.3.5.2 and Figure 2-57). Only 24 out of 61 welded conductors did not have the curved striations; 18 of these were from enlarged screw heads and some were from partially welded conductors (see Tables 2-9 and 2-10). Neither the enlarged screw head nor partial melting are present in the melted conductor shown in Figure 3-49.

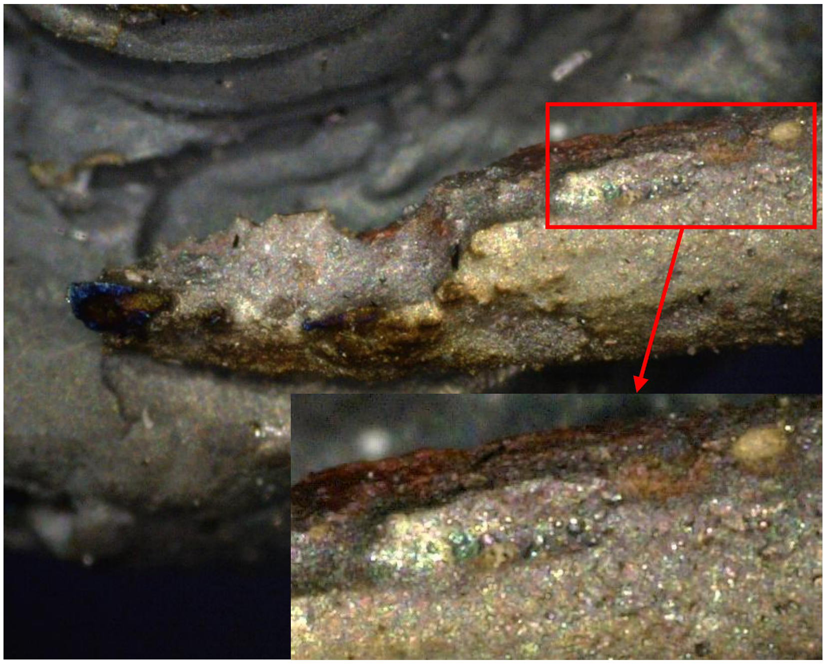


Figure 3-46. Photograph of melted copper wiring showing irregular, tapered end and pitting from an energized thermoset receptacle (E041).

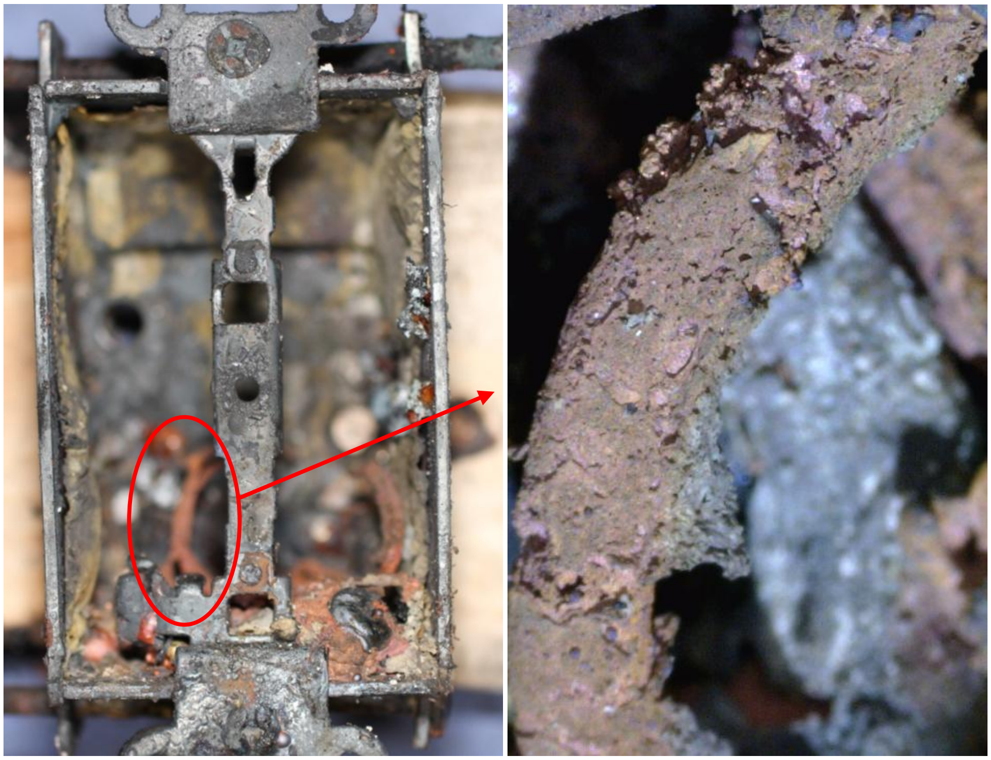


Figure 3-47. Photograph of melted copper wiring showing severe pitting and effects of gravity from an energized polypropylene receptacle (LEV361).

Figure 3-48. Photograph of melted copper wiring showing irregular end and effects of gravity from a non-energized PVC receptacle (PSE386).

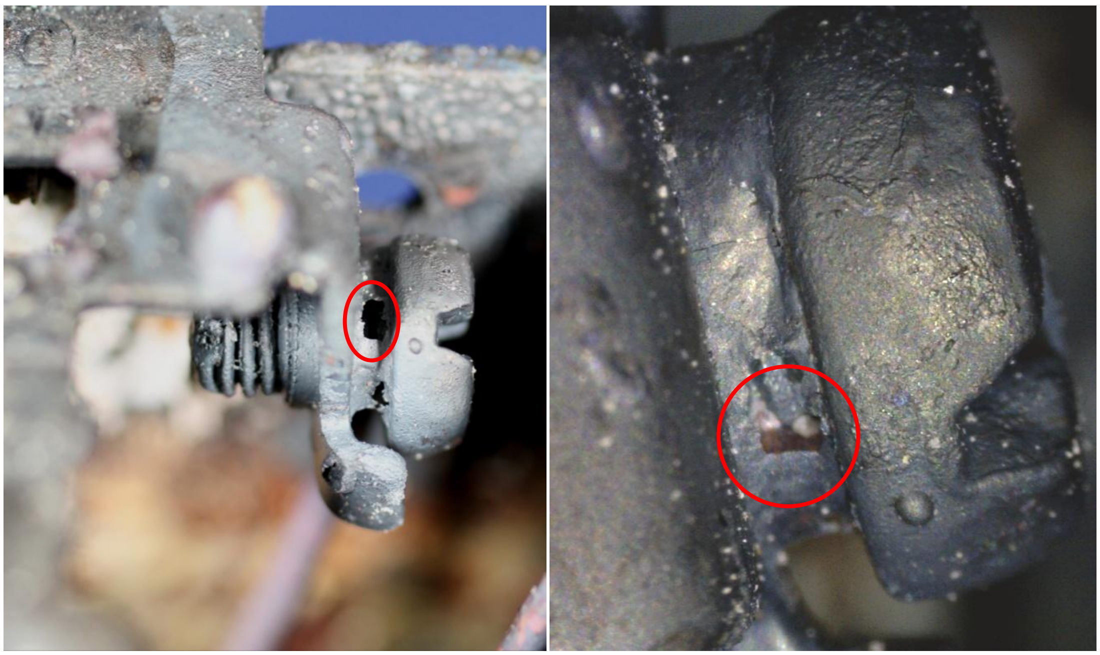


Figure 3-49. Photograph of melted copper wiring around ground screw terminal from a non-energized PVC receptacle (PSE386).

The lack of observation of fire melted copper connections that appear similar to the welded conductors from glowing does not preclude the possibility of this occurring. However, the formation of welded conductors with curved striations by fire is rather unlikely. First, the melting due to glowing occurs in a slow progression (i.e., hours), which creates the curved striations. Melting due to fire is rather quick (i.e., minutes) and in general will not occur in such a uniform motion that would produce the curved striations. Also, in order for all of the copper to melt between the steel screw and brass terminal, the temperatures would have to be hotter than the melting point of brass. This would probably lead to melting of a different appearance, e.g., as shown in Figure 3-42. But, in the case of steel conductors (i.e., grounding straps and screws), it was possible for the copper to melt and flow between the two conductors. However, in this case, the reason for extended duration current flow through the ground connection would also have to be established for the melting to be linked to a glowing connection.

Due to the location of the extension cords in the path of the burner (see Figure 3-40), there was not much melted stranded wire remaining from the furnace fire tests. Melting of stranded wiring was observed with some similar characteristics as melted solid wiring. However, the difference in configurations between the solid (in an outlet box) and stranded (in the open) wiring meant that some of the unique melted copper evidence shown for the solid copper wiring did not appear for the stranded wiring. For example, the flat wire ends, severe pitting, clear line of demarcation, and copper drawing lines visible outside the damage area were generally not observed for the stranded wiring. The majority of melted stranded wiring had rough round globules at the end of the wire such as the one pictured in Figure 3-50. The two globules are rather large compared to the size of the wire and the wire strands actually run through the smaller of the globules. Some of the melted stranded wiring exhibited partially fused strands in the vicinity of the melted globule (see Figure 3-51). This is also an indication that the damage is not localized and that there is not a clear line of demarcation between the un-melted and melted sections of wiring.

Figure 3-50. Photograph of melted stranded copper wiring for an energized extension cord from a thermoset receptacle; wire strands running through melt globule circled in red (E098).

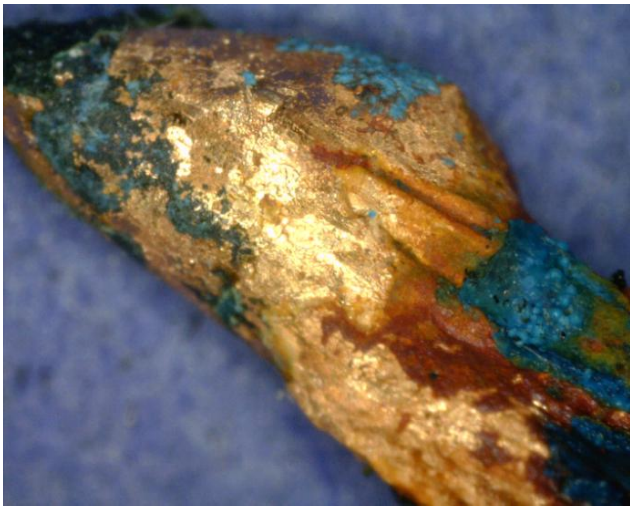


Figure 3-51. Photograph of melted stranded copper wiring showing fused strands form an energized extension cord from a thermoset receptacle (E098).

3.3.6.2 Thermal Exposures for Melting of Brass and Copper Receptacle Components

Fifty-four receptacles had maximum exposure temperatures greater than the melting point of brass (940ºC) but did not have brass melting in the receptacle. The average maximum exposure temperature for these receptacles was 1041ºC (range: 952–1202ºC). Ten receptacles had maximum exposure temperatures greater than the melting point of copper (1080ºC) but did not have copper melting in the receptacle. The average maximum exposure temperature for these receptacles was 1158ºC (range: 1096–1202ºC). Also, 64 of the 90 receptacles with melted brass had maximum exposure temperatures greater than the melting point of copper but did not have copper melting in the receptacle. The average maximum exposure temperature for these receptacles was 1188ºC (range: 1090–1238ºC).

There are two likely reasons why the metal components in the receptacles did not melt when the maximum fire exposure temperature was above their melting point. First, the maximum fire exposure temperature was not necessarily applied for a long enough time for the bulk of the brass and copper components to heat up enough for melting to occur. The high thermal conductivity of the metals (brass, copper, and steel) from the receptacles would also serve to dissipate some the heat from the fire. And with the receptacles installed within the wall assembly and the copper and brass components recessed behind the wall assembly some of the receptacles were shielded from direct fire exposure by the wall, faceplates or the receptacle material itself. Table 3-19 lists the minimums, maximums, averages and standard deviations for the maximum exposure temperatures for brass and copper melting damage in receptacles. Figure 3-52 is a histogram plot of the frequency for brass and copper melting as a function of the maximum exposure temperature range. This data is presented for all of the receptacles having brass and copper melting, irrespective of the receptacle material, faceplate material, or energized state of the receptacle. In all cases where copper melting was observed, the brass receptacle components had also melted.

Table 3-19. Summary of Maximum Exposure Temperature Data for Receptacles with Melted Brass and Copper Components.

Damage Category	Qty.	Min. of Maximum Exposure Temperature (ºC)	Max. of Maximum Exposure Temperature (ºC)	Avg. Maximum Exposure Temperature (ºC)	Std. Dev. of Maximum Exposure Temperature (ºC)
Brass Melting	90	964	1238	1140	81
Copper Melting	36	1000	1251	1184	52

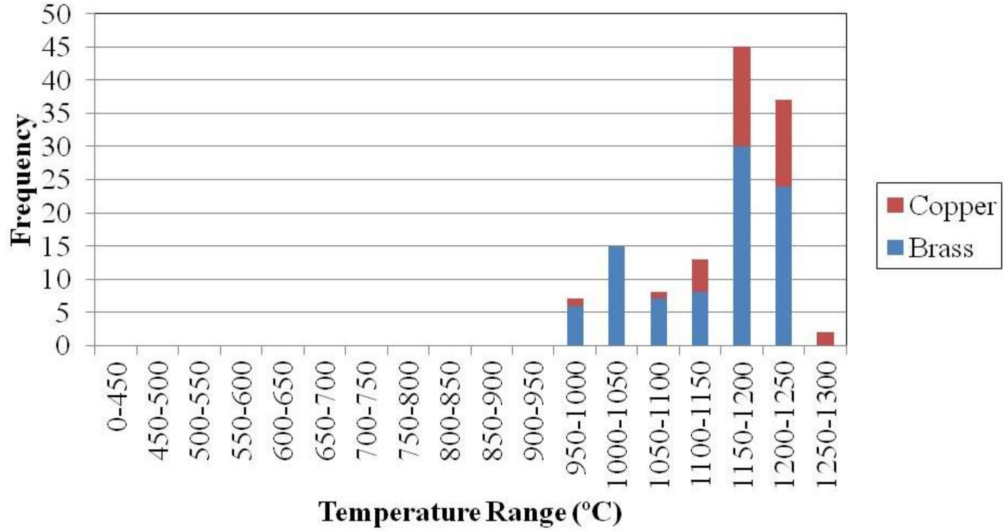


Figure 3-52. Histogram plot of the number of receptacles with metal melting as a function of the maximum exposure temperature range.

All but two receptacles that had brass or copper melting had fire exposure temperatures greater than the melting point of the brass or copper, respectively. These two receptacles, LEV398 and LEV400, had significant copper melting but had maximum exposure temperatures of 1000 and 1055ºC, respectively (see Figure 3-53). Melting of steel faceplates at temperatures lower than the melting points was also observed (see Section 3.3.3.2). Both receptacles were energized polypropylene receptacles, installed in steel outlet boxes with steel faceplates. Also, both receptacles had solid, plated plugs installed. Maximum exposure temperatures were calculated using the furnace characterization tests (see Section 3.3.1.1.1). However, the furnace characterization was conducted with an inert wall assembly that did not burn, while the furnace fire tests, on the other hand, were conducted with receptacles, wood studs, and wiring insulation that did burn. It is possible that the contribution of the burning receptacles, wiring, and/or faceplate materials produced higher temperatures within the outlet boxes for some receptacles causing the copper to melt. The differences between the maximum exposure temperatures in these two cases and the melting point of copper were 25ºC and 80ºC; these differences are not that large.

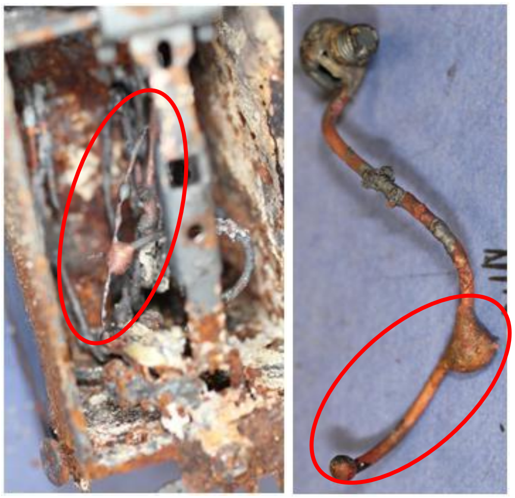


Figure 3-53. Photographs of melted copper wiring from energized polypropylene receptacles LEV398 (left) and LEV400 (right).

There does not seem to be any significant trend with regard to the effect of the receptacle material on the maximum exposure temperature for brass melting. Table 3-20 lists the minimums, maximums, averages and standard deviations for the maximum exposure temperatures for each receptacle material having melted brass. Figure 3-54 is a histogram plot of the melted brass damage category frequency for each receptacle material as a function of the maximum exposure temperature range. This data is presented for all of the receptacles with melted brass components over all fire exposure testing, irrespective of faceplate material energized state of the receptacle. There is a rather large overlap between the three ranges of maximum exposure temperatures producing melting of brass for polypropylene, PVC, and thermoset receptacles. Even though the minimums, maximums, and averages of the maximum exposure temperatures are quite close (within approximately 20ºC of each other), they are in the expected order based on material. Polypropylene which will completely melt has the lowest temperatures, PVC which completely chars has the second lowest, and the most resilient material, thermosets, have the highest.

Table 3-20. Summary of Maximum Exposure Temperature Data for Receptacles with Melted Brass Components, by Receptacle Material.

Receptacle Material	Qty.	Min. of Maximum Exposure Temperature (ºC)	Max. of Maximum Exposure Temperature (ºC)	Avg. Maximum Exposure Temperature (ºC)	Std. Dev. Of Maximum Exposure Temperature (ºC)
Polypropylene	36	964	1231	1121	89
PVC	29	982	1238	1143	79
Thermosets	25	1026	1238	1166	62

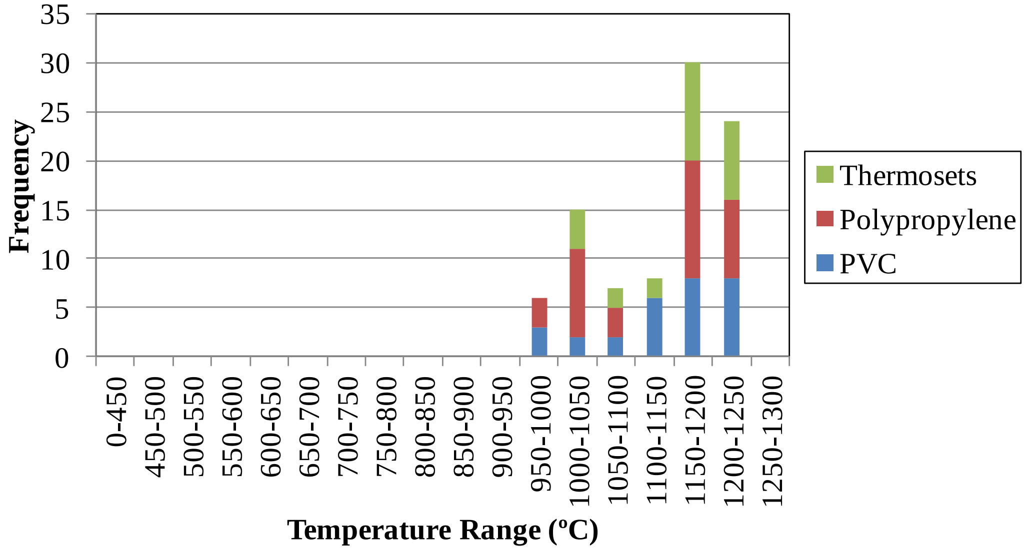


Figure 3-54. Histogram plot of brass receptacle components melting as a function of the maximum exposure temperature range.

Receptacles with melted copper exhibit the same behavior as melted brass with respect to the receptacle material for the averages and ranges of maximum exposure temperatures. Table 3-21 lists the minimums, maximums, averages and standard deviations for the maximum exposure temperatures for each receptacle material having melted copper. Figure 3-55 is a histogram plot of the melted copper damage category frequency for each receptacle material as a function of the maximum exposure temperature range. This data is presented for all of the receptacles with melted copper components over all fire exposure testing, irrespective of faceplate material, or energized state of the receptacle.

Table 3-21. Summary of Maximum Exposure Temperature Data for Receptacles with Melted Copper Components, by Receptacle Material.

Receptacle Material	Qty.	Min. of Maximum Exposure Temperature (ºC)	Max. of Maximum Exposure Temperature (ºC)	Avg. Maximum Exposure Temperature (ºC)	Std. Dev. Of Maximum Exposure Temperature (ºC)
Polypropylene	16	1000	1204	1153	57
PVC	6	1136	1251	1197	44
Thermosets	13	1164	1251	1214	24

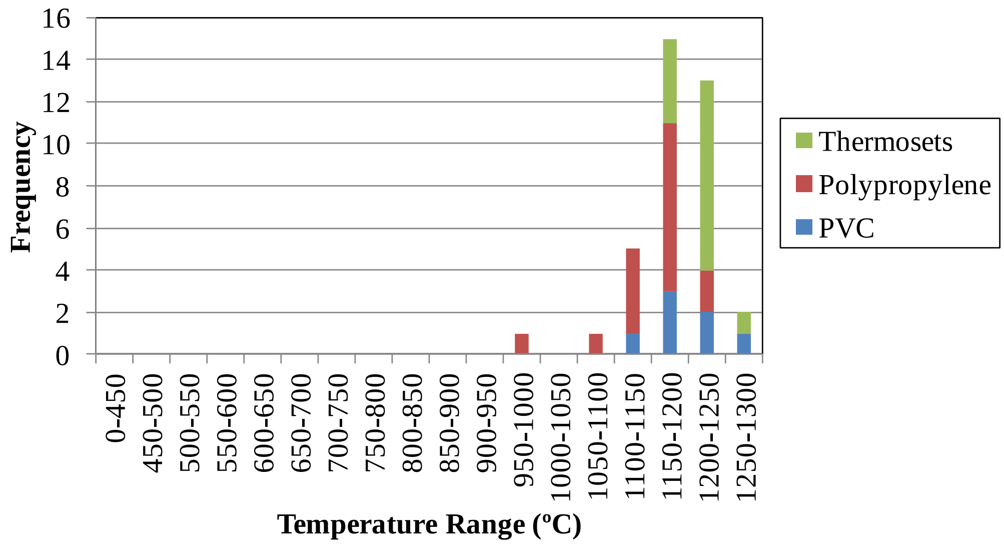


Figure 3-55. Histogram plot of copper receptacle components melting as a function of the maximum exposure temperature range.

Table 3-22 lists the averages and standard deviations for the maximum exposure temperatures for brass and copper melting as a function of the faceplate material. This data is presented for all of the receptacles with melted brass and copper over all fire exposure testing, irrespective of the receptacle material or energized state of the receptacle. Because the nylon faceplates readily fall off of the receptacles while the steel faceplates remain intact and partially shield the receptacles, it would follow that the average of the maximum exposure temperatures for nylon faceplates would be less than those of steel faceplates within the brass and copper melting categories. Based on the data in Table 3-22, this is the case for brass melting and not copper melting.

Table 3-22. Summary of Maximum Exposure Temperature Data for Receptacles with Melted Copper and Brass Components, by Faceplate Material.

Faceplate Material	Qty.	Avg. [Std. Dev.] of Maximum Exposure Temperature for Brass Melting (ºC)	Qty.	Avg. [Std. Dev.] of Maximum Exposure Temperature for Copper Melting (ºC)
Plastic	23	1070 [76]	24	1201 [27]
Metal	67	1165 [68]	12	1151 [70]

3.3.7 Arcing Damage

Arcing evidence that was found in the post-fire examinations for compartment fire and furnace fire tested receptacles was identifiable using low powered microscopes. The process of identifying arcing damage consisted of first determining that the damage was not from fire melting and, second, determining which conductors were involved in the arcing. Determining whether the evidence was due to melting involved an examination for the characteristics of melting of copper or brass as described in Section 3.3.6.1. Also, in some cases the potential of melting could be eliminated based on other contextual evidence. For instance, if a potential arc site was identified in the copper wiring behind a receptacle, but the receptacle itself was intact and did not show any evidence of melting of the brass components, it was not possible for the potential arc site to be due to melting. This is because in the scenarios tested, the fire exposure was from the front of the outlet box (and receptacle) and would cause the brass components (with a lower melting point than copper) in the front of the outlet box to melt before the copper wiring in the back of the outlet box.

3.3.7.1 Arcing Damage Location

In the compartment fire testing and furnace fire testing, there were a combined 251 receptacles that were energized. Of these 251 receptacles, 50 did not trip the circuit breaker during the test nor was arcing or melting evidence found in the brass and copper components. The only receptacles that did not trip the circuit breaker were in compartment fire Tests 1 through 6. All of the energized receptacles with extension cords tripped the circuit breakers. There were a number of locations of arcing that were common through all of the fire exposure tests. Arcing was determined by visual inspection of the receptacle contacts, grounding strap, outlet box, faceplate, and wiring. Arcing was identified in cases where one or more of the following characteristics were observed:

- Localized damage with a sharp line of demarcation around the damaged area;
- Corresponding damage on the opposing conductor;
- Resolidification waves;
- Copper drawing lines or metal edges and lettering visible outside the damaged area;
- Spatter deposits;
- Small beads or globules near arc area;
- Notches in metal components;
- Multiple divots, arc spots; and
- Transfer of metal between conductors.

A portion of the arcing damage samples from fire exposures was examined for the presence of the proposed NFPA 921 [2014] characteristics of arcing and melting; see Section 4.0 for results and discussion. Table 3-23 lists the quantities of arcing instances for each of the different primary arc locations as a function of the secondary arc location. The primary arc location is defined as the energized (i.e., hot) component of the receptacle installation where arcing occurred. Figures 1-3 and 1-4 detail the receptacle components for the new receptacles used in testing. Figures throughout this section illustrate the various arcing locations observed. The primary arcing locations included the female plug contacts, the break off tab on the female plug contacts, receptacle wiring (solid) and extension cord wiring (stranded). The break off tab was included as a separate location from the plug contacts for two reasons: in some installations, this item is removed to isolate the two outlets from each other and there were enough unique cases of arcing for this item that it warranted separation. The secondary arcing location is a conductor involved in the arcing other than the hot conductor such as part of the ground system (i.e., steel faceplate, metal outlet box, ground strap, or ground wire) or the neutral wire.

Table 3-23. Summary of arc locations in energized receptacles and cords.

Primary Arc Location	Secondary Arc Location	Quantity of Locations w/ Confirmed Arcing	Quantity of Locations w/ Possible Arcing
Female Plug Contact (Hot)	Faceplate	41	3[A]
	Ground Strap	24	1[A]
	Outlet Box	1	0
	Total	**66**	**4**
Break Off Tab (Hot)	Faceplate (**Total**)	**34**	**5[B]**
Receptacle Wiring (Hot wire)	Ground Wire	20	0
	Neutral Wire	19	0
	Faceplate	1	0
	Outlet Box	7	0
	Unknown[C]	4	0
	Total	**51**	**0**
Extension Cord Wiring (Hot wire)	Ground Wire	7	0
	Neutral Wire	5	0
	Unknown	**0**	**6[D]**
	Total	**12**	**0**
Unknown[E]	**Total**	**N/A**	**23**

A – Brass melting evident; arc location on ground strap or faceplate identified.
B – Four because of brass melting, 1 because of rust.
C – Only a single conductor was found with arcing damage; no corresponding arc location.
D – Large section of wire melted away. Arcing location in cord wiring was possible b/c of very quick time to breaker tripping.
E – Evidence of arcing not found.

For 23 receptacles, the circuit breaker had tripped during the fire exposure, but evidence of arcing was not identified in the receptacles. This was about 11% of the receptacles that tripped the circuit breakers during the tests. These 23 receptacles had a mix of receptacle, outlet box, and faceplate materials as well as a variety of damage levels for each component. Melted plastic, charred plastic, rust, scaling of steel components, and melting of brass and copper contributed to the difficulty of identifying arcing damage in these receptacles. Whether the energized receptacles had a load during the test did not appear to affect whether the receptacle arced, how fast the receptacle arced, where the receptacle arced, or the appearance of the arcing evidence. Six of the unknown arcing cases for receptacles with plugs and extension cords in the furnace fire testing were listed as possible arcing in the cord because the time to tripping was much quicker (<1 minute) than arcing that occurred in receptacles (>2 minutes) due to the location of the cord in the pathway of the front burner. There is some discussion at the end of Section 3.3.6.1.2

which describes the melting of these cords. It is likely that the extensive melting destroyed any arcing evidence for these extension cords.

Arcing damage was split into two categories: confirmed and possible. Confirmed arcing was where arcing damage was identified on both the primary and secondary locations and confirmed through visual examination with respect to the characteristics of arcing (see Section 3.3.7.2). Possible arcing was where arcing damage was only identified on either the primary or secondary locations. Additional circumstantial evidence (i.e., location of arcing damage on the conductor, melting of certain components, or lack of melting) aided in this determination. Each instance of potential arcing damage was evaluated on a case by case basis using all of the information at hand including the test details, receptacle installation configuration, whether the circuit breaker tripped, etc.

In four cases where possible arcing was identified for the female plug contacts, the plug contacts were all or partially melted, but the faceplate or grounding straps were not melted. Evidence of arcing on the grounding strap and faceplates, located in the vicinity of where the plug contacts would have contacted those components, indicated that arcing was possible. The same was true for the 5 cases of possible arcing on the break off tabs where arcing was not confirmed on both the primary and secondary items. One such case was for a PVC receptacle (PSE2115, see Figure 3-56). The break off tab has some apparent arcing damage on the tip where it would have come into contact with the faceplate. However, the arcing damage is not as obvious as a deep notch and the faceplate is quite rusty in the vicinity of where the break off tab would have contacted it. This rust is enough to cover up and potentially destroy any potential arcing damage. Four instances of arcing were found in receptacle wiring where only one conductor was found with arcing damage. In these cases, arcing damage was not visually identified on other wiring, outlet boxes, faceplates, or grounding straps, but was rather obvious based on the arcing characteristics in Section 3.3.7.2 (see Figure 3-57). In addition, no other evidence of copper melting was found for these four receptacles.

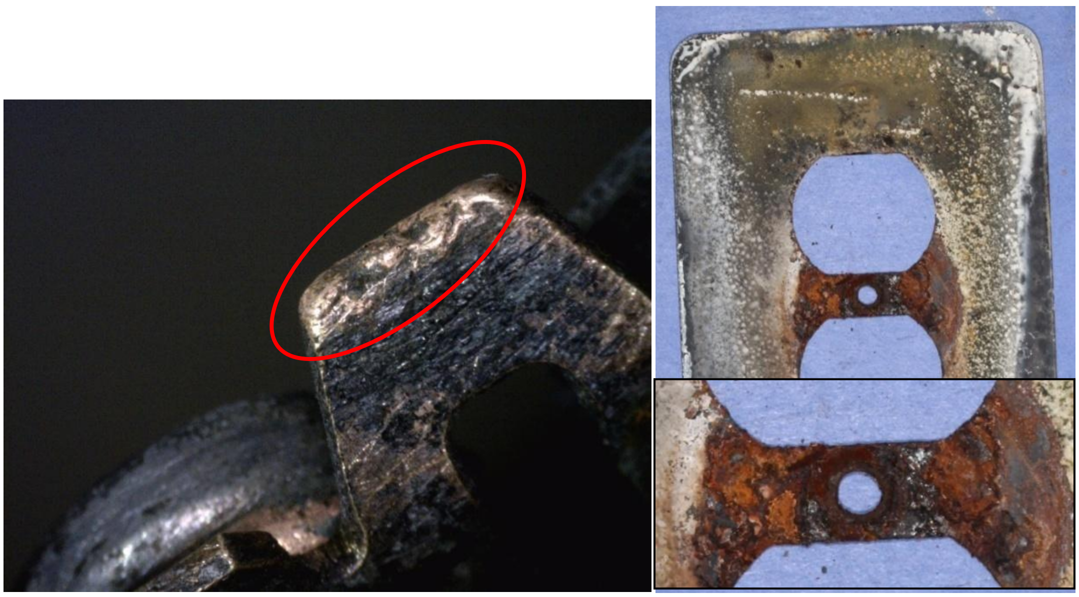


Figure 3-56. Photos of possible arcing damage on break off tab of energized PVC receptacle (PSE251, left) and rusted steel faceplate (right).

Figure 3-57. Arcing evidence on wiring from four thermoset receptacles
(From left to right: B010, D035, E078, and E083).

The conductors within the outlet box and receptacle installations tended to be rather crowded and close together. These conductors, other than the internal plug contacts, were not routed in any manner that would prevent contact from each other in the event that the insulation degraded enough. Also, the amount of wiring in each outlet box and the manner in which it was folded and placed in the outlet box was not strictly controlled. Given the variations and randomness associated with some aspects of the installations (i.e., wire arrangement in outlet box), it would follow that the arcing locations would be more random. However, this is not the case. There are some rather obvious trends with respect to the relationship between the primary arc location and the secondary arc location (see Table 3-23). The receptacle material and construction also appears to have a rather large impact on the primary arcing location. Table 3-24 lists the primary arcing location as a function of the receptacle material. For each primary arc location, the percentage of the total number of arcing locations identified for each material is listed. Arcing in the extension cords is not included in Table 3-24 as this was independent of the receptacle material.

Table 3-24. Arcing Location as a Function of Receptacle Material Type.

Primary Arc Location	Receptacle Material	Total Quantity (w/ Steel faceplate; w/ Nylon faceplate)	Percentage of Total Arcing Instances for the Receptacle Material
Female Plug Contact	Polypropylene	58 (47; 11)	73%
	PVC	10 (5; 5)	15%
	Thermosets	2 (2; 0)	6%
	Total	**70 (54; 16)**	-
Break Off Tab	Polypropylene	1 (1; 0)	1%
	PVC	38 (38; 0)	55%
	Thermosets	0	0%
	Total	**39 (39; 0)**	-
Receptacle Wiring	Polypropylene	13 (2; 11)	16%
	PVC	10 (2; 8)	15%
	Thermosets	29 (11; 18)	80%
	Total	**52 (15; 37)**	-
Unknown	Polypropylene	7 (2; 5)	9%
	PVC	10 (4; 6)	15%
	Thermosets	6 (1; 5)	16%
	Total	**23 (7; 16)**	-

The most obvious trend in the arcing locations is that every instance of arcing on the break off tab occurred with a steel faceplate. The majority (97%) of these instances occurred for PVC receptacles and 55% of the arcing locations in PVC receptacles were located on the break off tab. When a steel faceplate is installed on the PVC receptacles, there was about 3.5 mm (0.14 in.) of space between the break off tab and the faceplate. The break off tabs on the PVC receptacles are bent slightly more towards the faceplate than the polypropylene receptacles (see Figure 3-58). Also, the break off tab sits slightly forward of the rest of the internal plug contacts and is not covered by any insulation, whereas for the polypropylene receptacles the break off tab is recessed behind the other parts of the internal plug contacts. The internal plug contacts of all receptacles are normally covered by the body material of the receptacle. When a steel faceplate is installed on the polypropylene receptacles, there was about 4.8 mm (0.19 in.) between the break off tab and the faceplate. There was a wide range of different manufacturers and configurations of the thermoset receptacles, but a sample of these revealed that the distances between the break off tabs and the faceplates were comparable to both the PVC and polypropylene receptacles. A number of thermoset receptacles were also observed that had insulation between the break off tab and where the faceplate would sit.

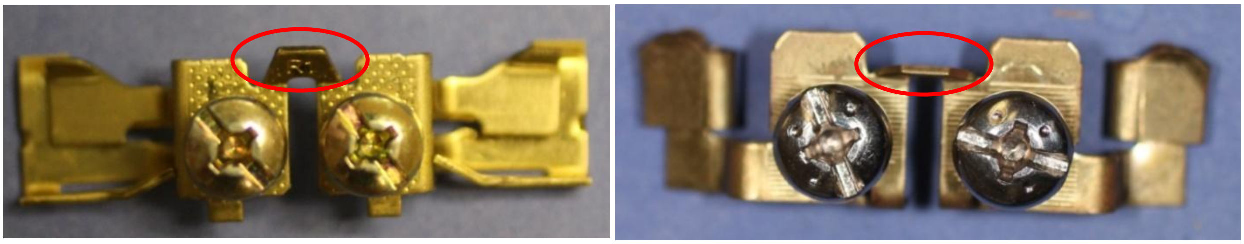


Figure 3-58. Exemplar PVC internal plug contacts (left) and polypropylene internal plug contacts (right); break off tabs circled.

Each of the receptacle materials has one particular primary arc location where the majority of arcing incidents were located. The configuration of the break off tab for the PVC receptacles seems to play a large role in where arcing will occur for these receptacles. However, the tendency for PVC receptacles to have arcing in the break off tab is also a function of the material properties. Compared to the thermoset receptacles, some which have comparable separation distances between the break off tabs and faceplates, the PVC receptacles had 38 instances of arcing in this location and thermosets had none. A possible explanation for this difference is that when heated, the PVC receptacles will deform and the spring force from the wiring behind the receptacles attached to the internal plug contacts will push the contacts towards the faceplate. This can be seen in Figure 3-59 which shows arcing between the break off tab from a PVC receptacle and a steel faceplate. Notice in the leftmost photograph that the internal contacts have been pushed outward from the receptacle. Thermoset receptacles, on the other hand, tend to retain their rigidity at much higher temperatures than the PVC. Therefore, the material resists the forces from the wires behind that would otherwise tend to cause the internal contacts to touch the faceplate and arc.

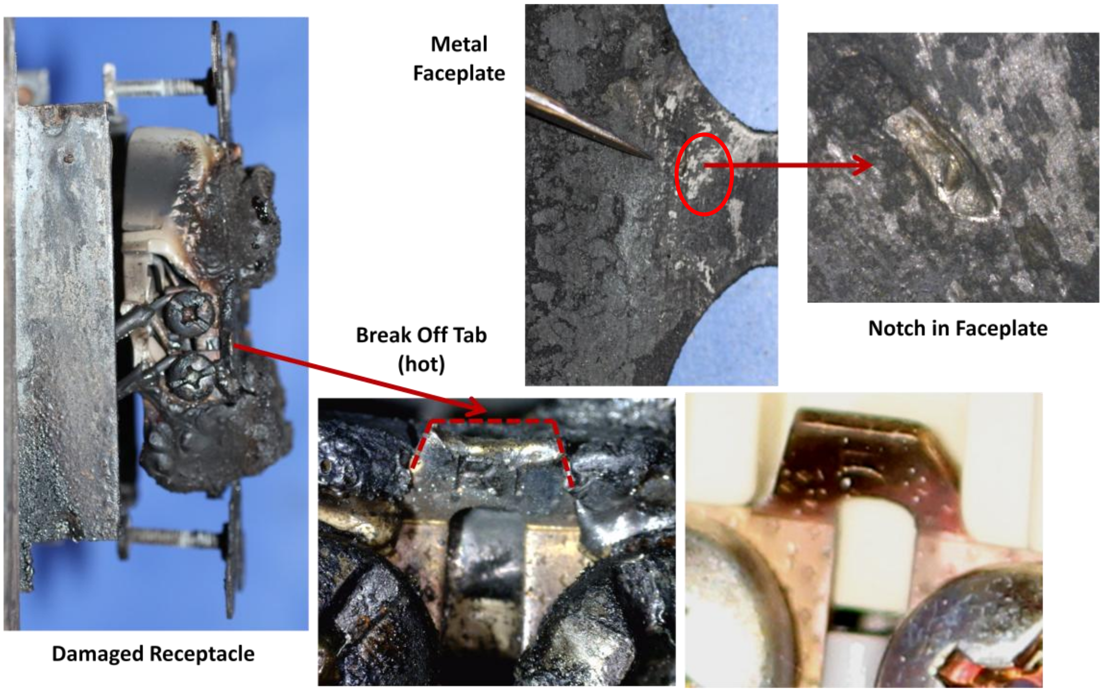


Figure 3-59. Photographs of damaged PVC receptacle (PSE085) showing arcing damage on the hot break off tab and steel faceplate; exemplar break off tab also shown.

The majority (73%) of arcing instances in polypropylene receptacles occurred on the female plug contacts. Of all of the arcing instances on female plug contacts, 43 out of the 44 with faceplates and 15 out of 25 with ground straps were from polypropylene receptacles. Similar to the PVC receptacles, both the construction of the internal plug contacts and the material properties impacted the tendency to arc in certain locations. The internal contacts for the polypropylene receptacles were constructed such that there was a brass tab located above the screw terminals that stuck out further than the break off tab (see Figure 3-58). When heated by the fire, the polypropylene receptacles would melt and run, uncovering the internal contacts below the body material. The spring force of the receptacle wiring would push the contacts into the steel faceplate. Figure 3-60 shows an example of this where the bottom hot internal contact arced to the steel faceplate. A deep notch is visible on the hot contact while a shallow notch was created on the faceplate. These specific instances of arcing also illustrate the impact of a steel faceplate on the location of arcing. For the 69 receptacles with nylon faceplates installed (not including those with extension cords): 37 (54%) of the arcing instances were in the receptacle wiring, 16 (23%) were on the plug contacts and 16 (23%) were unknown. For the 115 receptacles with steel faceplates installed (not including those with extension cords): 15 (13%) of the arcing instances were in the receptacle wiring, 54 (47%) were on the internal plug contacts, 39 (34%) were on the break off tab, and 7 (6%) were unknown.

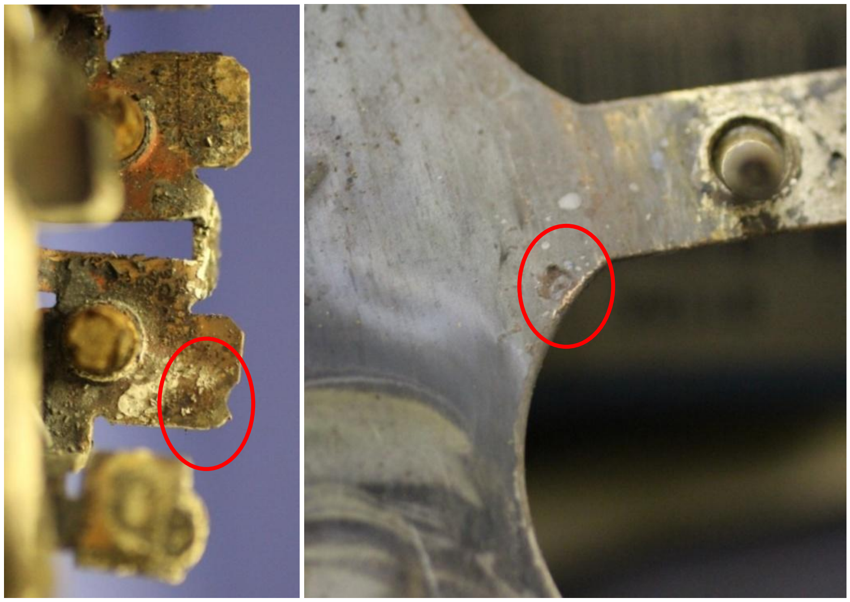


Figure 3-60. Photographs of arcing damage on hot female plug contacts (left) and steel faceplate (right) from a polypropylene receptacle (LEV336).

There was some discussion in Section 2.3.7.1 about the propensity of the different receptacle materials having shorting failure events due to overheating. It was observed that the thickness of the insulation between the grounding strap and the internal plug contacts along with the material behavior would dictate the likelihood for a receptacle to fail due to shorting in this location. This observation is somewhat bolstered by an analysis of arcing occurring as a result of fire effects. Of the 25 receptacles with arcing between the internal plug contacts and the ground strap due to fire, one was in a thermoset receptacle, ten were in PVC receptacles, and 14 were in polypropylene receptacles. This is compared to the shorting failure events due to overheating, zero of which were for thermoset receptacles, two for PVC receptacles, and 19 for polypropylene receptacles. It is obvious from these data sets that arcing in thermoset receptacles between the internal contacts and the grounding strap is highly unlikely due to the thermal stability of the thermoseting plastics. On the other hand, arcing in this location for polypropylene receptacles is rather likely due to its tendency to melt and run. The trend is not as strong for PVC receptacles which had, proportionally, many more arcing events due to fire than due to overheating. It is probable that both the time scale of heating (i.e., days for laboratory testing and minutes for fire) and the installation of the receptacles (i.e., open air for most of the laboratory testing and in outlet boxes for fire exposure testing) could have contributed to the differences for PVC and not for thermoset or polypropylene receptacles.

Two examples of arcing between the internal plug contacts and the receptacle grounding strap are shown in Figure 3-61 and Figure 3-62 for a polypropylene receptacle and PVC receptacle, respectively. In Figure 3-61 the hot internal contacts can be seen where, prior to examination, they were in contact with the receptacle grounding strap but the two pieces were not fused together. At this location, arcing had taken place as evidenced by the notch in the internal contact and the bead on the ground strap. Even though the location of contact was readily apparent, the internal contacts and the ground strap needed to be cleaned to remove some melted polypropylene that had deposited in and around the arc location. When the PVC receptacle in Figure 3-62 was first examined, there was significant charred material covering the internal contacts and the grounding strap which masked the location of contact. In fact, the two conductors had shifted significantly after arcing such that they were not in contact at the end of the test. The charred material had been removed during the examination in to reveal the underlying arc damage. Despite having some rust on the grounding strap, the arcing damage to that item was still identifiable.

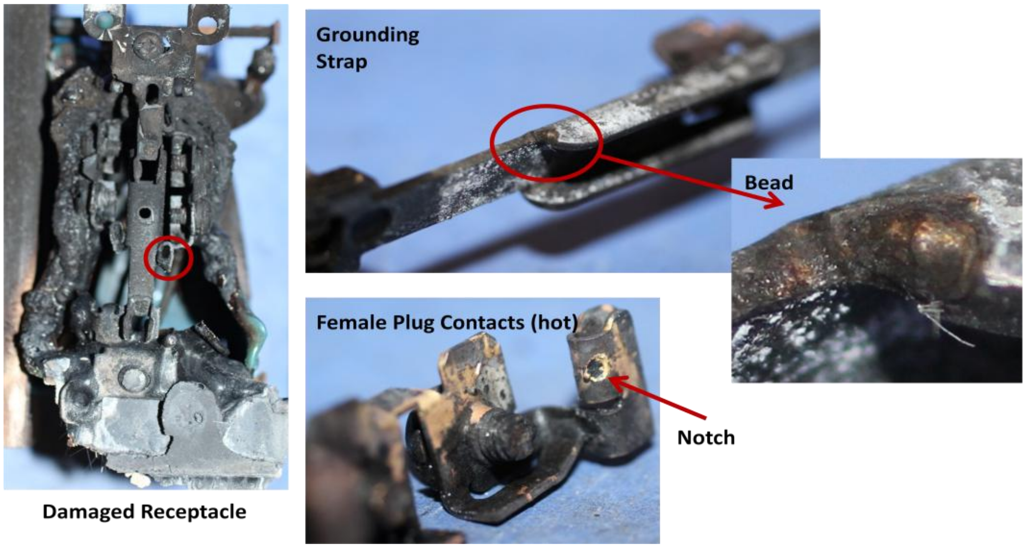


Figure 3-61. Photographs of damaged polypropylene receptacle (LEV082) showing arcing damage on the hot female plug contact and grounding strap.

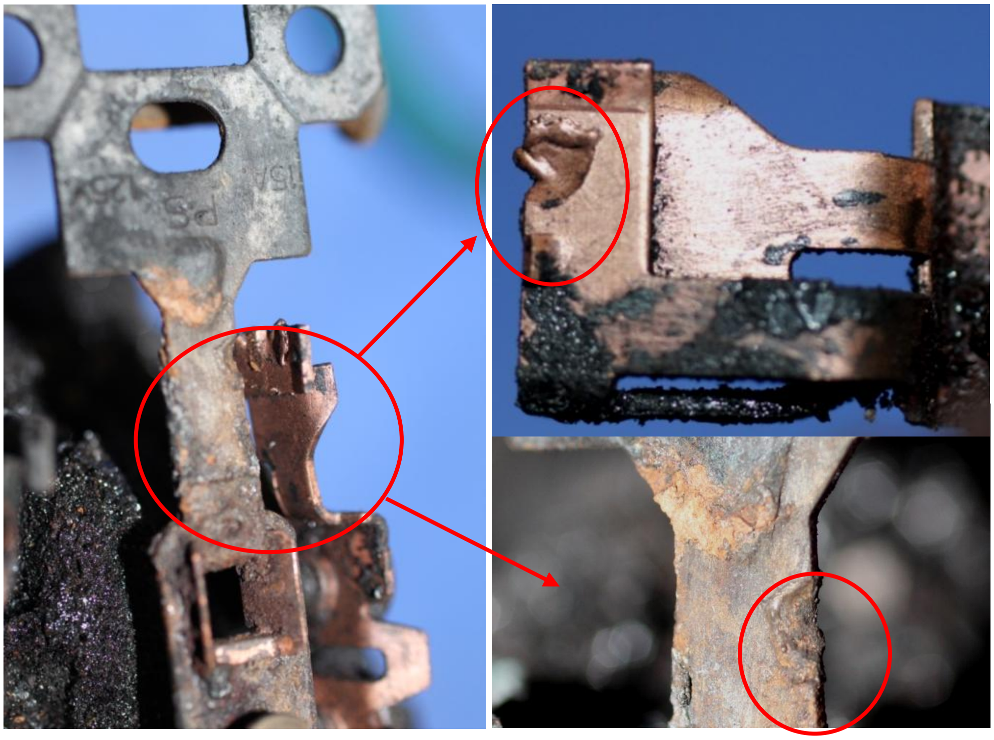


Figure 3-62. Photographs of arcing damage between hot female plug contacts (top right) and grounding strap (bottom right) from a PVC receptacle (PSE142).

As was discussed previously, the robust nature of the thermoset receptacles with respect to thermal degradation tends to reduce the likelihood of arcing occurring on the internal contacts of these receptacles. In fact, the material properties of the thermosets appear to have a large impact on where arcing occurs. There were 11 cases of arcing in the wiring of thermoset receptacles where the receptacle was intact with only some charring and cracking of the surface. Figure 3-63 shows three receptacles with charring or cracking of the thermosetting plastic that had confirmed arcing in the receptacle wiring. The majority (80%) of arcing locations in thermoset receptacles were located in the receptacle wiring. Of the remaining receptacles with arcing, 16% were in unknown locations and the other 6% were between the female plug contacts and either the faceplate or ground strap. Observations of the damage to the various thermoset receptacles did not seem to indicate that the construction and configuration of the thermoset receptacles or their internal contacts had any impact on the locations of arcing. For thermoset receptacles, it was necessary to carefully inspect all of the receptacle wiring regardless of whether the damage to the receptacle appeared outwardly minimal. On the other hand, three PVC receptacles and zero polypropylene receptacles had both partial melting and arcing damage. All three of the PVC receptacles had arcing located on the break off tab and none in the receptacle wiring.

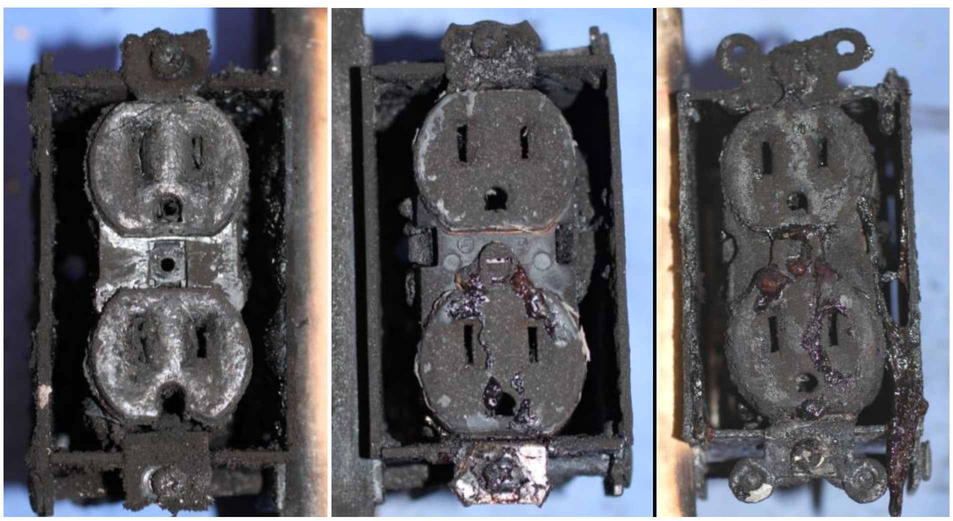


Figure 3-63. Photographs of three thermoset receptacles with arcing damage on wiring (left to right: B010, D016, and E033)

3.3.7.2 Characteristics of Arcing

Characteristic traits of arcing (based on the literature and findings of this work) in brass receptacle components, copper wiring, and steel receptacle components, outlet boxes, and faceplates were determined based on the visual evaluation of the evidence produced for energized receptacles and extension cords where the circuit breakers had tripped during the fire exposure tests. The characteristics of arcing for brass, copper, and steel components were, for the most part, similar to each other and different from those for melting (see Section 3.3.6.1). The majority of literature focuses on electrical arcing in copper wiring, both stranded and solid, with some attention paid to steel (i.e., conduits), and relatively little mention of brass. This is despite the relatively equal presence of copper, steel, and brass in receptacles and similar devices. Analysis of chiefly copper wiring also overlooks some of the nuances of arcing in components that are flat or have irregular shapes such as the internal plug contacts of a receptacle.

The two most common visual characteristics of arcing in brass, copper, and steel components observed in this testing were a clear line of demarcation between the damaged and undamaged areas and corresponding arcing damage on two conductors at different electrical potentials. Arcing between copper wires produced notches and beads that were round and smooth in appearance. A few instances of arcing were observed that had arc beads with large internal pores and resolidification waves. The two most common characteristics are aimed at establishing that arcing occurred, but what also must be considered is whether the damage could have been due to melting from the fire or other means (i.e., alloying). This means that the characteristics of melting (see Section 3.3.6.1) should not be present in an arcing location for the arcing location to be confirmed; they can be present in a location remote from the arcing location.

Recognizing that the damage from fire melting of brass and copper tends to be spread somewhat uniformly over the conductors, it becomes important to establish that arcing evidence exhibits a localized area of damage where the conductors have contacted. The brass and steel components of receptacles are stamped and bent during manufacturing, which leads to rather sharp and defined edges being present on the components. Sometimes these components will also be stamped with lettering. When an arc occurs in the vicinity of these edges or lettering, the edges and lettering will remain defined and undamaged outside of the arcing location. The grounding straps and female contacts shown with arcing damage in Figure 3-61 and Figure 3-62 all have clearly defined edges of the metal components immediately outside of the arc location. This is also exhibited for the lettering on the brass break off tab in Figure 3-59, the steel outlet box in Figure 3-64, and the plug contacts and faceplate in Figure 3-60. A similar indicator of the lack of melting on copper wiring is the visibility of the copper drawing lines immediately outside of the arc location. These lines are formed as a result of the extrusion process used to manufacture copper wiring. These lines or striations are visible on the copper wiring in Figure 3-64.

The interior and exterior surfaces of the steel outlet boxes used in this testing were plated with zinc for corrosion resistance. At fire exposure temperatures up to 883ºC, this plating will remain (see Table 3-17). This would suggest that if the zinc plating remains on the steel, the exposure temperatures would have likely been below the melting point of brass and copper (i.e., 930ºC and 1080ºC, respectively). This metric can also be helpful in assessing whether melting likely produced the evidence at hand. Figure 3-64 shows arcing damage from the contact between the hot copper conductor and the steel outlet box. The outlet box has damage (i.e., a shallow notch with a bead) quite similar to shape and position as the damage on the copper wire (i.e., a shallow notch with a bead). The plating on the outlet box is still intact as evidenced by its overall shiny appearance.

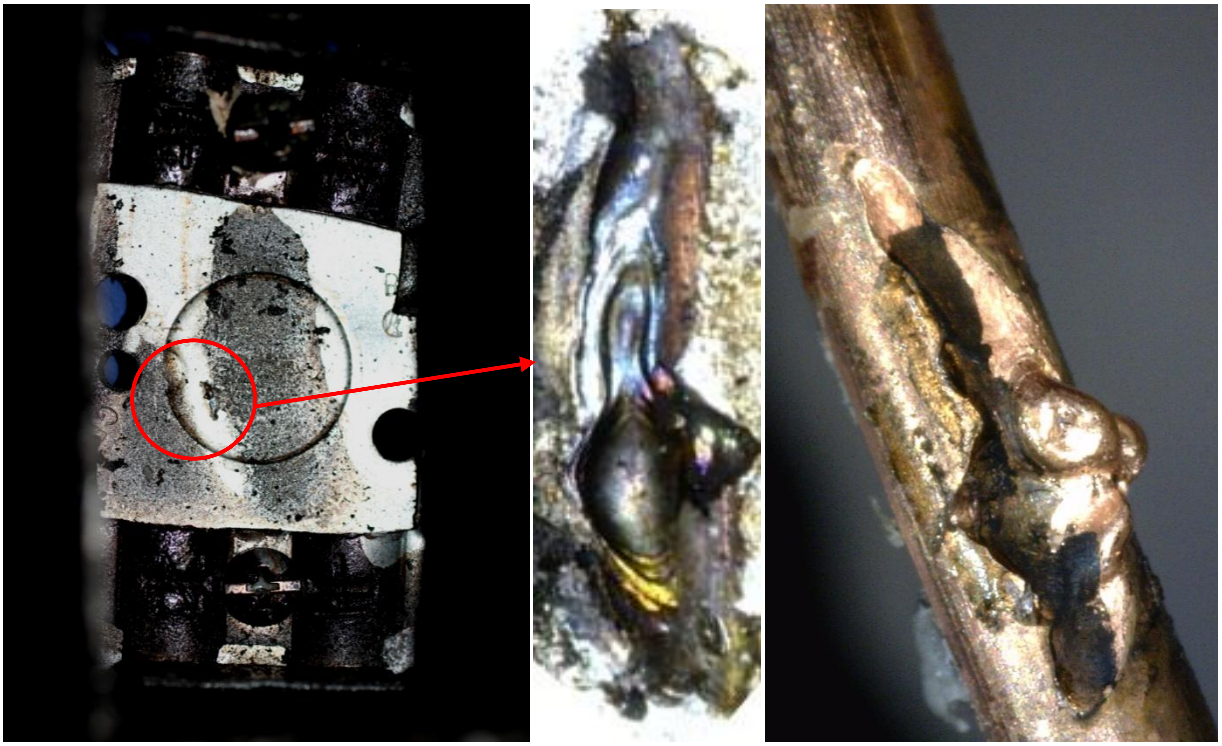


Figure 3-64. Photographs of damage from arcing between the hot copper conductor (right) and grounded steel outlet box (left and center) for a thermoset receptacle (D012).

Arcing that occurs between two conductors, such as parallel arcs, and which causes a circuit breaker to trip will typically leave damage on both conductors. This is a result of the very high temperatures associated with the arc (see Section 1.1.2). Of the 201 receptacles that tripped a circuit breaker during the fire exposure testing, 159 (79%) of these had arcing damage on two different conductors. Nineteen (10%) were found with only one confirmed location of arcing damage and 23 (11%) had no confirmed arcing locations on any of the conductors. The corresponding damage on two conductors is perhaps the most reliable and informative indicator of arcing in receptacles and wiring. Not only does the arcing damage itself tell that an arc occurred, but the location, size, shape, and orientation of the damage can provide some insight into how the arc occurred. The size and shape of the arcing damage can show how the conductors contacted each other, especially for the brass and steel components. Because these components have flat edges and surfaces, there may be a line of contact rather than a point of contact. For instance, the arcing damage on the conductors in Figure 3-64 and those in Figure 3-59 match up very closely with each other. This can give an indication as to the orientation of the wiring or receptacle plug contacts at the time of arcing. However, two notches and beads on two copper wires (e.g., Figure 3-65) do not necessarily show the orientation of the conductors at the time of the arc.

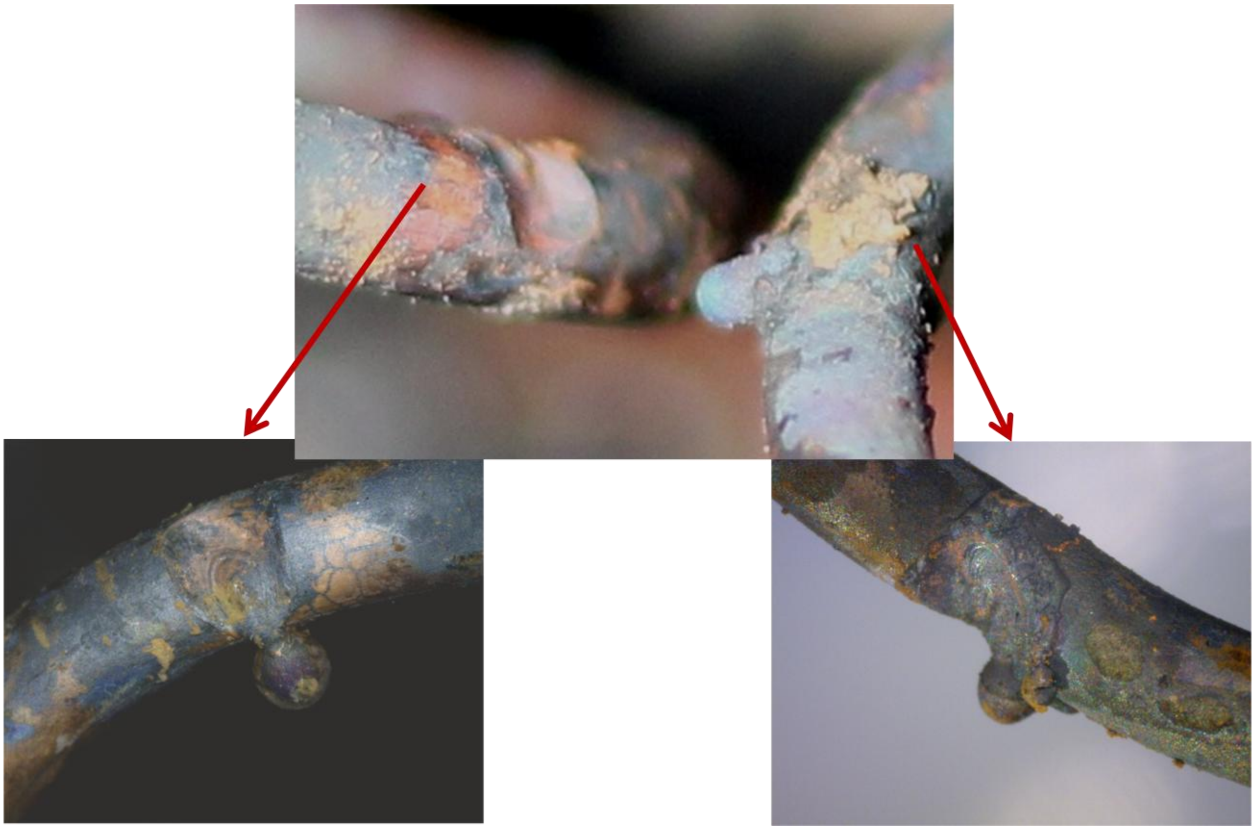


Figure 3-65. Photographs of arcing between solid hot and ground wires from a polypropylene receptacle (LEV366).

Arcing in stranded copper extension cords produced much the same characteristic traits as the solid copper wiring, brass receptacle components, and steel items. Three cases of arcing in stranded wiring are shown in Figure 3-66, Figure 3-67, and Figure 3-68. All of these arcing instances exhibit corresponding damage on both conductors as well as clear lines of demarcation between the damaged and undamaged areas. None of these extension cords show signs of melting. Severing of some or all of the wire strands was observed in arcing for stranded extension cords. The severed strands also exhibited clear lines of demarcation and mechanical breakage and melting could be ruled out as the cause of severing based on the appearance of the strands. The beads within the notches of the stranded wires were round and relatively smooth. Figure 3-69 shows the two ends of a severed neutral wire from a stranded extension cord. There is a rather large bead on one end but more of a notch on the other. The scanning electron microscope (SEM) images of the two sections of wire accentuate the lines of demarcation between the arc location and the undamaged strands, which is difficult to visualize in the photographs due to some debris.

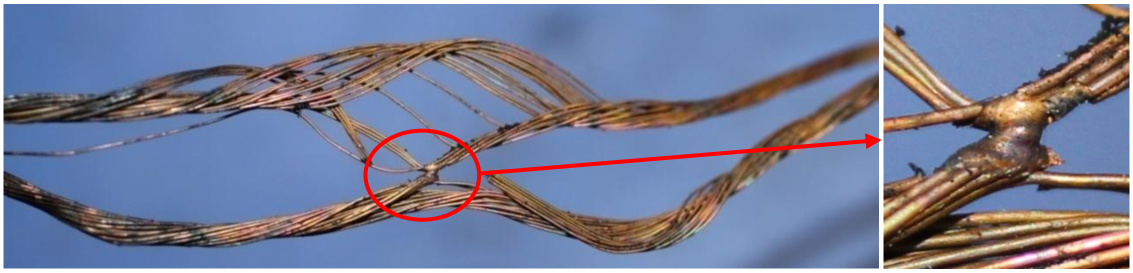


Figure 3-66. Photographs of arcing between stranded hot and neutral wires from an extension cord attached to a polypropylene receptacle (LEV319).

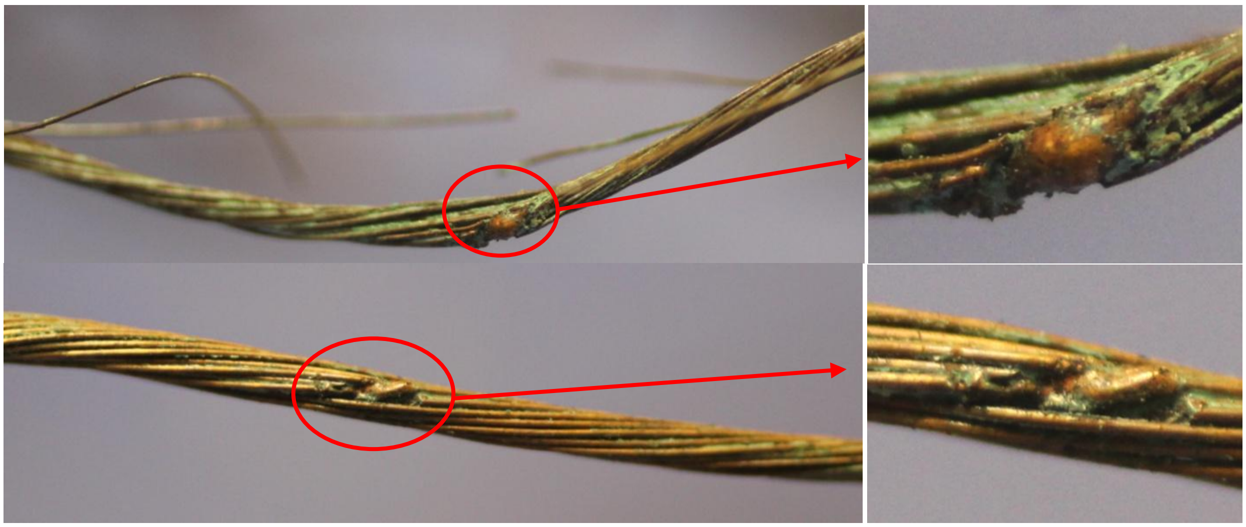


Figure 3-67. Photographs of arcing between stranded hot and ground wires from an extension cord attached to a PVC receptacle (PSE333).

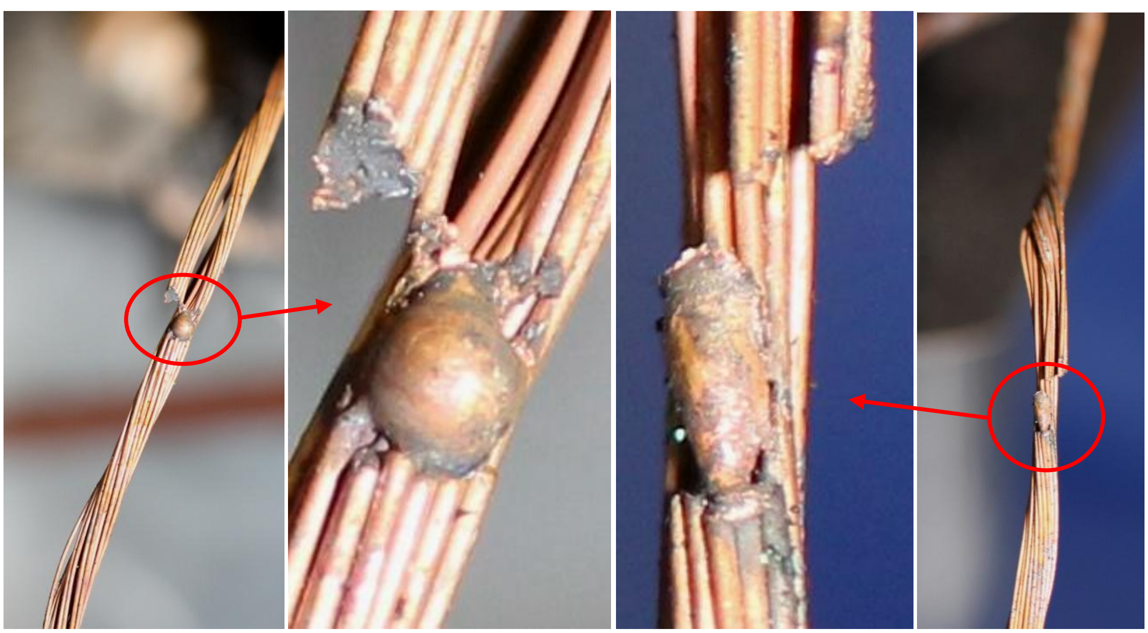


Figure 3-68. Photographs of arcing between stranded hot and ground wires from an extension cord attached to a polypropylene receptacle (LEV340).

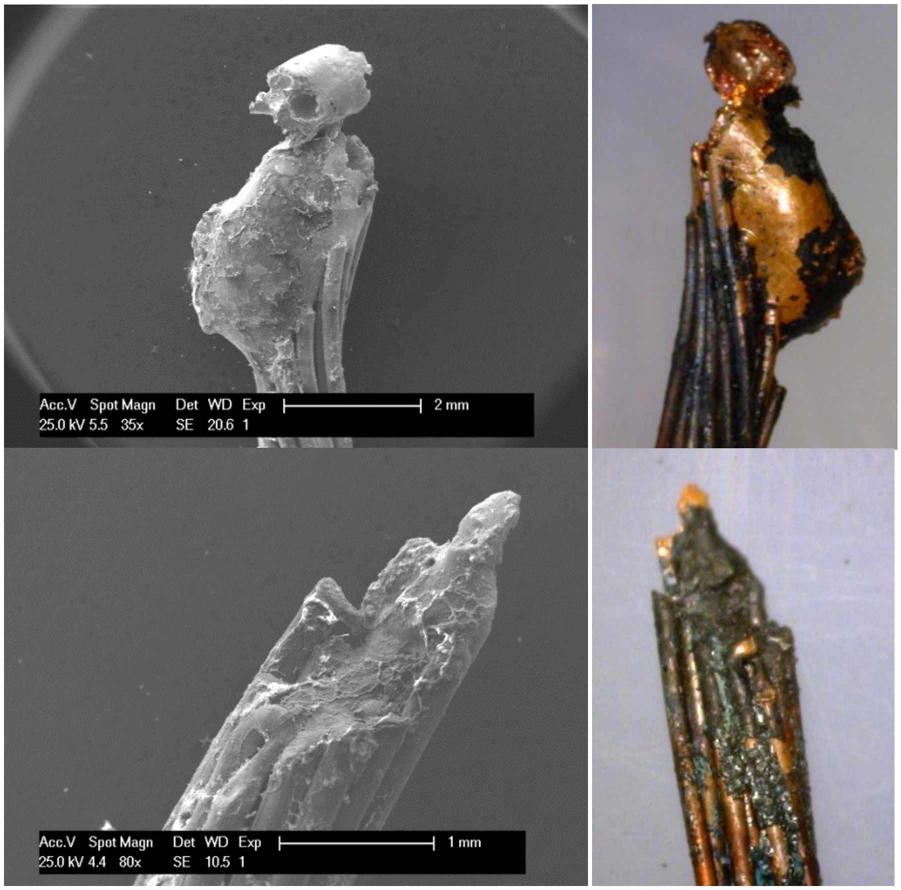


Figure 3-69. SEM images and photographs of a stranded neutral wire severed by arcing from an extension cord attached to a polypropylene receptacle (LEV318).

Some of the arcing locations in receptacle and extension cord wiring had the two wires fused together by the arcing such as those shown in Figure 3-66. During the examination of some of these wire pairs, the two wires broke apart, revealing the internal structure of the arc bead. Two cases of arcing in receptacle wiring with fused beads that separated are shown in Figure 3-70 and Figure 3-71. Both of these instances show rather large voids within the bead that connected the two wires. The presence of high internal porosity within copper arc beads compared to low internal porosity in melted copper has been studied in the literature (see Section 1.1.5), but there have not been any studies which attempt to quantify this difference. In addition, there has been no systematic study of whether arcing damage in brass or steel exhibits similar porosity characteristics as those proposed by some researchers for copper. Internal porosity in arcing damage produced in testing was further examined in Section 4.6.

Figure 3-70. Photograph of arcing in receptacle hot and neutral wires showing internal porosity from a thermoset receptacle (B020).

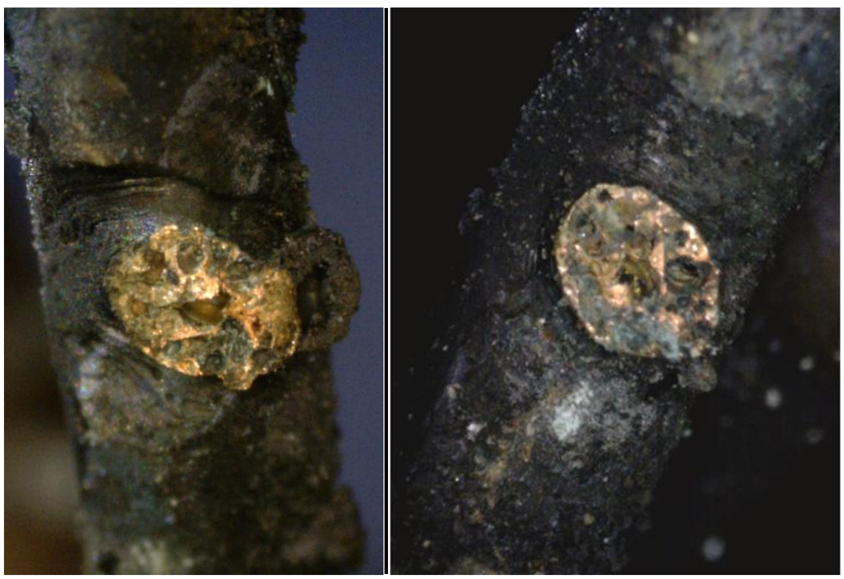


Figure 3-71. Photograph of arcing in receptacle hot and neutral wires showing internal porosity from a thermoset receptacle (D028).

3.3.7.3 Thermal Insult

As discussed in Section 3.3.2, the amount of damage to the receptacles was somewhat proportional to the maximum exposure temperature. It would follow that the potential for arcing and tripping a circuit breaker is also proportional to the maximum exposure temperature for the receptacle. This is because the arcing is related to the extent and location of damage to the receptacle as discussed in Section 3.3.7.1. The minimums, maximums, averages, and standard deviations for the maximum exposure temperatures at the time the circuit breakers tripped are reported as a function of the primary arc location and receptacle material in Table 3-25. Arcing in the extension cords is not included in Table 3-25 as this was independent of the receptacle material. The average maximum temperature at the time of tripping does not appear to be dependent on the location of arcing. However, for the female plug contact and break off tab primary arc locations, the receptacle material that had the highest quantity of arcs for these locations also had the lowest average temperature at the time of tripping. And for each receptacle material, the arcing location that had the highest quantity of arcs for that material had the lowest average maximum temperature at the time of tripping.

Fifty receptacles did not trip circuit breakers or exhibit arcing due to fire exposure. The average maximum exposure temperature for these 50 receptacles was 646ºC (range: 515ºC–886ºC). This was slightly above the average maximum temperature at the time of tripping for all receptacles (620ºC). Of these 50 receptacles, 12 were thermoset, 24 PVC, and 14 polypropylene; 20 had nylon faceplates and 30 had steel faceplates.

Table 3-25. Summary of Maximum Exposure Temperature Data at Time of Tripping as a Function of Receptacle Material.

Primary Arc Location	Receptacle Material	Qty.	Maximum Exposure Temperature @ Trip (ºC)			
			Minimum	Maximum	Average	Std. Dev.
Female Plug Contact	Polypropylene	59	402	839	580	124
	PVC	10	634	858	753	79
	Thermosets	2	840	973	906	94
	Total	**70**	**402**	**973**	**613**	**141**
Break Off Tab	Polypropylene	1	621	621	621	0
	PVC	38	371	788	561	120
	Thermosets	0	-	-	-	-
	Total	**39**	**371**	**788**	**562**	**119**
Receptacle Wiring	Polypropylene	13	453	810	642	125
	PVC	10	465	759	617	108
	Thermosets	29	491	1009	709	205
	Total	**52**	**453**	**1009**	**675**	**175**
Unknown	Polypropylene	7	440	781	604	110
	PVC	10	463	838	635	120
	Thermosets	5	503	919	606	176
	Total	**22**	**440**	**919**	**618**	**125**
All	Polypropylene	79	402	839	592	123
	PVC	68	371	858	608	129
	Thermosets	36	491	1009	706	203
	Total	**183**	**371**	**1009**	**620**	**150**

The minimums, maximums, averages, and standard deviations for the maximum exposure temperatures at the time the circuit breakers tripped are reported as a function of the primary arc location and faceplate material in Table 3-26. Arcing in the extension cords is not included in Table 3-26 as this was independent of the faceplate material. Because the nylon faceplates tended to melt and fall off of the receptacles resulting in direct fire exposure, it would follow that the increased thermal exposure to the receptacles would cause tripping to occur at lower temperatures. However, the data in Table 3-26 does not show this trend. For the unknown arcing locations and arcing on the female plug contacts, the average maximum temperatures at the time of tripping were higher for plastic than steel faceplates. The opposite was shown for arcing in receptacle wiring.

Table 3-26. Summary of Maximum Exposure Temperature Data at Time of Tripping as a Function of Faceplate Material.

Primary Arc Location	Receptacle Material	Qty.	Maximum Exposure Temperature @Trip (ºC)			
			Minimum	**Maximum**	**Average**	**Std. Dev.**
Female Plug Contact	Metal	54	402	973	600	138
	Plastic	16	430	858	660	147
	Total	**70**	**402**	**973**	**613**	**141**
Break Off Tab	Metal	39	371	788	562	119
	Plastic	0	-	-	-	-
	Total	**39**	**371**	**788**	**562**	**119**
Receptacle Wiring	Metal	15	457	1009	776	215
	Plastic	37	453	937	634	139
	Total	**52**	**453**	**1009**	**675**	**175**
Unknown	Metal	7	440	653	538	85
	Plastic	15	503	919	657	125
	Total	**22**	**440**	**919**	**618**	**125**
All	Metal	115	371	1009	606	156
	Plastic	68	430	937	645	137
	Total	**183**	**371**	**1009**	**620**	**150**

3.3.8 Arc Fault Current Analysis

A Hioki power analyzer was used in some of the compartment fire tests to analyze the voltage and current during arcing events. This device monitored the voltage and current of up to four receptacles (see Section 3.1.1.6). In three of the ten cases where arcing events were recorded, two faults occurred for the same receptacle before the circuit breaker tripped. The maximum arc fault currents for the first and second faults, the time between faults, and the arcing location are presented for each receptacle monitored in Table 3-27.

The average peak fault current measured for arcing events that did not trip the circuit breaker was 231amps. The average peak fault current for arcing events that did trip the circuit breaker was 380 amps. The minimum peak fault current that caused a circuit breaker to trip was 337 amps (B010); the maximum peak fault current that did not cause a circuit breaker to trip was 264 amps (LEV253). In all cases where the first arc did not trip the circuit breaker, the second arc did trip the circuit breaker. The times between the first and second arcs were between 1 and 13 seconds with an average of 6.66 seconds. The likely reason that the circuit breakers were not tripped by the initial arcs was that the events were too brief and/or the current was too low.

Table 3-27. Summary of Arc Fault Data from Compartment Fire Tests.

Test	Receptacle S/N	Receptacle Material	Peak Fault Current, 1st (amps)	Peak Fault Current, 2nd (amps)	Time Between Faults (sec)	Arcing Location
5	PSE248	PVC	229	360	1	Between hot plug contact and grounding strap
	PSE249	PVC	374	N/A	N/A	Between hot plug contact and grounding strap
	LEV253	Polypropylene	264	372	13	Between hot plug contact and grounding strap
	LEV254	Polypropylene	201	365	6	Between hot plug contact and grounding strap
6	B010	Thermoset	337	N/A	N/A	Hot wire and unknown
	B011	Thermoset	Did not arc or trip circuit breaker.			
	B012	Thermoset	Did not arc or trip circuit breaker.			
	C019	Thermoset	350	N/A	N/A	Unknown
8	PSE318	PVC	465	N/A	N/A	Between hot break off tab and faceplate
	PSE319	PVC	424	N/A	N/A	Between hot break off tab and faceplate
	LEV323	Polypropylene	385	N/A	N/A	Between hot plug contact and faceplate
	LEV324	Polypropylene	370	N/A	N/A	Between hot plug contact and faceplate

Circuit breakers are designed to trip according to a trip curve (see Figure 3-72). The curve indicates the minimum trip time for a certain current. For the circuit breakers used in this testing a current 15 or more times the rating of the breaker (i.e., 300A= 15*20A rating) has a maximum allowable trip time of 1 cycle (1/60 of a second). For a fault current of about 10 times the rating of the breaker (i.e., 200A= 10*20A rating), the maximum allowable trip time increases to about 30 cycles (½ of a second). Figure 3-73 and Figure 3-74 show the arcing events that occurred for two receptacles. All of the arcing events recorded by the Hioki power meter were less than ½ cycle (1/120 of a second), including those that did trip the circuit breaker and those that did not. In Figure 3-74, anomalies can be seen on the voltage waveform for the three cycles prior to the circuit breaker activation. These anomalies were likely caused by tripping of other branch circuits connected to the same circuit breaker panel which caused a dip in the voltage.

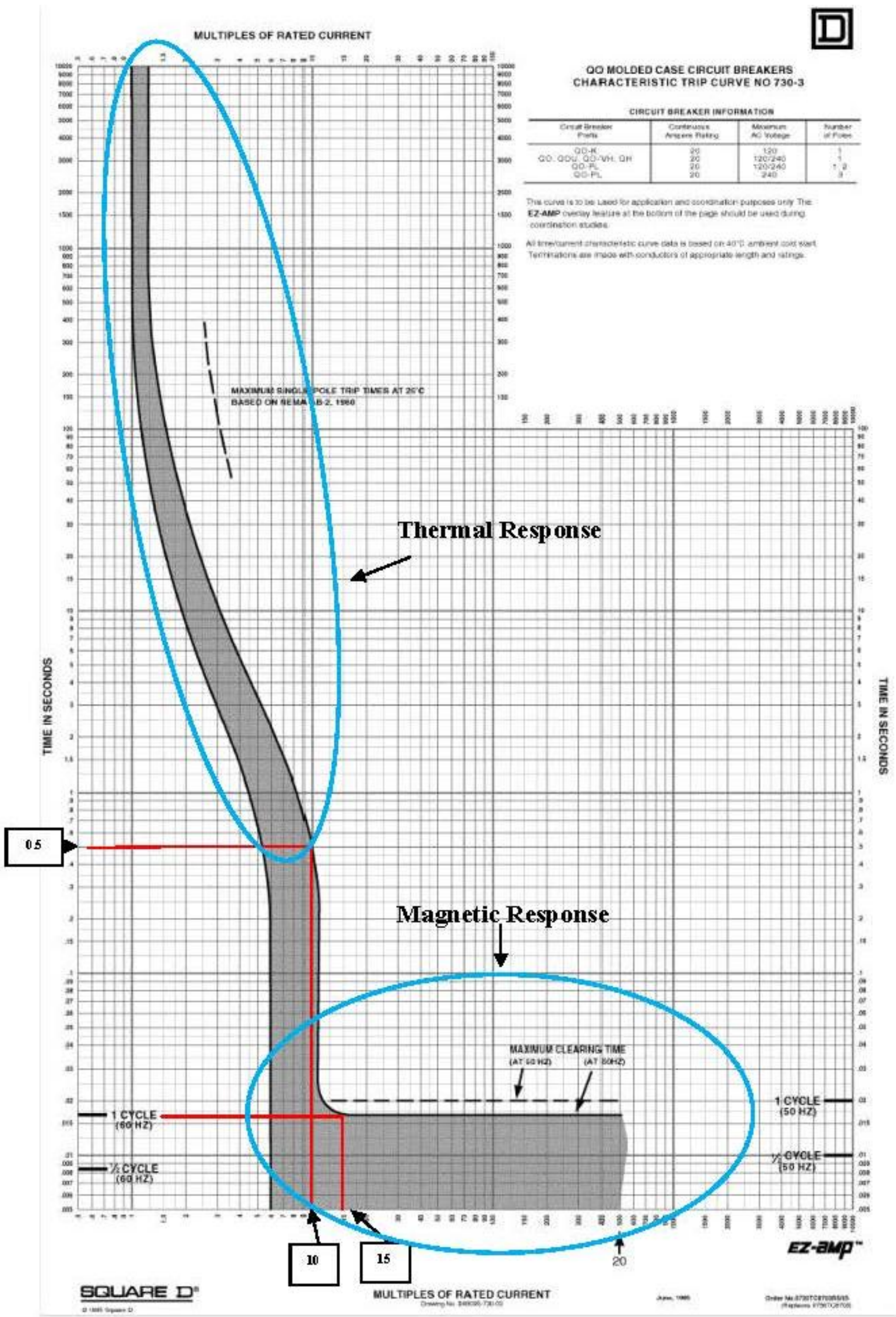


Figure 3-72. Trip curve for 20 amp Square D circuit breaker similar to those used in testing.

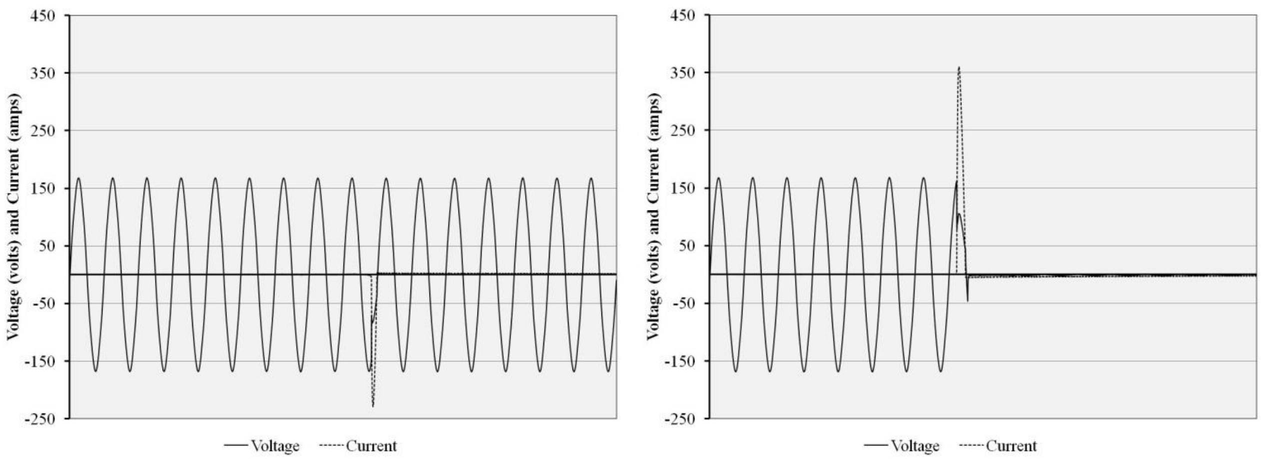


Figure 3-73. Voltage and current for receptacle PSE248 for two arc faults; breaker tripped on the second arc (right).

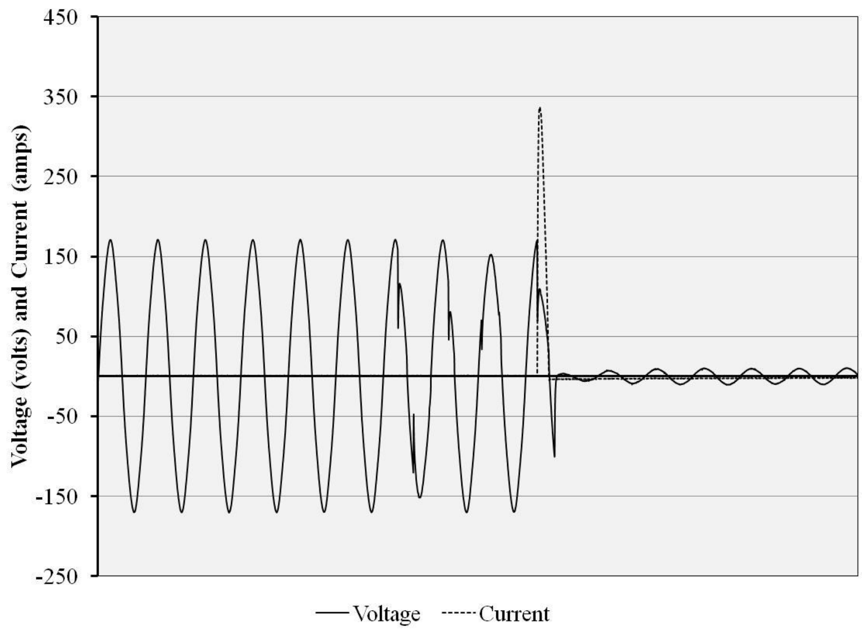


Figure 3-74. Voltage and current for receptacle B010 for single arc fault; leakage current after circuit breaker tripped.

The arc durations (i.e., less than ½ cycle) were below the required trip times whether the fault current was approximately 300 A (1/60th second required) or approximately 200 A (½ second required). Most residential circuit breakers, including the ones used in this testing, are of the thermal-magnetic type [NFPA 921, 2011]. The thermal element provides protection for moderate over currents, while the magnetic element provides protection for short circuits and ground-faults [NFPA 921, 2011]. The upper left portion of the circuit breaker trip curve (see Figure 3-72) displays the circuit breakers thermal response. The lower right portion of the circuit breaker trip curve (see Figure 3-72) displays the circuit breakers magnetic response. The magnetic limits of the circuit breakers are factory set on most residential circuit breakers. It is likely that the arc faults that did not trip the circuit breaker were below the magnetic limit of the circuit breaker and fell into the thermal response part of the trip curve.

There was only one direct comparison between a receptacle having two faults before tripping and one having only one fault before tripping where the arcing occurred in the same location. The arcing damage for PSE248 (2 faults) and PSE249 (1 fault) is shown in Figure 3-75. Both receptacles have a small notch on the ground strap and on the top inside of the internal plug contacts. The damage for the two receptacles looks remarkably similar although the damage on the ground strap for PSE249 is difficult to see due to the presence of some rust. Based on these two receptacles, there does not seem to be any indication that the occurrence of two faults before the circuit breaker tripped versus only one fault occurring has any impact on the visual evidence of arcing. However, this is only one case.

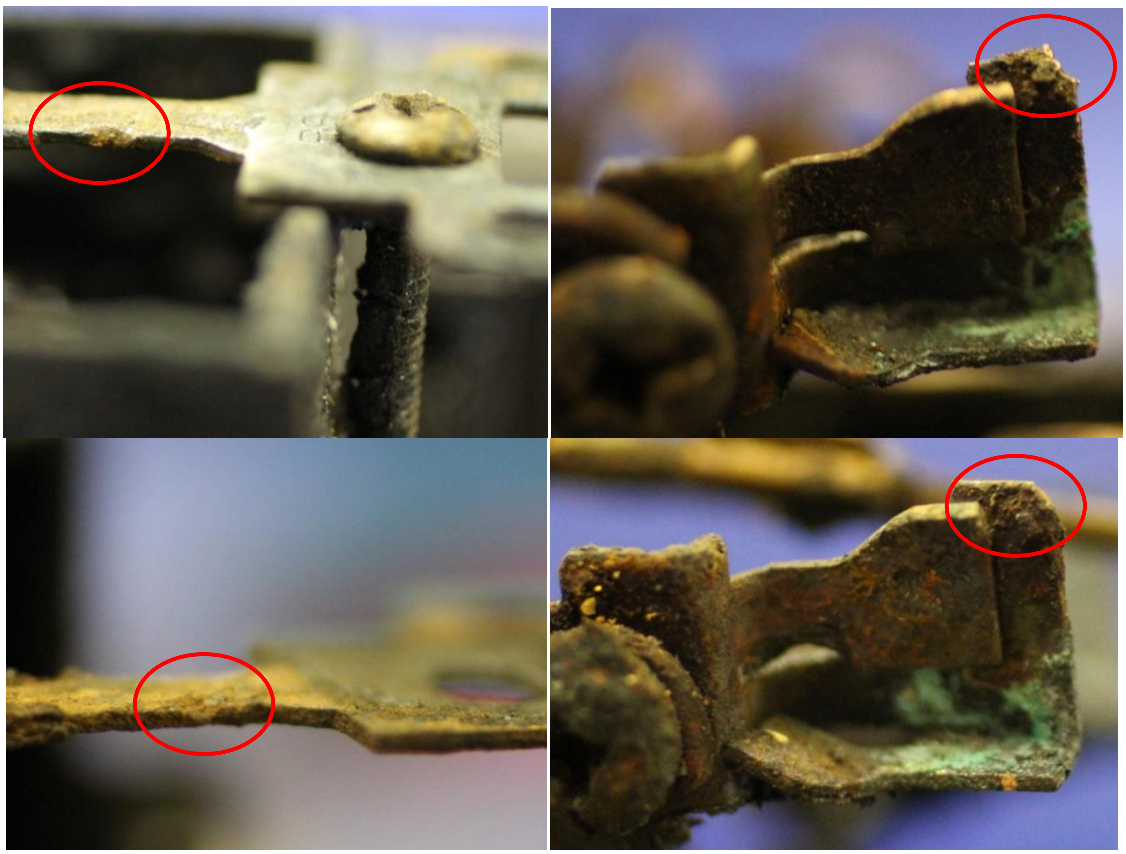


Figure 3-75. Arcing damage from PVC receptacles PSE248 (top left and right) and PSE249 (bottom left and right).

3.3.8.1 Screw Terminal Loosening Torque

Because it was found that very loose connections were required to form overheating connections (see Section 2.3.7.3.1), an analysis was performed to evaluate whether a post-fire terminal torque measurement could be used to estimate the pre-fire terminal torque. The method of measuring the loosening torque was to use the digital torque screwdriver (see Section 2.1.2.1) to measure the maximum torque required to loosen the screw connection while holding the internal plug contacts stable with pliers. However, there were limitations to this process. First, the internal plug contacts from the receptacles exposed to the furnace fires tended to be rather soft from the intense heat exposure and, in some cases, would bend with relatively little torque. Therefore, the loosening torque on these receptacles was not tested. Also, the torque measurements were highly dependent on the amount of grit, grime, melted plastic, or char that was on the terminal. In a large number of cases, the melted plastic needed to be heated to the point where it became soft before the screw terminal could be tested. It is possible that this heating could have affected torque measurements, but without heating, the torque could not have been measured for these terminals. In receptacles with relatively minor thermal damage from the fire exposures, the method was fairly accurate, but in these cases, it would have been rather easy to identify overheating damage based on the specific failure signatures noted from the laboratory testing (see Section 2.3.3.1). Under specific conditions (i.e., terminals without much debris), measurement of the loosening torque could be useful to rule out overheating by demonstrating a high torque. However, due to the uncertainty in the measurement, it has limited value for indicating a loose connection.

3.3.8.2 Plug Blade Retention Force

Because it was found that very loose plug connections were required to form overheating connections (see Section 2.3.7.3.2), an analysis was performed to evaluate whether a post-fire measurement of the plug blade retention force could be used to estimate the pre-fire retention force. The method of measuring the retention force was to use the digital force gauge (see Section 2.1.2.3) to measure the maximum force required to remove a plug blade from the receptacle while holding the internal plug contacts stable. This measurement method had similar drawbacks as the screw terminal loosening torque, including: presence of debris, softening of brass contacts, melting of the receptacle which obscured the plug slots, etc. Under specific conditions (i.e., receptacles without much damage), measurement of the plug blade retention force could be useful to rule out overheating by demonstrating a high force. However, due to the uncertainty in the measurement, it has limited value for indicating a loose plug connection.

3.3.9 Persistence of Damage from Overheating Connections after Fire Exposure

Twenty-one of the receptacles having had overheating failure events and one receptacle with a partially welded conductor were placed in furnace exposure test 4 and subjected to maximum exposure temperatures between 976ºC and 1060ºC. Table 3-28 lists the quantities of receptacles with each type of overheating evidence placed into the furnace by the receptacle material. Some receptacles had more than one type of evidence. In addition to these receptacles, two sets of wires showing signs of arcing from a prior compartment fire test were installed in outlet boxes as shown in Figure 3-7. In general, the physical evidence of overheated connections (e.g., melted copper conductors, enlarged screw heads, severed conductors, and arcing) did persist even after the furnace exposure. The primary visual changes that occurred with the evidence were to the color. Due to the high temperature exposure, the localized damage to the receptacle body materials (see Section 2.3.3.1) due to overheating was not present because the receptacle had been mostly or totally consumed.

Table 3-28. Summary of Receptacles with Prior Overheating Damage Placed in Furnace Exposure Test 4.

Event	Number of Receptacles	Welded Conductors (With Curved Striations)	Enlarged Screw Heads	Evidence of Arcing	Severed Conductor Type on Wire (On Screw)
Conductor Severed, w/ Arc	4	2 (0)	2	0	2 Rounded, 2 Irregular[A] (1 Rounded, 3 Irregular)
Conductor Severed, w/o Arc	5	4 (4)	1	0	5 Rounded[A] (5 Rounded)
Conductor Severed, Arc Unknown	4	4 (4)	2	0	3 Rounded, 1 Irregular [B] (4 Rounded)
Shorted, Hot to Ground	4	0	0	4	N/A
Shorted, Neutral to Ground	3	0	0	2	N/A
Flaming Ignition	1	1 (1)	0	0	Rounded[A] (Irregular)
None	1	2[C] (2)	0	0	N/A
Wiring w/ Previous Arc Beads	2	N/A	N/A	2	N/A

A – One loose severed conductor left out of furnace test.
B – Two loose severed conductors left out of furnace test.
C – Thermoset receptacle E002 had two partially welded conductors.

3.3.9.1 Welded Conductors

Twelve receptacles with a total of thirteen combined welded conductors were exposed to furnace fire Test 5. Of these thirteen welded conductors, 11 had curved striations visible prior to furnace exposure. After the furnace fire exposure, all of the welded conductors remained identifiable. However, the curved striations could only be identified on nine out of the 11 welded conductors that previously had curved striations. In general, the curved striations became more difficult to see after the furnace exposure. Figure 3-76 and Figure 3-77show two welded conductors with curved striations before and after the furnace exposure. Even though the brass contacts had begun to melt beneath the melted copper conductor in Figure 3-76, the welded conductor did not show any visual damage. There was some surface discoloration and the welded conductor became somewhat shinier. The welded conductor in Figure 3-77 appears to be redder in color and the curved striations became somewhat more dulled. It is possible that the red discoloration is copper oxides produced by the fire heating.

The welded conductor after the furnace exposure in Figure 3-78 (center) appears to be rather similar to the one shown in Figure 3-77 (right) in terms of the red surface appearance. This welded conductor (LEV275) was ultrasonically cleaned in a mild detergent and re-examined. The image of the cleaned conductor in Figure 3-78 (right) shows that underneath the surface coating the welded conductor is a dull grey color similar to the appearance of the welded conductor before the furnace exposure. Also, the curved striations stand out more and appear to be somewhat copper in color in comparison to the rest of the welded conductor.

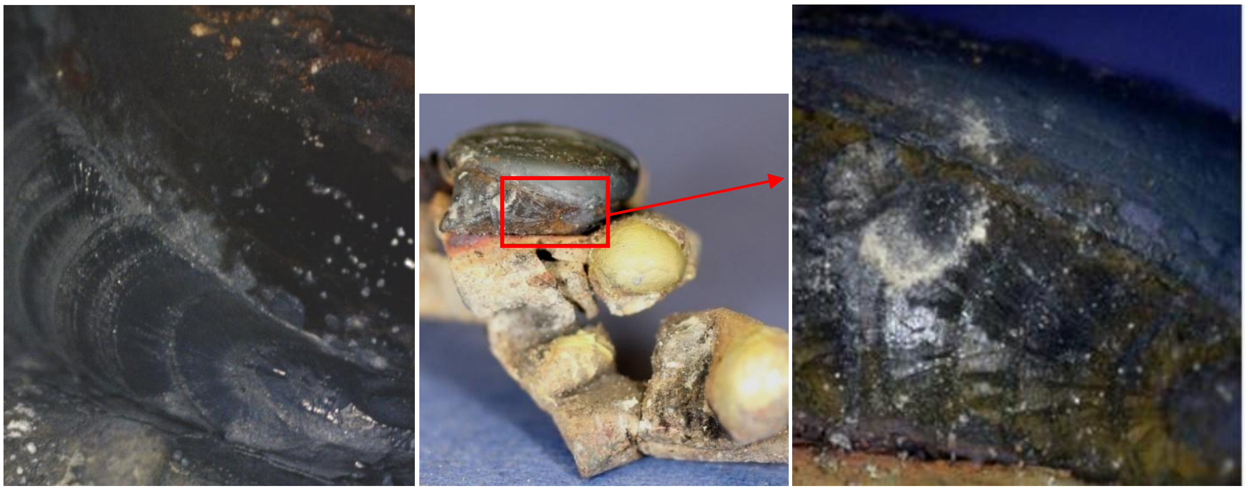


Figure 3-76. Welded conductor with curved striations from a thermoset receptacle before (left) and after (center, right) furnace fire exposure (E002); melting of brass contacts (center).

Figure 3-77. Welded conductor with curved striations before (left) and after (right) furnace fire exposure (LEV272)

Figure 3-78. Welded conductor with curved striations before furnace exposure (left), after furnace exposure (center), and after furnace exposure with ultrasonic cleaning (right), (LEV275).

One of the two welded conductors that had visible curved striations prior to the furnace exposure, but where those curved striations were not present after the furnace exposure is shown in Figure 3-79. For both of these receptacles, the welded conductor was confirmed to be present after the furnace fire exposure. The image of the curved striations prior to the furnace exposure (Figure 3-79, left) shows a few faint curved striations, but the image after the fire exposure shows only an irregular welded conductor. The other instance where the curved striations were not observed after the furnace exposure was similar in appearance both before and after the furnace exposure to the conductor and screw shown in Figure 3-79. In general, both the presence and appearance of welded conductors persisted even after an intense fire exposure. This evidence remained unique when compared to fire melting of copper components (see Figure 3-42 and Figure 3-49).

Figure 3-79. Welded conductor with curved striations before (left) and after (right) furnace fire exposure (PSE021).

3.3.9.2 Enlarged Screw Heads

Five receptacles with enlarged screw heads were exposed to furnace fire Test 5. After the furnace fire exposure, four out of five of the enlarged screw heads remained identifiable. In general, the shape of the enlarged screw heads remained, but the color changed. The one case where the enlarged screw head was not identifiable after the furnace exposure is shown in Figure 3-80. Prior to the furnace exposure, this enlarged screw head only had a partial surface buildup (see Figure 3-80, left). After the furnace fire exposure, the buildup on the enlarged screw head was not distinctly different from the normal screw head (see Figure 3-80, right). However, the enlarged screw head did exhibit extensive red oxidation products compared to the normal screw head after the furnace.

Figure 3-80. Enlarged screw head from PVC receptacle before (left) and after (right) furnace exposure (PSE023).

Figure 3-81and Figure 3-82 show two examples of enlarged screw heads before and after the furnace exposure. Both of these enlarged screw heads were grey in color before the furnace exposure, but changed slightly after the exposure. The enlarged screw head from PSE132 (Figure 3-81) changed to a brownish red color after the furnace exposure and the enlarged screw head from PSE133 (Figure 3-82) changed to a dark black color. Even with the majority of the PVC receptacle consumed by the furnace exposure, both of these enlarged screw heads persisted and remained unique compared to fire effects. This was also true for the other two enlarged screw heads.

Figure 3-81. Enlarged screw head from PVC receptacle before (left) and after (right) the furnace exposure (PSE132).

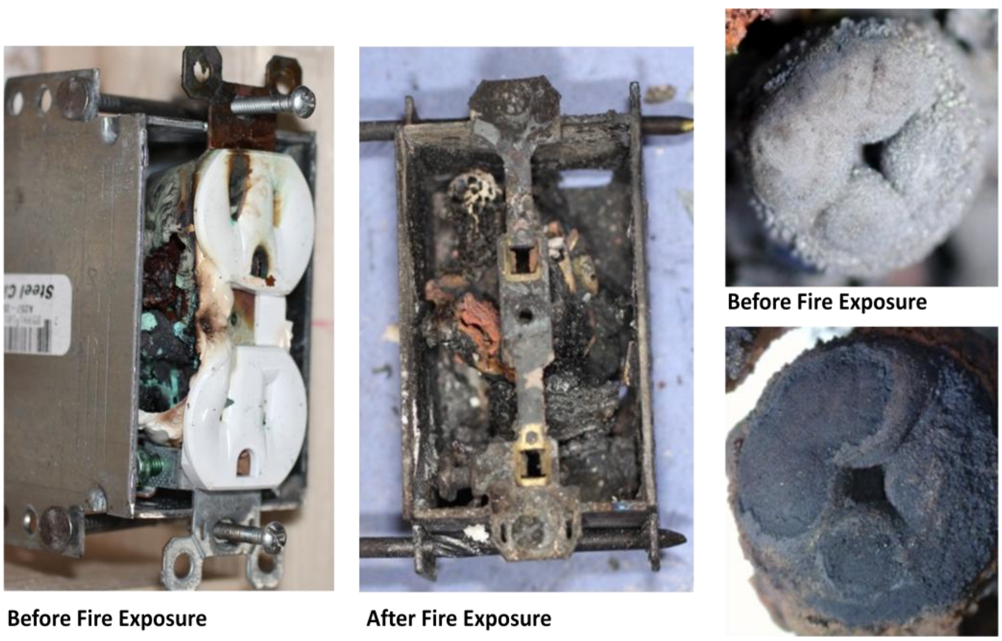


Figure 3-82 PVC receptacle with enlarged screw head before (left) and after (center) furnace fire exposure; enlarged screw head before (top right) and after (bottom right) fire exposure (PSE133).

The enlarged screw head from PSE133 (Figure 3-82) was cross-sectioned and polished after the furnace exposure to examine the extent of the corrosion buildup, its chemical makeup, and its microstructure. This sectioned specimen was compared to the enlarged screw head that was sectioned without any additional fire exposure (see Section 2.3.5.3). Section 3.2.3.3 discusses the sectioning and polishing methodology. A photograph of the cross-sectioned and polished screw in the brass receptacle contact is shown in Figure 3-83. The thickness of the corrosion layer atop the screw was approximately 1.1 mm (0.043 inches) at the thickest point. The corrosion covered almost the whole surface of the screw and threads but was not a constant thickness over the entire surface. It can be seen that the corrosion byproducts are primarily surface growth with some loss of volume of bulk steel. An exemplar cross-sectioned screw is shown for reference in Figure 2-65. The plating overtop the steel screw was approximately 4-5 μm thick.

A SEM examination was conducted of the cross-sectioned screw. Figure 3-84 shows a back-scatter image of the corrosion layer atop the steel (a red square in Figure 3-83 indicates the approximate location of the SEM image). There appears to be a boundary (indicated by a dotted red line) between two layers of the corroded material indicated by the difference in color. Unlike the corrosion layers in Figure 2-66, these two layers do not appear to be different densities. However, both layers do appear to be porous, much like the other sectioned screw. In order to determine the chemical makeup of the corrosion, an EDS mapping of the area shown in Figure 3-83 was conducted. Carbon, chlorine, copper, iron, manganese, oxygen and silicone were mapped, with the results shown in Figure 3-85. Each element is plotted as a relative concentration.

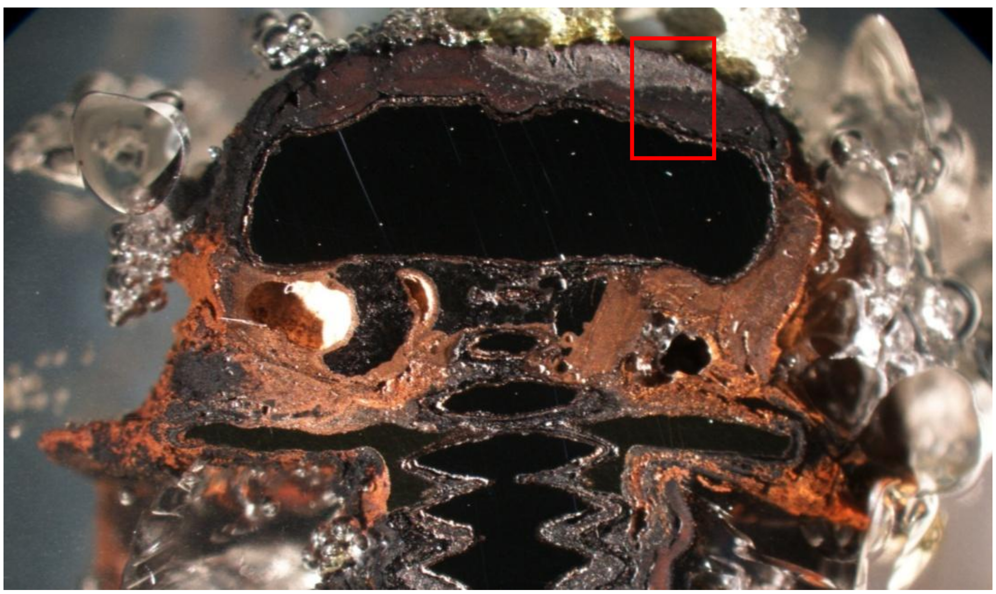


Figure 3-83. Sectioned and polished enlarged screw head from PSE133 after fire exposure. Note: square indicates area of EDS mapping.

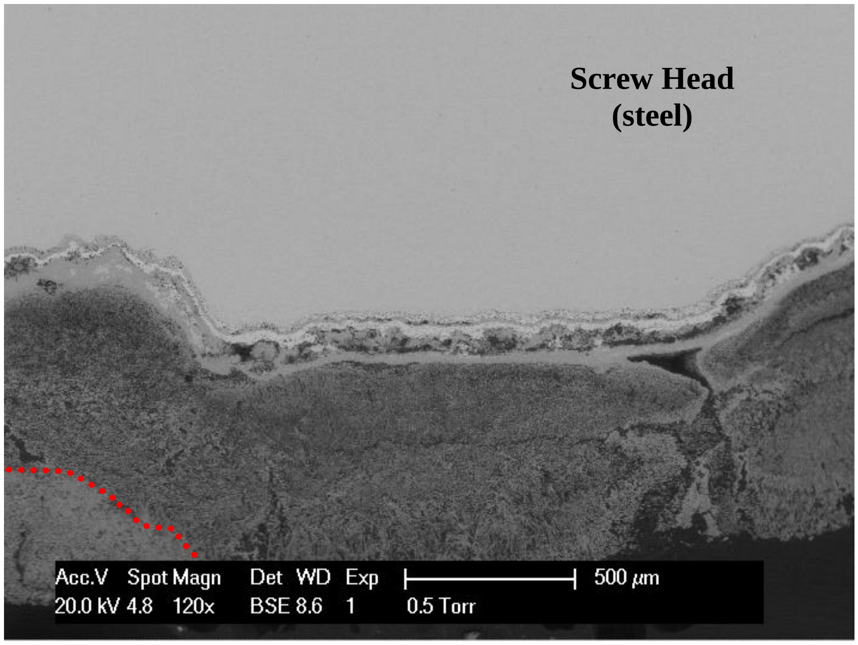


Figure 3-84. SEM image (120x) showing layer of corrosion for sectioned PSE133 enlarged screw.

The EDS mapping of the corrosion layers revealed is very similar to the sectioned screw from PSE170 (see Figure 2-68). It should be noted that carbon and some of the Cl, O, and Si show up from to the resin that the sample was mounted in and background measurements. Similar to the sectioned screw from PSE170, the corrosion layer is largely iron and oxygen, most likely iron oxides. But, where a slight change in concentration at the boundary between the different corrosion layers was shown for PSE170 there is no clear distinction in Figure 3-85. The layers of chlorine, copper, and manganese that were observed on the surface of the enlarged screw head for PSE170 are not present for PSE133. However, it is not very surprising, given the change in colors of the enlarged screw heads post-furnace exposure, that the outer layers of corrosion would be different. Also, the distinctive layer of copper at the interface of the bulk steel and the corrosion was present in this sample after the fire exposure. The layer of copper is also visible under a microscope as well (Figure 3-86). The similarities between the EDS mapping of the two sectioned enlarged screw heads indicates that the chemical signatures of the enlarged screw head likely persist after the fire exposure. Additional sectioning and polishing of enlarged screw heads, both with and without additional fire exposure, would be necessary to quantify the effects of the fire exposure on the enlarged screw head chemistry.

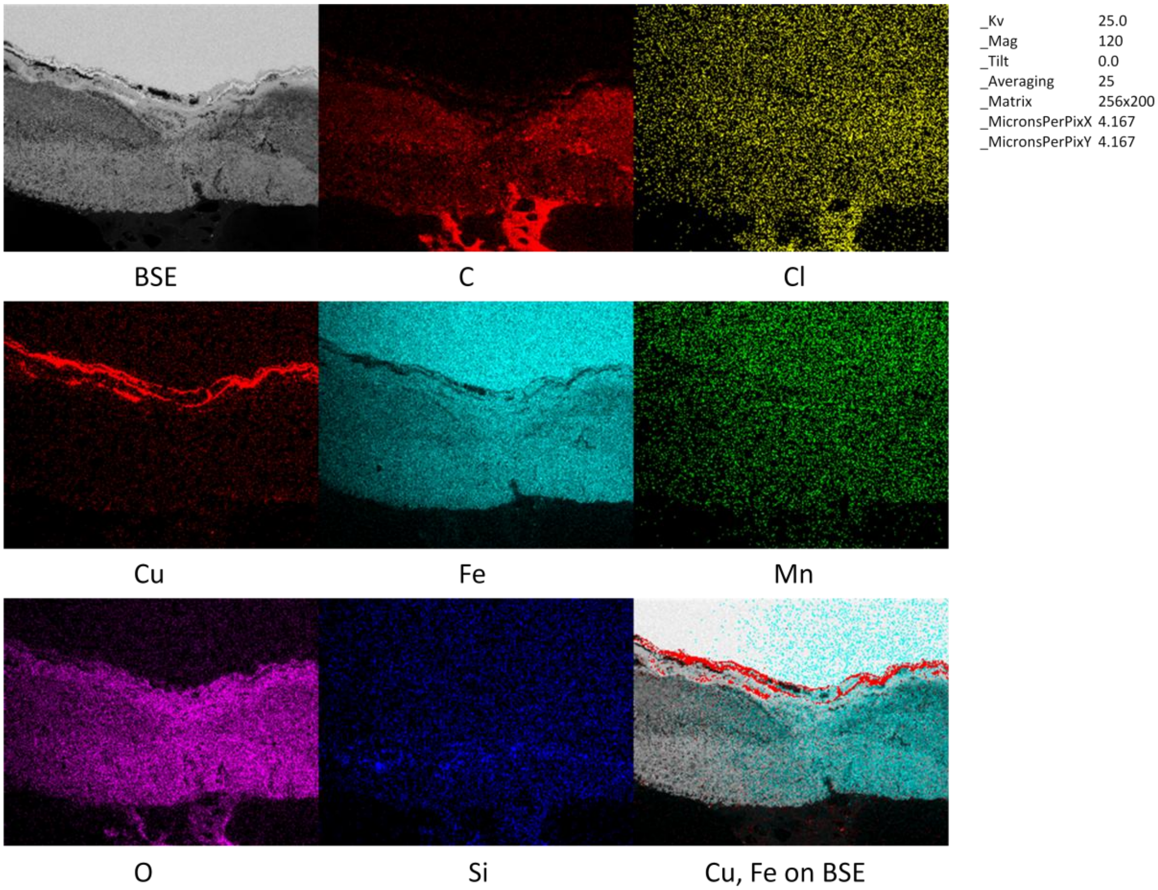


Figure 3-85. EDS Mapping of Oxide Layer for sectioned screw from PSE133.

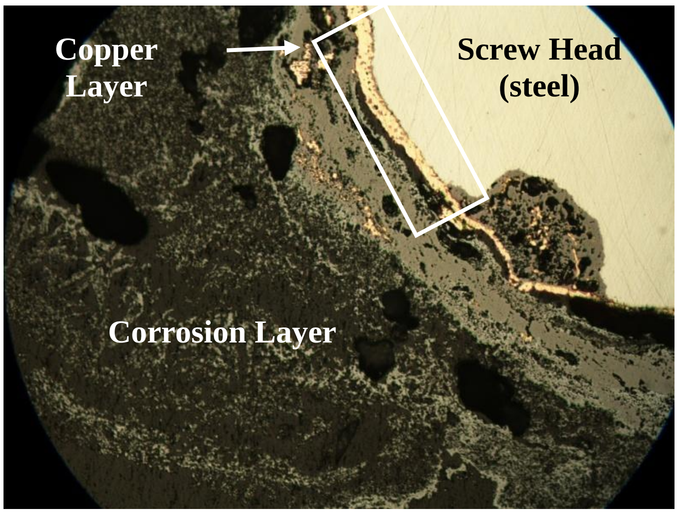


Figure 3-86. Microscope image (200x) of PSE133 showing copper at surface of screw beneath corrosion layer of enlarged screw head after fire exposure.

Two terminal screws after fire exposure from the intermediate-scale furnace had similar appearances to some of the enlarged screw heads resulting from overheating connections. These two terminal screws are shown in Figure 3-87; the photograph on the left shows a screw found at the bottom of the furnace after Furnace Test 4. This screw is referred to as "Furnace Screw X" because it is unknown what receptacle it came from. This screw's slot appeared to be narrowed and the screw was grayish in color. The photograph on the right of Figure 3-87 was from a PVC receptacle (PSE362) and had a swollen, rusty appearance with the screw's slot also narrowed. At the time of fire exposure, neither of the screws had any prior overheating. While both screws have visual characteristics similar to the enlarged screw heads formed as a result of overheating and corrosion, certain indicators clearly set them apart. For instance, Furnace Screw X has a shiny appearance and its surface did not appear as porous as the majority of enlarged screw heads. And the screw from PSE362 had a bright red color consistent with rust rather than the dark red, black, or grey seen for enlarged screw heads. The surface of this screw was also rather irregular compared to the smooth, rounded surfaces of the enlarged screw heads.

Figure 3-87. Photographs of screws from furnace testing; one located at bottom of furnace (left) and other from PSE362 (right).

Both the screw from PSE362 and Furnace Screw X were sectioned and polished to examine the surface buildup and its microstructure for comparison to the enlarged screw heads previously sectioned. Section 3.2.3.3 discusses the sectioning and polishing methodology. Photographs of the sectioned screws are shown in Figure 3-88. The thickness of the corrosion layers atop the screws were comparable to those observed for enlarged screw heads (see Figure 2-68 and Figure 3-83). In addition, the corrosion layers covered almost the whole surface of the screws and threads but were not a constant thickness over the surfaces, much like the enlarged screw heads. It can be seen that the corrosion byproducts are primarily surface growth with some loss of volume of the bulk steel. These visual/microscopic characteristics of the corrosion layers atop the screw from PSE362 and Furnace Screw X are quite similar to those for the enlarged screw heads despite visual differences of the exterior surface. Furnace Screw X had relatively thick deposits of copper within the oxide and at the interface of the oxide and bulk screw material as shown in Figure 3-88. The screw from PSE362 did not have any visible copper deposits in the oxide or at the interface of the oxide and bulk screw material.

Some differences between the two screws shown in Figure 3-88 and enlarged screw heads are evident. As shown in Figure 3-89, the corrosion on the screw from PSE362 appears to have several layers with voids between the layers and the corrosion on Furnace Screw X has rather large pores compared to the more dense corrosion found on the enlarged screw heads (see Figure

2-68 and Figure 3-83). Another indication that the screw from PSE362 has not undergone overheating and corrosion similar to the enlarged screw heads is that the copper wire and brass contact show no evidence of severe overheating or glowing (i.e., reduction in thickness, heavy oxidation, or dezincification) compared to what would be expected for an enlarged screw head. No brass conductor or copper wire segments were found with Furnace Screw X.

In order to determine the chemical makeup of the corrosion, an EDS mapping was conducted for each of the areas shown in Figure 3-88. Carbon (C), copper (Cu), iron (Fe), manganese (Mn), oxygen (O) and calcium (Ca) were mapped, with the results shown in Figure 3-90 and 3-91. Each element is plotted as a relative concentration. The corrosion layer of Furnace Screw X is primarily iron oxides with a relatively thick, discontinuous layer of copper near the bulk steel; this is similar to what was observed for the enlarged screw heads except the copper layer is not continuous. The copper is also deposited through the thickness of the surface buildup which was not typical of the enlarged screw heads. The voids in the corrosion layer appear to be filled with a carbonaceous substance; this could be a result of the corrosion layer forming in a sooty environment or in a pile of charred material at the bottom of the furnace.

The corrosion layer of the screw from PSE362 is primarily iron oxides with no distinct layer of copper near the bulk screw; this is different than what was observed for the two enlarged screw heads and Furnace Screw X. There is a layer of calcium on the surface of the copper wire; calcium concentrations were not mapped because calcium was not present in the other screws sectioned and polished.

Table 3-29 summarizes the evidence of overheating, visual characteristics, appearance of the corrosion layer, corrosion layer chemistry, and the forensic determination for each of the terminal screws that was sectioned and polished. The differences between the EDS mapping of the two sectioned enlarged screw heads (PSE133 and PSE170) and the two other sectioned screw heads (PSE362 and Furnace Screw X) indicate that the chemical signatures of the enlarged screw heads are unique compared to evidence having similar external visual appearances (i.e., false positives). However, the limited numbers of terminals evaluated using this technique precludes evaluation of the quantitative differences between the evidence examined. A complete examination of the receptacle and screw terminal and receptacle, including the characteristics presented in Table 3-29, is necessary to determine whether the subject screw was caused by overheating or other means.

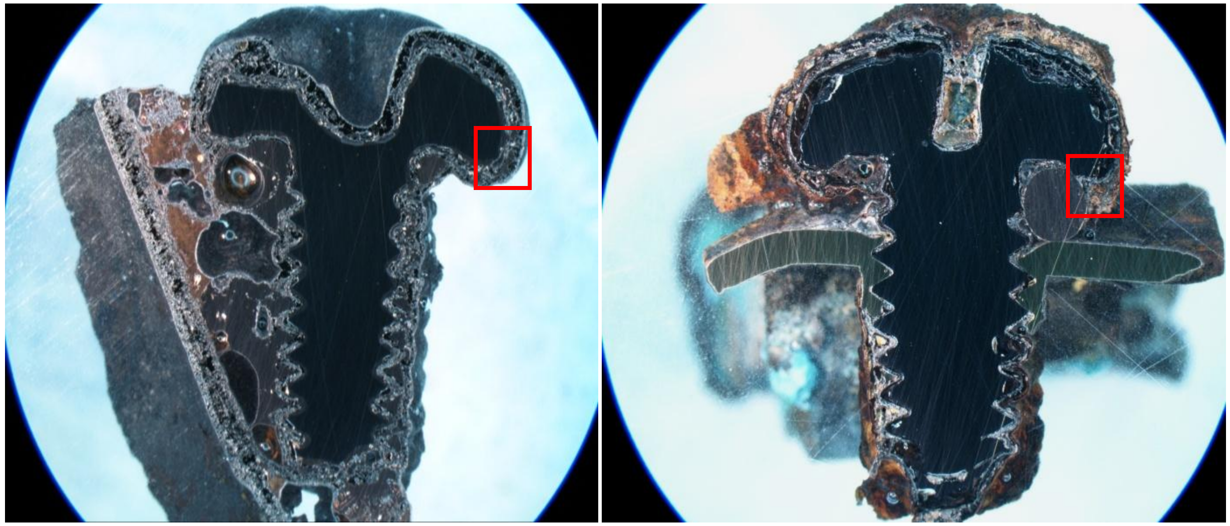


Figure 3-88. Sectioned and polished screws from furnace testing; Furnace Screw X (left) and screw from PSE362 (right). Note: Squares indicate areas of EDS mapping.

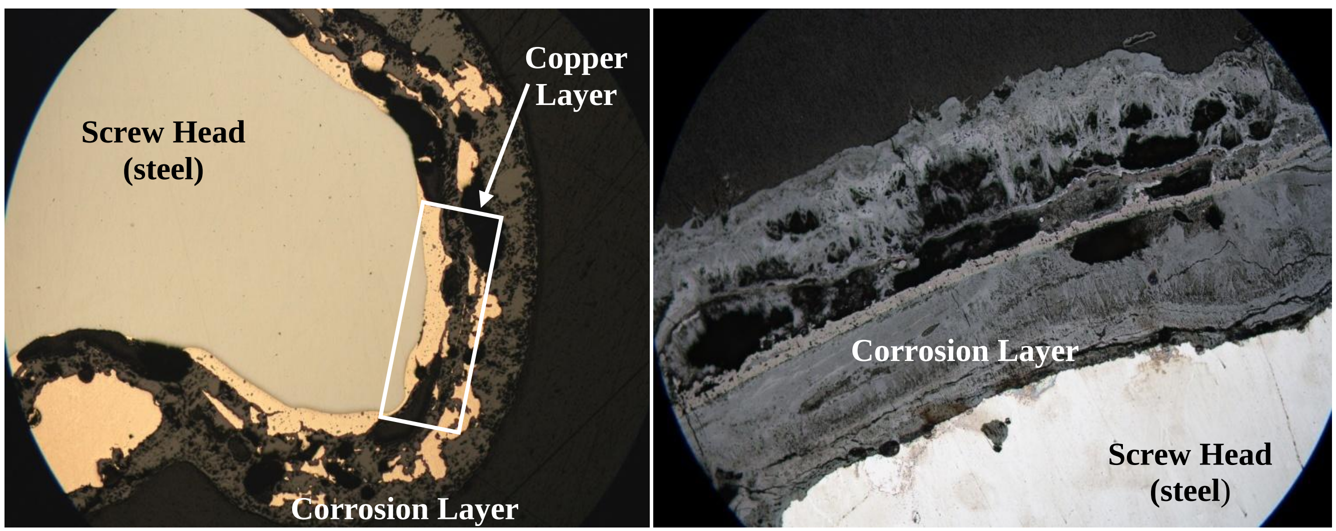


Figure 3-89. Microscope images of; Furnace Screw X (left; with copper layer and corrosion) and screw from PSE362 (right; without copper layer beneath corrosion).

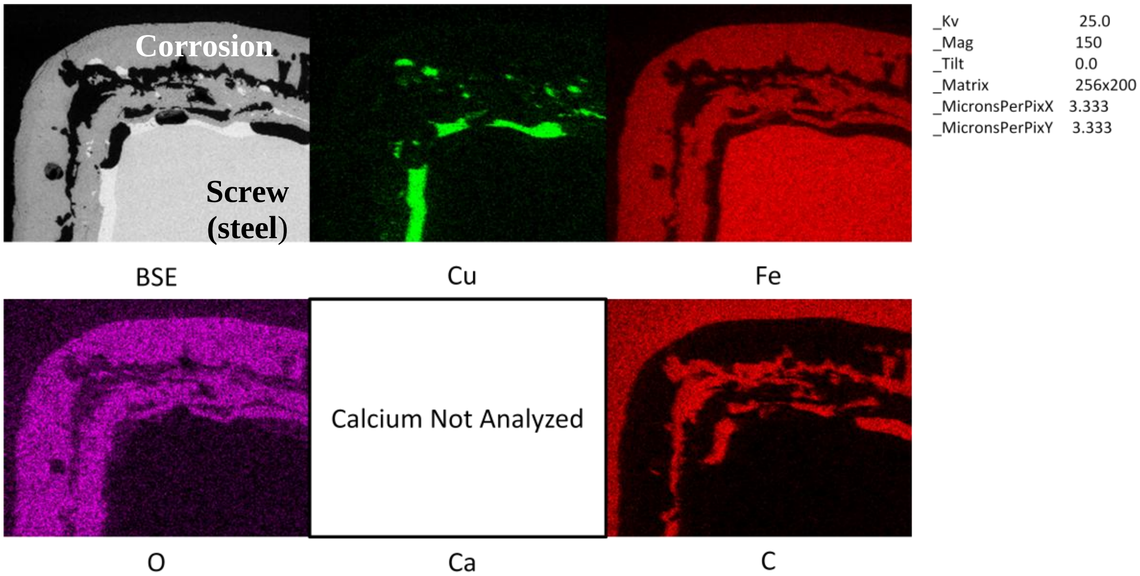


Figure 3-90. EDS Mapping of oxide layer for sectioned Furnace Screw X.

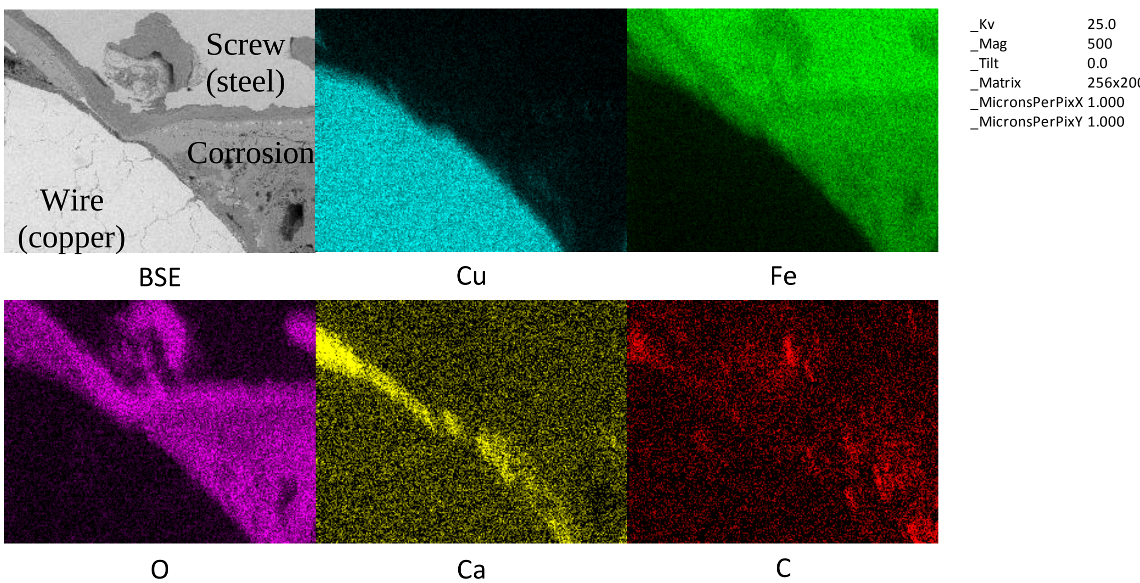


Figure 3-91. EDS Mapping of oxide layer for sectioned screw from PSE362.

Table 3-29. Comparison of Visual and Chemical Indicators Associated with Sectioned and Polished Screws.

Screw	Exposure	Evidence of Overheating	External Visual Appearance			Corrosion Layer Appearance	Corrosion Layer Chemistry	Forensic Determination
			Color	Roughness/ Porosity	Screw Slot Narrowed?			
PSE170	Overheating	Welded conductor with curved striations, thinned/pitted brass contacts, severed conductor	Grey	Smooth, Porous	Yes	Dense, small pores, two distinct layers.	Mostly iron oxides; distinct and thin copper layer between oxide and screw, and second copper layer at outside surface of oxide.	Enlarged screw head.
PSE133	Overheating and Furnace	Thinned/pitted brass contacts, severed conductor, welded conductor.	Grey *(Before Exposure)* Black *(After Exposure)*	Smooth, Porous	Yes	Dense, small pores, one distinct layer	Mostly iron oxides; distinct and thin copper layer between oxide and screw.	Enlarged screw head.
PSE362	Furnace	None	Bright Red	Rough, Porous	Yes	Several layers with voids between layers.	Mostly iron oxides.	Primarily rusting.
Furnace Screw X	Furnace	None. *(no conductor or brass contacts found)*	Grey	Smooth, Non-Porous	Yes	Dense, large pores, one distinct layer.	Mostly iron oxides; distinct carbonaceous layer; thick copper deposits between oxide and screw;	Oxidation due to heating.

3.3.9.3 Evidence of Arcing

Six receptacles which had overheating, shorting failure events and two sets of wires (1 set solid copper, 1 set stranded copper) with arc beads or notches from arcing in the compartment fire tests were exposed to furnace fire Test 5. One set of wires was comprised of three stranded copper extension cord wires and the other set of wires was comprised of two solid copper wires used for a receptacle in compartment fire Test 6. These wires were installed without a faceplate.

Of the six receptacles with shorting failure events, only one of the receptacles had arcing evidence that was visible prior to the furnace exposure (see LEV008, Figure 2-54). Two of these arcing events were confirmed by X-ray images such as the one shown in Figure 3-92. X-rays of the other four were not conclusive. The receptacle body material was mostly intact up until the furnace exposure for the receptacles with shorting failure events. After the furnace fire exposure, the arcing evidence on all of the six receptacles was visible due to the consumption of the combustible materials and remained unique compared to melting. Figure 3-92 shows an X-ray image of the identified arcing location in a polypropylene receptacle before the furnace exposure and photographs of the arcing damage after the fire exposure. There was no evidence of melting for this receptacle. The corresponding damage on both conductors and clear line of demarcation of the damage on the internal plug contacts confirms that the damage was from arcing.

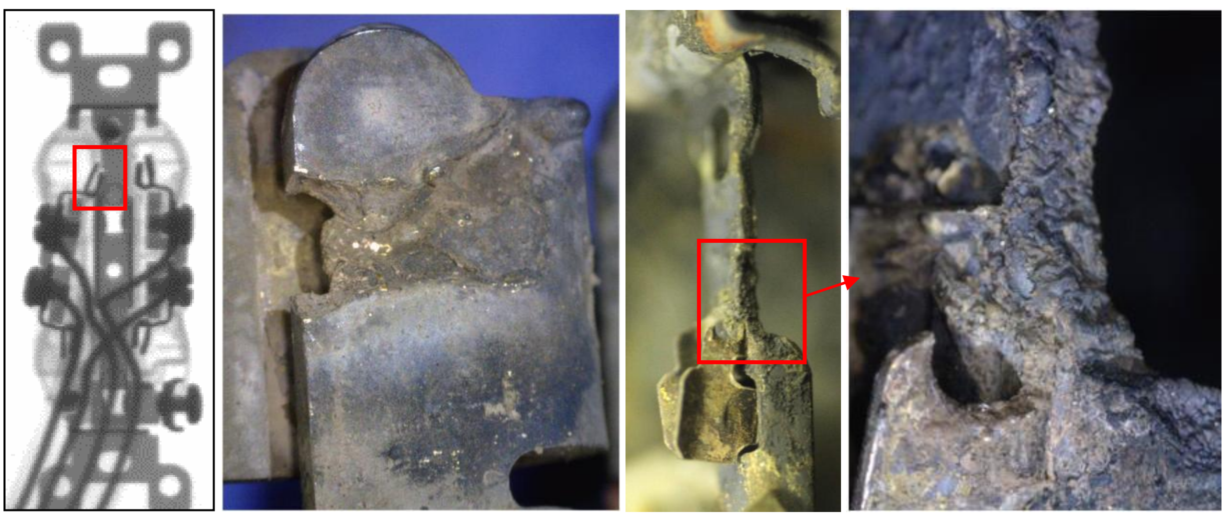


Figure 3-92. X-ray image before (left) and photographs after (right three) of arcing damage from a polypropylene receptacle failure event (LEV011).

Of the two sets of arc beads and arc notches on wire conductors from the compartment fire tests, only the solid copper wires having arcing damage persisted after the furnace exposure. The set of stranded copper wires retain the general appearance of the arc beads and notches from before the fire exposure, but the characteristics of arcing exhibited by these wires did not remain. Figure 3-93 and Figure 3-94 show SEM images of the two pieces of the neutral wire from LEV318 both before the furnace exposure and after. Before the furnace exposure, the individual copper strands were distinct and smooth. But, the furnace exposure caused some of the strands to begin to fuse together and take on a rough appearance. This eliminates the characteristic of a clear line of demarcation between the damaged and undamaged areas from these wires. In their post-furnace exposure state, it would be more difficult to conclusively classify the damage as a result of arcing.

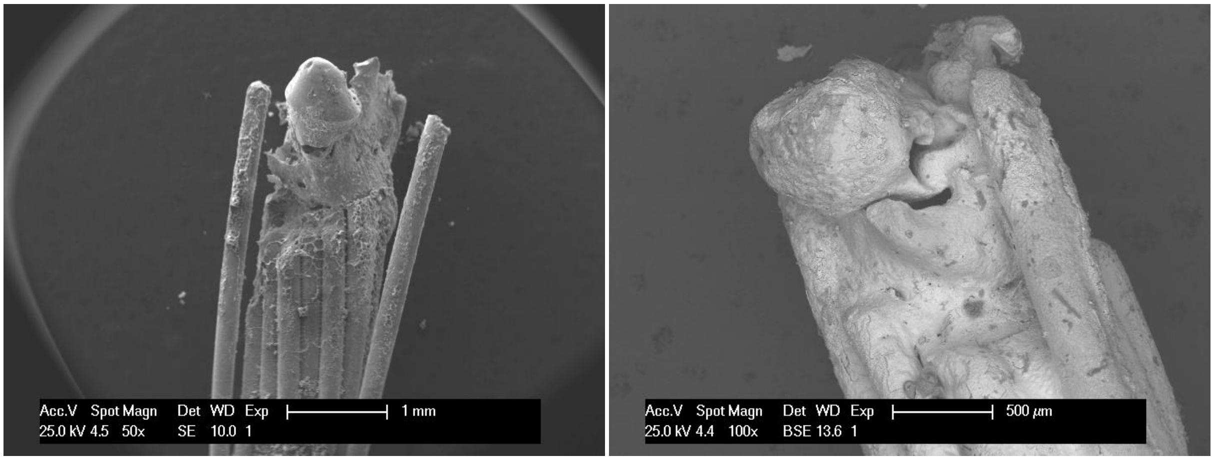


Figure 3-93. SEM images of stranded hot wire with arc bead from extension cord (LEV318) before (left) and after (right) furnace exposure.

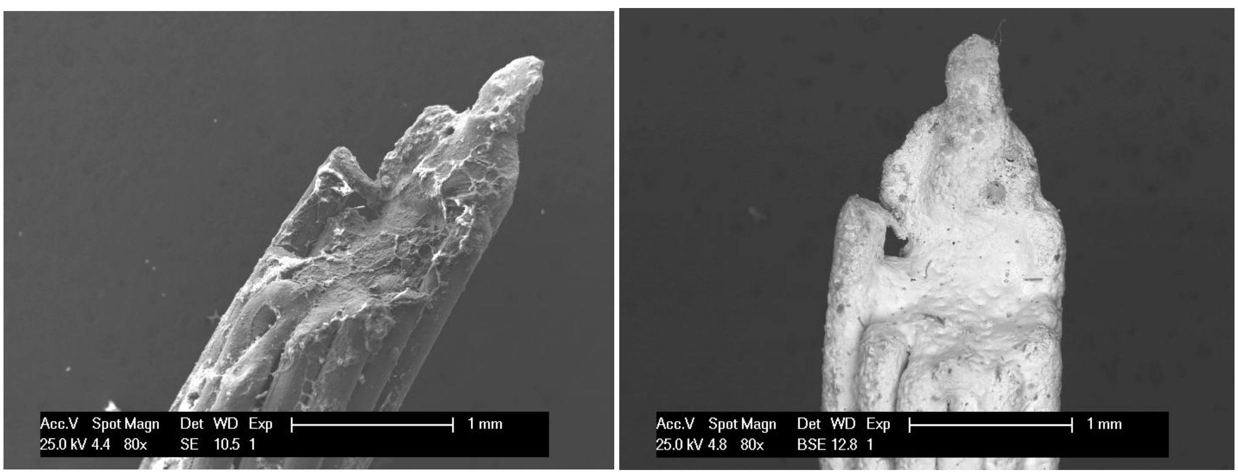


Figure 3-94. SEM images of stranded neutral wire with arc notch from extension cord (LEV318) before (left) and after (right) furnace exposure.

The set of solid copper wires from arcing in a thermoset receptacle did retain the general appearance of the arc beads and notches from before the fire exposure as well as the original characteristics of arcing. Figure 3-95 and Figure 3-96 show SEM images of the neutral and hot wires, respectively, from B007 both before the furnace exposure and after. Before the furnace exposure, both wires had a notch that had a clear line of demarcation between the arcing damage and the undamaged conductor. The hot wire also had a bead located within the notch that was round and smooth. After the furnace exposure the solid wires, much like the stranded wires, took on an overall rough appearance. This rough appearance did not affect the cylindrical shape of the wire and both wires retained their clear line of demarcation (indicated by dashed red lines on the SEM images). In their post-furnace exposure state, the damage on the wires could still be conclusively classified as arcing damage.

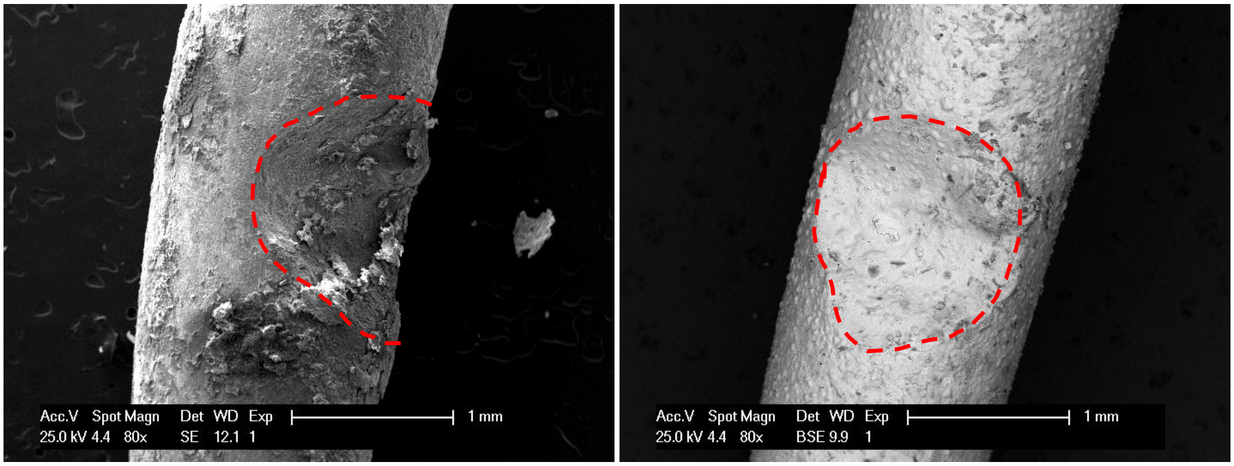


Figure 3-95. SEM images of neutral wire with arc notch from thermoset receptacle (B007) before (left) and after (right) furnace exposure.

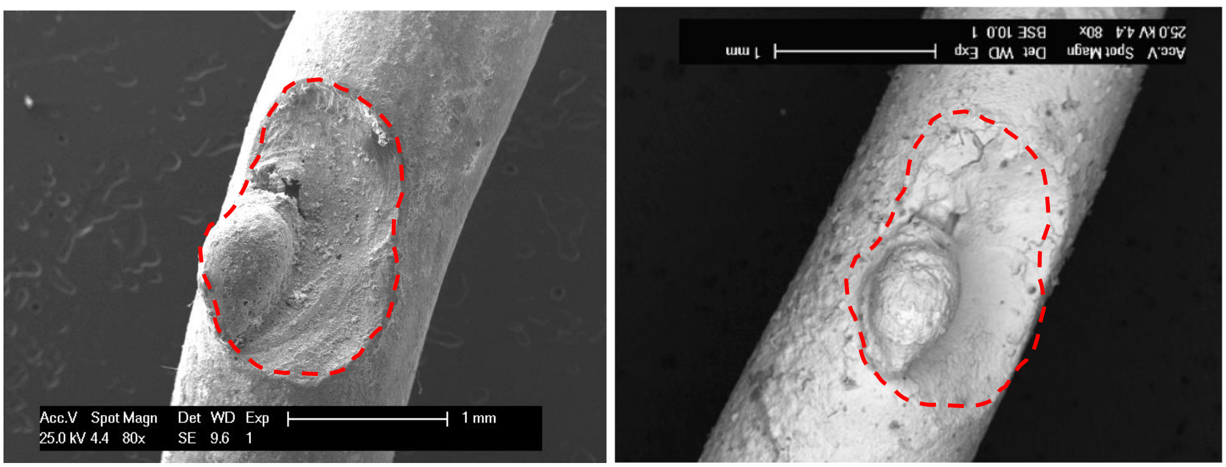


Figure 3-96. SEM images of hot wire with arc notch and bead from thermoset receptacle (B007) before (left) and after (right) furnace exposure.

3.3.9.4 Severed Conductors

Fourteen receptacles that had overheating, severed conductor failure events were exposed to furnace fire Test 5. The severed wire ends from five of the receptacles were not included in this test. Of the nine wire ends from severed conductors that were exposed to the furnace, all nine samples were identifiable as conductors severed by glowing after the exposure. One example of a rounded wire end from a severed conductor is shown before and after the fire exposure in Figure 3-97. Much like the welded conductors with curved striations, the only change in the appearance of the severed conductor ends was a color change from shiny grey to dark and red. The red is probably from a surface coating of copper oxides. The general shape of the severed conductors did not change due to the furnace exposure, which reached temperatures of 1000°C for 10 minutes. This change in appearance was typical for the rest of the wire sides of the severed conductors after the furnace fire exposure regardless of their original shape (i.e., round or irregular).

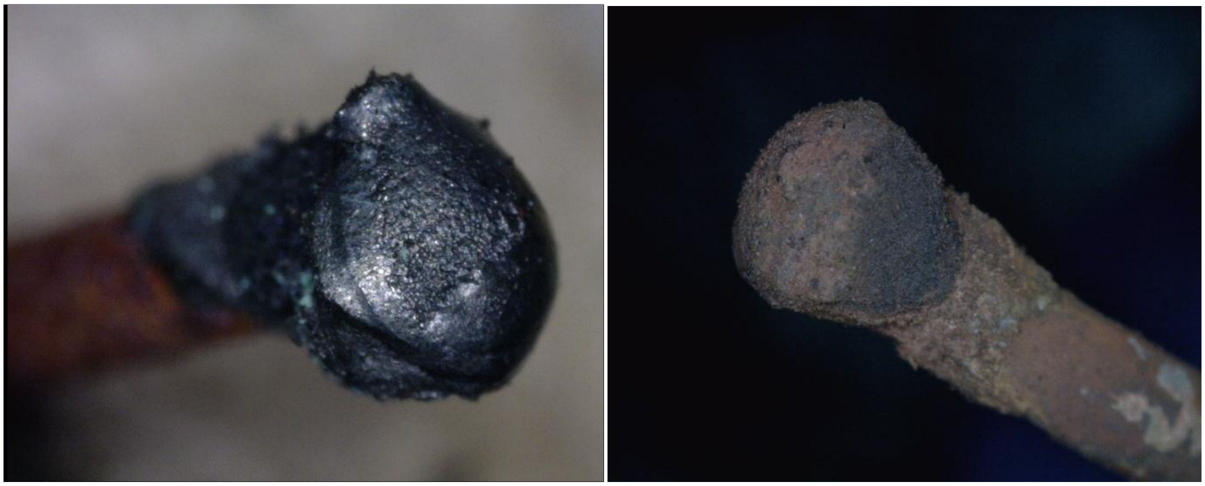


Figure 3-97. Photographs of severed conductor end on wire from PVC (PSE023) receptacle before (left) and after (right) furnace exposure.

Thirteen of the fourteen screw sides of the severed conductor ends had characteristic shapes that persisted after the fire exposure. The only screw side of the severed conductor that did not persist after the furnace exposure showed some signs of melting of the copper conductor at the location where the conductor severed. Figure 3-98 shows the screw side of the severed conductor from a PVC receptacle. The shape, including the dimple at the center of the severed conductor, did not change due to the furnace exposure. The shiny, smooth appearance changed to a dull black-reddish (from copper oxides) color after the furnace exposure. These changes in appearance were typical for the rest of the screw-side severed conductors after the furnace fire exposure regardless of their original shape (i.e., round or irregular).

Figure 3-98. Severed conductor end on screw side from polypropylene (LEV272) receptacle before (left) and after (right) furnace exposure.

3.3.9.5 Severe Oxidation

After the furnace exposure to receptacles with prior overheating, a number of PVC receptacles were observed with internal contacts that were severely thinned by oxidation and overheating. Due to the plastic that had remained on the receptacles after the failure events, these contacts could not be seen in their entirety prior to the furnace exposure. Three examples of the thinned contacts are shown in Figure 3-99, Figure 3-100, and Figure 3-101. Two of the three receptacles had enlarged screw heads (PSE023 and PSE021) and all three receptacles had welded conductors with curved striations. The thinning of the contacts occurred in the vicinity of the screw connection that was overheating and was relatively uniform over the contacts. In general, the thickness of the contacts was reduced to about half of the original thickness. Both Figure 3-100 and Figure 3-101 show the thinned part of the contacts and the non-thinned part.

Figure 3-99. Photograph of internal plug contacts thinned by oxidation and overheating from PVC receptacle (PSE023).

Figure 3-100. Photograph of internal plug contacts thinned by oxidation and overheating from PVC receptacle (PSE021).

The appearance of the thinned contacts from oxidation and overheating is different than the thinned contacts from melting (see Figure 3-33, Figure 3-36, and Figure 3-39). The thinned contacts from melting tend to be a result of the molten brass running down the contacts. As a result of this, internal contacts that have melted will also generally be thicker than original at some point. The thinned contacts were only viewed after the furnace exposure and as such it is unclear whether or not they had changed due to the furnace exposure. However, due to the lack of melting of the internal plug contacts in these three receptacles, it is unlikely that the appearance changed as a result of the furnace exposure. This thinning was also not in the vicinity of the locations where arcing was observed to occur.

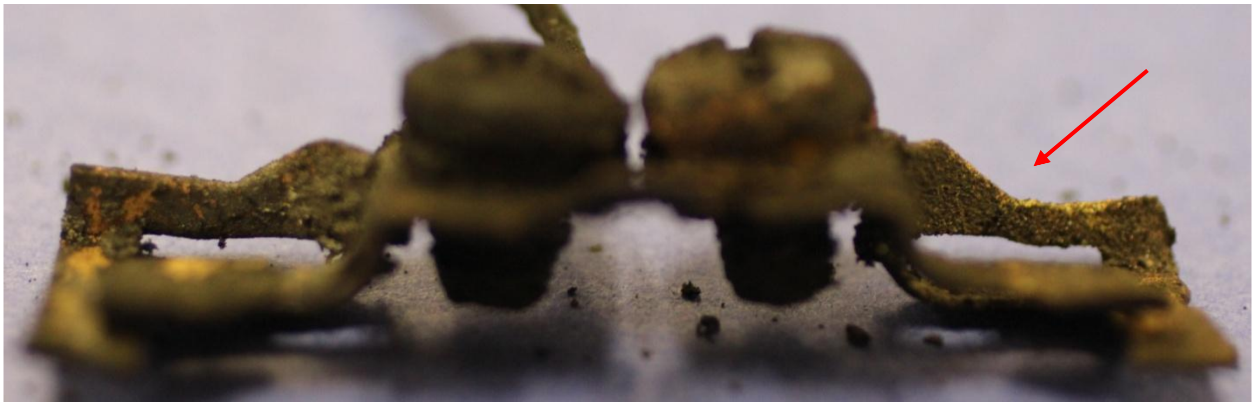


Figure 3-101. Photograph of internal plug contacts thinned by oxidation and overheating from PVC receptacle (PSE024).

4.0 DISTINGUISHING ARC FROM MELT DAMAGE

Distinguishing between arcing and thermal melting damage was based on the presence of visual indicators of arcing and/or melting in the evidence as listed in the proposed changes to NFPA 921 [2014], with some additions. The following characteristics are listed in the proposed changes to NFPA 921 [2014] as frequently exhibited in arc damaged conductors:"

- Localized point of contact
- Sharp demarcation between damaged and undamaged area
- Copper drawing lines visible outside of damaged area
- Corresponding damage on the opposing conductor
- Resolidification waves
- Locally enlarged grain size
- High internal porosity when viewed in a cross-section
- Localized round depressions
- Small beads & divots over a limited area
- Round, smooth shape of artifact

The presence of tooling marks, such as defined edges and stamped lettering outside of the damaged area for arcing in brass and steel receptacle components was used as an analogous characteristic to the presence of copper drawing lines for copper wiring. Another characteristic of arcing is spatter of molten material produced during arcing which can deposit on surfaces near the arcing location. There are no mechanisms associated with melting to suggest that spatter would be created. The following characteristics are listed in the proposed changes to NFPA 921 [2014] as indicators of fire-melted conductors:

- Extended area of damage without sharp demarcation from undamaged material
- Gradual necking of the conductor (assuming this is not due to mechanical break)
- Blisters on the surface (assuming gross overload was ruled out)
- Visible effects of gravity on the artifact
- Low internal porosity when viewed in a cross-section

In addition, thinning, formation of holes, and surface pitting were commonly observed in fire-melted receptacle components.

A portion of the arcing and melting damage produced in this work was evaluated for the presence of nine characteristic traits of arcing damage and 5 traits of melting damage (see subsequent sections). These traits were taken from the literature (e.g., NFPA 921 [2014]) and from observations made during the forensic examinations conducted as part of this work. The purpose of this exercise was to assess which characteristic traits were effective in assessing potential arcing damage on receptacle components and wiring. All of the 39 receptacles which failed due to overheating and also had arcing damage were evaluated; this included 95 individual conductors. For the failure events, one back-wired receptacle, five receptacles with plug connections, and 33 receptacles with screw terminal connections were evaluated. Forty-seven receptacles with fire induced arcing were evaluated for the presence of characteristics of arcing and melting; this included 87 individual conductors. All of the evaluated receptacles with fire-induced arcing were energized or energized with a load. Fire-melting was present in some of these receptacles, but it was not in the vicinity of the arcing location or was on a material not involved in the arcing (i.e., brass melted when arcing was found in the copper). Thirty-seven receptacles with fire-melting were evaluated; this included 57 individual conductors. All of the receptacles evaluated for fire-melting were non-energized receptacles exposed in the furnace tests.

Each receptacle was evaluated for presence of the aforementioned characteristics of arcing and melting with the exception of the grain structure (i.e., locally enlarged grain size). This characteristic was omitted because it was not able to be evaluated visually. Where multiple conductors exhibited damage from arcing or melting, each conductor was evaluated independently. For each characteristic, there were three possible outcomes: Yes, No, and Possible. Yes indicated that the characteristic was judged to be present on the particular conductor; no indicated that the characteristic was judged not to be present on the conductor. Possible indicated that confirmation could not be made either for or against the presence of the characteristic. This was either due to the presence of dirt, debris, or corrosion which could not easily be removed and prohibited confirmation of the characteristic, where the conductor was completely arced or melted away, or where it was open to interpretation as to whether the characteristic was present or not. All of the evaluations were conducted by the same person. Every effort was made to evaluate the conductors in a consistent manner; however, there is some subjectivity present in the evaluations due to the qualitative nature of the characteristic traits and the spectrum of possible variations. The following sections outline the results of the evaluations for each characteristic of arcing and melting. Each characteristic is broken down by conductor material and for receptacle failures, fire induced arcing, and melting.

4.1 Corresponding Damage on the Opposing Conductor

Corresponding damage on the opposing conductor is a characteristic of arcing that is typically present. This is because arcing, at a minimum, requires two conductors, whether they are two parts of the same conductor in series or two separate conductors in parallel. However, dirt, debris, physical damage, thermal damage, or corrosion can destroy or obscure the damage on one or both conductors. For the purpose of these evaluations, corresponding damage on the opposing conductor was defined as damage located on another conductor proximate to the area of interest. Corresponding damage on the opposing conductor could only be confirmed where both conductors were present; where one conductor was missing (i.e., completely arced or melted away) the corresponding damage was classified as possible. Arcing in receptacles was only found in certain locations within the receptacles due to the configuration of the conductors; therefore, arcing between certain components was unlikely (see Section 3.3.7.1). For example, arcing between the hot and neutral plug contacts is generally not possible due to the grounding strap being positioned between the two sets of contacts. For the conductors where corresponding damage was identified, it was independently evaluated for the presence of other characteristics traits of arcing and melting. Tables 4-1, 4-2, and 4-3 list the presence of corresponding damage on another conductor for receptacle failures, fire induced arcing, and receptacles with melting, respectively.

Table 4-1. Corresponding Damage on Opposing Conductor for Receptacle Failures.

Conductor Material	Yes	No	Possible
Brass	46	0	0
Solid Copper	13	0	1
Steel	34	0	1
Total	93	0	2

Table 4-2. Corresponding Damage on Opposing Conductor for Fire Induced Arcing.

Conductor Material	Yes	No	Possible
Brass	23	3	1
Solid Copper	19	2	0
Stranded Copper	10	0	0
Steel	26	2	1
Total	78	7	2

Table 4-3. Corresponding Damage on Opposing Conductor for Receptacles with Melting.

Conductor Material	Yes	No	Possible
Brass	0	25	0
Solid Copper	0	28	0
Stranded Copper	4	0	0
Total	4	53	0

In this study, a large portion of conductors from fire induced arcing (98%) and arcing in receptacle failures (96%) had a positive identification of corresponding damage on the opposing conductor. Only two of the conductors (2%) from receptacle failures had possible corresponding damage on the opposing conductor. Both of these conductors were from receptacles which had flaming ignition failure events. As discussed in Section 2.3.4.1, parallel arcing that occurred in receptacles experiencing flaming ignition failures occurred for extended periods which produced arcing damage and loss of material that was over a larger area than a single arc. The loss of material that accompanied the extended arcing for receptacles PSE175 (solid copper) and PSE166 (steel) prevented confirmation of the corresponding damage on the opposing conductor. A photo of the damage to the steel grounding strap for PSE166 is shown in Figure 2-45.

The majority of conductors with fire induced arcing that did not have corresponding damage on the opposing conductor were not due to extended arcing which was seen for the receptacle failures. Two receptacles had arcing identified in the solid copper receptacle wiring where only one conductor was identified with damage. For these receptacles, there was no fire-melting of the copper wiring identified. Corresponding damage could not be confirmed for four receptacles (3 no; 1 possible) with arcing damage on the break-off tab. For these receptacles, it was likely that the arcing occurred between the break-off tab and the faceplate due to their close proximity, but rust and/or scaling on the faceplate prevented identification or confirmation of corresponding damage on the faceplate. Two other receptacles had arcing damage identified on the faceplate or grounding strap, but the brass plug contacts had been mostly or completely melted away.

Only four (7%) of the conductors with fire melting had corresponding damage on the opposing conductor. These four conductors (two pairs of stranded copper wires) were fused together as a result of the fire exposure. A photograph showing two of the fused wires is shown in Figure 4-1. While these two instances of melting were not visually similar to any of the arcing damage observed in this test series, it is important to note that there is a possibility that melted conductors can exhibit corresponding damage, particularly for conductors that fuse over a small contact area, which could break apart later. The results demonstrate that corresponding damage on conductors is highly correlated to arcing events and only occurred in melting events with stranded copper wire. Consequently, this trait is a reliable indicator of arcing.

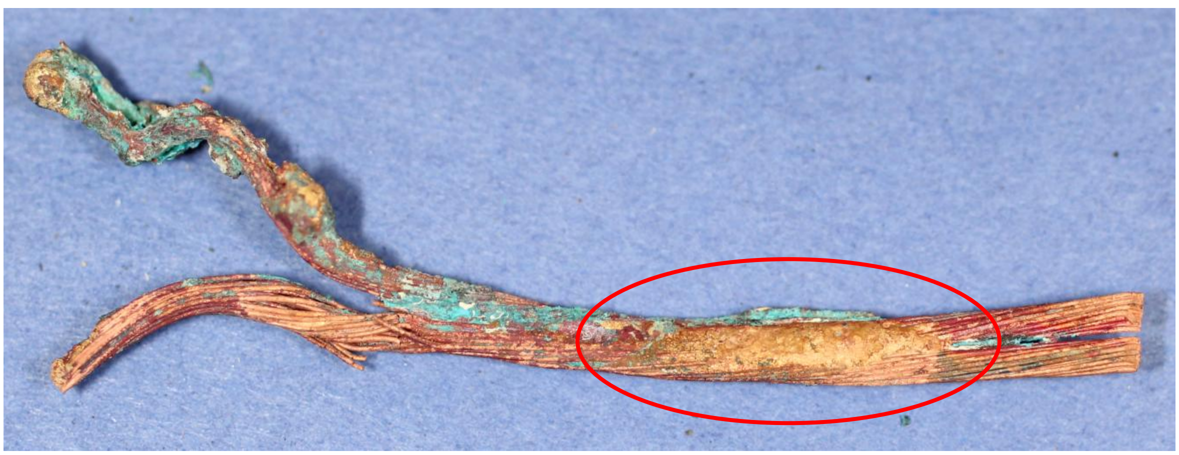


Figure 4-1. Corresponding damage on opposing conductor(s) for receptacle with melting (LEV397).

4.2 Localized Point of Contact with a Sharp Line of Demarcation

Because individual arcs are typically small in size (<1 cm), short in duration (<<1 second), and high in temperature (>5000°C), damage to the conductors tends to be localized with a sharp line of demarcation between damaged and undamaged areas. Where multiple arcs occur in the same location, the damage area can grow in size and thus become non-localized. The authors did not define a cutoff for the size of the damage area for determining whether something was localized. Tables 4-4, 4-5, and 4-6 list the presence of a sharp line of demarcation between the damaged and undamaged material for receptacle failures, fire induced arcing, and receptacles with melting, respectively.

Table 4-4. Localized Point of Contact with a Sharp Line of Demarcation for Receptacle Failures.

Conductor Material	Yes	No	Possible
Brass	41	1	4
Solid Copper	14	0	0
Steel	31	1	3
Total	86	2	7

Table 4-5. Localized Point of Contact with a Sharp Line of Demarcation for Fire Induced Arcing.

Conductor Material	Yes	No	Possible
Brass	25	0	2
Solid Copper	21	0	0
Stranded Copper	10	0	0
Steel	27	0	2
Total	83	0	4

Table 4-6. Localized Point of Contact with a Sharp Line of Demarcation for Receptacles with Melting.

Conductor Material	Yes	No	Possible
Brass	0	25	0
Solid Copper	7	16	5
Stranded Copper	0	4	0
Total	7	45	5

An example of an arcing location with a localized point of contact and sharp line of demarcation between the damaged and undamaged areas is shown in Figure 4-2. This receptacle (LEV015) had a hot-to-ground short as a result of an overheating connection. The differences in color between the undamaged brass contact (black; covered in soot) and the damaged area (brass; melted from arcing) occur sharply at the edge of the arcing damage (notched area) noted by the dashed line. In addition, the damage is only on a portion of the plug contact corresponding to where it shorted to the grounding strap.

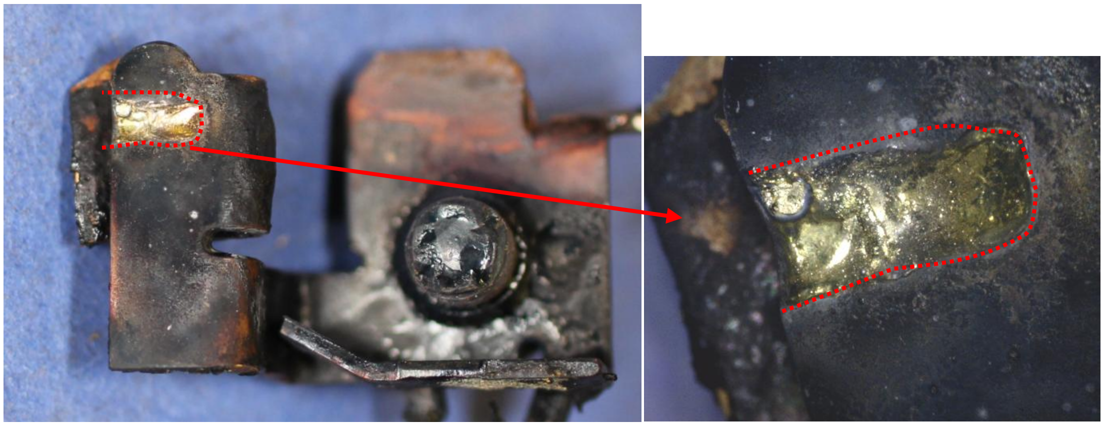


Figure 4-2. Localized point of contact with sharp line of demarcation noted as a dashed line around the notch (LEV015).

A large portion of conductors from fire induced arcing (95%) and arcing in receptacle failures (90%) had a positive identification of localized damage with a sharp line of demarcation. Those few conductors without localized damage with a sharp line of demarcation were brass and steel only. Figure 4-3 shows an example of arcing damage that is localized in the vicinity of the top-hot side of the grounding strap without a sharp line of demarcation. The presence of various degrees of damage and globules over the large area of arcing does not indicate a sharp line of demarcation.

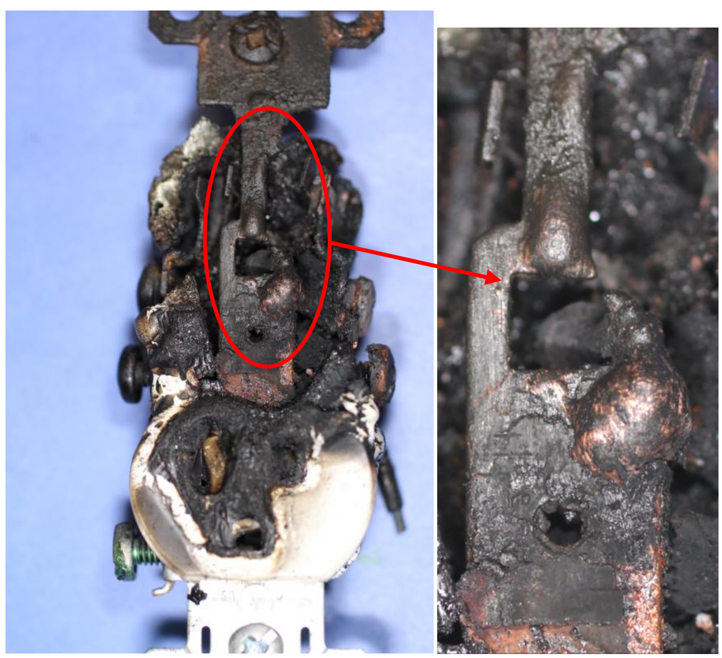


Figure 4-3. Localized point of contact without a sharp line of demarcation (PSE 285).

Only seven conductors (12%) from receptacles with melting had damage that was localized and had a sharp line of demarcation between the damaged and undamaged areas. All of these instances, as well as the five conductors with possible classifications, were observed on solid copper receptacle wiring. This was likely due to the nature of the fire exposure to receptacles; that is, the receptacles were exposed only from the front surface. The distinct line of demarcation of wire damage can be explained by the directional fire exposure (i.e., from front to back of the receptacle) with the wires located behind the receptacle in the box (see Section 3.3.1). One example of a melted copper conductor with localized damage and a clear line of demarcation between the damaged and undamaged areas is shown in Figure 4-4. Overall, the data clearly shows a strong correlation for a sharp line of demarcation with arcing damage and a weak correlation for melting.

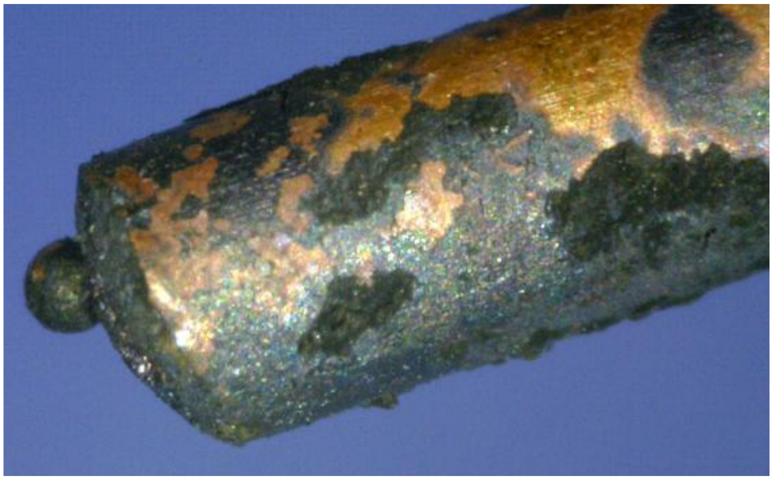


Figure 4-4. Localized point of contact with a sharp line of demarcation (LEV391).

4.3 Round, Smooth Shape

The round, smooth shape often exhibited by arcing damage on wiring has led to the use of the generic term of arc bead for describing arcing damage. While the proposed changes to NFPA 921, for the 2014 edition, include the round smooth shape as a characteristic trait of arcing, Section 8.11.1.2 of NFPA 921 [2011] states that arcing damage can be "notches in the sides of the conductors, or rounded or irregular-shaped beading on the end of a severed conductor." This information provided by NFPA 921 [2011], while accurate, is not clear guidance on differentiating between arcing and melting in that it essentially states that both regular (i.e., round and smooth) as well as irregular arc damage can be observed. This description also does not account for the appearance of arcing damage on non-cylindrical objects such as receptacle components. In addition, the proposed changes to NFPA 921 [2012] do not include an irregular shape or notch as characteristic traits for arcing damage.

For the purpose of this evaluation, arcing and melting damage was considered to be round and smooth if some (e.g., a round globule in a notch) or all of the damage was rounded without jagged or rough surfaces and edges. For example, a shallow notch in a conductor was only considered to be round if the notch had a round globule in it or if the notch was without irregular depressions. Figure 4-5 shows an example of a notch in a brass plug contact which was not round and smooth; in this receptacle, arcing occurred between the steel faceplate and brass plug contact. Figure 4-6 shows an example of a notch in a steel faceplate which was round and smooth; where arcing occurred between the brass plug contact and the faceplate. Tables 4-7, 4-8, and 4-9 list the presence of a round smooth shape for receptacle failures, fire induced arcing, and receptacles with melting, respectively.

Figure 4-5. Notch in brass plug contact which is not round and smooth (LEV144).

Figure 4-6. Notch in steel faceplate which is round and smooth (PSE331).

Table 4-7. Round, Smooth Shape for Receptacle Failures.

Conductor Material	Yes	No	Possible
Brass	17	23	6
Solid Copper	4	7	3
Steel	18	16	1
Total	39	46	10

Table 4-8. Round, Smooth Shape for Fire Induced Arcing.

Conductor Material	Yes	No	Possible
Brass	5	22	0
Solid Copper	11	9	1
Stranded Copper	10	0	0
Steel	8	21	0
Total	34	52	1

Table 4-9. Round, Smooth Shape for Receptacles with Melting.

Conductor Material	Yes	No	Possible
Brass	0	24	1
Solid Copper	7	21	0
Stranded Copper	0	4	0
Total	7	49	1

Only 41% of the conductors from arcing in receptacle failures, 39% of the conductors from fire induced arcing, and 12% of melted conductors had damage which was round and smooth in shape. While a notable number of arcing conductors had this trait, the lack of a large difference in proportions of arcing and melting damage which are round and smooth in shape suggests that this trait is not a strong differentiating indicator between arcing and melting. There is no physical reason, similar to those for corresponding damage and localized damage with a sharp line of demarcation, that all arcing damage should be round and smooth. The other characteristics (i.e., localized damage, corresponding damage) are quasi-universal because they apply to arcing and not just one type or style of conductor.

Due to surface tension, small suspended volumes of liquids tend to form round or spherical drops or beads with relatively uniform surfaces. Both arcing and fire-melting can produce molten drops of brass or copper conductors; when these re-solidify, they can form round and smooth shapes. However, because melting and resolidification occurs much quicker for arcing than fire-melting, arcing may be more likely to form spherical beads (see Figure 4-7) than fire melting beads which can be affected by gravity (see Section 4.9)

Figure 4-7. Round and smooth bead on end of wire severed by arcing (E001).

4.4 Resolidification Waves

Resolidification waves in arcing damage arise from the rapid cooling associated with arcing events. This trait appears as concentric rings (i.e., waves or ripples) emanating from the center of the arcing damage (see Figure 4-8). Resolidification waves sometimes formed only along the outer portions of the arcing damage and around the entire perimeter of the damage. For long, thin areas of damage, the resolidification waves, generally appeared to be more pronounced along the major axis of the damage area (see Figure 4-9). For conductors classified as having possible resolidification waves, the damage appeared to have concentric rings that were either not very pronounced or obscured by rust or other debris. Tables 4-10, 4-11, and 4-12 list the presence of resolidification waves for receptacle failures, fire induced arcing, and receptacles with melting, respectively.

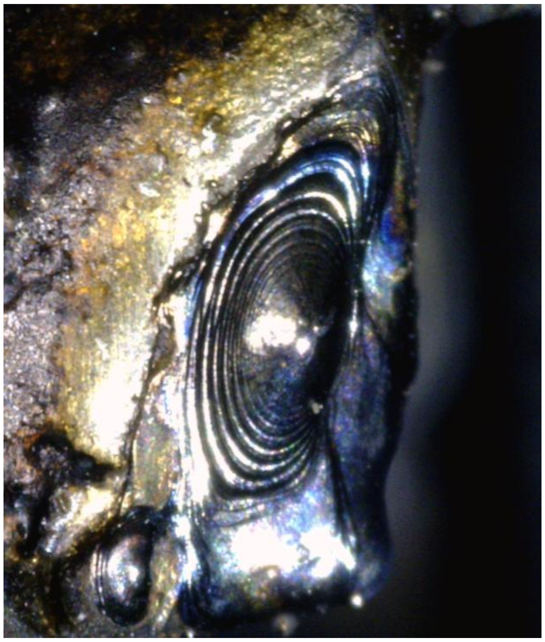


Figure 4-8. Arcing damage on grounding strap showing resolidification waves (LEV276).

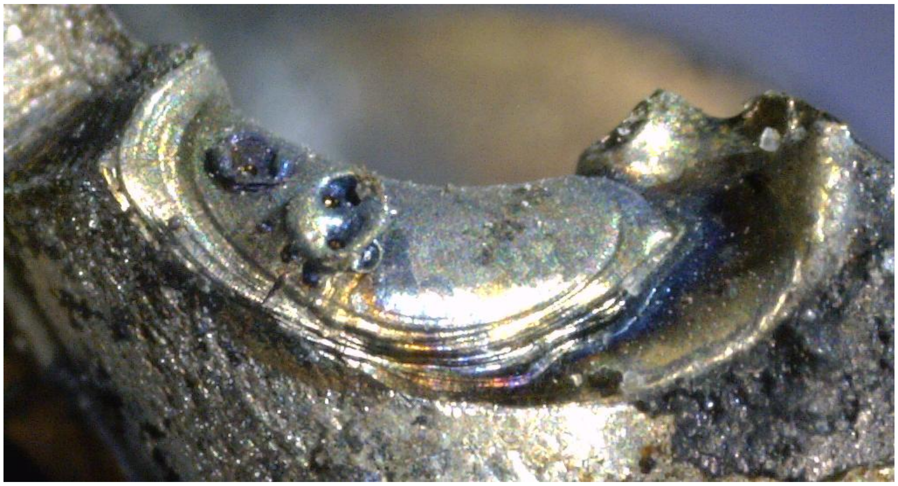


Figure 4-9. Arcing damage on grounding strap showing resolidification waves that are more pronounced on the major axis (LEV174).

Table 4-10. Resolidification Waves for Receptacle Failures.

Conductor Material	Yes	No	Possible
Brass	3	40	3
Solid Copper	4	9	1
Steel	13	20	2
Total	20	69	6

Table 4-11. Resolidification Waves for Fire Induced Arcing.

Conductor Material	Yes	No	Possible
Brass	0	27	0
Solid Copper	0	17	4
Stranded Copper	0	9	1
Steel	1	27	1
Total	1	80	6

Table 4-12. Resolidification Waves for Receptacles with Melting.

Conductor Material	Yes	No	Possible
Brass	0	25	0
Solid Copper	0	28	0
Stranded Copper	0	4	0
Total	0	57	0

Only a small portion (21%) of conductors with arcing damage from receptacle failures and a single conductor (1.1%) with fire induced arcing damage (see Figure 4-6) exhibited resolidification waves. Resolidification waves were observed on steel, brass, and copper conductors, but were most often on the steel receptacle components than the copper wires and brass components. Murray and Ajersch [2009] observed resolidification waves on copper and steel; these researchers also tested brass and aluminum conductors but did not state whether resolidification waves were observed on these metals. The resolidification waves observed in this work were similar in appearance to those observed by Murray and Ajersch [2009].

One instance of resolidification waves is shown in Figure 4-10 where the waves are located on only a portion of the copper arc bead. It is possible that this wire, from a receptacle failure event, had multiple arcs: one to create the bead and another to cause the resolidification waves in a localized spot on the bead. None of the conductors with melting damage were observed with resolidification waves. Despite the low percentages of arc damaged conductors with resolidification waves present, this characteristic trait is a strong indicator that arcing occurred. The resolidification waves themselves are unique compared to the visual appearance of melting. The regular, concentric rings are not able to be produced by fire melting due to the relatively slow process of fire-melting and cooling compared to arcing.

Figure 4-10. Arcing damage on copper wire showing resolidification waves (LEV172).

4.5 Tooling Marks Visible Outside Area of Damage

Tooling marks come from the manufacturing process of metal components of receptacles and wiring. These processes mar the surface with a regular pattern or form a distinct shape (see Figure 4-11). Tooling marks include defined edges and lettering for stamped and bent brass and steel receptacle components and copper drawing lines for copper wires. When exposed to temperatures on the order of the melting temperature of the conductor, these tooling marks can begin to be destroyed. In addition, oxidation of copper, dezincification, and rusting can also destroy these tooling marks. Tables 4-13, 4-14, and 4-15 list the presence of tooling marks visible outside the area of damage for receptacle failures, fire induced arcing, and receptacles with melting, respectively.

Figure 4-11. Typical stamped number (circled), bent brass plug contact with crisp edges from an exemplar PVC receptacle.

Table 4-13. Tooling Marks Visible Outside Area of Damage for Receptacle Failures.

Conductor Material	Yes	No	Possible
Brass	40	4	2
Solid Copper	5	9	0
Steel	32	3	0
Total	77	16	2

Table 4-14. Tooling Marks Visible Outside Area of Damage for Fire Induced Arcing.

Conductor Material	Yes	No	Possible
Brass	27	0	0
Solid Copper	10	8	3
Stranded Copper	6	2	2
Steel	25	2	2
Total	68	12	7

Table 4-15. Tooling Marks Visible Outside Area of Damage Receptacles with Melting.

Conductor Material	Yes	No	Possible
Brass	1	16	8
Solid Copper	0	28	0
Stranded Copper	0	4	0
Total	1	48	8

A large portion of conductors from fire induced arcing (78%) and arcing in receptacle failures (81%) had a positive identification of tooling marks outside (adjacent) the area of damage. This characteristic trait of arcing is a parallel method of confirming that damage to the conductor is localized and has a sharp line of demarcation, but is less likely to be present if exposure temperatures were close to the melting temperature of the subject material. Of the 169 conductors having localized arcing damage with a sharp line of demarcation, 23 (14%) of the conductors do not have positive identification of tooling marks visible outside the area of damage. This would indicate that the tooling marks cannot withstand as much of a thermal exposure as the localized damage with sharp line of demarcation before being destroyed.

Only one non-energized conductor (1.7%) with melting damage had tooling marks visible outside the damage area. This brass contact is shown in Figure 4-12, with the damage circled. This melting damage was localized on the plug contacts and the sharp edges of the conductor are visible adjacent to the damage. Though it is possible that tooling marks outside of the damage area can be present on damage after minimal fire-melting, the presence of this trait is a fair indicator that arcing occurred at the damage site.

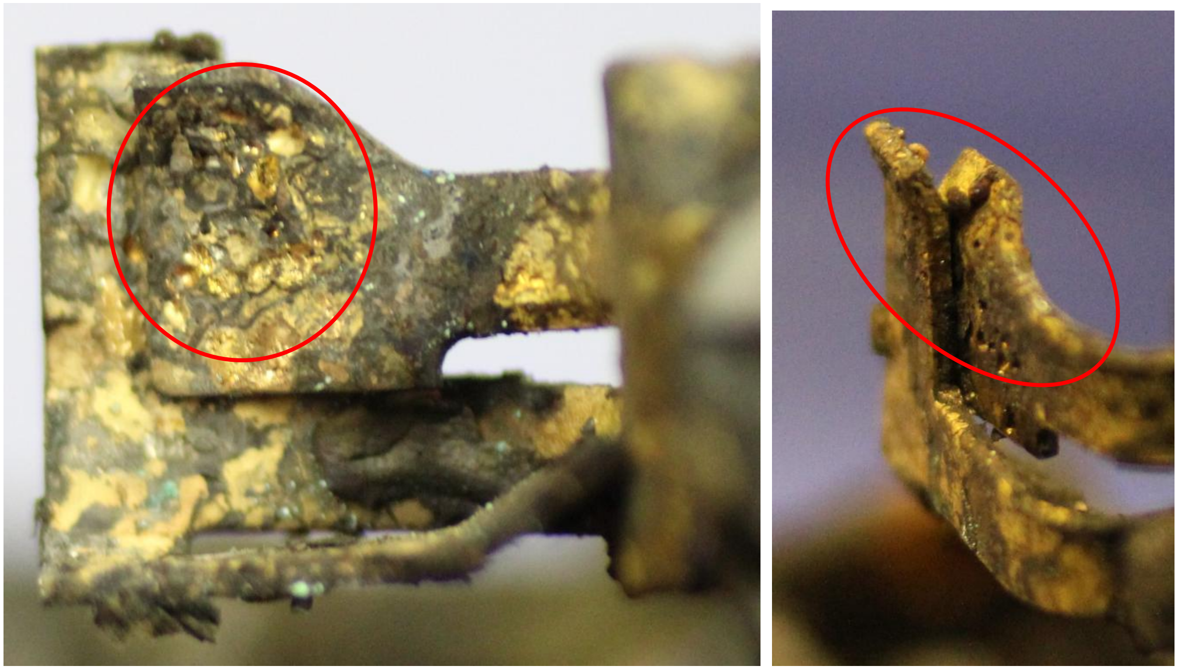


Figure 4-12. Photos of melting damage on non-energized plug contact which has tooling marks (sharp edges) visible outside the damaged areas (PSE359).

4.6 Internal Porosity

In general, the evaluations of arcing and melting damage were external evaluations of the conductors; the internal structure of the damaged material was not systematically evaluated. However, some of the arcing locations examined had two conductors fused together by arcing. During the examination, these conductors were pulled apart to reveal the internal structure of the connecting arc bead. In 21 conductors, large voids were observed inside the arc bead. An example of a brass conductor with large internal voids (i.e., the dark areas) in the arc damaged area is shown in Figure 4-13. This conductor arced to the steel grounding strap and only partially fused along the damaged area (circled in Figure 4-13).

In eight conductors, porosity was visually evident on the surface of the conductor, but the amount of internal porosity and/or size of the voids was not able to be evaluated. These conductors were classified as having possible high internal porosity. One such conductor is shown in Figure 4-14 where the arc damage on the solid copper wire has one large void, but no other visible voids. Internal porosity was not examined for all of the conductors with arcing and it was not evaluated for conductors with melting damage. Various researchers [Lewis and Templeton, 2008; Buc, 2012; Levinson, 1977] have shown that arcing and melting can cause porosity to form in metals, typically creating greater porosity for arcing compared to melting. However, because there has not been any rigorous study which quantifies the size and percent by volume of voids in arc beads or melted conductors, the value of this characteristic trait in an arc damage determination is limited.

Figure 4-13. Arcing damage on brass plug contact showing large voids (LEV266).

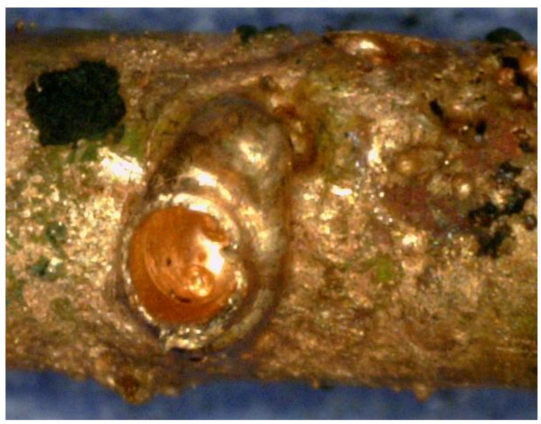


Figure 4-14. Arcing damage on solid copper wire with possible high internal porosity (LEV173).

4.7 Spatter Deposits

Spatter, or sprayed molten material, is often ejected outward in all directions from the arc location when arcing occurs. This material is then deposited on surfaces up to inches away from the arcing location. Spatter consists of very small spherical particles of the metal(s) which were involved in arcing. Since the particles cool very quickly, they generally retain their spherical shape when they impact a surface. These spheres are typically on the order of 0.1 mm or less, but some can be larger. Two examples of spatter from receptacle failure events are shown in Figure 4-15 and Figure 4-16. While fire melting can produce molten metal that falls (in the direction of gravity) onto surfaces, these do not tend to cool rapidly and can deform when striking the surface. Therefore, the very small spherical spatter particles from arcing are generally unique compared to the deposits produced by melting. SEM/EDS analysis of the particles may be useful in determining the chemical makeup of particles to differentiate metals and from other spherical solids. Tables 4-16, 4-17, and 4-18 list the presence of spatter deposits for receptacle failures, fire induced arcing, and receptacles with melting, respectively. The process of locating and identifying spatter is the most difficult of the arcing characteristics because the spatter is often located away from the arcing location. This increases the search area for particles that can be difficult to see with the naked eye.

Figure 4-15. Spatter from arcing, deposited on PVC outlet box (LEV172).

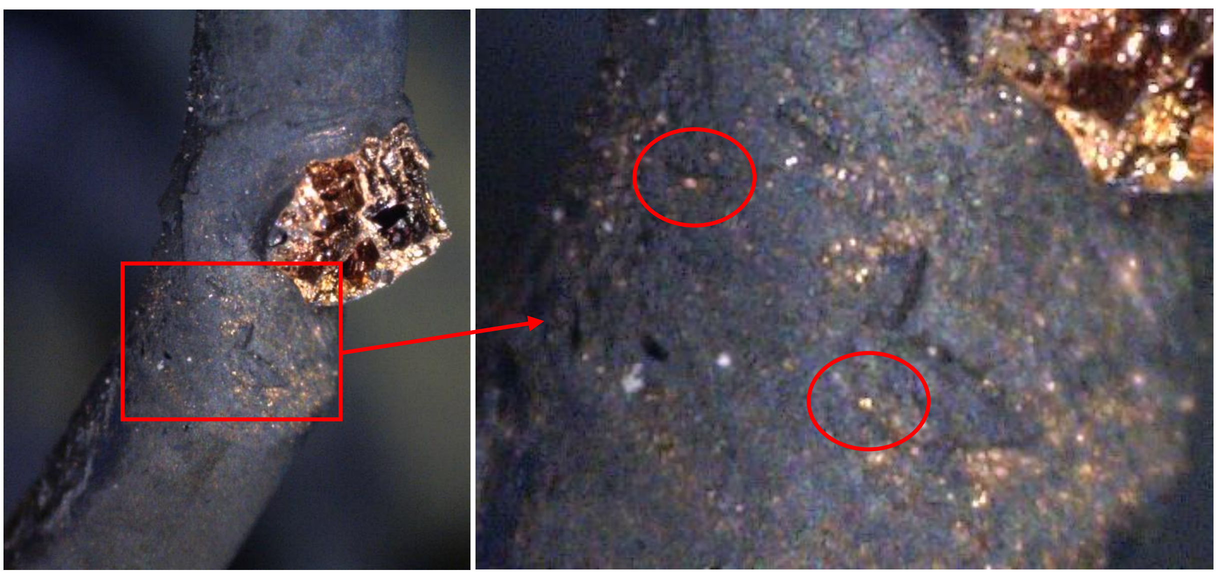


Figure 4-16. Possible spatter near arcing damage, circled (B020).

Table 4-16. Spatter Deposits for Receptacle Failures.

Conductor Material	Yes	No	Possible
Brass	13	32	1
Solid Copper	5	8	1
Steel	10	24	1
Total	28	64	3

Table 4-17. Spatter Deposits for Fire Induced Arcing.

Conductor Material	Yes	No	Possible
Brass	0	27	0
Solid Copper	1	18	2
Stranded Copper	1	9	0
Steel	0	29	0
Total	2	83	2

Table 4-18. Spatter Deposits for Receptacles with Melting.

Conductor Material	Yes	No	Possible
Brass	0	25	0
Solid Copper	1	27	0
Stranded Copper	0	4	0
Total	1	56	0

A small portion of conductors from fire induced arcing (2.3%) and arcing in receptacle failures (29%) had a positive identification of spatter; only one instance (1.7%) of melting had evidence that could be visually interpreted as spatter. The presence of spatter did not favor one conductor material over another. An example of what is likely brass and steel spatter is shown in Figure 4-15. This spatter was deposited on the PVC outlet box and multiple globules in various sizes are circled. The large brass colored globule circled in Figure 4-15 is rather irregular in shape; it is possible that various molten globules agglomerated during the arcing to form this larger particle. There were many more conductors with spatter identified for the receptacle failures (28) than the fire induced arcing (2).

The melted conductor identified with spatter had a single spherical particle on the end of the conductor (see Figure 4-4); the spherical particle was on the larger side of what could be considered spatter and was located on the conductor, not remote from the damage site. Another example of possible spatter is shown in Figure 4-16 where the particles are located near the arc damage site. This spatter was classified as possible because the limited magnification of the microscope (90x max) used prevented confirmation of the shape of the particles.

Despite the low percentages of arc damaged conductors with spatter present, this characteristic trait is a strong indicator to differentiate arcing from melting. The small spherical particles are not readily produced by melting nor would they be deposited in all directions; melting droplets can only fall in the direction of gravity. The proposed changes to NFPA 921 [2014] make a statement regarding the possibility of finding spatter from arcing, but do not include it as a trait frequently exhibited by arc damaged conductors.

4.8 Small Beads and Divots over a Limited Area

Small beads and divots over a limited area (only evaluated for arcing); localized round depressions (only evaluated for arcing); and blisters on the surface (only evaluated for melting) are grouped together in this section because they are similar traits. That is, in the generic sense blisters are similar to beads; and divots are similar to depressions. The proposed changes to NFPA 921 [2014] include these three traits as indicators used to differentiate between arcing and melting. While NFPA 921 [2014] will include a limited number of photographs of these traits, clear definitions for each are not presented. Carey and Daeid [2007] found that conductors with damage from arcing through char could exhibit small beads and divots over a limited area; a photo of one of their tested conductors is included in the proposed changes to NFPA 921 [2012]. Blisters on the surface of a conductor have the caveat that gross electrical overload must be ruled out. Gross overload was not possible in this test program because the melted conductors were non-energized at the time of exposure and the constant current through the energized conductors was limited to 20A by the circuit breakers.

Tables 4-19 and 4-20 list the presence of small beads and divots over a limited area for receptacle failures and fire induced arcing, respectively. Tables 4-21 and 4-22 list the presence of localized round depressions for receptacle failures and fire induced arcing, respectively. Table 4-23 lists the presence of blisters on the surface for receptacles with melting.

Table 4-19. Small Beads and Divots Over a Limited Area for Receptacle Failures.

Conductor Material	Yes	No	Possible
Brass	3	43	0
Solid Copper	1	13	0
Steel	1	34	0
Total	5	90	0

Table 4-20. Small Beads and Divots Over a Limited Area for Fire Induced Arcing.

Conductor Material	Yes	No	Possible
Brass	0	27	0
Solid Copper	1	20	0
Stranded Copper	0	10	0
Steel	0	29	0
Total	1	86	0

Table 4-21. Localized Round Depressions for Receptacle Failures.

Conductor Material	Yes	No	Possible
Brass	0	45	1
Solid Copper	0	14	0
Steel	2	32	1
Total	2	91	2

Table 4-22. Localized Round Depressions for Fire Induced Arcing.

Conductor Material	Yes	No	Possible
Brass	0	27	0
Solid Copper	0	21	0
Stranded Copper	1	9	0
Steel	0	29	0
Total	1	86	0

Table 4-23. Blisters on the Surface for Receptacles with Melting.

Conductor Material	Yes	No	Possible
Brass	0	25	0
Solid Copper	1	27	0
Stranded Copper	2	2	0
Total	3	54	0

A small portion of conductors with arcing damage had small beads and divots (3%) and localized round depressions (2%); only 5.3% of conductors with melting damage had blisters on the surface. Figure 4-17 shows an example of small divots over a limited area on the grounding strap of a receptacle (LEV008). This conductor was also classified as having localized round depressions. This damage was from neutral-to-ground arcing that occurred during the receptacle failure event. Since series arcs are limited by the current in the circuit, these arcs were not high enough in current to create larger notches that were observed for hot-to-ground or hot-to-neutral shorts. The prolonged arcing, which occurred over minutes, caused the formation of multiple divots. Figure 4-18 shows an example of a stranded copper wire exposed to fire which had localized round depressions on one of the globules at the end of the wire. Figure 4-19 shows an example of blisters on the surface of a melted conductor. This conductor was wired to a PVC receptacle subjected to the furnace fire exposure.

Figure 4-17. Small divots (and localized round depressions) on a grounding strap from a neutral to ground arc during receptacle failure (LEV008).

Because small beads and divots and localized round depressions were observed in only a few conductors with arcing damage and because they are not well defined in the literature, these characteristic traits are poor indicators of arcing. The same is true for blisters on the surface for melting damage. These traits might be specific to certain melting or arcing scenarios. For instance, the small beads and divots as well as the localized round depressions could be indicative of arcing through char, prolonged series arcing, or multiple parallel arcs.

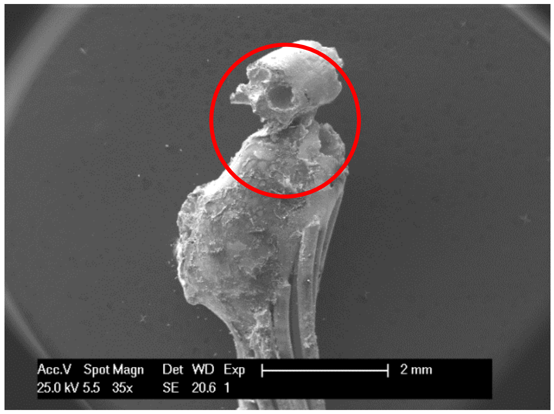


Figure 4-18. Localized round depressions on stranded copper wire for fire induced arcing (LEV318).

Figure 4-19. Solid copper conductor with blisters on the surface (PSE385).

4.9 Indicators of Melting

Receptacles with arcing damage and conductors with fire-melt damage were examined for the presence of fire melting using characteristics of melting listed in Section 4.0. Conductors with fire-melting damage were examined for the presence of each individual characteristic of fire-melting, while receptacles with arcing damage were examined for the presence of fire-melting in areas other than the location of the arcing damage. The presence of fire-melting in a receptacle with arcing damage can be problematic for a fire investigator because it indicates that the fire exposure was severe enough to cause fire melting. However, depending if the fire-melting damage is near the arcing damage or if the conductor with fire melting has a different melting temperature, then the investigator’s confidence in the arcing determination can increase or decrease. For instance, if fire-melting is found at the end of a copper conductor in a receptacle, and the arcing damage is identified close to the melting damage, then the confidence in the identification of the arcing damage would be lessened.

Tables 4-24 and 4-25 list the presence of fire-melting for conductors from receptacle failures and fire induced arcing, respectively. Only a small portion of conductors with arcing damage from receptacle failures (10%) and fire induced arcing damage (17%) were found to have fire-melting present. However, the majority of these had melting that was on a conductor of a metal with a lower melting temperature and the remaining conductors had melting that was in a different location than the arcing damage. For these receptacles, the arcing damage could still be accurately identified despite the presence of fire-melting damage. As was discussed in Section 4.1, fire-melting prevented the identification of corresponding damage on the opposing conductor in two cases of fire-induced arcing. The presence of fire-melting in a device or on a conductor does not nullify the identification of arcing damage, but does require some explanation as to why melting was identified in certain locations and not in others. For receptacles, this may occur because the exposure is from front to back or because for PVC and thermoset receptacles, the charred remains of the receptacle may block certain areas from the fire exposure and not others.

Table 4-24. Fire-Melting Present for Receptacle Failures.

Conductor Material	Yes	No	Possible
Brass	3	40	3
Solid Copper	3	10	1
Steel	4	29	2
Total	10	79	6

Table 4-25. Fire-Melting Present for Fire Induced Arcing.

Conductor Material	Yes	No	Possible
Brass	1	26	0
Solid Copper	10	11	0
Stranded Copper	0	10	0
Steel	4	25	0
Total	15	72	0

4.9.1 Visible Effects of Gravity

When conductors melt due to fire exposure they tend to sag or form globules; these globules can become elongated or tear-drop shaped as a result of gravity. Visible effects of gravity on the conductor indicate that the cooling process of the event was slow enough to allow the molten metal to deform in the direction of gravity. This characteristic trait of melting has not been systematically studied in the literature. Because the orientation of the receptacles and wiring was controlled during installation, the direction of gravity was known for the tested receptacles (and fire-melted conductors). However, in the field, the direction of gravity may be unknown for a conductor which may be separated from where it was installed. Knowing the direction of gravity helps to substantiate the presence of this indicator of fire-melting. Figure 4-20 shows visible effects of gravity on part of a set of fire-melted brass plug contacts (left) and a solid copper wire (right). Since cooling of arcing damage occurs rather quickly, effects of gravity on arcing damage are not expected; no conductors were observed where the arcing damage had visible effects of gravity. A small portion (28%) of conductors with fire-melting damage had visible effects of gravity; the majority (94%) of these conductors were brass conductors. For receptacles installed in a wall, the exposure from an external fire tends to be from the front to the back rather than uniformly on the entire device. The brass conductors were parallel to the plane of exposure and more of the material was exposed to the fire at one time compared to the copper wires which were folded in the back of the box and pointed outward toward the screw contact. The larger exposure geometry for the brass conductors and lower melting temperature resulted in more incidents of melting and the effects of gravity to be more apparent for the brass than the copper conductors. This same geometry is the reasoning behind why localized damage with a sharp line of demarcation was observed in seven fire-melted solid copper wires from receptacles (see Table 4-6 and Figure 4-4). Table 4-26 lists the presence of effects of gravity for conductors with melting damage. Although only a small portion of conductors with melting damage exhibited effects due to gravity and no arcing damage exhibited effects due to gravity, this characteristic trait is a fair indicator of melting. And while only one solid copper wire was observed with effects of gravity, copper conductors in the open may be more likely to exhibit effects of gravity compared to solid copper conductors in receptacle installations.

Table 4-26. Visible Effects of Gravity for Receptacles with Melting.

Conductor Material	Yes	No	Possible
Brass	15	9	1
Solid Copper	1	27	0
Stranded Copper	0	4	0
Total	16	40	1

Figure 4-20. Visible effects of gravity on fire-melted brass plug contacts (left, PSE376) and solid copper wire (right, C023); arrow indicates direction of gravity.

4.9.2 Gradual Necking of Conductor

Gradual necking of the conductor is an indication that damage to that conductor was not localized with a sharp line of demarcation. Conductors with gradual necking exhibit tapering of the conductor; conductors may also appear to be elongated. The caveat to this characteristic trait as being indicative of melting is that mechanical breakage must be ruled out since it can produce similar evidence. In this test program, mechanical breakage was not possible given the installation of receptacles in outlet boxes with faceplates. Figure 4-21 shows an example of a copper wire with gradual necking. Table 4-27 lists the presence of gradual necking for conductors with melting damage. Gradual necking was found on 17% of the fire-melted conductors examined. All of the conductors with gradual necking were solid copper wires. Perhaps the reason that gradual necking was not found on the brass conductors was that the brass contacts tend to thin (see Section 4.9.3). While gradual necking was not found on a large portion of fire-melted conductors, it is a fair indicator of melting. This is because it indicates that the damage is not localized with a sharp line of demarcation, which was found to be a strong indicator of arcing. In addition, there are no physical phenomena associated with arcing that would cause arcing damage to appear to be gradually necked.

Figure 4-21. Gradual necking of copper wire due to fire-melting (C023).

Table 4-27. Gradual Necking of Conductor for Receptacles with Melting.

Conductor Material	Yes	No	Possible
Brass	0	24	1
Solid Copper	10	12	4
Stranded Copper	0	4	0
Total	10	42	5

4.9.3 Pitting, Thinning, and Presence of Holes

Surface pitting, thinning, and holes forming on conductors with melting damage were observed. Surface pitting and thinning from melting was different from the pitting/thinning observed on receptacles with overheating. Pitting/thinning from melting was typically located in patches on the conductor which indicated that the fire exposure to the conductor was not uniform over the entire conductor. The pits from melting were also irregular in shape, size, and depth. On the other hand, pitting/thinning from overheating was more uniform over the portion of the conductor near the overheating (see Figures 3-97, 3-98, and 3-99) and the pits were uniformly shallow. For the brass conductors, when pits grew to a large enough depth on the conductor, they would eventually form holes. These holes were typically accompanied by thinning of the conductor. Thinning was defined as a relatively uniform reduction in thickness of the conductor; this is different from gradual necking. Table 4-28 and 4-29 list the presence of pitting and thinning and holes for conductors with melting damage, respectively.

Table 4-28. Pitting on Conductors for Receptacles with Melting.

Conductor Material	Yes	No	Possible
Brass	20	4	1
Solid Copper	5	23	0
Stranded Copper	0	4	0
Total	25	31	1

Table 4-29. Thinning and Presence of Holes on Conductors for Receptacles with Melting.

Conductor Material	Yes	No	Possible
Brass	23	2	0
Solid Copper	0	28	0
Stranded Copper	0	4	0
Total	23	34	0

Surface pitting was present on a notable portion (44%) of conductors with melting damage. Figure 4-22 shows pitting on a solid copper wire with melting damage. This pitting was localized at the end of the copper wire where melting had occurred; beyond this damage area no pitting was observed. The majority of brass conductors with melting damage had pitting present, whereas the majority of solid copper wires and all stranded copper wires with melting damage did not. It is possible that the larger surface area and lower melting temperature for the brass conductors preferentially allowed pitting to occur on the brass conductors compared to the copper conductors. The small diameter of the individual strands of the stranded copper wires likely prevented surface pitting from occurring. Figure 4-23 shows pitting, thinning, and holes present on a brass plug contact.

Figure 4-22. Pitting of copper wire due to fire-melting (LEV391).

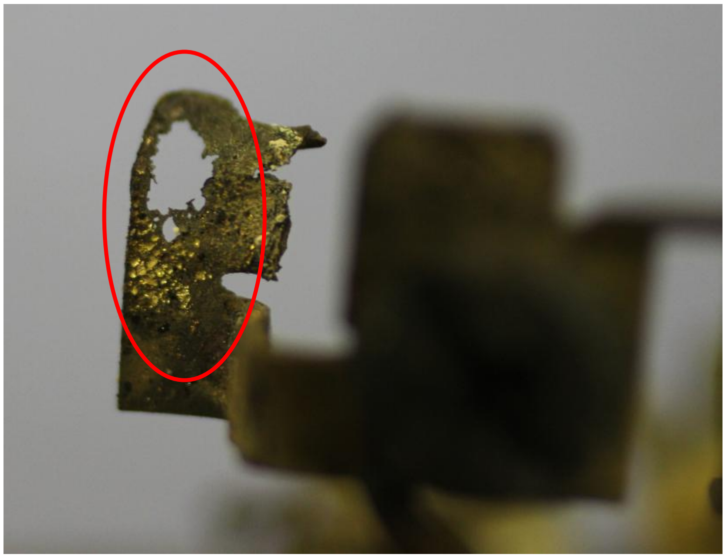


Figure 4-23. Pitting, thinning, and presence of holes on brass plug contacts due to fire-melting (LEV358).

Thinning and holes were present on a notable portion (40%) of conductors with melting damage, but was only observed on the brass conductors. The shape of the brass conductors (i.e., flat and bent) was most likely the reason why thinning and holes were able to form on the conductors compared to the copper wiring. Because one dimension of the brass conductors was much smaller (i.e., the thickness) than the other dimensions, pitting could progress to the point where a hole was formed. The cylindrical shape (i.e., same thickness in two dimensions) of the conductors would prohibit melting from causing localized holes to form, instead the conductors would sever. Figure 4-24 shows a hole that formed in a brass conductor which eventually opened on one side. Although a notable portion of the fire-melted conductors exhibited pitting, thinning, and holes, these characteristic traits are not strong indicators of fire-melting in all conductors. However, because a much larger portion of brass conductors exhibited pitting, thinning, and holes, these are stronger indicators of fire melting for brass conductors. Thinning and pitting due to fire melting could be differentiated from thinning and pitting due to overheating based on its location, uniformity, and size, shape, and depth of the pits. Thinning, pitting, and holes were not typically observed on the damage to conductors from arcing.

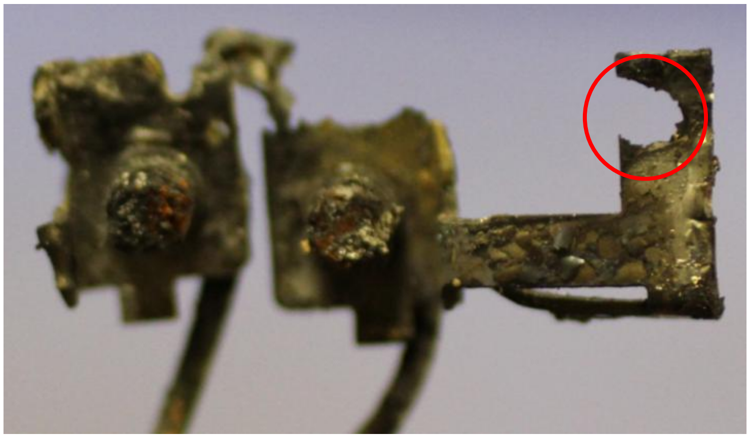


Figure 4-24. Holes formed on brass plug contacts due to fire-melting (PSE381).

4.10 Summary of Arcing and Melting Damage and Identification

Melting and arcing in cords/wiring (i.e., what most of the literature has studied) can be different in appearance from melting and arcing in receptacles or other complex devices from an overall standpoint. This is mostly due to geometrical considerations; cords/wiring are cylinders of standard dimensions, while receptacles and other devices have multiple pieces (including wiring) which are often bent and stamped metal parts of varying configurations. Despite the complicated geometries of receptacles and other devices, an investigator will typically know the components and their orientation within a device based on an exemplar device. This can aid in telling which components can arc to each other and which ones cannot. Cords/wires not installed in receptacles can be twisted, coiled, laying over another conductor, producing a large number of possible configurations.

In addition, cords/wires used in residential settings are typically one metal (i.e., copper or aluminum) with the same cylindrical geometry and size, while receptacles and other devices are comprised of multiple metals (i.e., copper, aluminum, brass, and/or steel) which have different geometries, sizes, and thicknesses. This can affect the progression of what melts first based on melting temperatures and orientation. If something is closer to the fire (i.e., front of the receptacle), it should melt prior to the items further away provided the melting temperatures are not drastically different. And if the melting temperatures are different enough, the items with the lowest melting temperature will melt first. This does not mean that all brass in a receptacle (T_{melt} = 930ºC) must melt before even a small area of copper (T_{melt} = 1080ºC) can begin to melt.

A portion of the arcing and melting damage produced in this work was evaluated for the presence of nine characteristic traits of arcing damage and five traits of melting damage. These traits were taken from the literature (e.g., NFPA 921 [2014]) and from observations made during the forensic examinations conducted as part of this work. Corresponding damage on the opposing conductor, localized damage with a sharp line of demarcation, and tooling marks outside of the area of damage were observed on significant portions of arc damaged conductors and small numbers of conductors with melting damage; these characteristics were found to be strong indicators of arcing. Resolidification waves and spatter deposits were observed in limited conductors with arcing damage; no fire-melted conductors were observed with resolidification waves. However, these characteristics were very distinct from melting damage and were therefore strong indicators of arcing. Although internal porosity was not systematically evaluated, a number of conductors with arcing damage were observed to have significant porosity. This characteristic trait has the possibility of being a strong indicator of arcing if quantitative evaluation criteria are developed. A round, smooth shape; small beads and divots; and localized round depressions were observed in limited numbers on arc damaged conductors and similar characteristic traits were observed in fire-melted conductors. Due to the lack of clear definitions in the literature, these characteristic traits were poor indicators of arcing.

Limited numbers of fire-melted conductors were found with effects of gravity, gradual necking, pitting, thinning of the conductor or holes formed in the conductor. These characteristic traits were rarely observed in arc damaged conductors and were fair indicators that the damage present was due to fire-melting. Some conductors with fire-melting damage were observed to have characteristic traits of arcing (i.e., localized damage with a sharp line of demarcation or corresponding damage on the other conductor). However, other indicators of melting were also present. A small portion of receptacles with arc damaged conductors also had fire-melting observed in the receptacle. Typically, this melting was either not close to the arc damage location or was on a metal with a lower melting temperature.

Most of the characteristic traits of arcing and melting are qualitative and not well defined in NFPA 921 [2014], which leads to more subjective evaluations. And though some characteristic traits were strong indicators of either arcing or melting, an investigator should never rely solely on the presence of one characteristic trait for arcing vs. fire-melting determination. Using multiple characteristic traits and contextual information for arcing vs. fire-melting determination provides greater confidence in the evaluation of damage. In addition, visual examinations were found to be reliable indicators of both arcing and fire-melting for most conductors. However, there are some cases which would require more advanced examination techniques including SEM/EDS examinations, X-ray, CT scanning (X-ray computed tomography), cross-sectioning and polishing, or other metallurgical methods.

4.11 Case Study: Distinguishing Arc from Melt Damage Using SEM/EDS

A Scanning Electron Microscope (SEM) was used to document some of the forensic evidence gathered in the laboratory testing and fire exposure testing. In particular, the SEM was used to image two break-off tabs from PVC receptacles. Both of the break-off tabs are shown in Figure 4-24. The damage on one of these break-off tabs is from melting of a non-energized receptacle (PSE358 – Figure 4-25, left) and the other is from arcing between the break off tab and a steel faceplate (PSE323 – Figure 4-25, right). A cursory examination of both of the break-off tabs appears to show that the notches in the top of the break off tabs exhibit rather clear lines of demarcation between the area of damage and the undamaged area. This type of notch was frequently observed for arcing between break-off tabs and steel faceplates. In the case of PSE358, there was no corresponding damage on the faceplate indicative of arcing and there was some pitting of the brass contacts indicating melting had begun (see Figure 4-26, left). In the case of PSE323 receptacle, there was no indication of melting in the internal plug contacts and there was evidence of a corresponding arcing location on the faceplate (see Figure 4-26, right).

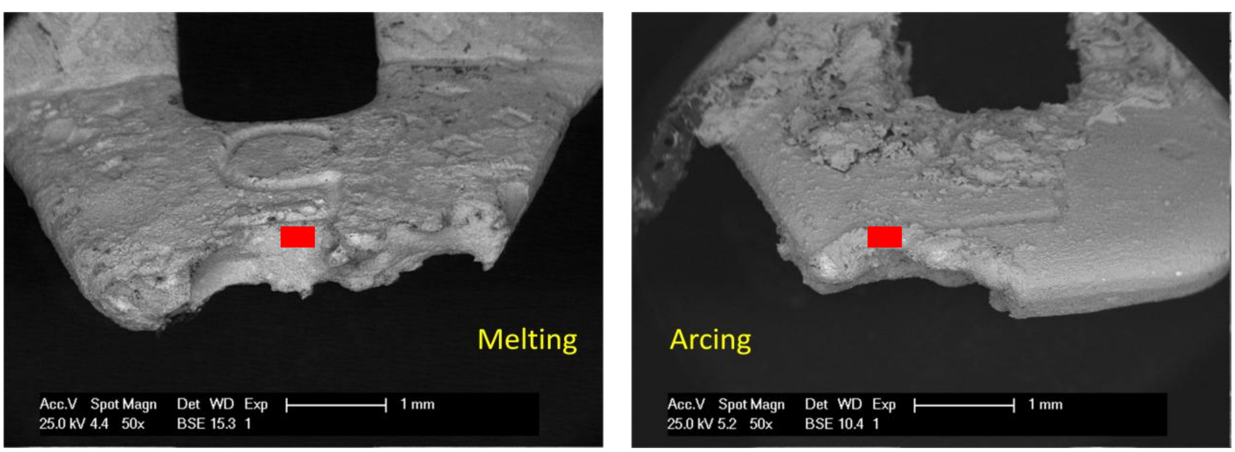


Figure 4-25. SEM images of break-off tabs from two PVC receptacles: PSE358 (left) and PSE323 (right) – EDS location noted by red box.

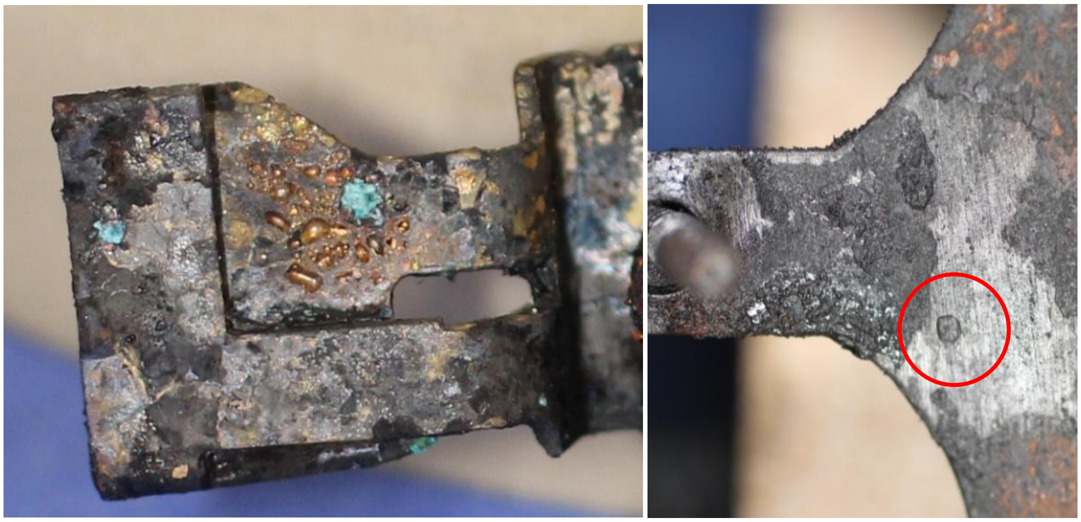


Figure 4-26. Surface pitting on brass contacts from PSE358 (left) and corresponding arcing damage on faceplate from PSE323 (right).

The determination of arcing vs. melting for these two items was rather simple in terms of a visual inspection of the whole receptacle. However, if only the notch on the break off tab was examined with no other context, then the determination of arcing vs. melting would become more difficult due to the similar appearance of these two items. A SEM/EDS analysis of each of the notches was performed in order to determine the chemical makeup of the damaged area to assist with arcing vs. melting determination. The EDS locations are noted as red boxes in Figure 4-25. The results of the EDS measurements are presented in Figure 4-27, with the spectra for PSE358 (melting) as the blue outlined curve and the spectra for PSE323 (arcing) as the red solid curve. For PSE323, which had arcing between the break off tab and the steel faceplate, there is a very large peak for iron, indicating that there was transfer of metal that occurred during the arc. On the other hand, PSE358 shows a very small peak for iron, which is possibly a result of surface rust or scale deposits from the faceplate or ground strap. The EDS spectra for PSE358 does show relatively higher peaks for copper and zinc, both of which are components of brass, than the spectra for PSE323. This EDS analysis clearly indicates that arcing between brass and steel components will produce transfer of metal between the two items.

Distinguishing between arcing and melting may be accomplished using SEM and chemical analyses if the arcing is between two different metals (i.e., brass and steel); this is based on the transfer of metal occurring in arcing particularly when metals with higher melting temperatures are deposited on metals with lower melting temperatures such as steel onto brass.

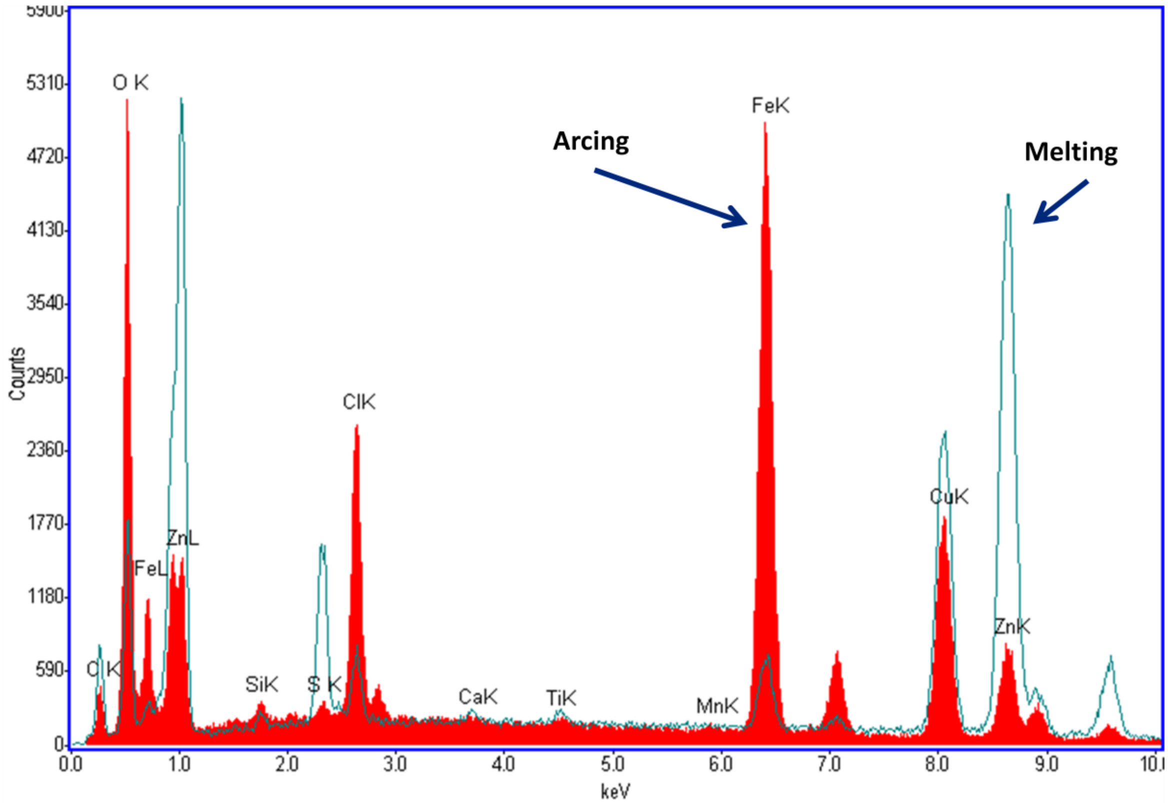


Figure 4-27. Overlaid EDS spectra for PSE358 (melting, outlined plot) and PSE323 (arcing, solid plot).

5.0 SUMMARY OF FINDINGS

Laboratory testing of receptacle and plug connections consisted of 528 trials of 490 receptacles, with tests lasting up to 511 days. Fire exposure testing of receptacles and plugs consisted of 13 wall assemblies, each with 36 receptacles exposed to various fires. The following is a summary of the key findings from the laboratory and fire exposure test series.

Receptacles with Screw Terminal Connections

- 3 in-lb torque or greater – no visible signs of overheating on any receptacles
- 1 in-lb torque and less – majority of receptacles show visible signs of overheating with a 15A load
- Only one instance of visible signs of overheating was observed for a receptacle with torque less than 1 in-lb with a 6A load (but not with a 3A load), this receptacle did not lead to an electrical failure event
- 83 receptacles with torques of 1 in-lb or less and with a 15A load had an overheating condition that resulted in an electrical failure event (0.50 failures/year; time to failure: 5 days–12 months)
- Only one receptacle failure for a receptacle with torque less than 1 in-lb with a 9A load (0.02 failures/year)

- 11 receptacles with torques of 1 in-lb or less and with a 15A load had an overheating condition that resulted in a flaming ignition event (0.07 failures/year time to failure: 18 days–10 months)
- One out of 11 flaming ignition events tripped the circuit breaker

Receptacles with Back Wired Push-in Connections

- 5% (2 of 42) of back wired receptacles had visible signs of overheating (i.e., discoloration, charring, and/or melting)
- These two receptacles were subjected to routine vibrations (each had two wire removal and re-insertion cycles and were run continuously at 15A); neither electrically failed (energized for 12 months)
- One back wired receptacle had an electrical failure event (flaming ignition) after 341 days (0.02 failures/year); this receptacle had one wire removal and re-insertion cycle and was subjected to routine vibrations

Receptacles with Plug Connections

- All receptacles with plug connections tested with 15A load; some with 32A startup current
- Vinyl plugs with solid brass blades – no visible signs of overheating for any receptacles, but some had signs of series arcing at blade/receptacle connection
- Three of six receptacles with non-modified retention forces (i.e., between 1.5 kg (3.3 lb) and 3.2 kg (7.05 lb)) showed visible signs of overheating; one had a folded brass plug blade and two had nickel plated brass plug blades
- Receptacles with nominal retention forces of 0.1 kg (0.22 lb) and less – majority of plugs show visible signs of overheating
- Five of the 114 receptacles (0.04 failures/year) with loose plug connections (i.e., nominal retention force 0.01 kg (0.02 lb) and 0.1 kg (0.22 lb)) had an overheating condition that resulted in an electrical failure event (time to failure: 2–9 months)
    - These five receptacles all had low-profile plugs with nickel plated plug blades
    - All five failure events resulted in a flaming ignition
    - Two out of five flaming ignition events tripped the circuit breaker

Signatures of Electrical Failure – Receptacles with Screw Terminal Connections

- Severe oxidation and corrosion of conductors were indicators of overheating connections (dismantling of the receptacle may be needed to observe these indicators)
- Electrical failure events produced various distinct signatures including: welded conductors with or without distinct curved striations; severed wires near the screw terminal; and enlarged screw heads. Arcing was identified as a signature of electrical failure, but also occurred due to external fire exposures
- Flaming ignition failure events included a variety of these signatures; no one signature was more indicative of flaming ignition than the others

- In two flaming ignition failure events, none of the distinct signatures of overheating failure events, with the exception of arcing, were observed

Signatures of Electrical Failure – Receptacles with Plug Connections

- Severe oxidation and corrosion of plug blades were indicators of overheating connections
- Thermal damage to receptacles and plugs from overheating connections is localized around the overheating connection
- Loss of nickel plating and dezincification were visual indicators of corrosion occurring at the overheating connection
- The electrical failure events in plug connections did not produce distinct signatures similar to those observed for screw terminal connections

Signatures of External Fire Exposure

- Thermal damage to receptacles and plugs from external fire exposure is relatively uniform across the exposed face and progresses from the front to the rear of the receptacle
- Melting of copper and brass had similar characteristics, but some nuances were observed due to the differences in configuration between brass (stamped and bent contacts) and copper (wiring) components
- Melting of brass and copper components was generally uniform across the plane of exposure
- In all cases where melting of copper was observed, melting of brass components was also observed
- Melted copper conductors had various shapes including tapered ends, flat ends, pointed ends, irregular ends, and round globules

Arcing from External Fire Exposure

- Arcing evidence identifiable using low powered microscopes
- Of the 201 receptacles that tripped circuit breakers, all but 23 had identifiable arcing damage; some were melted past the point of being able to identify the potential arcing damage
- Of the 50 receptacles that did not trip the circuit breakers and remained energized throughout the fire exposure, none had arcing damage
- A number of common locations of arcing were identified:
    - Primary arcing locations (i.e., hot conductors) include: internal receptacle contacts, the break off tab on the internal receptacle contacts, receptacle wiring (solid), and extension cord wiring (stranded)
    - Secondary arcing locations (i.e., ground or neutral conductor) include: grounding straps, steel outlet boxes, steel faceplates, receptacle wiring (solid), and extension cord wiring (stranded)

Differentiating between Arcing and Melting damage

- Characteristics of Arcing Damage
  - Corresponding damage on opposing conductor, localized damage with a sharp line of demarcation, and tooling marks outside of the area of damage were observed on significant portions of arc damaged conductors and small numbers of conductors with melting damage; these characteristics were strong indicators of arcing
  - Resolidification waves and spatter deposits were observed in limited conductors with arcing damage; no fire-melted conductors were observed with resolidification waves; these characteristics were very distinct from melting damage and strong indicators of arcing
  - Though not systematically evaluated, arcing damage with significant porosity was observed; this characteristic trait has the possibility of being a strong indicator of arcing if quantitative evaluation criteria are developed
  - Round, smooth shape; small beads and divots; and localized round depressions were observed in limited numbers on arc damaged conductors and fire-melted conductors; these characteristic traits were poor indicators of arcing
  - Some arc damaged conductors were found with characteristics of melting; typically this was in different locations than the arcing damage
- Characteristics of Melting
  - Limited numbers of conductors were found with effects of gravity, gradual necking, pitting, thinning of the conductor, or holes formed in the conductor
  - These characteristics were not observed in arc damaged conductors in the location of the arc
  - Some conductors with melting damage were found with characteristic traits of arcing (i.e., localized damage with a sharp line of demarcation or corresponding damage on the other conductor); however, other indicators of melting were also present
- Differentiating between arcing and melting
  - Multiple characteristic traits should be used to distinguish between arcing and melting in evidence
  - Identification of arcing damage may be accomplished using SEM/EDS analyses to identify transfer of dissimilar metals
  - Most of the characteristic traits of arcing and melting are qualitative and not well defined in NFPA 921 [2014]; this leads to more subjective determination of arcing vs. melting

Differentiating between Electrical Failure and External Fire Exposure

- Localized thermal damage to receptacles and plugs from overheating connections may remain distinguishable from damage due to external fire exposure depending on the level of damage

- The majority of signatures of electrical failure will persist and remain unique after an intense fire exposure; the only significant changes to the signatures are their coloring
- Analysis of cross sections of screws using SEM/EDS analyses may aid in differentiating between enlarged screw heads and other evidence that may be visually similar to enlarged screw heads
- Fire exposures which are hot enough to melt copper wiring may destroy the signatures of electrical failure

6.0 CONCLUSIONS

6.1 Overheating Connections

This report addresses the impact of a wide range of variables on the formation of overheating receptacle connections and overheating plug connections. The primary variables of study were the looseness of the connection (i.e., receptacle terminal torque and plug blade nominal retention force), receptacle materials, electrical load, and surrounding materials (i.e., installation in an outlet box with faceplate); only copper wiring was used. These variables were selected to be representative of a range of conditions expected to be found in the field. Laboratory testing of receptacle and plug connections consisted of 528 trials of 490 receptacles, with tests lasting up to 511 days.

A number of visual indicators of overheating receptacle connections were observed. These included oxidation, corrosion, and dezincification of metal components; and discoloration, melting, dripping, cracking, and charring of plastics. For receptacle screw terminal connections, it was found that nearly all of the loosest screw terminals (i.e., less than 3 in-lb) developed visible signs of overheating connections when subjected to loads of 15A. This is in good agreement with work conducted by Ferrino-McAllister et al. [2006] and Meese and Beausoliel [1977] who found overheating that developed in connections less than 1 in-lb and ⅛ turn loose (from 2 in-lb), respectively. When subjected to loads of 3A and 6A, regardless of the looseness of the connection, none of the receptacle connections developed significant signs of overheating. Only one receptacle subjected to a 6A current load showed some discoloration at the screw terminals. This receptacle was installed in a PVC outlet box with a Nylon faceplate, and no damage was obvious from an external inspection. When subjected to a load of 9A, approximately half of the receptacles with the loosest screw terminals (i.e., less than 3 in-lb) developed visible signs of overheating. At screw terminal torques of 3 in-lb or above, visible signs of overheating were not observed regardless of the electrical load. Based on this testing, both a very loose connection (< 3 in-lb) and a relatively high current load (9A or higher) are required for overheating to begin at a receptacle screw connection. The receptacle body material was not a prominent factor in determining whether or not a receptacle would overheat. However, the receptacle material typically affected the visual signs of overheating as the three types of receptacles (PVC, polypropylene, and thermosets) behaved differently when heated.

Only three of the 42 back-wired push-in connected receptacles showed indicators of overheating, with one ultimately failing (0.02 failures/year). All of these receptacles were subjected to daily vibrations and were installed with one prior insertion and removal cycle for each wire. The only back-wired push-in receptacle to fail overheated to the point of flaming ignition. Despite some negative reputations in the past, likely due to early designs of back wired connections, the changes to UL486 [1986] affecting the testing of back wired push-in connections appear to have led to notable improvements of the robustness of this type of connection. Aged receptacles with back wired push-in connections were not tested in this research, but prior studies have indicated that early designs of back wired push-in connections had issues related to overheating [Biss, 1989; Oda, 1978]. Not only were loose connections and relatively high currents required to develop overheating of back wired push-in connections, but mechanical vibration of the receptacle was as well.

In addition to receptacle connections with branch circuit wiring, the connections between plugs and receptacles were systematically studied. The majority of plugs with folded brass blades and plated brass blades connected to receptacles having reduced nominal retention forces (i.e., 0.01 and 0.1 kg) showed some signs of overheating. However, the vinyl plugs with solid brass blades only showed evidence of series arcing at the plug-receptacle connection, not overheating. This was attributed to a variety of possible factors including the blade-wire connection within the plug, the plug materials, the plug blade materials, and even the receptacle that the plug was connected to. The plugs with the folded blades and plated blades had crimp-on connections to the cord wiring with the body of the plug molded around them. The plugs with solid brass blades had a tight screw connection to the shunted wire and open space within the plug body, which helped to reduce the heat at the plug blade connections. And while receptacle screw terminal connections only overheated when loose connections were present, three receptacles having non-modified plug connections showed signs of overheating. The plugs were taken from cords with 16 ga stranded copper wire rated to 13A. Even with a modest over current of 2A (i.e., a 15A load), these receptacles still degraded to the point of visible damage to the plug without any additional thermal insulation or manipulation.

One primary mechanism leading to overheating of receptacle and plug connections was the formation of copper oxides at terminal connections involving copper wiring. All observations indicated that the oxide development in loose terminal connections followed that described in the literature whereby heat was first generated at a loose connection due to reduced contact area; then the heated copper wire oxidized; and finally the semi-conductive copper oxides formed a high resistance connection producing more heat and continuing the cycle. A second possible mechanism of overheating connections involved only the PVC receptacles. As the PVC receptacles were thermally degraded due to an overheating connection, they would release HCl vapors which would condense and form a white crystalline deposit on the surface of the conductors. The corrosion products may have then precipitated more heat and continue the heating-corrosion-heating cycle much like the copper oxides.

Glowing connections were formed on both plug connections and receptacle screw terminal connections. Two types of glowing were established: glowing connections with a bright orange glow over the entire screw terminal or plug connection (size ≈ 6.3 mm (0.25 in.)) and glowing connections with a small area of bright white glow (size of glow spot ≈ 1.5 mm (0.06 in.)). Both types were observed for receptacle connections, while only the overall glow was observed for plug connections. While the formation of glowing connections was limited to only the loosest screw connections (i.e., 1 in-lb and less) and plug connections (i.e., 0.1 kg (0.22 lb) and less), their development and appearance was rather inconsistent. Some glowing connections lasted for multiple days. Some would begin glowing, stop, and re-start without any apparent reason. Other overheating connections which had not glowed previously would transition to glowing immediately after the current was cycled on. Sometimes, when a connection was glowing and current was cycled off, the glow would reappear when power was cycled on even up to hours later. Other times, the glow would disappear for days before re-establishing. Despite their fickle nature, glowing connections formed at terminal torques of 1 in-lb and less without any manual intervention. This was contrary to the work published by Ferrino-McAllister et al. [2006], which stated that manual manipulation of loose connections was required for glowing connections to develop. The difference between this study and that of Ferrino-McAllister et al. [2006] is time. The development of glowing in loose receptacle connections requires time; often that time can be as long as months or years. The measured power dissipation in glowing connections was between 12 and 47 W. This was consistent with the range of power dissipations measured by a variety of researchers for copper connections.

Glowing receptacle connections produced distinct metallurgical evidence including: welded copper conductors around screw terminals, severed conductors at or near the screw head, and enlarged screw heads due to severe corrosion. These types of evidence are unique in appearance compared to melting and arcing events from external fire exposure. Arcing in stranded or solid copper wiring can sometimes sever one or more conductors involved in the arcing [NFPA 921, 2011]. However, the conductors severed due to the glowing connections were always severed near the screw terminal (i.e., within 1.3 cm (0.5 in.)) and only the severed conductor itself showed damage. In no cases of arcing from fire exposure did any of the solid copper wires sever due to the arcing. Also, all of the arcing observed in solid copper wires from receptacles was more than 1.3 cm (0.5 in.) away from the screw terminals and involved more than just one conductor. Temperatures upwards of 1100ºC at the bright glow spots on the copper conductors were measured. These temperatures were greater than the melting point of copper, which caused the copper conductor to become molten at the point of glowing. Even though the glow spot temperatures were higher than the melting points of copper and brass, in no cases did the brass receptacle contacts melt as a result of the glowing connection. This glow spot moved around the screw head, melting the copper conductor and welding it to and between the screw and screw terminal. The glow movement produced distinct curved striations in the welded conductor. This type of melting was unique compared to both arcing and melting from a fire exposure. Korinek et al. [2013] observed similar evidence for glowing connections between a copper wire and a receptacle screw. No cases were observed where fire melted copper connections were formed that were visually similar to the welded conductors produced from glowing connections. As the glow spot moved along the conductor and around the screw, it would get to the point where the conductor separated from underneath the screw head. At this point, the conductor would begin to neck at the glow spot, eventually severing and producing bead-like structures at the screw side and wire side of the parted copper conductor. Round, irregular, and flat severed conductors were observed. The severed conductors were visually unique compared to external fire induced arcing and melting damage. Whereas arc beads are generally smooth and copper colored, the round severed conductor ends were more of a round cap appearance and were dark grey in color. Irregular severed conductor ends were not tapered in the fashion that is usually observed for melted wires. And the flat severed conductor ends were distinct from the flat shaped melted conductors in that the conductors severed from a hot glow spot did not have the pitted flat surface that was found for melted wires. The round severed conductor ends were observed to have a cap of copper oxides atop a flat end; this evidence was also produced in experimentation by Korinek et al. [2013]. Glowing plug connections did not develop the bright glow spots, but tended to be an overall glow at the connection. Glowing in these connections did not produce any distinct metallurgical evidence.

Glowing connections in PVC receptacles sometimes produced what was termed an enlarged screw head as a result of severe corrosion of the terminal screw. This evidence was distinguishable by its swollen appearance and reduced size of the screwdriver notches. Cross-sections taken of the enlarged screw heads revealed that the majority of the surface corrosion was iron oxide. There was also a distinct thin copper layer at the base of the corrosion separating it from the bulk metal of the screw. It is unclear what physiochemical interaction caused the formation of the copper layer. Cross-sections and SEM/EDS chemical mapping were taken for four screws which were either enlarged screw heads or visually similar to enlarged screw heads (i.e., possible false positives). The cross-sectioned samples were an enlarged screw head (pre-fire), an enlarged screw head (post-fire), a screw with melting and corrosion from furnace exposure (Furnace Screw X), and a screw with rust deposits. Analysis of the cross-sections and EDS mapping revealed that the enlarged screw heads were unique compared to the screw with rust deposits. While the potential false positive samples had visual characteristics similar to the enlarged screw heads formed as a result of overheating and corrosion, certain indicators clearly set them apart. In order to differentiate between these screws, comparison of multiple characteristics of the screw and corrosion (i.e., color, shape, roughness/porosity, oxidation layering, and EDS mapping) was necessary.

A number of receptacles with evidence of overheating, including welded conductors, enlarged screw heads, and severed conductors, were placed in a furnace exposure with temperatures upwards of 1000–1250ºC to simulate flashover conditions. The majority of the evidence of glowing on these receptacles remained after the fire exposure with only some changes in the color of the evidence. All of the 13 welded conductors persisted and remained identifiable after the fire exposure. On nine out of 11 welded conductors with curved striations present, the curved striations remained and persisted after the fire. Four out of 5 enlarged screw heads persisted after the fire exposure; the fifth was only partially enlarged prior to the exposure and it was not clearly evident after the fire exposure that it had been partially enlarged. Only one of the 23 severed conductor ends (screw side and wire side combined) did not persist after the fire exposure. This one conductor had signs of melting of the copper wiring. At temperatures below the melting point of copper (1080ºC), the evidence of glowing connections persisted and remained unique compared to arcing and melting damage. Because the evidence of glowing connections primarily involves copper, copper oxides, steel, and steel oxides, the evidence will persist even at temperatures high enough to melt brass components (i.e., 930ºC).

While indicative of an issue within the receptacle or plug connection, the visual signs of overheating (i.e., melting, charring, discoloration, oxidation, and corrosion) did not always lead to a failure of the receptacle. Even though the majority (~80%) of very loose receptacle (1 in-lb and less) and plug (nominally 0.1 kg (0.22 lb) and less) connections subjected to a load of 15A showed signs of overheating, failure rates for very loose receptacle screw terminal connections (0.5 failures/year) and for very loose plug connections (0.04 failures/year) were rather low. Failures were not observed in non-modified plug connections, receptacles with torques of 3 in-lb or greater, solid brass blade plugs, folded blade plugs, or receptacles with loads of 6A and less. Only one failure event occurred for a receptacle subjected to a load of 9A. As was stated previously, the development of glowing connections took time and so did the receptacle failures.

The range of times to failure for receptacle and plug connections was between 5 and 365 days; the average was 161 days. There were no trends observed with respect to the time to failure for variables including screw terminal torque, vibration, duty cycle, nominal plug retention force, or the failure mode.

The wide range of times to failures is significant with respect to implications for fire investigations both for the shortest and the longest time to failure. First, the quickest time to failure (5 days) is a rather short span of time in the expected life of a receptacle, which is typically on the order of a few decades. This implies that a specific receptacle failure could be tied to a certain event (i.e., receptacle modification, installation, addition of load, etc.). On the other hand, the longest time to failure of 365 days is noteworthy in that it suggests that failure events can be quite removed from the initial installation or modification, especially considering the receptacle and/or plug may not be in use continuously.

Multiple receptacle and plug connection failure modes were identified in the laboratory testing including: shorting of conductors, severed conductors at or near the screw terminal, series arcing at screw terminals, and flaming ignition. Approximately 19% of all failure events were flaming ignition failures (14% of receptacle failures; 100% of plug failures). Flaming ignition events were large enough to potentially ignite a range of proximate materials both in flame size and duration. Flame sizes up to 61 cm (24 inches) were observed and flaming ignition events lasted for periods up to about 6 minutes. However, the large flame sizes were only observed for the first 10% or so of the flaming duration. All of the flaming ignition events self-extinguished. Due to the additional plastics present, flaming ignition events for receptacles installed in outlet boxes with faceplates were generally larger in size. The outlet box also contributed to the likelihood of flaming ignition events. Failure rates for PVC and polypropylene receptacles (with 15A load) installed in outlet boxes with faceplates that led to flaming ignition were much higher (0.47 failures/year) compared to PVC and polypropylene receptacles installed in open air (with 15A load) that led to flaming ignition (0.07 failures year).

Evidence of arcing in flaming ignition events was not always present. Only nine of the 17 flaming ignition events had parallel arcing evidence and only three of these nine tripped a circuit breaker. While none of the flaming ignition events led to the complete consumption of the receptacle and/or outlet box and faceplate, the lack of circuit breakers tripping has significant implications for fire investigation. It indicates that circuit protection does not necessarily activate for an overheating receptacle that fails and ignites a flaming fire. Flaming ignition events occurred both with and without the distinct evidence associated with glowing connections. Some receptacles had welded conductors, some did not; some receptacles had curved striations on the welded conductors, some did not; and some of the plug connections had dezincification on the plug blade, some did not.

6.2 Fire Damage to Receptacles and Plugs

In addition to assessing the impact of a wide range of variables on the formation of overheating connections, this report also addressed the damage and potential forensic signatures of a wide range of electrical receptacle configurations when exposed to fire. The fire exposure testing characterized the thermal damage to receptacle components as a function of maximum exposure temperature, assessed the characteristics of arcing damage due to fire exposure, and assessed the characteristics of melting of copper and brass receptacle components due to fire exposure. The objectives of this test series were to improve the forensic examination of electrical receptacles and their components and to evaluate the utility of forensic analysis techniques. The primary variables of the test series were the fire exposure level, receptacle materials, outlet box materials, faceplate materials, and energized state of the receptacle (i.e., non-energized, energized, and energized with load); only copper wiring was used. These variables were selected to be representative of a range of conditions expected to be found in the field. Fire exposure testing of receptacle and plug connections consisted of 468 receptacle trials. A range of fire exposures were used including: ventilation limited (i.e., non-flashover) fires, flashover fires, and furnace fire exposures (representing extended, high temperature flashover fires).

A number of categories of thermal damage were created for each type of receptacle, outlet box, and faceplate in order to discretize the end-state of the thermal damage observed for each item relative to the maximum exposure temperature. The methodology consisted of first evaluating the damage category for each component; second, using the maximum measured exposure temperatures for each component to determine temperature ranges for each damage category; and third, to evaluate the classification scheme by assessing a particular fire environment based on estimated temperature ranges for exposed components from their component thermal damage categories. Ideally, the thermal environment would be characterized using the entire time-temperature and/or time-heat flux history for each receptacle. But, fully characterizing these temporal parameters in a concise manner proved too complex. A sample receptacle was evaluated using the methodology developed in this work. The range of temperatures for this sample did encompass the actual maximum exposure temperature, but the range was also quite large. Additional analysis of thermal damage to receptacles from a broader range of fire scenarios would strengthen this methodology for broader applicability. Further development of this method could provide fire investigators with a practical metric to describe the fire environment that is also suitable for field use and has a familiar quantifiable meaning.

The thermal damage from fire exposures was consistent in its general behavior; it tended to be uniform across the exposed face and advanced from the exposed face towards the rear of the receptacle. With respect to heating, the individual material behaviors observed in the fire exposure testing were similar to those found in the laboratory testing (i.e., melting, charring, cracking, etc.). The progression of damage from the front of the receptacle to the rear of the receptacle is consistent with observations in the literature [Babrauskas, 2003] and is quite distinguishable from the localized damage that is due to overheating. This distinction follows logically from the fact that the damage is a response to the thermal insult (i.e., fire or overheating connection) and the location of the thermal insult dictates the location of the damage. This type of visual determination of the damage location is analogous to a heat and flame vector analysis as discussed in NFPA 921 [2011]. The thermal damage to receptacles, plugs, outlet boxes, and faceplates due to overheating connections will generally remain distinguishable from damage due to external fire exposure depending on the extent of the damage. As the thermal damage from the fire exposure increases, the chances of identifying localized damage from overheating connections decreases.

Since overheating connections were highly correlated to the screw terminal torque, an effort was made to evaluate whether a post-fire terminal torque measurement could be used to estimate the pre-fire terminal torque. There has been no study of this type of forensic examination method in the literature. In this work, limitations to this process were identified, including softening of brass due to heat exposure and measurement dependence on the amount of grit, grime, melted plastic, or char that was on the terminal. Under specific conditions (i.e., terminals without much debris), measurement of the loosening torque can be useful to rule out overheating by demonstrating a high torque. However, the reverse is not true; due to the uncertainty in the measurement and the effects of heating and handling potentially causing connections to loosen, post-fire loosening torques are not reliable for indicating pre-fire loose connections.

Melting of brass and copper receptacle components due to external fire exposure was only observed in the furnace fire exposure tests. The maximum exposure temperature in any of the compartment fire tests in the vicinity of the receptacles was 903ºC, which is less than the melting point of brass (930ºC). The melting evidence for receptacles exposed in the furnace was identified using the naked eye or low powered microscopes. There were no strong trends relating the receptacle material or faceplate material with whether or not melting occurred for a particular receptacle.

In general, melted brass and copper receptacle components exhibited similar characteristic traits. The melting of brass and copper components generally occurred uniformly across the exposed area of the receptacle. For brass receptacle components, the following were observed: effects of gravity, thinning of brass components, holes through brass components, pitting of surface, and round globules. The following were observed for stranded and solid copper wiring: gradual necking of conductor, surface pitting, effects of gravity, terminal screws separated from the conductor, and fusing of wire strands. In most occasions, more than one characteristic was observed for a melted component. With the exception of holes forming in brass components, the melting characteristics observed in this work are consistent with the literature [NFPA 921, 2014]. The holes that formed from melting were unique to the brass internal receptacle contacts. Although these holes are not specifically called out in the literature with respect to being a characteristic trait of melting, this is mostly due to the fact that the literature has been primarily focused on arcing and melting in copper wires.

In every case where melting of copper was identified in a receptacle, melting of brass components was also evident. This result is intuitive because the melting point of brass is approximately 150ºC below that of copper. As such, in a receptacle with brass components and copper wiring, the brass should melt before the copper does. Observations of thermal damage to receptacles from external fire exposures indicate that the damage progresses from the front of the receptacle to the rear. Because the brass components in a receptacle are typically at the front of the receptacle with the wiring extending towards the rear, it follow that since the damage progressed from front to back, the items in the front melted first.

A Scanning Electron Microscope (SEM) was used to document some of the forensic evidence gathered in the laboratory testing and fire exposure testing. In particular, the SEM was used to image two damaged break off tabs from PVC receptacles; one from melting and the other from arcing (brass-steel). A visual examination of these break off tabs showed notches with a clear line of demarcation between the area of damage and the undamaged area. Distinguishing between arcing and melting was partially accomplished in this case using SEM and chemical analyses. The chemical analysis revealed significant iron on the break off tab having arcing damage, but very little on the break off tab having melting damage. If the arcing is between two different metals (i.e., brass and steel), this method of analysis may be used to determine whether transfer of metal, a typical occurrence during arcing, is identified. Care must be taken when conducting this type of analysis as alloying or dripping of metals can cause one metal to appear to have been deposited on another due to arcing [NFPA 921, 2011]. However, in the cases where metals with higher melting temperatures are deposited on metals with lower melting temperatures, such as steel onto brass, alloying and dripping may be ruled out.

Arcing evidence in the post-fire examinations for compartment fire and furnace fire tested receptacles was identifiable using low powered microscopes. The process of identifying arcing damage consisted of first determining that the damage was not from fire melting and second, determining which conductors were involved in the arcing. In the compartment fire testing and furnace fire testing, there were a combined 251 receptacles that were energized. Of these 251 receptacles, 201 receptacles tripped the circuit breakers during the test; all receptacles with extension cords installed tripped the circuit breaker. Arcing damage associated with parallel arcing was identified in all but 23 of the receptacles that tripped circuit breakers. For the receptacles that did trip the circuit breaker but did not have evidence of arcing, there was often significant melting of copper and/or brass that potentially destroyed arcing damage or the melted and/or charred remains of the receptacle potentially covered the arcing damage. In all of the 50 energized receptacles that did not trip the circuit breaker, arcing evidence was not found. This data suggests that fire induced arcing in receptacles will cause circuit breakers to trip, but also that evidence of arcing may not be able to be identified even if the circuit breaker trips.

Even though the fire induced arcing in this test series always caused circuit breakers to trip, the literature states that parallel arcing does not always trip circuit breakers [NFPA 921, 2011; Twibell, 2004; Babrauskas, 2003]. This phenomenon was observed through monitoring of several fire induced arc faults. Twelve receptacles were instrumented with a Hioki power meter to record the voltage and current associated with arcing events. Ten of the 12 receptacles had an arc fault that tripped the circuit breaker during the fire exposure test. Three of these ten receptacles had two arc faults separated by between 1 and 13 seconds. There were no visual differences between the arcing damage from only one arc fault or the arcing damage where two arc faults occurred. The first arc fault, which was typically lower in current than the second arc fault, did not trip the circuit breaker, but in all cases the second arc fault did. This means that fire induced arcing in a receptacle that does not trip a circuit breaker is a plausible scenario.

There were a number of locations of arcing that were common through all of the fire exposure tests. The locations of arcing were characterized as a pair of locations: the primary location (i.e., hot conductor) and the secondary location (i.e., neutral or ground conductor). The primary arcing locations included the female plug contacts, the break-off tab on the female plug contacts, receptacle wiring (solid) and extension cord wiring (stranded). The secondary arcing location is a conductor involved in the arcing other than the hot conductor such as part of the ground system (i.e., steel faceplate, metal outlet box, ground strap, or ground wire) or the neutral wire. Arcing damage on the steel faceplate was confirmed in 76 out of the 133 energized receptacles with steel faceplates where arcing damage was identified. Arcing damage on the outlet box was present in only eight out of 161 energized receptacles with steel outlet boxes where arcing damage was identified. When examining a receptacle for signs of fire induced arcing, it is not enough to only examine the receptacle; the whole installation (i.e., receptacle, wiring, outlet box, and faceplate) should be examined.

6.3 Arcing and Melting Damage Examination

The majority of literature focuses on electrical arcing in copper wiring, both stranded and solid, with some attention paid to steel (i.e., conduits), and relatively little mention of brass. This is despite the relatively equal presence of copper, steel, and brass in receptacles and similar devices. Proposed changes to NFPA 921 [2012] for the upcoming 2014 edition of the code include the addition of locally enlarged grain size [Murray and Ajersch, 2009; Lewis and Templeton, 2008], resolidification waves [Murray and Ajersch, 2009], and high internal porosity [Buc, 2012; Lewis and Templeton, 2008] as additional characteristic traits of arcing. Enlarged grain size was not examined because this trait could not be examined using visual methods alone.

Arcing damage in overheating connections (i.e., non-flaming ignition failure events) and external fire induced arcing in receptacles were rather similar in size, shape, and location. The size of arcing damage from overheating connections and fire induced arcing was typically limited to a single arc location resulting from a single point of contact. However, in some cases of arcing from flaming ignition events, the damage was extended beyond just one arcing location, with significant damage to the conductors. Other than by visual indicators, there was no attempt in this work to distinguish between external fire induced arcing and arcing that could have been the source of the fire. There has been research into this topic [Man et al., 2011; Anderson, 1996], but such work has yet to provide a conclusive determination of fire cause vs. fire effect [Babrauskas, 2004].

Distinguishing between arcing and thermal melting damage was based on the presence of visual indicators of arcing and/or melting in the evidence as listed in the proposed changes to NFPA 921 [2014], with some additions. A portion of the receptacles from this test program was evaluated for the presence of the aforementioned characteristic traits of arcing and fire-melting damage. The purpose of this exercise was to assess which characteristic traits were effective in assessing potential arcing damage on receptacle components and wiring.

Corresponding damage on the opposing conductor, localized damage with a sharp line of demarcation, and tooling marks outside of the area of damage were observed on significant portions of arc damaged conductors and small numbers of conductors with melting damage; these characteristics were found to be strong indicators of arcing. This was expected as these traits are fundamentally tied to the physical attributes of arcing, including very high temperatures, high temperature gradients, and quick time scales for melting and cooling. Corresponding damage and a sharp line of demarcation are widely accepted in the literature as indicators of arcing [NFPA 921, 2011; Babrauskas, 2003; Murray and Ajersch, 2009; Lewis and Templeton, 2008; Twibell, 2004]. Tooling marks, including copper drawing lines, sharp edges or stamped letters and numbers, were a parallel method of determining whether localized damage with a sharp line of demarcation was present.

Resolidification waves and spatter deposits were observed in limited conductors with arcing damage; no fire-melted conductors were observed with resolidification waves. However, these characteristics were very distinct from melting damage and were therefore strong indicators of arcing. Although internal porosity was not systematically evaluated, a number of conductors with arcing damage were observed to have significant porosity. Various researchers [Lewis and Templeton, 2008; Buc, 2012; Levinson, 1977] have shown that arcing and melting can cause porosity to form in metals, typically creating greater porosity for arcing compared to melting. However, because there has not been any rigorous study which quantifies the size and percent by volume of voids in arc beads or melted conductors, the value of this characteristic trait in an arc damage determination is limited. A round, smooth shape; small beads and divots; and localized round depressions were observed in limited numbers on arc damaged conductors and similar characteristic traits were observed in fire-melted conductors. Due to the lack of clear definitions in the literature, these three characteristic traits were poor indicators of arcing. A small portion of receptacles with arc damaged conductors also had fire-melting observed in the receptacle. Typically, this melting was either not close to the arc damage location or was on a metal with a lower melting temperature.

Limited numbers of fire-melted conductors were found with effects of gravity, gradual necking, pitting, thinning of the conductor or holes formed in the conductor. These characteristic traits were rarely observed in arc damaged conductors and were fair indicators that the damage present was due to fire-melting. Some conductors with fire-melting damage were observed to have characteristic traits of arcing (i.e., localized damage with a sharp line of demarcation or corresponding damage on the other conductor). A number of instances were observed where accepted characteristics of arcing were found in melted copper conductors. These characteristics included a clear line of demarcation between damaged and undamaged areas and copper drawing lines visible outside of the arc damaged area. In this case, a myopic examination of the evidence with respect to these characteristics could cause a false indication of arcing. In cases such as this, other evidence of melting in the receptacle (i.e., in close proximity to the area in question) would preclude confirmation of arcing. It is easy to see why errors such as this could be made. Much of the research into characteristics of arcing and melting presents discussion of one or two characteristics individually [Murray and Ajersch, 2009; Lewis and Templeton, 2008; Buc, 2012; Hussain, 2012]. As such, this type of research often does not examine the evidence in its entire context as would be expected in a practical fire investigation. The myopic examination of individual characteristics of arcing and melting is required for fundamental research, but it is a potential pitfall that should be considered in a forensic examination.

Most of the characteristic traits of arcing and melting are qualitative and not well defined in NFPA 921 [2011], which leads to more subjective evaluations. And though some characteristic traits were strong indicators of either arcing or melting, an investigator should never rely solely on the presence of one characteristic trait for arcing vs. fire-melting determination. Using multiple characteristic traits and contextual information for arcing vs. fire-melting determination provides greater confidence in the evaluation of damage. In addition, visual examinations were found to be reliable indicators of both arcing and fire-melting for most conductors. However, there are some cases which would benefit from more advanced examination techniques including SEM/EDS examinations, X-ray, CT scanning (X-ray computed tomography), cross-sectioning and polishing, or other metallurgical methods.

6.4 Implications for Policy and Practice

The results of this study establish a baseline for post-fire assessment of whether electrical receptacles may have had an overheating event that lead to an electrical fault. New forensic signatures have been identified along with techniques for evaluating post-fire evidence to differentiate between electrical overheat/receptacle fire signatures and damage resulting from an external fire exposure. Conclusions from this study are being submitted to the NFPA 921 Technical Committee on Fire Investigations for inclusion in the next edition of the document. It is anticipated that the forensic signatures identified in this work will be utilized in assessing electrical receptacle fires.

6.5 Implications for Further Research

Due to the small fraction of actual occurrences of overheating events that lead to electrical faults and the potentially long times required to form such faults, more long term testing would be useful in providing a larger database. This study did not address various contaminants that may affect the development of overheating conditions in electrical connections. Consequently, work addressing a systematic study of potential contaminants would expand the understanding of conditions that can lead to electrical faults and possible fire events. An expansion of the analysis of arc locations and overheating signatures to include additional cross-sectioning and polishing, SEM/EDS analysis, CT scanning (X-ray computed tomography), or other metallurgical examination techniques would expand the understanding of what specific (non-visual) characteristics are associated with these pieces of evidence.

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APPENDIX A – SUMMARY OF LABORATORY TEST RACKS

The subsequent sections discuss the receptacle and plug variables, test conditions, and any changes that occurred for each of the laboratory test racks. A complete summary of each receptacle tested in the laboratory testing can be found in Appendix G.

A1.0 TEST RACK 1

Test Rack 1 contained 68 receptacles and the test began on June 8, 2011. Table A.1 lists the variables evaluated and the number of receptacles per individual variable for Test Rack 1. After 204 days (on December 29, 2011) of continuous power, there were no visible signs of overheating, arcing, or damage to any of the receptacles having screw terminal torques of 15, 7, 5, or 3 in-lb. The 38 receptacles having these torques were modified to 1 in-lb or the ¼ turn loose configuration. The test number for these 38 receptacles was changed from test 1 to test 1A. Four days after the modifications were made (on January 3, 2012), power cycling (see Section 2.1.3) began for this test rack. The cyclical loading (i.e., one hour off per day) ended on August 24, 2012 after 443 days. The test rack remained powered for an additional 68 days until October 31, 2012.

Table A-1. Summary of variables for Test Rack 1.
Note: Number of receptacles in parentheses.

Receptacle Material	Type of Wiring	Number of Removal and Re-insertion Cycles (back wired only)	Terminal Torque (side wired only)	Terminal Torque After Change (side wired only)
Polypropylene (34)	Back-wired (20)	0 (4)	15 in-lb (8)	1 in-lb (23)
PVC (34)	Side-wired (48)	1 (8)	7 in-lb (10)	¼ Turn Loose (25)
		2 (8)	5 in-lb (10)	
			3 in-lb (10)	
			1 in-lb (10)	

A2.0 TEST RACK 2

Test Rack 2 contained 52 receptacles and the test began on September 12, 2011. Table A-2 and Table A-3 list the variables evaluated and the number of receptacles per individual variable for Test Rack 2. Two months after the test began (on November 11, 2011), power cycling (Section 2.1.3) was initiated for this test rack. The cyclical loading (i.e., one hour off per day) ended on August 24, 2012 after 347 days. The test rack remained powered for an additional 68 days until October 31, 2012.

Table A-2. Summary of variables for Test Rack 2, plug connections. Note: Number of receptacles in parentheses.

Receptacle Material	Type of Plug	Blade Retention Force
Polypropylene (21)	Folded – brass (14)	0.01 kg (18)
PVC (21)	Solid – brass (14)	0.1 kg (18)
	Solid – plated (14)	Non-modified (6)

Table A-3. Summary of variables for Test Rack 2, receptacle terminal connections. Note: Number of receptacles in parentheses.

Receptacle Material	Terminal Torque
Polypropylene (5)	¼ Turn Loose (10)
PVC (5)	

A3.0 TEST RACK 3

Test Rack 3 contained 58 receptacles and the test began on January 13, 2012. Table A-4 lists the variables evaluated and the number of receptacles per individual variable for Test Rack 3. Vibration cycling (see Section 2.1.1.1) was performed the day the test began. The power supply for the vibration motor was initially set at 12 VDC, yielding vibration amplitude of 3G at 42Hz (see Figure 2-5). Approximately 109 days after the test began (on May 1, 2011), the DC voltage to the vibration motor was increased to 17 VDC, producing a vibration amplitude of 6G at 60Hz. The voltage to the vibration motor was increased because limited overheating in the receptacles had occurred up to that point. The vibration (i.e., one hour on per day) ended on August 24, 2012 after 224 days. The test rack remained powered for an additional 173 days until February 13, 2013.

Table A-4. Summary of variables for Test Rack 3. Note: Number of receptacles in parentheses.

Receptacle Material	Type of Wiring	Number of Removal and Re-insertion Cycles (back wired only)	Terminal Torque (side wired only)
Polypropylene (29)	Back-wired (22)	0 (8)	3 in-lb (8)
PVC (29)	Side-wired (36)	1 (8)	1 in-lb (14)
			¼ Turn Loose (14)

A4.0 TEST RACK 4

Test Rack 4 contained 78 receptacles and the test began on February 2, 2012. Table A-5 lists the variables evaluated and the number of receptacles per individual variable for Test Rack 4. The cyclical loading (i.e., one hour off per day) ended on August 24, 2012 after 204 days. The test rack remained powered for an additional 173 days until February 13, 2013. No modifications were made to this test rack throughout the test period. Outlet boxes were constructed of PVC and faceplates were constructed of Nylon.

Table A-5. Summary of variables for Test Rack 4. Note: Number of receptacles in parentheses.

Receptacle Material	Type of Wiring	Surrounding Materials	Terminal Torque
Polypropylene (39)	Side-wired (78)	Box/Faceplate (10)	3 in-lb (24)
PVC (39)		None (68)	1 in-lb (22)
			¼ Turn Loose (32)

A5.0 TEST RACK 5

Test Rack 5 contained 78 receptacles and the test began on February 2, 2012. Table A-6 lists the variables evaluated and the number of receptacles per individual variable for Test Rack 5. The initial current for this test rack was set at 3A. After approximately 90 days (on May 2, 2012), there were no visible signs of overheating, arcing, or damage to any of the 78 receptacles and the current was increased to 6A. The cyclical loading (i.e., one hour off per day) ended on August 24, 2012 after 204 days. On August 24, 2012 the load for Test Rack 5 was set to 9A. The test rack remained powered for an additional 192 days until March 4, 2013. Outlet boxes were constructed of PVC and faceplates were constructed of Nylon.

Table A-6. Summary of variables for Test Rack 5. Note: Number of receptacles in parentheses.

Receptacle Material	Type of Wiring	Surrounding Materials	Terminal Torque
Polypropylene (39)	Side-wired (78)	Box/Faceplate (10)	3 in-lb (24)
PVC (39)		None (68)	1 in-lb (22)
			¼ Turn Loose (32)

A6.0 TEST RACK 6

Test Rack 6 contained 78 receptacles and the test began on March 2, 2012. Table A-7 lists the variables evaluated and the number of receptacles per individual variable for Test Rack 6.

The cyclical loading (i.e., one hour off per day) ended on August 24, 2012 after 175 days. The test rack remained powered for an additional 192 days until March 4, 2013. No modifications were made to this test rack throughout the test period. Outlet boxes were constructed of PVC and faceplates were constructed of Nylon.

Table A-7. Summary of variables for Test Rack 6.
Note: Number of receptacles in parentheses.

Receptacle Material	Age of Receptacles	Type of Wiring	Surrounding Materials	Terminal Torque (side wired only)
Polypropylene (13)	New (26)	Side-wired (78)	Box/Faceplate (10)	3 in-lb (9)
PVC (13)	Aged – Cat. A (4)		None (68)	1 in-lb (21)
Thermosets (52)	Aged – Cat. B (6)			¼ Turn Loose (48)
	Aged – Cat. C (15)			
	Aged – Cat. D (9)			
	Aged – Cat. E (18)			

A7.0 TEST RACK 7

Test Rack 7 contained 78 receptacles and began on February 16, 2012. Table A-8 lists the receptacle variables evaluated and the number of receptacles per individual variable for Test Rack 7. After approximately 112 days (on June 7, 2012), the high startup current application began. In addition to the primary 15A load, a chop saw was plugged into the loaded outlet (see Section 2.1.3). Four times per weekday (i.e., every 2 hours), the chop saw was operated. The operation consisted of three cycles. Each cycle, the chop saw would be run for 3 seconds and the motor was allowed to come to a complete stop before the next cycle. The chop saw was unplugged from the test rack between operations to prevent any inadvertent activation. The high startup current testing ended on August 24, 2012 after 190 days. The test rack remained energized an additional 192 days until March 4, 2013. Outlet boxes were constructed of PVC and faceplates were constructed of Nylon.

Table A-8. Summary of variables for Test Rack 7.
Note: Number of receptacles in parentheses.

Receptacle Material	Type of Blade	Blade Retention Force	Surrounding Materials
Polypropylene (39)	Folded – brass (34)	0.01 kg (46)	Box/Faceplate (10)
PVC (39)	Solid blade w/ ground (44)	0.1 kg (32)	None (68)

APPENDIX B – SUMMARY OF COMPARTMENT FIRE TESTS

The subsequent sections discuss the receptacle and plug variables, test conditions, and any significant changes that occurred for each of the compartment fire tests. Sections 3.1, 3.1.1.4, 3.1.1.5, 3.1.1.6 contain some pertinent information regarding differences for the construction and configuration between tests. A plot of the compartment heat release rate is included for each compartment fire test in order to illustrate the fire severity; an overview of the compartment fire test data can be seen in Table 3-1. A complete summary of each receptacle tested in the compartment fire testing can be found in Appendix H. Additional temperature measurement, heat release rate measurement, and heat flux measurement data can be found in Mealy and Gottuk [2013].

B1.0 TEST 1

Compartment fire Test 1 had some differences in construction compared to subsequent tests as noted in Section 3.1. Figure B-1 shows a plot of the heat release rate from the compartment in Test 1. Figure B-2 shows a plot of the average temperatures in the compartment near the wall assembly in Test 1. Figure B-3 shows a plot of the heat fluxes in the compartment near the rear wall in Test 1. There were no heat flux gauges installed near the wall assembly for Test 1. The ventilation in this test was a full door opening; the primary spill location was on the floor; the flooring material was carpet. Table B-1 lists the variables evaluated and the number of receptacles per individual variable for compartment fire Test 1.

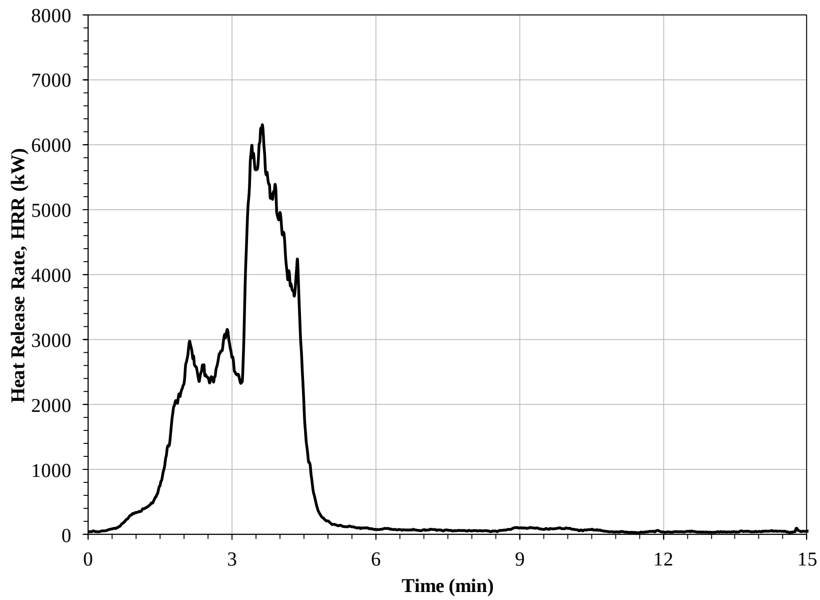


Figure B-1. Plot of Heat Release Rate (HRR) for compartment fire Test 1.

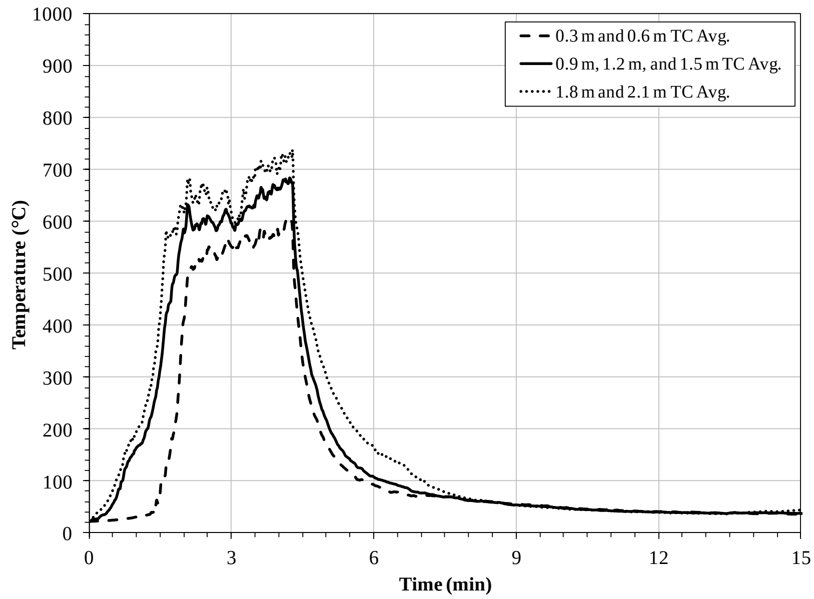


Figure B-2. Plot of the average temperatures in compartment near the wall assembly for compartment fire Test 1.

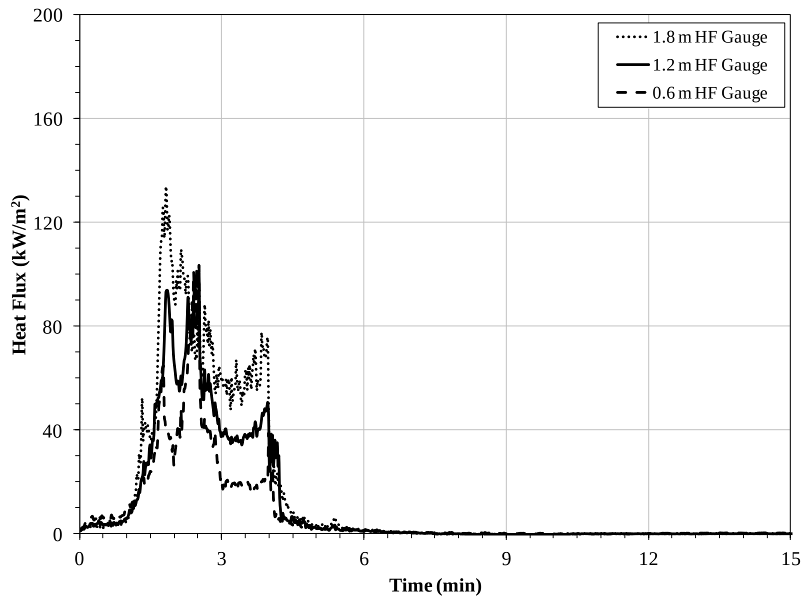


Figure B-3. Plot of the heat fluxes in compartment near the rear wall for compartment fire Test 1.

Table B-1. Summary of variables for receptacles in compartment fire Test 1. Note: Number of receptacles in parentheses.

Receptacle Material	Electrical State	Terminal Torque	Outlet Box Material	Faceplate Material
Polypropylene (18)	Non-Energized (12)	1 in-lb (18)	Steel (18)	Steel (18)
PVC (18)	Energized (12)	¼ Turn Loose (18)	PVC (18)	Nylon (18)
	Energized w/ Load (12)			

B2.0 TEST 2

Compartment fire Test 2 had some differences in construction compared to subsequent tests as noted in Section 3.1. Figure B-4 shows a plot of the heat release rate from the compartment in Test 2. Figure B-5 shows a plot of the average temperatures in the compartment near the wall assembly in Test 2. Figure B-6 shows a plot of the heat fluxes in the compartment near the wall assembly in Test 2. The ventilation in this test was a slit opening; the primary spill location was on the floor; the flooring material was carpet. Table B-2 lists the variables evaluated and the number of receptacles per individual variable for compartment fire Test 2.

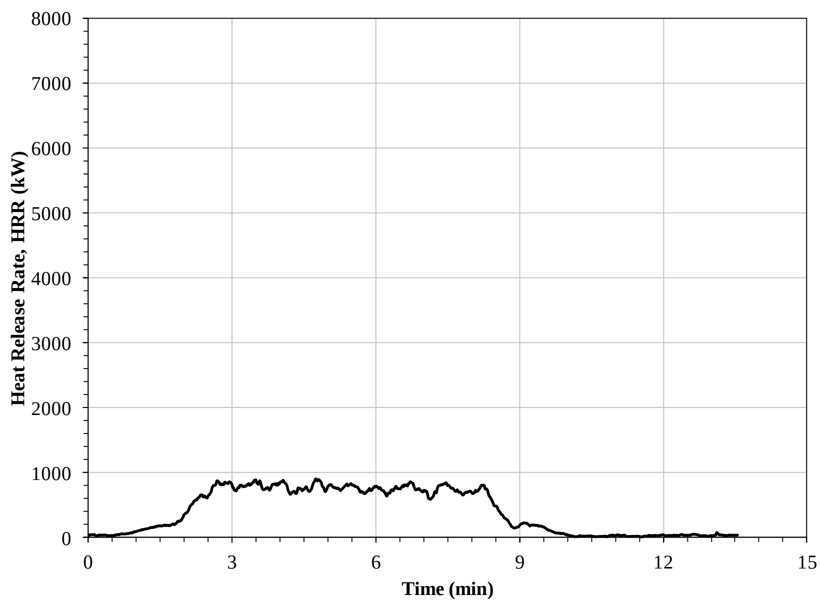


Figure B-4. Plot of Heat Release Rate (HRR) for compartment fire Test 2.

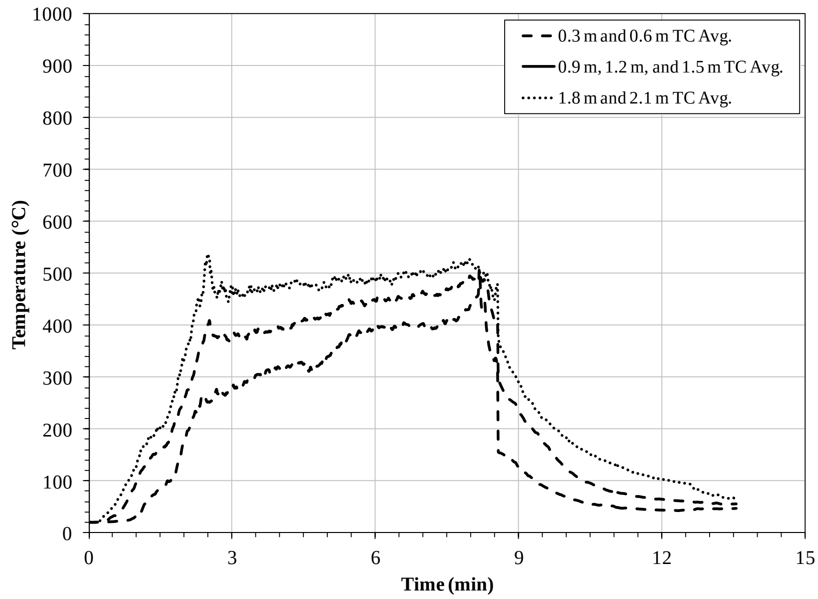


Figure B-5. Plot of the average temperature in the compartment near the wall assembly for compartment fire Test 2.

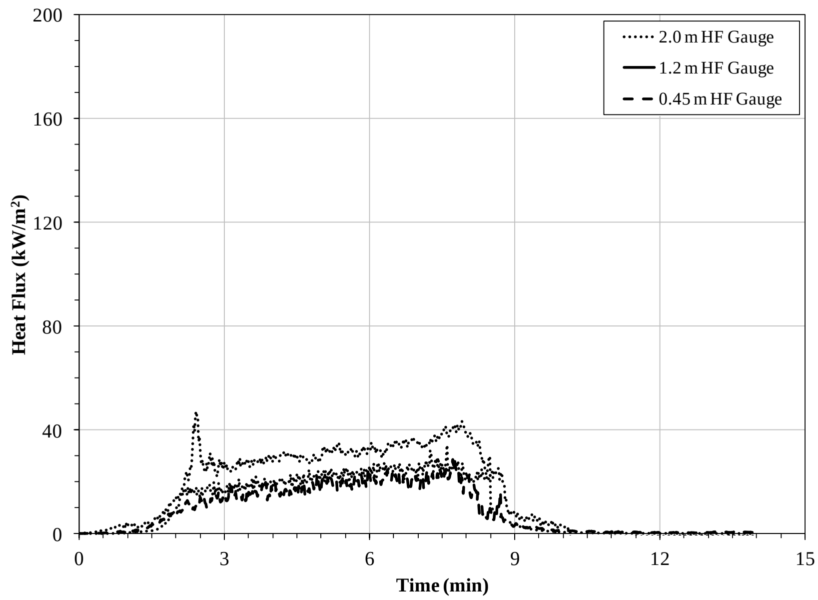


Figure B-6. Plot of the heat fluxes in compartment near the wall assembly for compartment fire Test 2.

Table B-2. Summary of variables for receptacles in compartment fire Test 2. Note: Number of receptacles in parentheses.

Receptacle Material	Electrical State	Terminal Torque	Outlet Box Material	Faceplate Material
Polypropylene (18)	Non-Energized (12)	1 in-lb (18)	Steel (18)	Steel (18)
PVC (18)	Energized (12)	3 in-lb (18)	PVC (18)	Nylon (18)
	Energized w/ Load (12)			

B3.0 TEST 3

Compartment fire Test 2 had some differences in construction compared to subsequent tests as noted in Section 3.1. Figure B-7 shows a plot of the heat release rate from the compartment in Test 3. Figure B-8 shows a plot of the average temperature in the compartment near the wall assembly in Test 3. Figure B-9 shows a plot of the heat fluxes in the compartment near the wall assembly in Test 3. The ventilation in this test was a full door opening; the primary spill location was on the upholstered chair; the flooring material was carpet. Table B-3 lists the variables evaluated and the number of receptacles per individual variable for compartment fire Test 3.

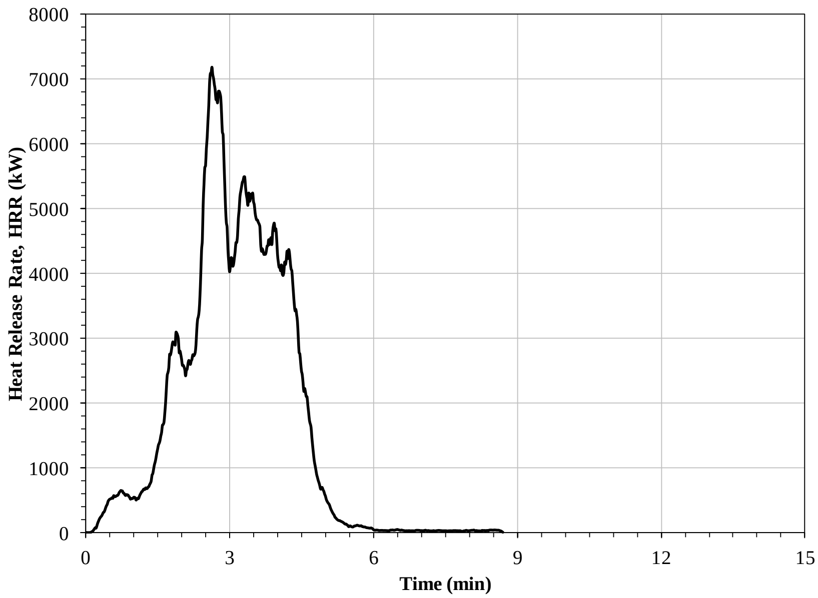


Figure B-7. Plot of Heat Release Rate (HRR) for compartment fire Test 3.

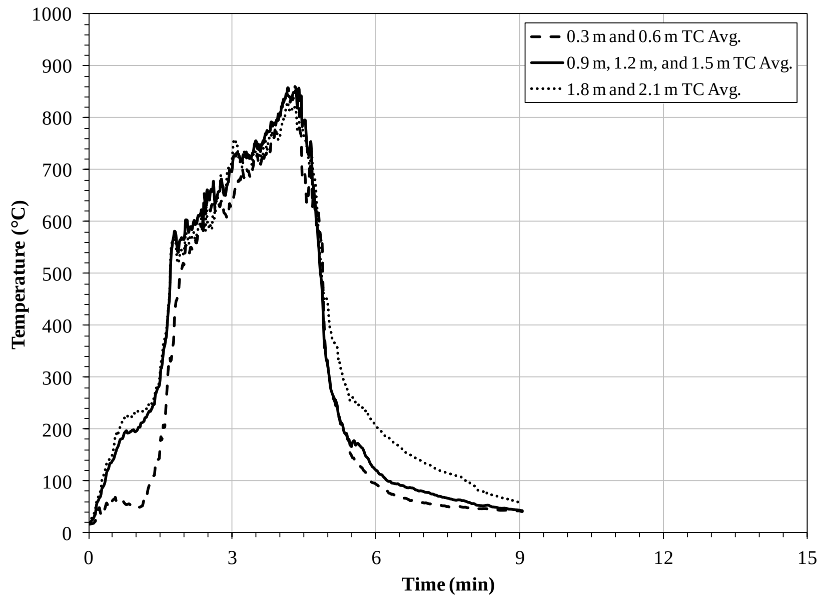


Figure B-8. Plot of the average temperature in the compartment near the wall assembly for compartment fire Test 3.

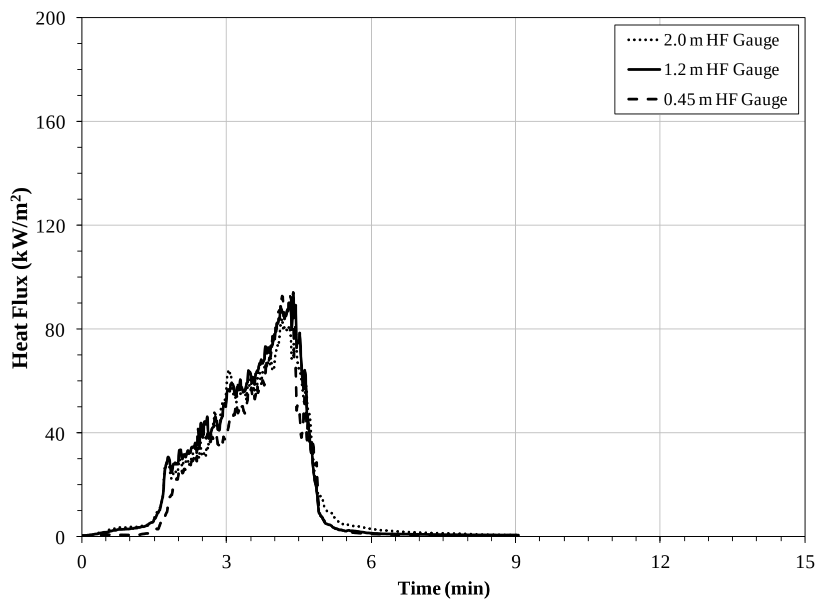


Figure B-9. Plot of the heat fluxes in compartment near the wall assembly for compartment fire Test 3.

Table B-3. Summary of variables for receptacles in compartment fire Test 3.
Note: Number of receptacles in parentheses.

Receptacle Material	Electrical State	Terminal Torque	Outlet Box Material	Faceplate Material
Polypropylene (18)	Non-Energized (12)	3 in-lb (18)	Steel (18)	Steel (24)
PVC (18)	Energized (12)	¼ Turn Loose (18)	PVC (18)	Nylon (12)
	Energized w/ Load (12)			

B4.0 TEST 4

Compartment fire Test 4 contained 36 receptacles with various variable combinations and the fire exposure was comparable to compartment fire Test 2. Figure B-10 shows a plot of the heat release rate from the compartment in Test 4. Figure B-11 shows a plot of the average temperature in the compartment near the wall assembly in Test 4. Figure B-12 shows a plot of the heat fluxes in the compartment near the wall assembly in Test 4. The ventilation in this test was a slit opening; the primary spill location was on the upholstered chair; the flooring material was carpet. Table B-4 lists the variables evaluated and the number of receptacles per individual variable for compartment fire Test 4.

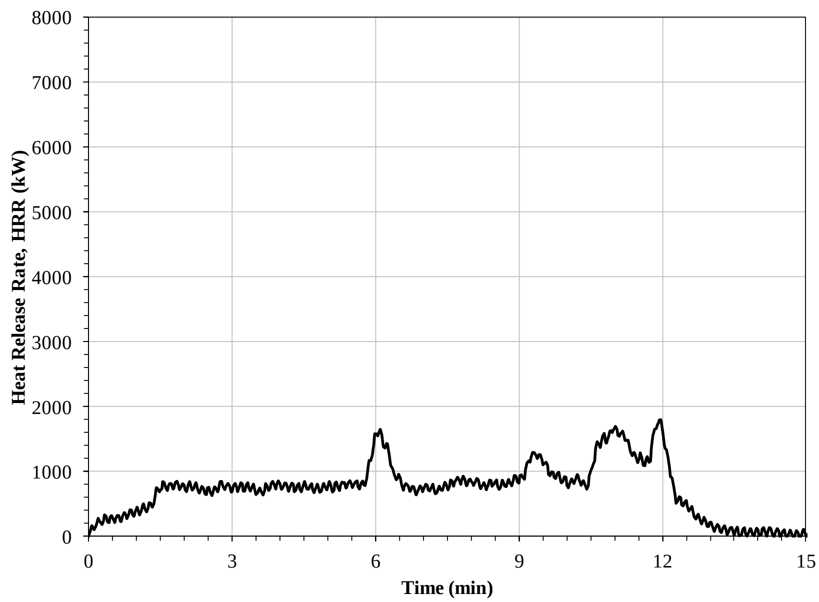


Figure B-10. Plot of Heat Release Rate (HRR) for compartment fire Test 4.

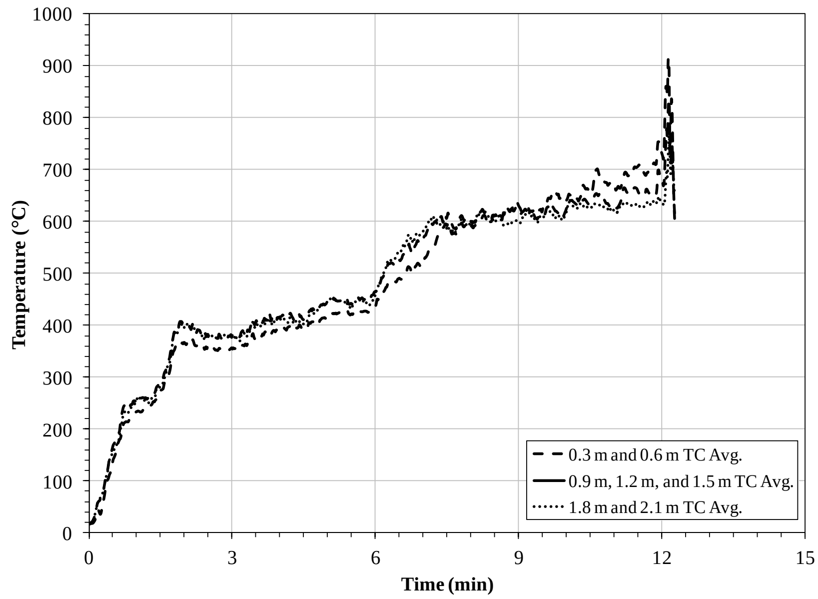


Figure B-11. Plot of the average temperature in the compartment near the wall assembly for compartment fire Test 4.

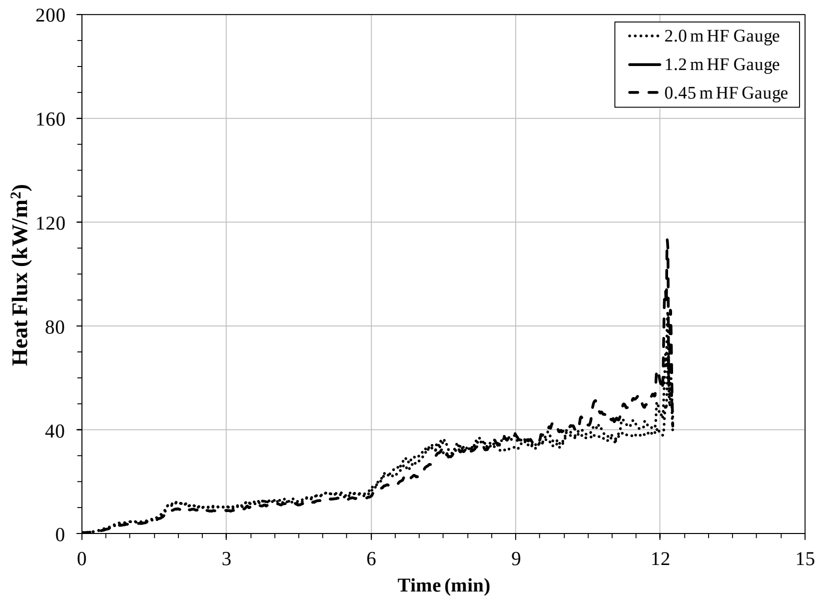


Figure B-12. Plot of the heat fluxes in compartment near the wall assembly for compartment fire Test 4.

Table B-4. Summary of variables for receptacles in compartment fire Test 4. Note: Number of receptacles in parentheses.

Receptacle Material	Electrical State	Terminal Torque	Outlet Box Material	Faceplate Material
Polypropylene (21)	Non-Energized (12)	1 in-lb (18)	Steel (18)	Steel (18)
PVC (15)	Energized (12)	3 in-lb (6)	PVC (18)	Nylon (18)
	Energized w/ Load (12)	¼ Turn Loose (12)		

B5.0 TEST 5

Compartment fire Test 5 contained 36 receptacles with various variable combinations and the fire exposure was comparable to compartment fire Test 3. Figure B-13 shows a plot of the heat release rate from the compartment in Test 5. Figure B-14 shows a plot of the average temperature in the compartment near the wall assembly in Test 5. Figure B-15 shows a plot of the heat fluxes in the compartment near the wall assembly in Test 5. The ventilation in this test was a full door opening; the primary spill location was on the floor; vinyl flooring was used. Table B-5 lists the variables evaluated and the number of receptacles per individual variable for compartment fire Test 5.

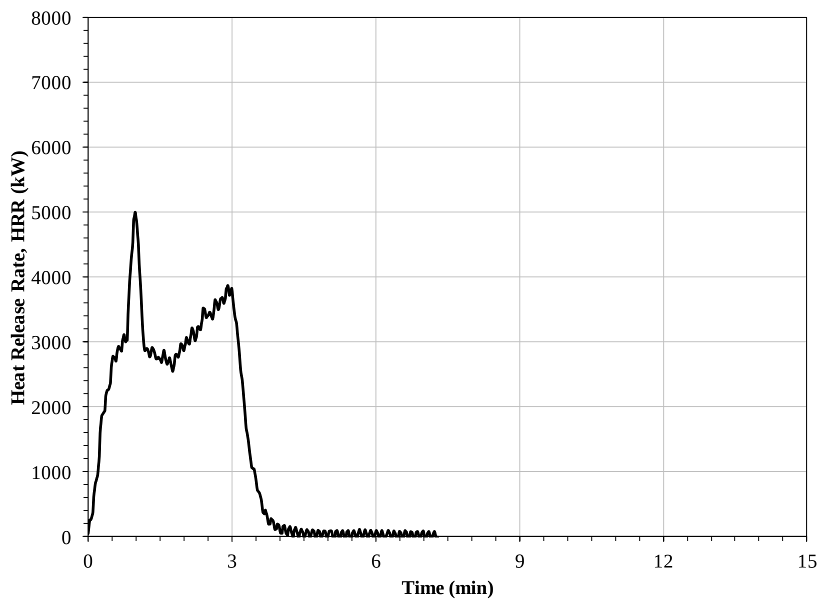


Figure B-13. Plot of Heat Release Rate (HRR) for compartment fire Test 5.

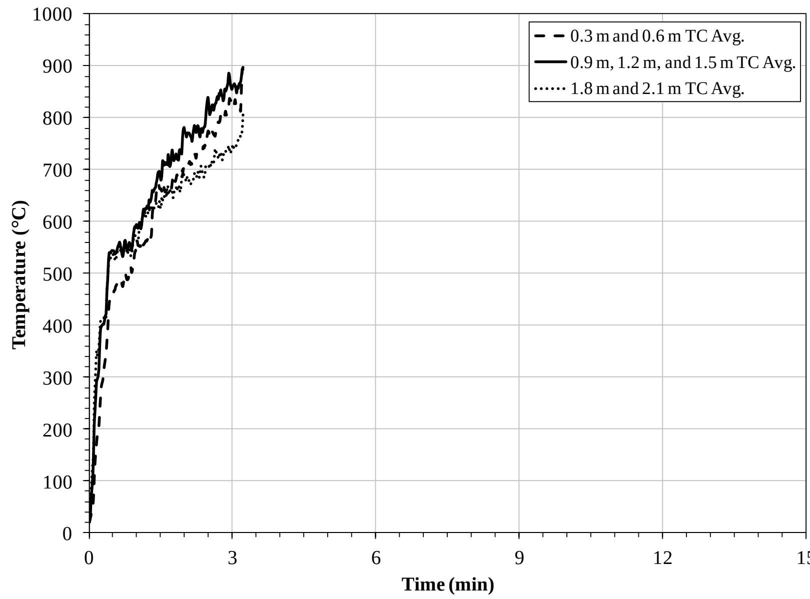


Figure B-14. Plot of the average temperature in the compartment near the wall assembly for compartment fire Test 5.

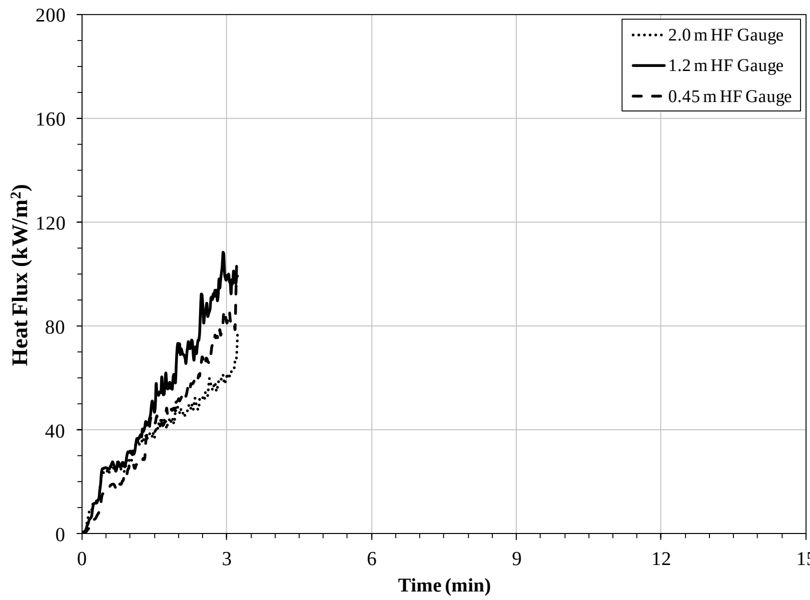


Figure B-15. Plot of the heat fluxes in compartment near the wall assembly for compartment fire Test 5.

Table B-5. Summary of variables for receptacles in compartment fire Test 5. Note: Number of receptacles in parentheses.

Receptacle Material	Electrical State	Terminal Torque	Outlet Box Material	Faceplate Material
Polypropylene (18)	Non-Energized (12)	1 in-lb (9)	Steel (18)	Steel (18)
PVC (18)	Energized (12)	3 in-lb (15)	PVC (18)	Nylon (18)
	Energized w/ Load (12)	¼ Turn Loose (12)		

B6.0 TEST 6

Compartment fire Test 6 contained 36 receptacles all of which were energized, installed in steel outlet boxes, and had terminal torques of 7 in-lb. This was the first compartment fire test to use thermoset receptacles and have extension cords plugged into some receptacles (see Section 3.1.1.4). PVC outlet boxes and the energized with load electrical state were removed as variables in Tests 6 through 8. Preliminary results had indicated that whether the circuit had a load or not did not appear to have any effect on the forensic evidence, whether thermal or electrical. In addition, forensic examination of receptacles in PVC outlet boxes tended to be more arduous and destructive due to melting of the plastic around the receptacle and wiring remains. Figure B-16 shows a plot of the heat release rate from the compartment in Test 6. Figure B-17 shows a plot of the average temperature in the compartment near the wall assembly in Test 6. Figure B-18 shows a plot of the heat fluxes in the compartment near the wall assembly in Test 6. The ventilation in this test was a slit opening; the primary spill location was on the floor; vinyl flooring was used. Table B-6 lists the variables evaluated and the number of receptacles per individual variable for compartment fire Test 6.

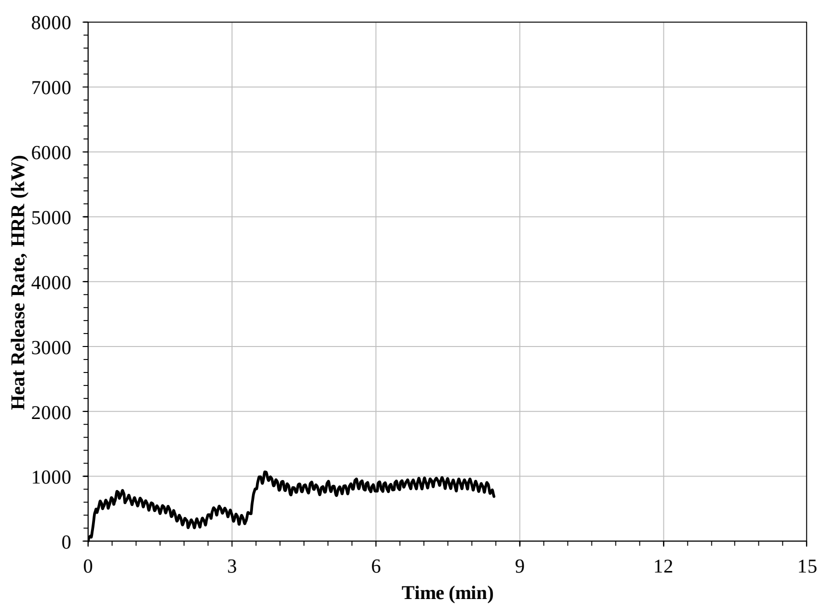


Figure B-16. Plot of Heat Release Rate (HRR) for compartment fire Test 6.

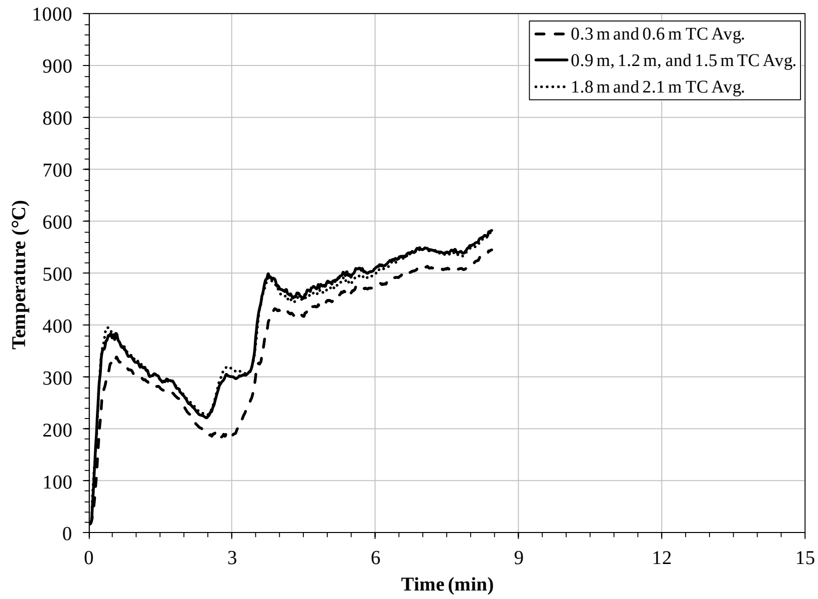


Figure B-17. Plot of the average temperature in the compartment near the wall assembly for compartment fire Test 6.

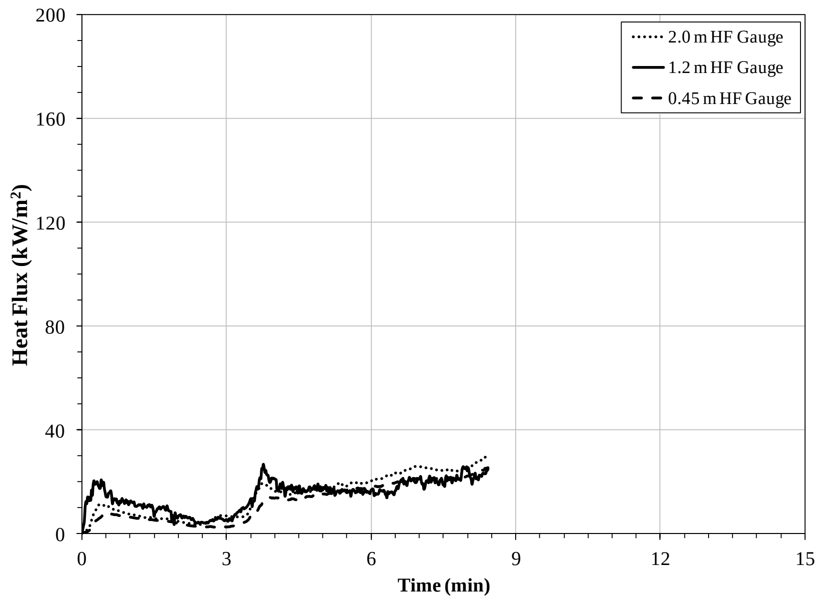


Figure B-18. Plot of the heat fluxes in compartment near the wall assembly for compartment fire Test 6.

Table B-6. Summary of variables for receptacles in compartment fire Test 6. Note: Number of receptacles in parentheses.

Receptacle Material	Receptacle Age	Device	Plug Blade	Faceplate Material
Polypropylene (6)	New (6)	Receptacle Only (30)	Folded Brass Blade (3)	Steel (18)
Thermosets (30)	Aged – Cat. B (6)	Receptacle w/ Plug (6)	Solid Plated Blade (3)	Nylon (18)
	Aged – Cat. C (6)			
	Aged – Cat. D (6)			
	Aged – Cat. E (12)			

B7.0 TEST 7

Compartment fire Test 7 contained 36 receptacles all of which were non-energized, installed in steel outlet boxes, and had terminal torques of 12 in-lb. Figure B-19 shows a plot of the heat release rate from the compartment in Test 7. Figure B-20 shows a plot of the average temperature in the compartment near the wall assembly in Test 7. Figure B-21 shows a plot of the heat fluxes in the compartment near the wall assembly in Test 7. The ventilation in this test was a full door opening; the primary spill location was on the upholstered chair; vinyl flooring was used. Table B-7 lists the variables evaluated and the number of receptacles per individual variable for compartment fire Test 7.

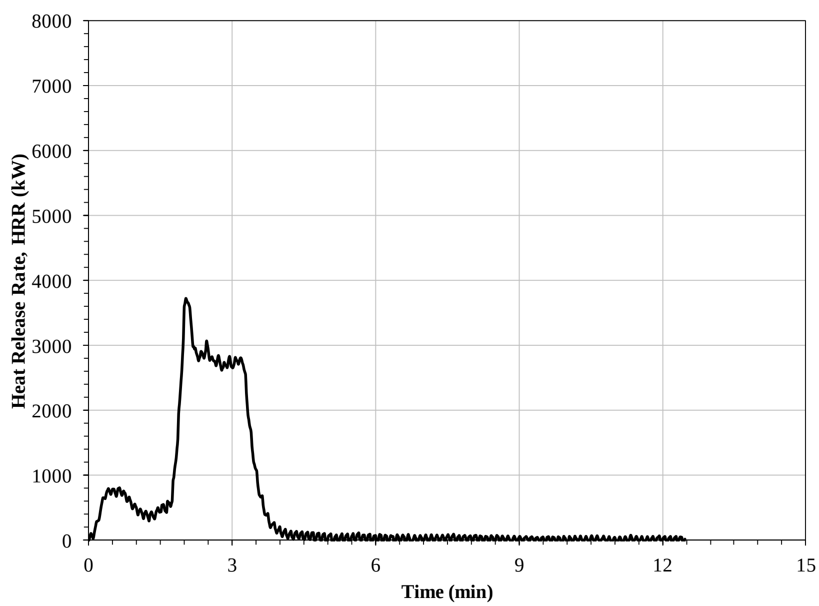


Figure B-19. Plot of Heat Release Rate (HRR) for compartment fire Test 7.

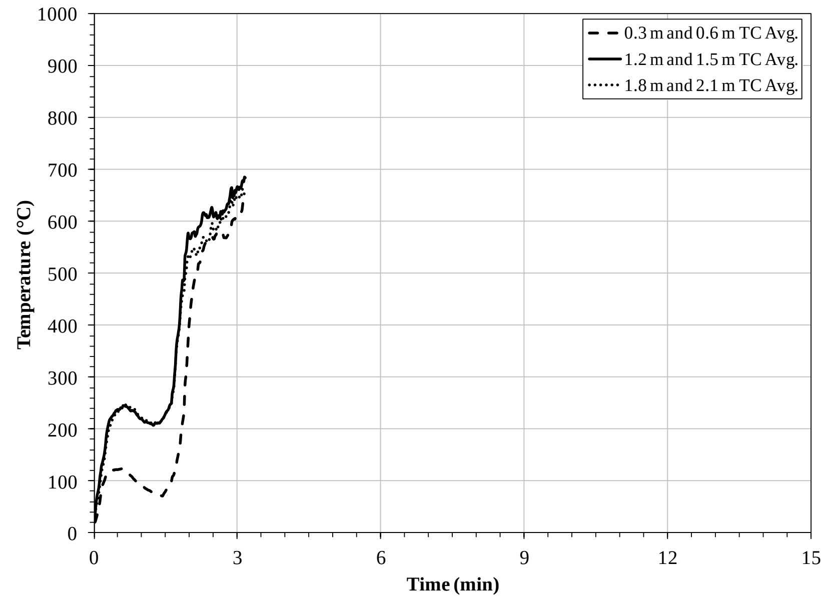


Figure B-20. Plot of the average temperature in the compartment near the wall assembly for compartment fire Test 7.

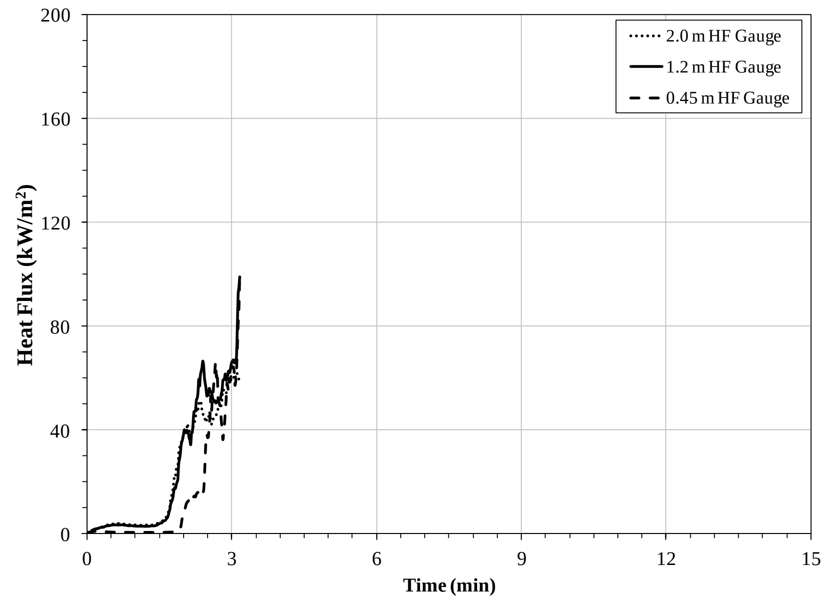


Figure B-21. Plot of the heat fluxes in compartment near the wall assembly for compartment fire Test 7.

Table B-7. Summary of variables for receptacles in compartment fire Test 7. Note: Number of receptacles in parentheses.

Receptacle Material	Receptacle Age	Device	Plug Blade	Faceplate Material
Thermosets (30)	New (6)	Receptacle Only (30)	Folded Brass Blade (3)	Steel (18)
PVC (6 New)	Aged – Cat. B (6)	Receptacle w/ Plug (6)	Solid Plated Blade (3)	Nylon (18)
	Aged – Cat. C (6)			
	Aged – Cat. D (6)			
	Aged – Cat. E (12)			

B8.0 TEST 8

Compartment fire Test 8 contained 36 receptacles all of which were energized and installed in steel outlet boxes. Figure B-22 shows a plot of the heat release rate from the compartment in Test 8. Figure B-23 shows a plot of the average temperature in the compartment near the wall assembly in Test 8. Figure B-24 shows a plot of the heat fluxes in the compartment near the wall assembly in Test 8. The ventilation in this test was a slit opening; the primary spill location was on the upholstered chair; vinyl flooring was used. Table B-8 lists the variables evaluated and the number of receptacles per individual variable for compartment fire Test 8.

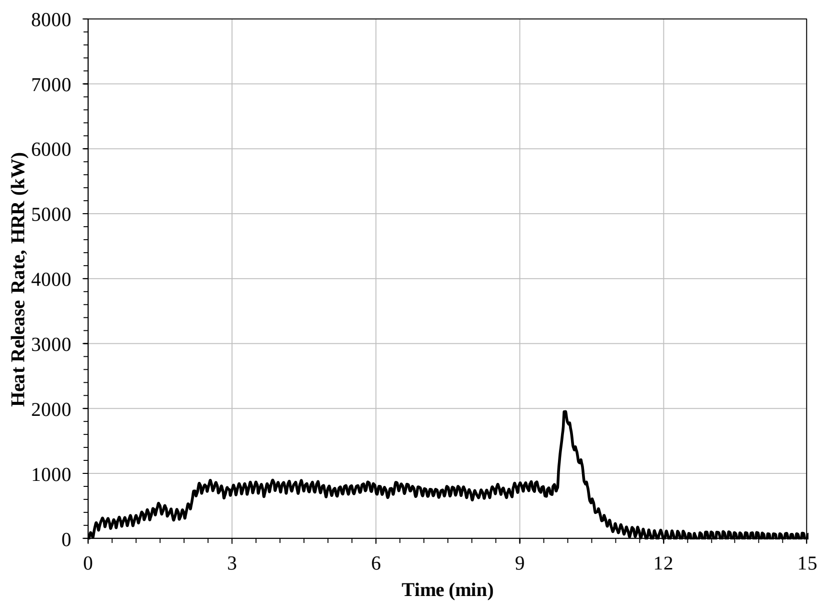


Figure B-22. Plot of Heat Release Rate (HRR) for compartment fire Test 8.

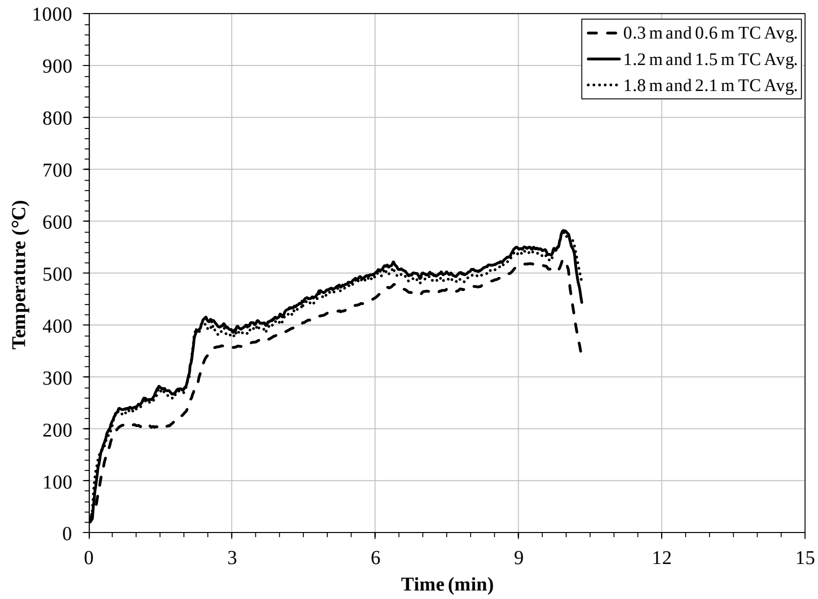


Figure B-23. Plot of the average temperature in the compartment near the wall assembly for compartment fire Test 8.

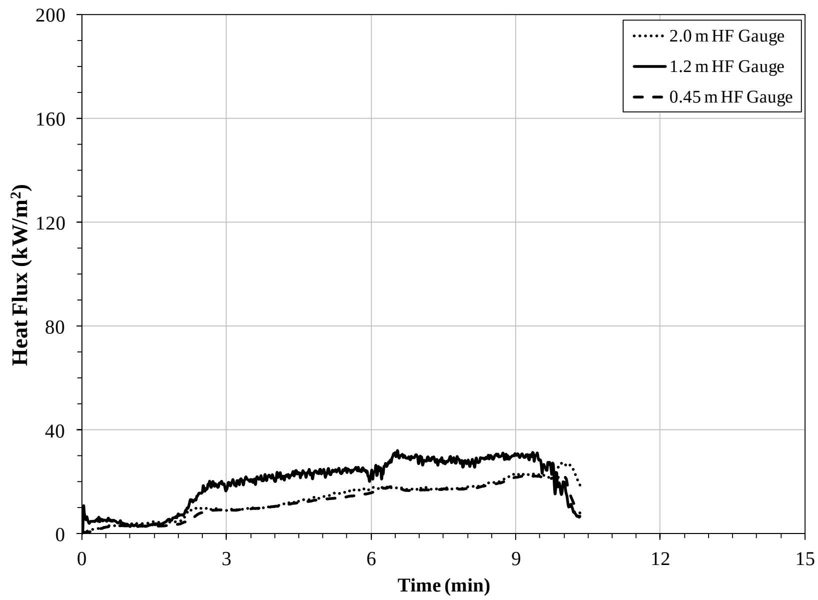


Figure B-24. Plot of the heat fluxes in compartment near the wall assembly for compartment fire Test 8.

Table B-8. Summary of variables for receptacles in compartment fire Test 8. Note: Number of receptacles in parentheses.

Receptacle Material	Device	Plug Blade	Terminal Torque	Faceplate Material
Polypropylene (18)	Receptacle Only (30)	Folded Brass Blade (3)	7 in-lb (18)	Steel (18)
PVC (18)	Receptacle w/ Plug (6)	Solid Plated Blade (3)	12 in-lb (18)	Nylon (18)

APPENDIX C – SUMMARY OF FURNACE FIRE TESTS

The subsequent sections discuss the receptacle and plug variables, test conditions, and changes that occurred for each of the furnace fire tests. A plot of the average furnace temperature is included for each test in order to illustrate the exposure severity. A complete summary of each receptacle tested in the furnace fire testing can be found in Appendix H.

C1.0 TEST 1

Furnace fire Test 1 contained 36 receptacles installed in steel outlet boxes. Figure C-1 is a plot of the average furnace temperature for furnace fire Test 1. Heat flux was not measured for furnace fire Test 1. The intent of this test was to have the furnace temperature above the melting point of brass, but below that of copper for long enough to melt some of the brass components. The gas flow for this test was terminated after 12.5 minutes and the sample was removed from the furnace approximately 5 minutes later. Table C-1 lists the variables evaluated and the number of receptacles per individual variable for furnace fire Test 1.

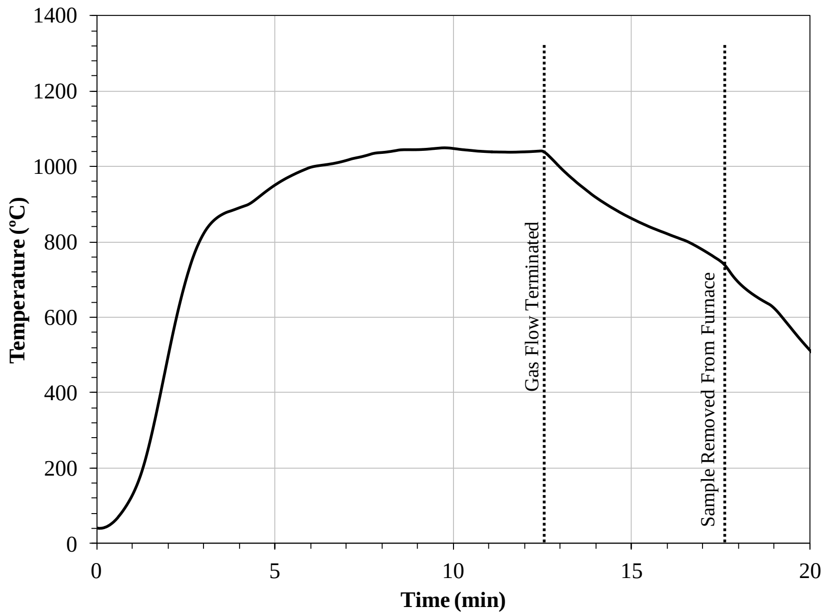


Figure C-1. Plot of average furnace temperature for furnace fire Test 1.

Table C-1. Summary of variables for receptacles in furnace fire Test 1. Note: Number of receptacles in parentheses.

Receptacle Material	Electrical State	Terminal Torque	Faceplate Material
Polypropylene (18)	Non-Energized (18)	1 in-lb (18)	Steel (24)
PVC (18)	Energized (18)	7 in-lb (18)	Nylon (12)

C2.0 TEST 2

Furnace fire Test 2 contained 36 receptacles installed in steel outlet boxes. Figure C-2 is a plot of the average furnace temperature for furnace fire Test 2. Figure C-3 is a plot of the heat flux for furnace fire Test 2. The intent of this test was to have the furnace temperature above the melting point of both brass and copper for long enough to melt some of the brass and copper components. The gas flow for this test was terminated after 13 minutes and the sample was removed from the furnace approximately 3 minutes later. Table C-2 lists the variables evaluated and the number of receptacles per individual variable for furnace fire Test 2.

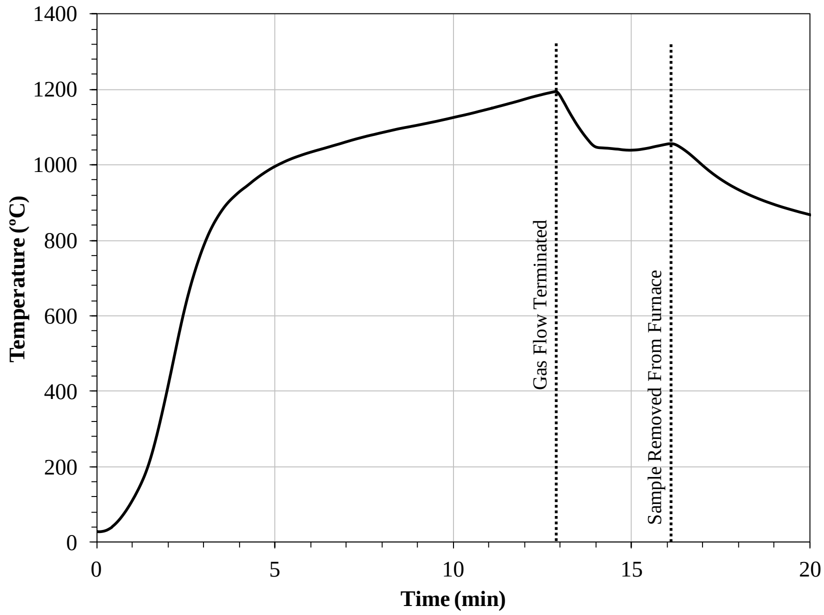


Figure C-2. Plot of average furnace temperature for furnace fire Test 2.

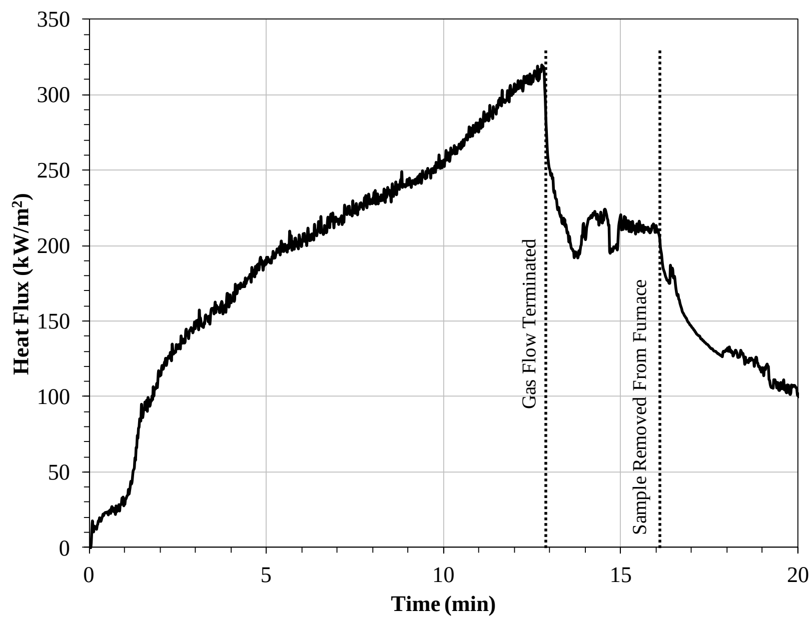


Figure C-3. Plot of heat flux for furnace fire Test 2.

Table C-2. Summary of variables for receptacles in furnace fire Test 2. Note: Number of receptacles in parentheses.

Receptacle Material	Electrical State	Terminal Torque	Faceplate Material
Polypropylene (18)	Non-Energized (18)	1 in-lb (18)	Steel (24)
PVC (18)	Energized (18)	7 in-lb (18)	Nylon (12)

C3.0 TEST 3

Furnace fire Test 3 contained 36 receptacles installed in steel outlet boxes. Figure C-4 is a plot of the average furnace temperature for furnace fire Test 3. Figure C-5 is a plot of the heat flux for furnace fire Test 3. The intent of this test was to have the furnace temperature above the melting point of both brass and copper for long enough to melt a significant portion of the brass and copper components. The gas flow for this test was terminated after approximately 14 minutes and the sample was removed from the furnace 3 minutes later. Table C-3 lists the variables evaluated and the number of receptacles per individual variable for furnace fire Test 3.

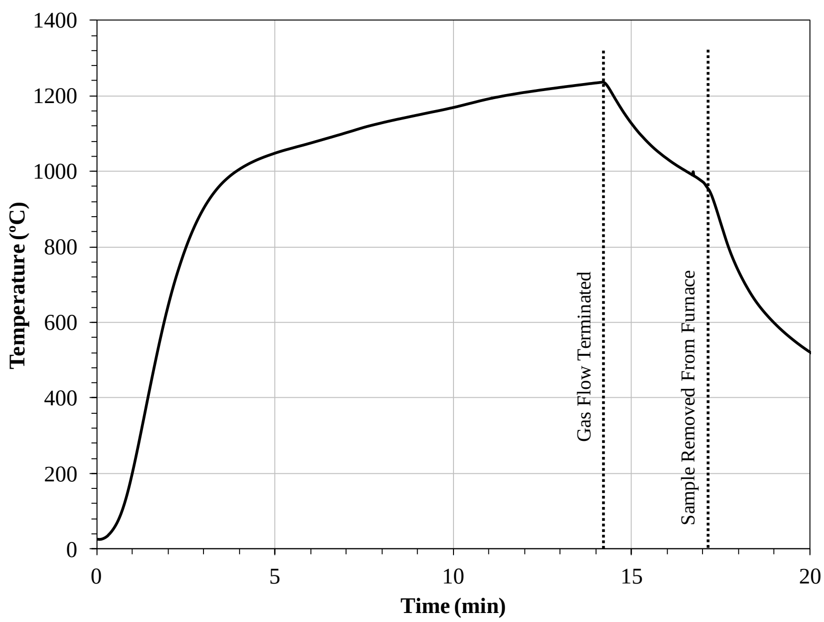


Figure C-4. Plot of average furnace temperature for furnace fire Test 3.

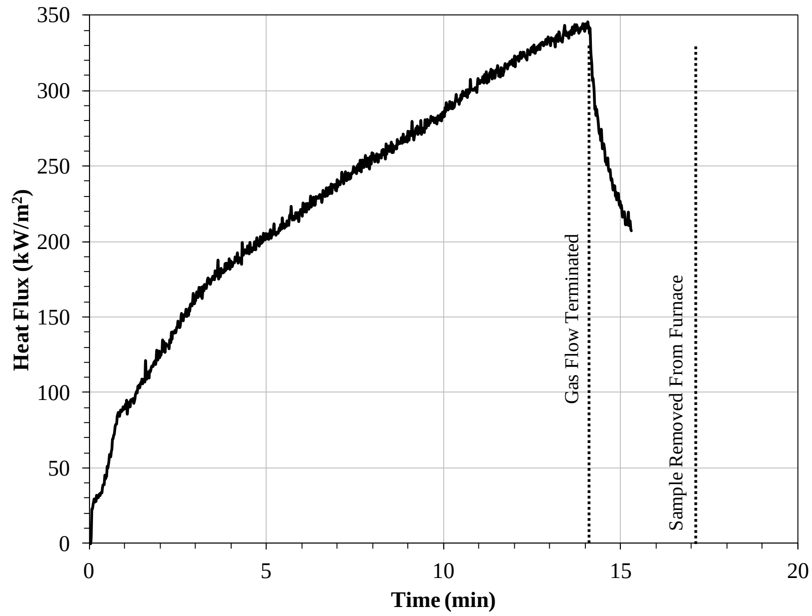


Figure C-5. Plot of heat flux for furnace fire Test 3.

Table C-3. Summary of variables for receptacles in furnace fire Test 3. Note: Number of receptacles in parentheses.

Receptacle Material	Electrical State	Terminal Torque	Faceplate Material
Polypropylene (18)	Non-Energized (36)	1 in-lb (18)	Steel (24)
PVC (18)		7 in-lb (18)	Nylon (12)

C4.0 TEST 4

Furnace fire Test 4 contained 36 receptacles installed in steel outlet boxes. This was the first furnace fire test to use aged receptacles and have extension cords plugged into some receptacles (see Section 3.1.2.4). All of the extension cords used in this test had plugs with folded brass blades. From preliminary results of the compartment fire tests, it was found that the aged receptacles (i.e., those made of thermosetting plastics such as phenolics and urea formaldehyde), retained their structure even when exposed to relatively severe fires. It was hypothesized that the copper and brass used with the thermoset receptacles would take longer to melt from the furnace exposure than for the thermoplastic receptacles (i.e., new receptacles) which themselves melt and deform at less severe exposures. Therefore, the furnace exposure for Test 4 was intended to be slightly more severe than that of the previous test such that the copper and brass components used with the thermoset receptacles would melt. Figure C-6 is a plot of the average furnace temperature for furnace fire Test 4. Figure C-7 is a plot of the heat flux for furnace fire Test 4. The gas flow for this test was terminated after 15 minutes and the sample was removed from the furnace approximately 3 minutes later. Table C-4 lists the variables evaluated and the number of receptacles per individual variable for furnace fire Test 4.

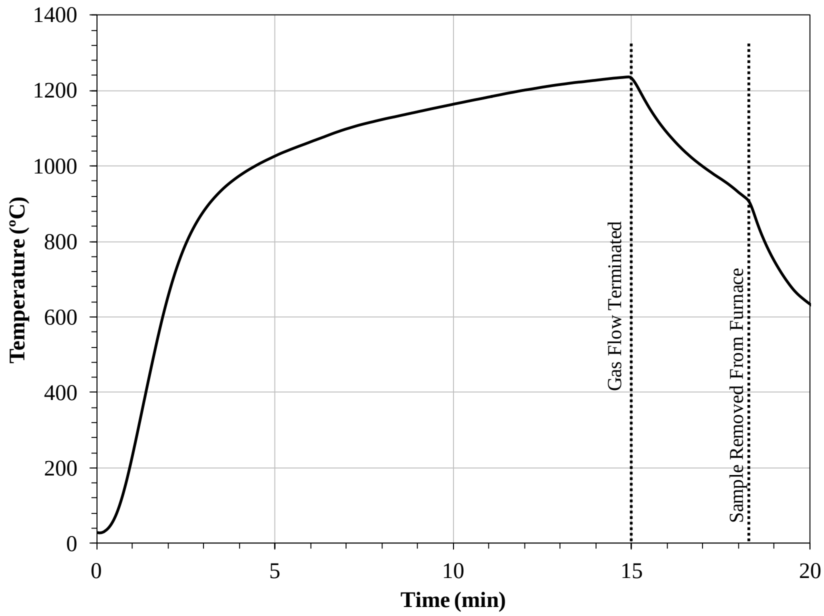


Figure C-6. Plot of average furnace temperature for furnace fire Test 4.

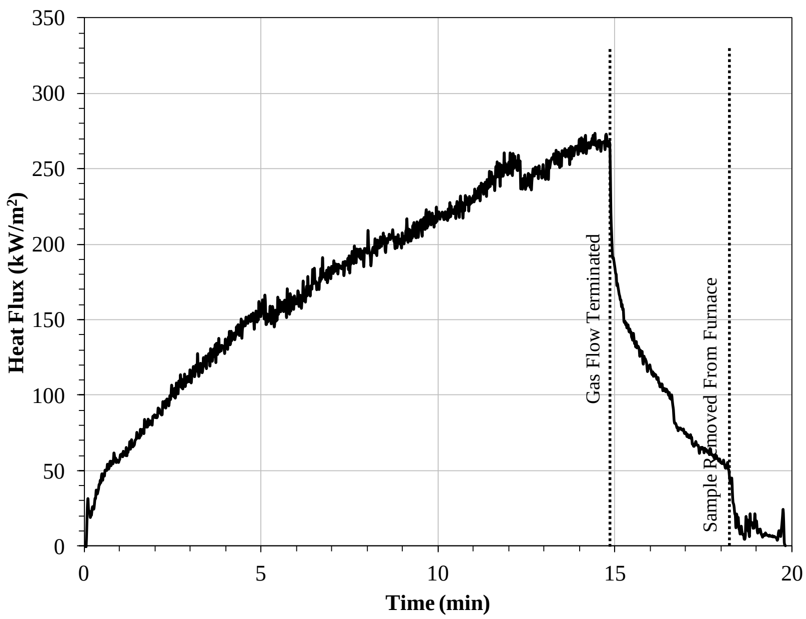


Figure C-7. Plot of heat flux for furnace fire Test 4.

Table C-4. Summary of variables for receptacles in furnace fire Test 4. Note: Number of receptacles in parentheses.

Receptacle Material	Receptacle Age	Electrical State	Device	Faceplate Material
Thermosets (36)	Aged – Cat. B (3)	Non-Energized (21)	Receptacle Only (30)	Steel (25)
	Aged – Cat. C (6)	Energized (15)	Receptacle w/ Plug (6)	Nylon (11)
	Aged – Cat. D (12)			
	Aged – Cat. E (15)			

C5.0 TEST 5

Furnace fire Test 5 contained 36 receptacles installed in steel outlet boxes. This test contained new receptacles, aged receptacles, receptacles with plugs, receptacles with prior damage from overheating, and sections of wiring with arc beads. All of the extension cords used in this test had low-profile plugs with plated brass blades. One of the objectives of this test was to determine whether indicators of overheating connections would persist after exposure to a fire. The intent was to expose the receptacles to an average furnace temperature above the melting point of brass but below that of copper such that it was likely that some evidence would remain for further examination. In addition, several sections of wire having arc beads from prior compartment fire testing were installed in receptacle boxes without faceplates in order to assess the affect of additional heating on the arc beads. Both the wire sections and the receptacles with prior damage from overheating were fully documented and examined prior to the test (see Section 3.2.3).

The gas flow for this test was terminated after 14 minutes and the sample was removed from the furnace approximately 3 minutes later. Figure C-8 is a plot of the average furnace temperature for furnace fire Test 5. Figure C-9 is a plot of the heat flux for furnace fire Test 2. Table C-5 lists the variables evaluated and the number of receptacles per individual variable for furnace fire Test 5.

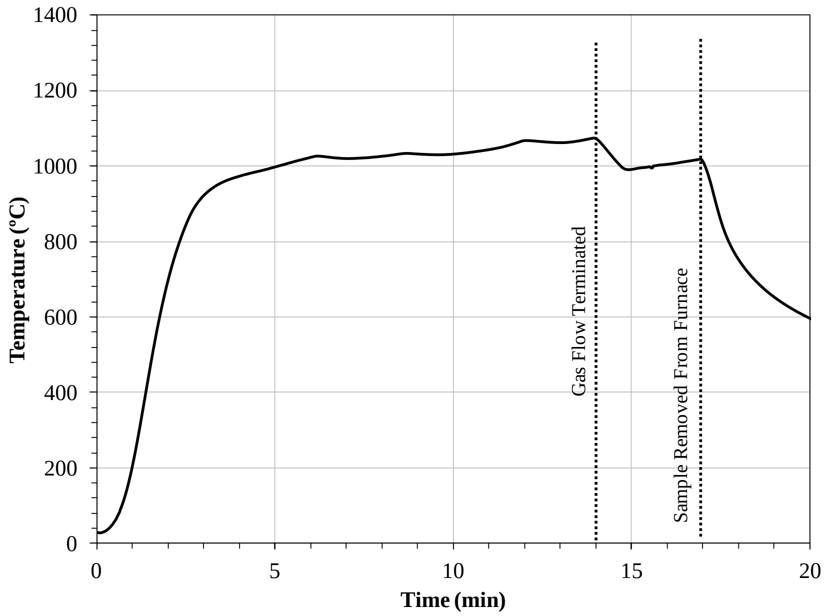


Figure C-8. Plot of average furnace temperature for furnace fire Test 5.

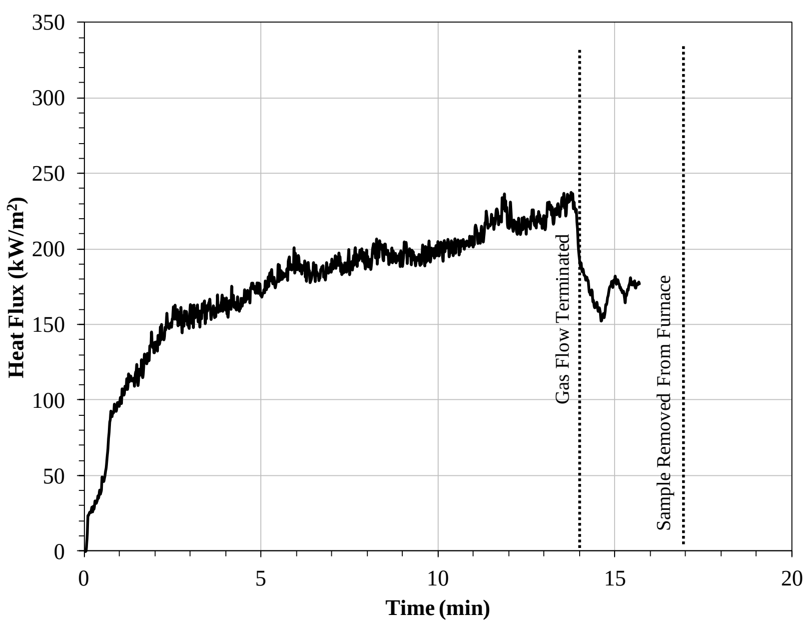


Figure C-9. Plot of heat flux for furnace fire Test 5.

**Table C-5. Summary of variables for receptacles in furnace fire Test 5.
Note: Number of receptacles in parentheses.**

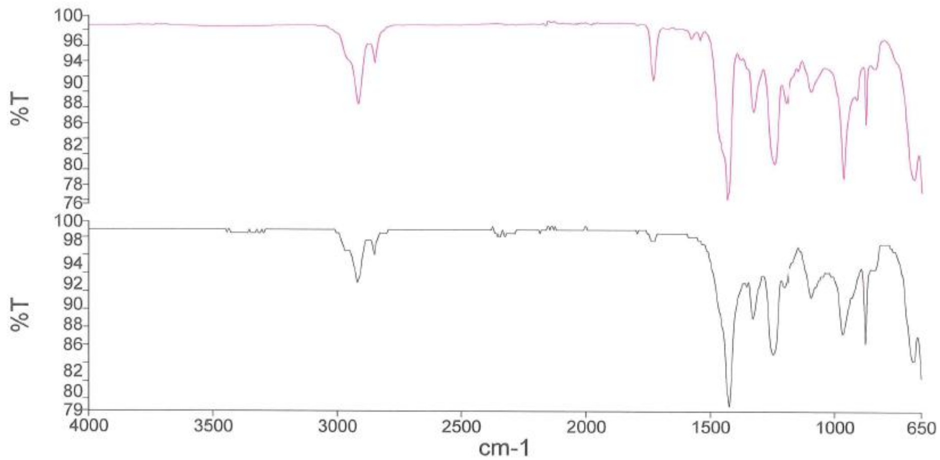
Receptacle Material (exemplar)	Receptacle Age (exemplar)	Receptacle State	Electrical State	Device	Faceplate Material
Polypropylene (6)	New (6)	Items w/ Prior Overheating Damage (24)	Non-Energized (27)	Receptacle Only (28)	Steel (31)
Thermosets (6)	Aged – Cat. E (6)	Exemplar (12)	Energized (9)	Receptacle w/ Plug (6)	Nylon (3)
				Sections of Wire (2)	None (2)

APPENDIX D – FTIR ANALYSIS OF PLASTICS

The figures in Appendix E are the FTIR spectra as measured by the Perkin Elmer FTIR machine at the Traveler's Engineering Laboratory. The plastics used for the construction of the new polypropylene and PVC receptacles were analyzed with this machine. In general, the machine seemed to select the correct plastics. However, as shown in Figure D-1 and Figure D-2 for the new PVC receptacles, "White PVC Pipe Charlotte Pipe N/E" was selected for both the back body and the front face of the receptacle. It is clear from a visual inspection of the receptacle that it is not a piece of pipe and is in fact grey (back body) or white (front face) in color. Therefore, the PVC receptacle was referred to as just PVC. Polypropylene was used to form both parts of the polypropylene receptacle body as noted in Figure D-3 and Figure D-4.

PerkinElmer Spectrum Version 10.03.06
Friday, June 01, 2012 9:42 AM

Analyst Administrator
Date Friday, June 01, 2012 9:42 AM



pse171 body — pse171 body
MM1019 — WHITE PVC PIPE CHARLOTTE PIPE N/E

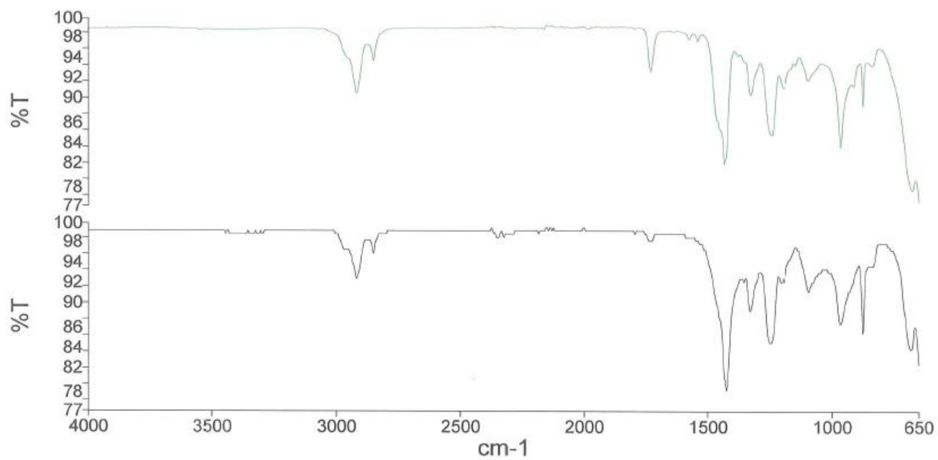
Source Spectra		
Sample Name	Search Best Hit	Search Best Hit Description
pse171 body	MM1019	WHITE PVC PIPE CHARLOTTE PIPE N/E

Searched References	
Search Score	Search Reference Spectrum Description
0.881935	WHITE PVC PIPE CHARLOTTE PIPE N/E
0.864354	GREY PVC
0.805109	POLY(VINYL CHLORIDE), CARBOXYLATED 1.8% CARBOXYLATED
0.787937	PVC CEMENT
0.75235	POLY(VINYL CHLORIDE) INHERENT VISCOSITY 1.26
0.738127	POLY(VINYL CHLORIDE) (N=0.90)
0.735186	POLY(VINYL CHLORIDE) (N=1.20)
0.733146	POLY(VINYL CHLORIDE) (N=0.73)
0.732212	POLY(VINYL CHLORIDE) (N=1.02)
0.732114	GREY CPVC

Figure D-1. FTIR Spectra and analysis for PVC back body plastic.

PerkinElmer Spectrum Version 10.03.06
Friday, June 01, 2012 9:48 AM

Analyst	Administrator
Date	Friday, June 01, 2012 9:48 AM



(green line)	pse171 white face	pse171 white face
(black line)	MM1019	WHITE PVC PIPE CHARLOTTE PIPE N/E

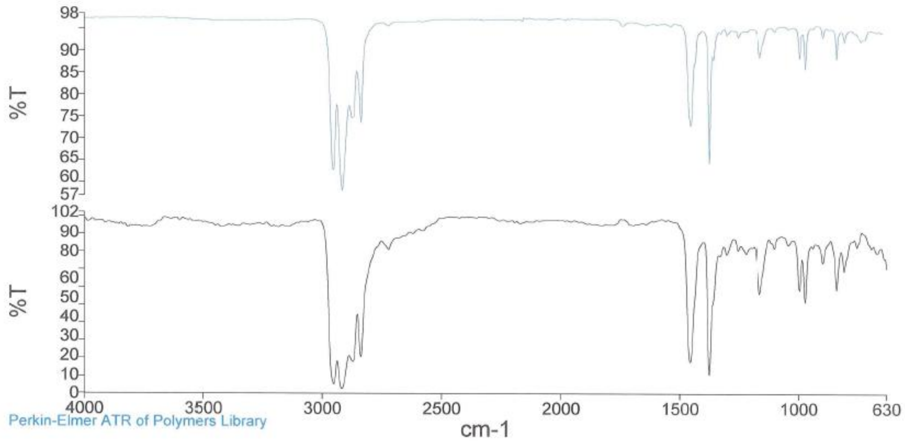
Source Spectra		
Sample Name	Search Best Hit	Search Best Hit Description
pse171 white face	MM1019	WHITE PVC PIPE CHARLOTTE PIPE N/E

Searched References	
Search Score	Search Reference Spectrum Description
0.874546	WHITE PVC PIPE CHARLOTTE PIPE N/E
0.856314	GREY PVC
0.793026	POLY(VINYL CHLORIDE), CARBOXYLATED 1.8% CARBOXYLATED
0.781165	PVC CEMENT
0.736954	GREY CPVC
0.736938	POLY(VINYL CHLORIDE) INHERENT VISCOSITY 1.26
0.72408	POLY(VINYL CHLORIDE) (N=0.90)
0.720659	POLY(VINYL CHLORIDE) (N=1.20)
0.71893	POLY(VINYL CHLORIDE) (N=0.73)
0.717232	POLY(VINYL CHLORIDE) (N=1.02)

Figure D-2. FTIR Spectra and analysis for PVC front face plastic.

PerkinElmer Spectrum Version 10.03.06
Friday, June 01, 2012 10:02 AM

Analyst Administrator
Date Friday, June 01, 2012 10:02 AM



———	lev277 black body	lev277 black body
———	AP0065	POLYPROPYLENE, ISOTACTIC

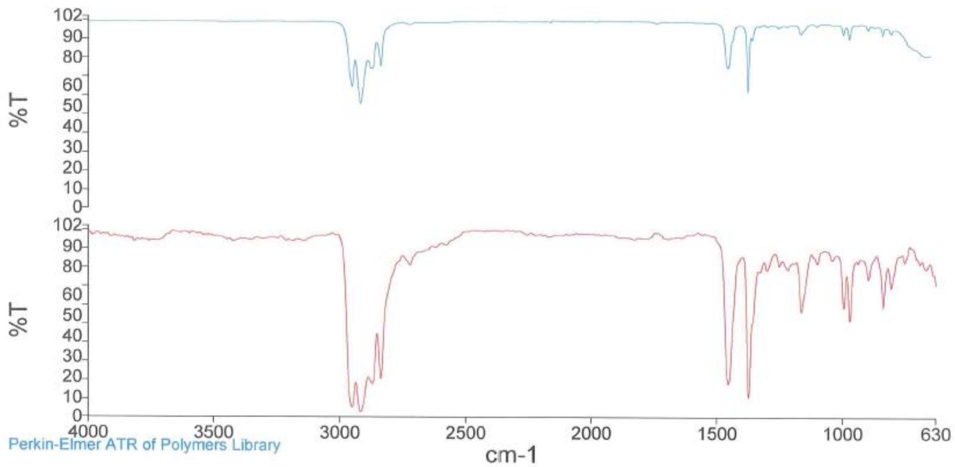
Source Spectra		
Sample Name	Search Best Hit	Search Best Hit Description
lev277 black body	AP0065	POLYPROPYLENE, ISOTACTIC

Searched References	
Search Score	Search Reference Spectrum Description
0.979832	POLYPROPYLENE, ISOTACTIC
0.885735	POLYOLEFIN [PP]
0.877015	2,6,10,14-TETRAMETHYLPENTADECANE
0.864519	HYDROCARBON "WHITE" OIL, MEDICINAL GRADE
0.855606	GULF HARMONY HYDRAULIC OIL WITH ANTI-WEAR ADDITIVE
0.85059	POLY(4-METHYL-1-PENTENE)(HMW/MI8)
0.845458	LIGROINE, PETROLEUM DISTILLATE (90-120 deg.C)
0.843918	SOLVENT NAPHTHENIC NEUTRAL BASE OIL
0.843842	POLY(4-METHYL-1-PENTENE)MELT INDEX 70
0.842038	20C2050104 ATF SAMPLE PETROLEUM GROUND

Figure D-3. FTIR Spectra and analysis for Polypropylene back body plastic.

PerkinElmer Spectrum Version 10.03.06
Friday, June 01, 2012 9:31 AM

Analyst Administrator
Date Friday, June 01, 2012 9:31 AM



LEV277-white LEV277 white body
AP0065 POLYPROPYLENE, ISOTACTIC

Source Spectra		
Sample Name	Search Best Hit	Search Best Hit Description
LEV277-white	AP0065	POLYPROPYLENE, ISOTACTIC

Searched References	
Search Score	Search Reference Spectrum Description
0.970278	POLYPROPYLENE, ISOTACTIC
0.889137	LIGROINE, PETROLEUM DISTILLATE (90-120 deg.C)
0.88596	2,6,10,14-TETRAMETHYLPENTADECANE
0.881936	HYDROCARBON "WHITE" OIL, MEDICINAL GRADE
0.881541	GULF HARMONY HYDRAULIC OIL WITH ANTI-WEAR ADDITIVE
0.876853	SOLVENT NAPHTHENIC NEUTRAL BASE OIL
0.870841	POLYOLEFIN [PP]
0.867104	ISO-OCTANES - MIXED ISOMERS
0.865555	ACHAIN SAW LUBRICANT
0.863426	SOLVENT PARAFFINIC BRIGHT STOCK BASE OIL

Figure D-4. FTIR Spectra and analysis for Polypropylene front face plastic.

APPENDIX E – SELECTED EDS SPECTRA FROM SEM EXAMINATION

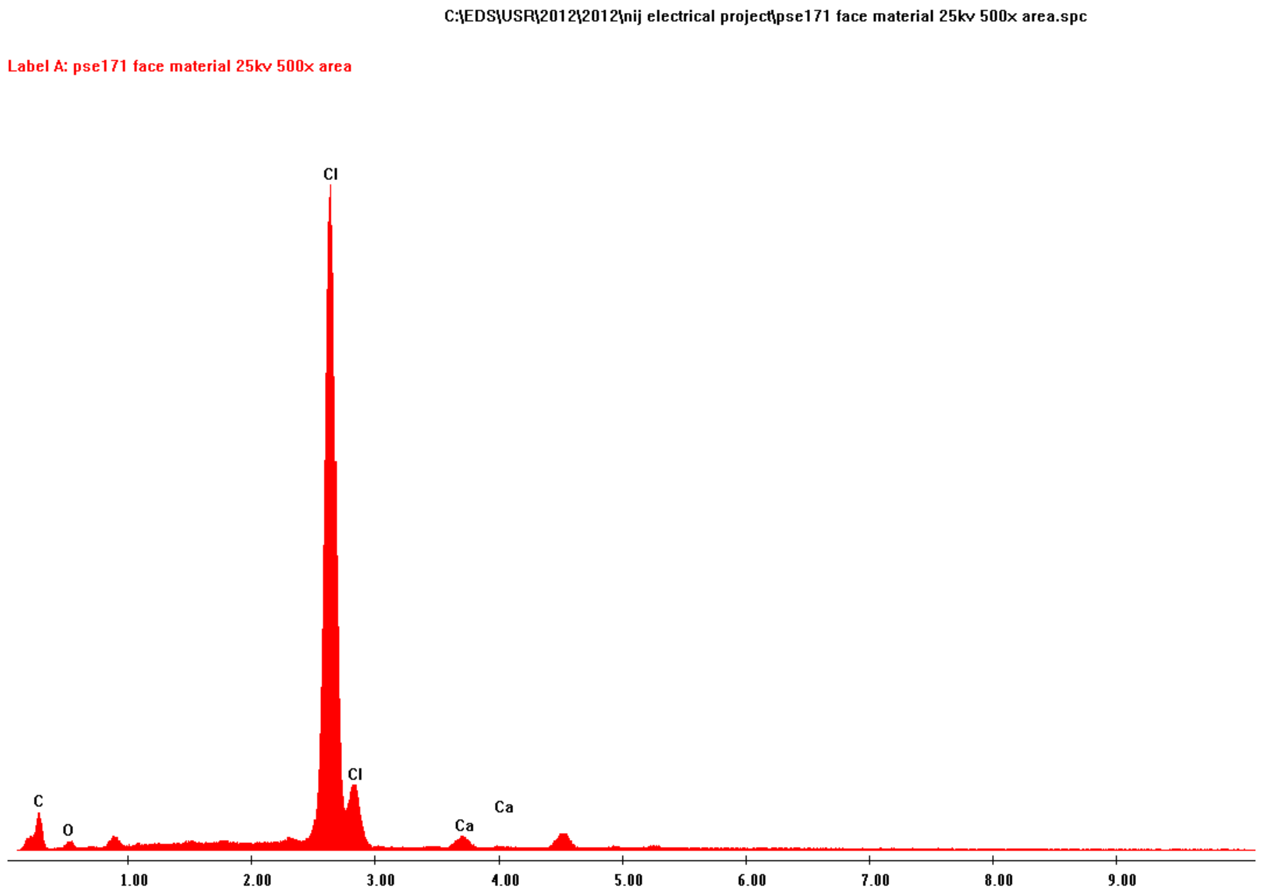


Figure E-1. EDS Spectra of front plastic face of PVC receptacle.

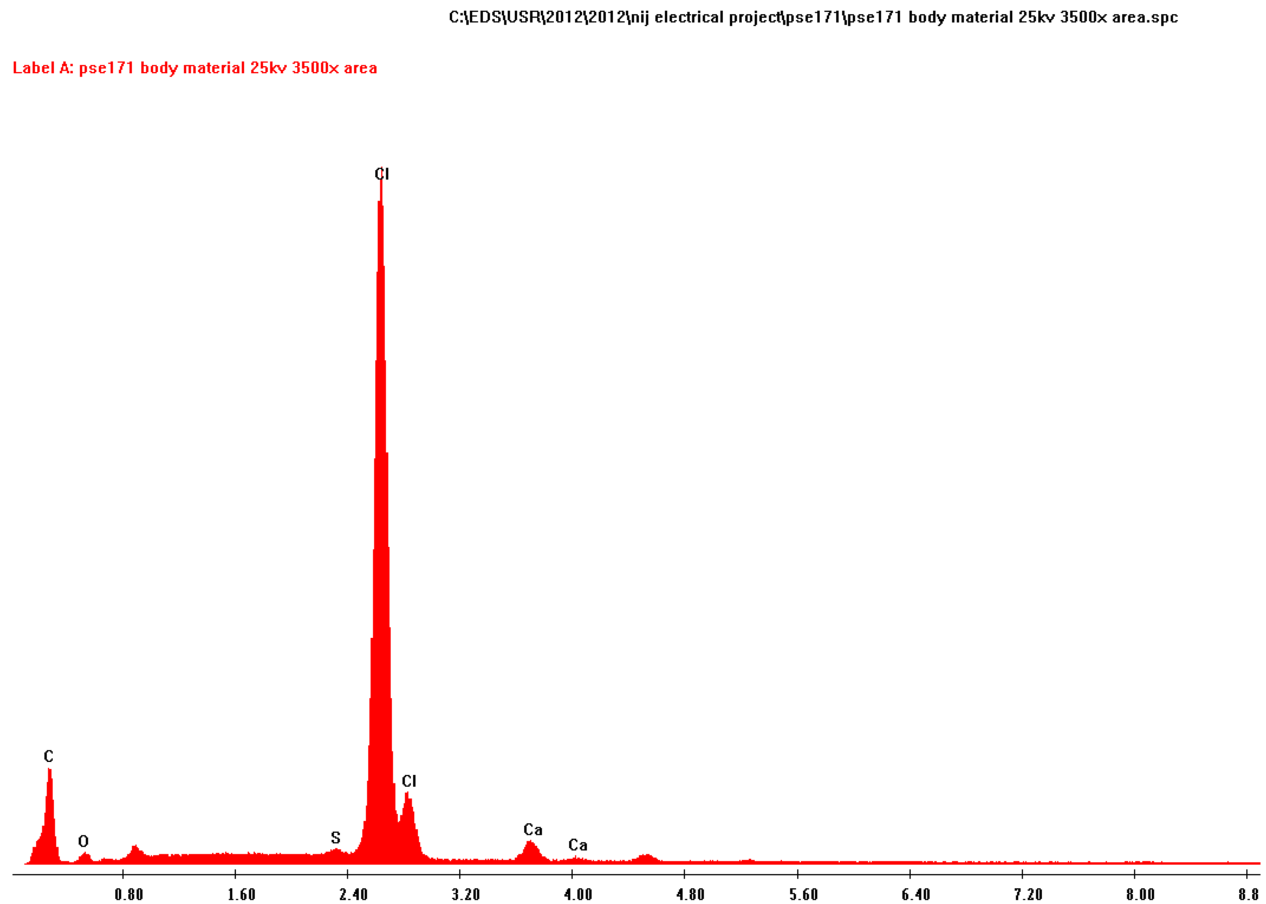


Figure E-2. EDS Spectra of back plastic body of PVC receptacle.

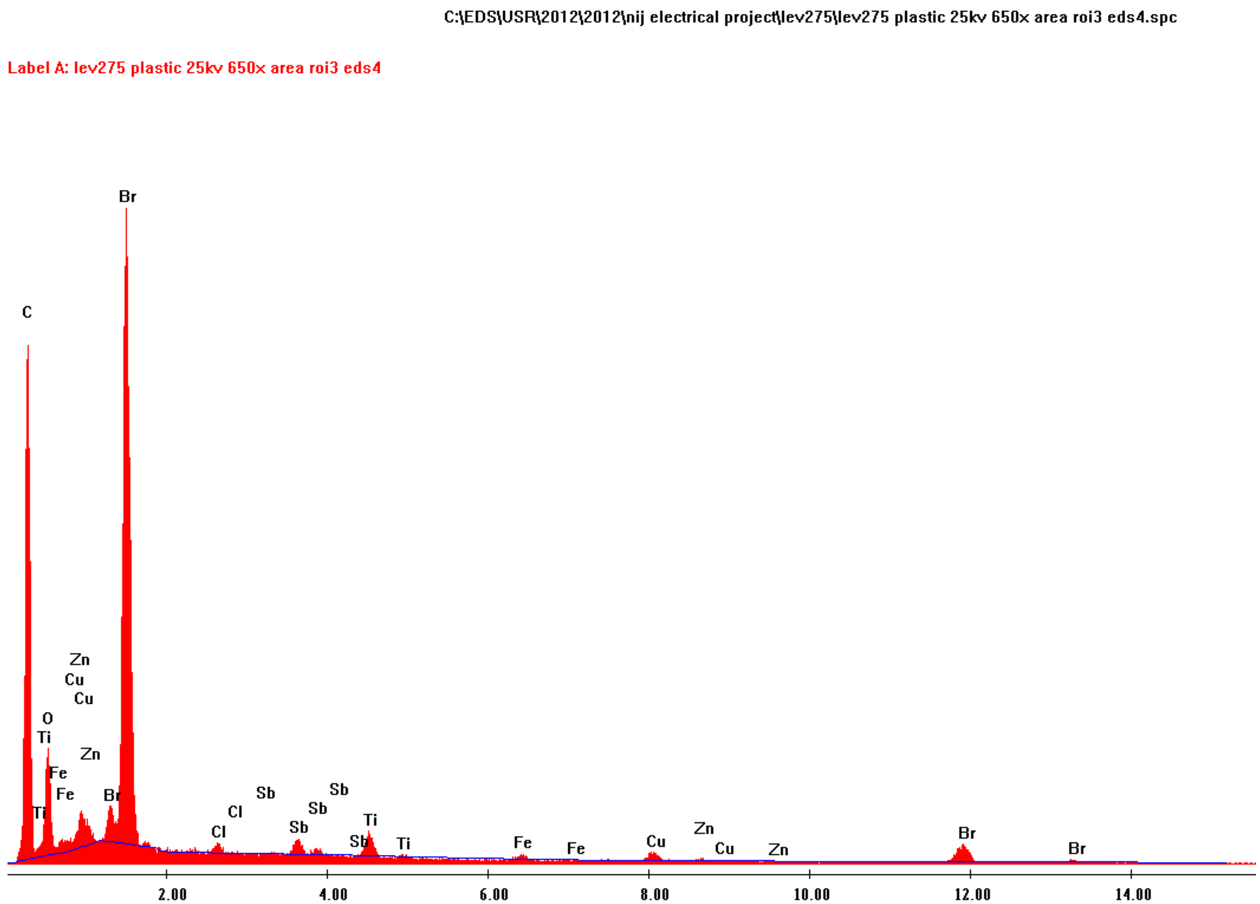


Figure E-3. EDS Spectra of front plastic face of polypropylene receptacle.

Figure E-4. EDS Spectra of back plastic body of polypropylene receptacle.

APPENDIX F – SUMMARY OF RECEPTACLES TESTED (LABORATORY TESTING)

																Evidence of Overheating Screw Terminal Connections					Evidence of Overheating Plug Connections	
Test No.	Receptacle Position	Current Draw (amps)	Receptacle S/N	Recpetacle Material	Wiring Method	Terminal Torque (in-lb)	# Insertions/ Removals	Type of Plug	Nominal Plug Retention Force (kg)	Current Duty Cycle	Vibration	Time to Failure Event (days)	Total time Tested (days)	Failure Event	Tripped Circuit Breaker During Failure Event?	Welded Conductor? With Curved Striations?	Bead Type? (wire)	Bead Type? (screw)	Enlarged Screw Head?	Evidence of Arcing?	Dezincification?	Corrosion?
1	3	15	LEV001	Polypropylene	SW	15	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	2	15	LEV002	Polypropylene	SW	15	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	1	15	LEV003	Polypropylene	SW	15	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	0	15	LEV004	Polypropylene	SW	15	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	13	15	LEV005	Polypropylene	SW	7	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	14	15	LEV006	Polypropylene	SW	7	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	15	15	LEV007	Polypropylene	SW	7	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	16	15	LEV008	Polypropylene	SW	7	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	17	15	LEV009	Polypropylene	SW	7	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	22	15	LEV010	Polypropylene	SW	5	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	21	15	LEV011	Polypropylene	SW	5	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	20	15	LEV012	Polypropylene	SW	5	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	19	15	LEV013	Polypropylene	SW	5	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	18	15	LEV014	Polypropylene	SW	5	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	33	15	LEV015	Polypropylene	SW	3	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	34	15	LEV016	Polypropylene	SW	3	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	35	15	LEV017	Polypropylene	SW	3	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	36	15	LEV018	Polypropylene	SW	3	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	37	15	LEV019	Polypropylene	SW	3	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	42	15	LEV020	Polypropylene	SW	1	-	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	41	15	LEV021	Polypropylene	SW	1	-	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	40	15	LEV022	Polypropylene	SW	1	-	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	39	15	LEV023	Polypropylene	SW	1	-	-	-	No	No	240	240	Flaming Ignition	No	No	N/A	N/A	No	No	-	-
1	38	15	LEV024	Polypropylene	SW	1	-	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	50	15	LEV025	Polypropylene	BW	-	0	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	51	15	LEV026	Polypropylene	BW	-	0	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	56	15	LEV027	Polypropylene	BW	-	1	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	57	15	LEV028	Polypropylene	BW	-	1	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	67	15	LEV029	Polypropylene	BW	-	1	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	66	15	LEV030	Polypropylene	BW	-	1	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	61	15	LEV031	Polypropylene	BW	-	2	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	60	15	LEV032	Polypropylene	BW	-	2	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	59	15	LEV033	Polypropylene	BW	-	2	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	58	15	LEV034	Polypropylene	BW	-	2	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	7	15	PSE001	PVC	SW	15	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	6	15	PSE002	PVC	SW	15	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	5	15	PSE003	PVC	SW	15	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	4	15	PSE004	PVC	SW	15	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	8	15	PSE005	PVC	SW	7	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	9	15	PSE006	PVC	SW	7	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	10	15	PSE007	PVC	SW	7	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	11	15	PSE008	PVC	SW	7	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	12	15	PSE009	PVC	SW	7	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	27	15	PSE010	PVC	SW	5	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	26	15	PSE011	PVC	SW	5	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	25	15	PSE012	PVC	SW	5	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	24	15	PSE013	PVC	SW	5	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	23	15	PSE014	PVC	SW	5	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	28	15	PSE015	PVC	SW	3	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	29	15	PSE016	PVC	SW	3	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	30	15	PSE017	PVC	SW	3	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	31	15	PSE018	PVC	SW	3	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	32	15	PSE019	PVC	SW	3	-	-	-	No	No	DNF	204	-	-	-	-	-	-	-	-	-
1	47	15	PSE020	PVC	SW	1	-	-	-	No	No	180	180	Conductor Severed, With Arc	No	No	Irregular	Irregular	No	No	-	-
1	46	15	PSE021	PVC	SW	1	-	-	-	No	No	179	179	Conductor Severed, Arc Unknown	No	Yes/Yes	Round	Round	Yes	No	-	-
1	45	15	PSE022	PVC	SW	1	-	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	44	15	PSE023	PVC	SW	1	-	-	-	No	No	175	175	Conductor Severed, Arc Unknown	No	Yes/Yes	Round	Round	Yes	No	-	-
1	43	15	PSE024	PVC	SW	1	-	-	-	No	No	142	142	Conductor Severed, Arc Unknown	No	Yes/Yes	Irregular	Round	No	No	-	-
1	48	15	PSE025	PVC	BW	-	0	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	49	15	PSE026	PVC	BW	-	0	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	52	15	PSE027	PVC	BW	-	1	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	53	15	PSE028	PVC	BW	-	1	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	54	15	PSE029	PVC	BW	-	1	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	55	15	PSE030	PVC	BW	-	1	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	65	15	PSE031	PVC	BW	-	2	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	64	15	PSE032	PVC	BW	-	2	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	63	15	PSE033	PVC	BW	-	2	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
1	62	15	PSE034	PVC	BW	-	2	-	-	No	No	DNF	511	-	-	-	-	-	-	-	-	-
2	0	15	LEV035	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	223	223	Conductor Severed, Without Arc	No	Yes/Yes	Round	Round	No	Yes, hot contact and ground strap	-	-
2	1	15	LEV036	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-

																Evidence of Overheating Screw Terminal Connections					Evidence of Overheating Plug Connections	
Test No.	Receptacle Position	Current Draw (amps)	Receptacle S/N	Recpetacle Material	Wiring Method	Terminal Torque (in-lb)	# Insertions/ Removals	Type of Plug	Nominal Plug Retention Force (kg)	Current Duty Cycle	Vibration	Time to Failure Event (days)	Total time Tested (days)	Failure Event	Tripped Circuit Breaker During Failure Event?	Welded Conductor? With Curved Striations?	Bead Type? (wire)	Bead Type? (screw)	Enlarged Screw Head?	Evidence of Arcing?	Dezincification?	Corrosion?
2	2	15	LEV037	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	62	62	Shorted, Hot to Ground	Yes	No	N/A	N/A	No	Yes	-	-
2	3	15	LEV038	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	4	15	LEV039	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	10	15	LEV040	Polypropylene	PLUG	-	-	Solid - Brass	Non-Mod	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	11	15	LEV041	Polypropylene	PLUG	-	-	Solid - Brass	0.1	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	12	15	LEV043	Polypropylene	PLUG	-	-	Solid - Brass	0.1	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	13	15	LEV045	Polypropylene	PLUG	-	-	Solid - Brass	0.1	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	14	15	LEV046	Polypropylene	PLUG	-	-	Solid - Brass	0.01	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	15	15	LEV047	Polypropylene	PLUG	-	-	Solid - Brass	0.01	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	16	15	LEV048	Polypropylene	PLUG	-	-	Solid - Brass	0.01	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	24	15	LEV049	Polypropylene	PLUG	-	-	Folded - Brass	Non-Mod	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	25	15	LEV050	Polypropylene	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	26	15	LEV051	Polypropylene	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	27	15	LEV052	Polypropylene	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	28	15	LEV053	Polypropylene	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	29	15	LEV056	Polypropylene	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	30	15	LEV057	Polypropylene	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	38	15	LEV058	Polypropylene	PLUG	-	-	Solid - Plated	Non-Mod	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	39	15	LEV059	Polypropylene	PLUG	-	-	Solid - Plated	0.1	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	40	15	LEV060	Polypropylene	PLUG	-	-	Solid - Plated	0.1	Yes	No	62	62	Flaming Ignition	No	N/A	N/A	N/A	N/A	Hot plug blade and hot receptacle contact	Yes	Yes
2	41	15	LEV061	Polypropylene	PLUG	-	-	Solid - Plated	0.1	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	42	15	LEV062	Polypropylene	PLUG	-	-	Solid - Plated	0.01	Yes	No	62	62	Flaming Ignition	No	N/A	N/A	N/A	N/A	Between hot plug blade and hot internal receptacle contact.	Yes	No
2	43	15	LEV063	Polypropylene	PLUG	-	-	Solid - Plated	0.01	Yes	No	268	268	Flaming Ignition	Yes	N/A	N/A	N/A	N/A	Arcing between hot receptacle contacts and ground strap.	No	No
2	44	15	LEV064	Polypropylene	PLUG	-	-	Solid - Plated	0.01	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	5	15	PSE038	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	6	15	PSE039	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	17	15	PSE040	PVC	PLUG	-	-	Solid - Brass	Non-Mod	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	18	15	PSE041	PVC	PLUG	-	-	Solid - Brass	0.1	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	19	15	PSE042	PVC	PLUG	-	-	Solid - Brass	0.1	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	20	15	PSE043	PVC	PLUG	-	-	Solid - Brass	0.1	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	21	15	PSE044	PVC	PLUG	-	-	Solid - Brass	0.01	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	22	15	PSE045	PVC	PLUG	-	-	Solid - Brass	0.01	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	23	15	PSE046	PVC	PLUG	-	-	Solid - Brass	0.01	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	31	15	PSE047	PVC	PLUG	-	-	Folded - Brass	Non-Mod	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	32	15	PSE048	PVC	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	33	15	PSE049	PVC	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	34	15	PSE050	PVC	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	35	15	PSE051	PVC	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	36	15	PSE052	PVC	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	37	15	PSE053	PVC	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	45	15	PSE054	PVC	PLUG	-	-	Solid - Plated	Non-Mod	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	46	15	PSE055	PVC	PLUG	-	-	Solid - Plated	0.1	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	47	15	PSE056	PVC	PLUG	-	-	Solid - Plated	0.1	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	48	15	PSE057	PVC	PLUG	-	-	Solid - Plated	0.1	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	49	15	PSE058	PVC	PLUG	-	-	Solid - Plated	0.01	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	50	15	PSE059	PVC	PLUG	-	-	Solid - Plated	0.01	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	51	15	PSE060	PVC	PLUG	-	-	Solid - Plated	0.01	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	7	15	PSE061	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	8	15	PSE062	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
2	9	15	PSE063	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	415	-	-	-	-	-	-	-	-	-
3	0	15	LEV101	Polypropylene	BW	-	0	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	1	15	LEV102	Polypropylene	BW	-	0	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	2	15	LEV103	Polypropylene	BW	-	0	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	3	15	LEV104	Polypropylene	BW	-	0	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	9	15	LEV105	Polypropylene	BW	-	1	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	10	15	LEV106	Polypropylene	BW	-	1	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	11	15	LEV107	Polypropylene	BW	-	1	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	12	15	LEV108	Polypropylene	BW	-	1	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	13	15	LEV109	Polypropylene	BW	-	1	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	15	15	LEV110	Polypropylene	BW	-	1	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	16	15	LEV111	Polypropylene	BW	-	1	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	24	15	LEV112	Polypropylene	SW	3	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	25	15	LEV113	Polypropylene	SW	3	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	26	15	LEV114	Polypropylene	SW	3	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	27	15	LEV115	Polypropylene	SW	3	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	32	15	LEV116	Polypropylene	SW	1	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	33	15	LEV117	Polypropylene	SW	1	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	34	15	LEV118	Polypropylene	SW	1	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	35	15	LEV119	Polypropylene	SW	1	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-

																Evidence of Overheating Screw Terminal Connections					Evidence of Overheating Plug Connections	
Test No.	Receptacle Position	Current Draw (amps)	Receptacle S/N	Recpetacle Material	Wiring Method	Terminal Torque (in-lb)	# Insertions/ Removals	Type of Plug	Nominal Plug Retention Force (kg)	Current Duty Cycle	Vibration	Time to Failure Event (days)	Total time Tested (days)	Failure Event	Tripped Circuit Breaker During Failure Event?	Welded Conductor? With Curved Striations?	Bead Type? (wire)	Bead Type? (screw)	Enlarged Screw Head?	Evidence of Arcing?	Dezincification?	Corrosion?
3	36	15	LEV120	Polypropylene	SW	1	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	37	15	LEV121	Polypropylene	SW	1	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	38	15	LEV122	Polypropylene	SW	1	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	46	15	LEV123	Polypropylene	SW	1/4 Turn Loose	-	-	-	No	Yes	59	59	Shorted, Neutral to Ground	No	No	N/A	N/A	No	No	-	-
3	47	15	LEV124	Polypropylene	SW	1/4 Turn Loose	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	48	15	LEV125	Polypropylene	SW	1/4 Turn Loose	-	-	-	No	Yes	59	59	Shorted, Neutral to Ground	No	No	N/A	N/A	No	Between top neutral contact and ground strap	-	-
3	49	15	LEV126	Polypropylene	SW	1/4 Turn Loose	-	-	-	No	Yes	122	122	Shorted, Hot to Ground	Yes	No	N/A	N/A	No	Between top hot contact and ground strap	-	-
3	50	15	LEV127	Polypropylene	SW	1/4 Turn Loose	-	-	-	No	Yes	118	118	Conductor Severed, Without Arc	No	Yes (2)/Yes (2)	Round	Round	No	No	-	-
3	51	15	LEV128	Polypropylene	SW	1/4 Turn Loose	-	-	-	No	Yes	117	117	Shorted, Hot to Ground	Yes	No	N/A	N/A	No	Yes	-	-
3	52	15	LEV129	Polypropylene	SW	1/4 Turn Loose	-	-	-	No	Yes	87	87	Shorted, Neutral to Ground	No	No	N/A	N/A	No	No	-	-
3	4	15	PSE107	PVC	BW	-	0	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	6	15	PSE108	PVC	BW	-	0	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	7	15	PSE109	PVC	BW	-	0	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	8	15	PSE110	PVC	BW	-	0	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	17	15	PSE111	PVC	BW	-	1	-	-	No	Yes	341	341	Flaming Ignition	No	N/A	N/A	N/A	N/A	Series arcing; bottom Neutral	-	-
3	18	15	PSE112	PVC	BW	-	1	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	19	15	PSE113	PVC	BW	-	1	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	20	15	PSE114	PVC	BW	-	1	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	21	15	PSE115	PVC	BW	-	1	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	22	15	PSE116	PVC	BW	-	1	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	23	15	PSE117	PVC	BW	-	1	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	28	15	PSE118	PVC	SW	3	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	29	15	PSE119	PVC	SW	3	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	30	15	PSE120	PVC	SW	3	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	31	15	PSE121	PVC	SW	3	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	39	15	PSE122	PVC	SW	1	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	40	15	PSE123	PVC	SW	1	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	41	15	PSE124	PVC	SW	1	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	42	15	PSE125	PVC	SW	1	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	43	15	PSE126	PVC	SW	1	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	44	15	PSE127	PVC	SW	1	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	45	15	PSE128	PVC	SW	1	-	-	-	No	Yes	DNF	397	-	-	-	-	-	-	-	-	-
3	53	15	PSE129	PVC	SW	1/4 Turn Loose	-	-	-	No	Yes	81	81	Shorted, Neutral to Ground	No	Yes/No	N/A	N/A	Yes	No	-	-
3	54	15	PSE130	PVC	SW	1/4 Turn Loose	-	-	-	No	Yes	243	243	Shorted, Hot to Ground	Yes	No	N/A	N/A	No	Top Hot contact and ground strap	-	-
3	55	15	PSE131	PVC	SW	1/4 Turn Loose	-	-	-	No	Yes	115	115	Shorted, Hot to Ground	Yes	No	N/A	N/A	No	Yes	-	-
3	56	15	PSE132	PVC	SW	1/4 Turn Loose	-	-	-	No	Yes	87	87	Conductor Severed, With Arc	No	Yes/No	Round	Irregular	Yes	No	-	-
3	57	15	PSE133	PVC	SW	1/4 Turn Loose	-	-	-	No	Yes	90	90	Conductor Severed, Without Arc	No	Yes/No	Round	Round	Yes	No	-	-
3	58	15	PSE134	PVC	SW	1/4 Turn Loose	-	-	-	No	Yes	112	112	Conductor Severed, With Arc	No	Yes/No	Irregular	Irregular	Yes	No	-	-
3	59	15	PSE135	PVC	SW	1/4 Turn Loose	-	-	-	No	Yes	235	235	Conductor Severed, With Arc	No	Yes/No	Irregular	Irregular	Yes	No	-	-
4	5	15	LEV169	Polypropylene	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	6	15	LEV170	Polypropylene	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	313	313	Conductor Severed, Arc Unknown	No	Yes (2)/No (2)	Round	Round, 3/4" away from screw	No	Series arcing; Hot wire	-	-
4	7	15	LEV171	Polypropylene	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	195	195	Shorted, Hot to Ground	Yes	No	N/A	N/A	No	Between top hot contact and ground strap/ground pin contact	-	-
4	8	15	LEV172	Polypropylene	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	324	324	Shorted, Neutral to Ground	No	Yes/Yes	Round	Irregular	No	Top Neutral wire to Bottom Hot wire; Top Neutral contact to ground strap	-	-
4	9	15	LEV173	Polypropylene	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	39	39	Flaming Ignition	No	Yes (2)/Yes (2)	2 Round	2 Round	No	Yes	-	-
4	21	15	LEV174	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	313	313	Shorted, Neutral to Ground	No	No	N/A	N/A	No	Top Hot contact and ground strap	-	-
4	22	15	LEV175	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	313	313	Shorted, Neutral to Ground	No	No	N/A	N/A	No	No	-	-
4	23	15	LEV176	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	322	322	Conductor Severed, Arc Unknown	No	Yes/No	Irregular	Round (concave)	Yes	No	-	-
4	24	15	LEV177	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	46	46	Shorted, Neutral to Ground	No	No	N/A	N/A	No	No	-	-
4	25	15	LEV178	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	26	15	LEV179	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	27	15	LEV180	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-

																Evidence of Overheating Screw Terminal Connections					Evidence of Overheating Plug Connections	
Test No.	Receptacle Position	Current Draw (amps)	Receptacle S/N	Recpetacle Material	Wiring Method	Terminal Torque (in-lb)	# Insertions/ Removals	Type of Plug	Nominal Plug Retention Force (kg)	Current Duty Cycle	Vibration	Time to Failure Event (days)	Total time Tested (days)	Failure Event	Tripped Circuit Breaker During Failure Event?	Welded Conductor? With Curved Striations?	Bead Type? (wire)	Bead Type? (screw)	Enlarged Screw Head?	Evidence of Arcing?	Dezincification?	Corrosion?
4	28	15	LEV181	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	29	15	LEV182	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	104	104	Shorted, Hot to Ground	Yes	Yes/Yes	N/A	N/A	No	Yes	-	-
4	30	15	LEV183	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	31	15	LEV184	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	43	15	LEV185	Polypropylene	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	44	15	LEV186	Polypropylene	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	45	15	LEV187	Polypropylene	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	46	15	LEV188	Polypropylene	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	47	15	LEV189	Polypropylene	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	48	15	LEV190	Polypropylene	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	49	15	LEV191	Polypropylene	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	50	15	LEV192	Polypropylene	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	51	15	LEV193	Polypropylene	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	52	15	LEV194	Polypropylene	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	53	15	LEV195	Polypropylene	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	66	15	LEV196	Polypropylene	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	67	15	LEV197	Polypropylene	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	68	15	LEV198	Polypropylene	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	69	15	LEV199	Polypropylene	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	70	15	LEV200	Polypropylene	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	71	15	LEV201	Polypropylene	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	72	15	LEV202	Polypropylene	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	73	15	LEV203	Polypropylene	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	74	15	LEV204	Polypropylene	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	75	15	LEV205	Polypropylene	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	76	15	LEV206	Polypropylene	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	77	15	LEV207	Polypropylene	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	0	15	PSE164	PVC	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	Unknown	330	Conductor Severed, Arc Unknown	No	Yes/No	Irregular	Irregular	Yes	No	-	-
4	1	15	PSE165	PVC	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	227	227	Flaming Ignition	No	Yes (2)/No (2)	2 Irregular	2 Irregular	Yes (3)	Top Hot contact and ground strap	-	-
4	2	15	PSE166	PVC	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	193	193	Flaming Ignition	No	No	N/A	N/A	No	Yes	-	-
4	3	15	PSE167	PVC	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	4	15	PSE168	PVC	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	10	15	PSE169	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	11	15	PSE170	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	146	146	Conductor Severed, With Arc	No	Yes/Yes	Irregular	Irregular	Yes	No	-	-
4	12	15	PSE171	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	13	15	PSE172	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	326	326	Conductor Severed, Arc Unknown	No	No	Irregular	Irregular	Yes	No	-	-
4	14	15	PSE173	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	279	279	Conductor Severed, Arc Unknown	No	Yes/No	Irregular	Round 1/4" from screw	Yes	No	-	-
4	15	15	PSE174	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	305	305	Flaming Ignition	No	Yes/No	Irregular	Irregular	Yes	No	-	-
4	16	15	PSE175	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	255	255	Flaming Ignition	No	Yes (2)/ No (2)	2 Irregular, 1 round (from arcing)	2 Irregular, 1 round (arcing 1/4" from screw)	Yes	Bottom Hot contact and ground strap	-	-
4	17	15	PSE176	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	318	318	Flaming ignition	No	Yes/No	Irregular	Irregular	Yes	No (evidence of melting of brass!!!)	-	-
4	18	15	PSE177	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	182	182	Conductor Severed, With Arc	No	Yes/No	Round	Round	Yes	No	-	-
4	19	15	PSE178	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	20	15	PSE179	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	32	15	PSE180	PVC	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	33	15	PSE181	PVC	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	34	15	PSE182	PVC	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	35	15	PSE183	PVC	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	36	15	PSE184	PVC	SW	1	-	-	-	Yes	No	225	225	Conductor Severed, Arc Unknown	No	Yes/Yes	Round	Round	No	No	-	-
4	37	15	PSE185	PVC	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	38	15	PSE186	PVC	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	39	15	PSE187	PVC	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	40	15	PSE188	PVC	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	41	15	PSE189	PVC	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	42	15	PSE190	PVC	SW	1	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	54	15	PSE191	PVC	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	55	15	PSE192	PVC	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	56	15	PSE193	PVC	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	57	15	PSE194	PVC	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	58	15	PSE195	PVC	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	59	15	PSE196	PVC	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	60	15	PSE197	PVC	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	61	15	PSE198	PVC	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	62	15	PSE199	PVC	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	63	15	PSE200	PVC	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-

																Evidence of Overheating Screw Terminal Connections					Evidence of Overheating Plug Connections	
Test No.	Receptacle Position	Current Draw (amps)	Receptacle S/N	Receptacle Material	Wiring Method	Terminal Torque (in-lb)	# Insertions/ Removals	Type of Plug	Nominal Plug Retention Force (kg)	Current Duty Cycle	Vibration	Time to Failure Event (days)	Total time Tested (days)	Failure Event	Tripped Circuit Breaker During Failure Event?	Welded Conductor? With Curved Striations?	Bead Type? (wire)	Bead Type? (screw)	Enlarged Screw Head?	Evidence of Arcing?	Dezincification?	Corrosion?
4	64	15	PSE201	PVC	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
4	65	15	PSE202	PVC	SW	3	-	-	-	Yes	No	DNF	377	-	-	-	-	-	-	-	-	-
5	5	3, 6, and 9	LEV208	Polypropylene	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	6	3, 6, and 9	LEV209	Polypropylene	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	7	3, 6, and 9	LEV210	Polypropylene	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	8	3, 6, and 9	LEV211	Polypropylene	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	9	3, 6, and 9	LEV212	Polypropylene	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	27	3, 6, and 9	LEV213	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	28	3, 6, and 9	LEV214	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	29	3, 6, and 9	LEV215	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	30	3, 6, and 9	LEV216	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	31	3, 6, and 9	LEV217	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	32	3, 6, and 9	LEV218	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	33	3, 6, and 9	LEV219	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	34	3, 6, and 9	LEV220	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	35	3, 6, and 9	LEV221	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	36	3, 6, and 9	LEV222	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	37	3, 6, and 9	LEV223	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	38	3, 6, and 9	LEV224	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	39	3, 6, and 9	LEV225	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	40	3, 6, and 9	LEV226	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	41	3, 6, and 9	LEV227	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	42	3, 6, and 9	LEV228	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	43	3, 6, and 9	LEV229	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	61	3, 6, and 9	LEV230	Polypropylene	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	62	3, 6, and 9	LEV231	Polypropylene	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	63	3, 6, and 9	LEV232	Polypropylene	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	64	3, 6, and 9	LEV233	Polypropylene	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	65	3, 6, and 9	LEV234	Polypropylene	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	66	3, 6, and 9	LEV235	Polypropylene	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	67	3, 6, and 9	LEV236	Polypropylene	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	68	3, 6, and 9	LEV237	Polypropylene	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	69	3, 6, and 9	LEV238	Polypropylene	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	70	3, 6, and 9	LEV239	Polypropylene	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	71	3, 6, and 9	LEV240	Polypropylene	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	72	3, 6, and 9	LEV241	Polypropylene	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	73	3, 6, and 9	LEV242	Polypropylene	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	74	3, 6, and 9	LEV243	Polypropylene	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	75	3, 6, and 9	LEV244	Polypropylene	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	76	3, 6, and 9	LEV245	Polypropylene	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	77	3, 6, and 9	LEV246	Polypropylene	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	0	3, 6, and 9	PSE203	PVC	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	1	3, 6, and 9	PSE204	PVC	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	2	3, 6, and 9	PSE205	PVC	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	3	3, 6, and 9	PSE206	PVC	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	4	3, 6, and 9	PSE207	PVC	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	10	3, 6, and 9	PSE208	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	11	3, 6, and 9	PSE209	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	12	3, 6, and 9	PSE210	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	13	3, 6, and 9	PSE211	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	14	3, 6, and 9	PSE212	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	15	3, 6, and 9	PSE213	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	16	3, 6, and 9	PSE214	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	17	3, 6, and 9	PSE215	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	18	3, 6, and 9	PSE216	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	190	190	Conductor Severed, Without Arc	No	Yes/No	Round	Round	Yes	No	-	-
5	19	3, 6, and 9	PSE217	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	20	3, 6, and 9	PSE218	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	21	3, 6, and 9	PSE219	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	22	3, 6, and 9	PSE220	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	23	3, 6, and 9	PSE221	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	24	3, 6, and 9	PSE222	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	25	3, 6, and 9	PSE223	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	26	3, 6, and 9	PSE224	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	44	3, 6, and 9	PSE225	PVC	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	45	3, 6, and 9	PSE226	PVC	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	46	3, 6, and 9	PSE227	PVC	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	47	3, 6, and 9	PSE228	PVC	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	48	3, 6, and 9	PSE229	PVC	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	49	3, 6, and 9	PSE230	PVC	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	50	3, 6, and 9	PSE231	PVC	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	51	3, 6, and 9	PSE232	PVC	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	52	3, 6, and 9	PSE233	PVC	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	53	3, 6, and 9	PSE234	PVC	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	54	3, 6, and 9	PSE235	PVC	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-

																Evidence of Overheating Screw Terminal Connections					Evidence of Overheating Plug Connections	
Test No.	Receptacle Position	Current Draw (amps)	Receptacle S/N	Recpetacle Material	Wiring Method	Terminal Torque (in-lb)	# Insertions/ Removals	Type of Plug	Nominal Plug Retention Force (kg)	Current Duty Cycle	Vibration	Time to Failure Event (days)	Total time Tested (days)	Failure Event	Tripped Circuit Breaker During Failure Event?	Welded Conductor? With Curved Striations?	Bead Type? (wire)	Bead Type? (screw)	Enlarged Screw Head?	Evidence of Arcing?	Dezincification?	Corrosion?
5	55	3, 6, and 9	PSE236	PVC	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	56	3, 6, and 9	PSE237	PVC	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	57	3, 6, and 9	PSE238	PVC	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	58	3, 6, and 9	PSE239	PVC	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	59	3, 6, and 9	PSE240	PVC	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
5	60	3, 6, and 9	PSE241	PVC	SW	1	-	-	-	Yes	No	DNF	192	-	-	-	-	-	-	-	-	-
6	10	15	A001	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	56	56	Serial Arcing-Open Circuit	No	No	N/A	N/A	No	Yes	-	-
6	11	15	A002	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	12	15	A003	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	13	15	A004	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	14	15	B001	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	206	206	Conductor Severed, With Arc	No	Yes (2)/Yes (2)	Round	Round	No	No	-	-
6	15	15	B002	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	16	15	B003	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	17	15	B004	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	18	15	B005	Phenolic	SW	3	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	19	15	B006	Phenolic	SW	3	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	20	15	C001	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	21	15	C002	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	53	53	Conductor Severed, Without Arc	No	Yes/Yes	Round	Round	No	No	-	-
6	22	15	C003	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	23	15	C004	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	161	161	Conductor Severed, With Arc	No	Yes/Yes	Round	Round	No	No	-	-
6	24	15	C005	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	25	15	C006	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	28	15	C007	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	30	15	C008	Phenolic	SW	1	-	-	-	Yes	No	255	255	Conductor Severed, Arc Unknown	No	Yes/Yes	Irregular	Round	No	No	-	-
6	26	15	C009	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	63	63	Conductor Severed, Without Arc	No	Yes/Yes	Round	Round	No	No	-	-
6	29	15	C010	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	27	15	C011	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	31	15	C012	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	32	15	C013	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	33	15	C014	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	34	15	C015	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	35	15	D001	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	36	15	D002	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	75	75	Conductor Severed, Without Arc	No	Yes/Yes	Round	Round	No	No	-	-
6	37	15	D003	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	314	314	Conductor Severed, Arc Unknown	No	Yes/Yes	Round	Round	No	No	-	-
6	38	15	D004	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	39	15	D005	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	40	15	D006	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	41	15	D007	Phenolic	SW	3	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	42	15	D008	Phenolic	SW	3	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	43	15	D009	Phenolic	SW	3	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	44	15	E001	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	342	342	Shorted, Hot to Neutral (wires)	No	No	2 Round/Irregular (from arcing)	2 Round/Irregular (from arcing)	No	Hot and Neutral wires 1" behind receptacle	-	-
6	45	15	E002	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	46	15	E003	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	26	26	Conductor Severed, Without Arc	No	Yes/Yes	Round	Round	No	No	-	-
6	52	15	E004	Phenolic	SW	1	-	-	-	Yes	No	115	115	Conductor Severed, Without Arc	No	Yes/Yes	Round	Round	No	No	-	-
6	53	15	E005	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	58	15	E006	Phenolic	SW	3	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	59	15	E007	Phenolic	SW	3	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	51	15	E008	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	47	15	E009	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	228	228	Conductor Severed, Arc Unknown	No	Yes (2)/Yes (1), No (1)	Round	Round	No	No	-	-
6	48	15	E010	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	278	278	Conductor Severed, Arc Unknown	No	Yes/Yes	Round	Round	No	No	-	-
6	54	15	E011	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	55	15	E012	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	56	15	E013	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	57	15	E014	Phenolic	SW	1	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	49	15	E015	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	50	15	E016	Phenolic	SW	1/4 Turn Loose	-	-	-	Yes	No	115	115	Conductor Severed, With Arc	No	No	Round	Round	No	No	-	-
6	60	15	E017	Phenolic	SW	3	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	61	15	E018	Phenolic	SW	3	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	5	15	LEV265	Polypropylene	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	213	213	Flaming Ignition	No	Yes/Yes	N/A	N/A	No	Hot contacts and ground strap; hot and neutral wires	-	-

															Evidence of Overheating Screw Terminal Connections					Evidence of Overheating Plug Connections	
Test No.	Receptacle Position	Current Draw (amps)	Receptacle S/N	Recpetacle Material	Wiring Method	Terminal Torque (in-lb)	# Insertions/ Removals	Type of Plug	Nominal Plug Retention Force (kg)	Current Duty Cycle	Vibration	Time to Failure Event (days)	Total time Tested (days)	Failure Event	Tripped Circuit Breaker During Failure Event?	Welded Conductor? With Curved Striations?	Bead Type? (wire)	Bead Type? (screw)	Enlarged Screw Head?	Evidence of Arcing?	Dezincification?	Corrosion?
6	6	15	LEV266	Polypropylene	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	279	279	Flaming Ignition	No	No	Irregular	Irregular	No	Hot contacts and ground strap	-	-
6	7	15	LEV267	Polypropylene	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	47	47	Conductor Severed, Without Arc	No	Yes/Yes	Round	Round	No	No	-	-
6	8	15	LEV268	Polypropylene	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	56	56	Shorted, Hot to Ground	Yes	No	N/A	N/A	No	Between top hot contact and ground strap	-	-
6	9	15	LEV269	Polypropylene	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	48	48	Flaming Ignition	Yes	Yes (2)/Yes (2)	Irregular	No	No	Yes	-	-
6	70	15	LEV270	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	254	254	Shorted, Hot to Ground	Yes	Yes/No	N/A	N/A	No	Top Hot contact and ground strap	-	-
6	71	15	LEV271	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	72	15	LEV272	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	19	19	Conductor Severed, Without Arc	No	Yes/Yes	Round	Round	No	No	-	-
6	73	15	LEV273	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	20	20	Shorted, Neutral to Ground	No	No	N/A	N/A	No	No	-	-
6	74	15	LEV274	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	75	15	LEV275	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	18	18	Flaming Ignition	No	Yes/Yes	Round	Irregular	No	No	-	-
6	76	15	LEV276	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	157	157	Shorted, Hot to Ground	Yes	No	N/A	N/A	No	Between top hot contact and ground strap	-	-
6	77	15	LEV277	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	62	62	Conductor Severed, With Arc	No	Yes (2)/Yes (2)	Round	Round	No	No	-	-
6	0	15	PSE260	PVC	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	225	225	Conductor Severed, Without Arc	No	Yes/No	Irregular	Irregular	Yes	Bottom Hot contact and ground strap	-	-
6	1	15	PSE261	PVC	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	2	15	PSE262	PVC	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	3	15	PSE263	PVC	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	62	62	Conductor Severed, With Arc	No	No	Round	None, part of brass terminal missing.	Yes	No	-	-
6	4	15	PSE264	PVC	Box - SW	1/4 Turn Loose	-	-	-	Yes	No	249	249	Conductor Severed, Arc Unknown	No	Yes/No	Round	Irregular	Yes	No	-	-
6	62	15	PSE265	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	63	15	PSE266	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	64	15	PSE267	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	65	15	PSE268	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
6	66	15	PSE269	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	365	365	Shorted, Hot to Ground	Yes	No	N/A	N/A	Yes	Top Hot contact and ground strap	-	-
6	67	15	PSE270	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	311	311	Conductor Severed, Without Arc	No	Yes/No	Round	Round	Yes	No	-	-
6	68	15	PSE271	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	213	213	Conductor Severed, Without Arc	No	Yes/Yes	Round	Round	Yes	No	-	-
6	69	15	PSE272	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	367	-	-	-	-	-	-	-	-	-
7	5	15	LEV278	Polypropylene	Box - PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	6	15	LEV279	Polypropylene	Box - PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	7	15	LEV280	Polypropylene	Box - PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	8	15	LEV281	Polypropylene	Box - PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	9	15	LEV282	Polypropylene	Box - PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	44	15	LEV283	Polypropylene	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	45	15	LEV284	Polypropylene	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	46	15	LEV285	Polypropylene	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	47	15	LEV286	Polypropylene	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	183	183	Flaming Ignition	No	N/A	N/A	N/A	N/A	Ground pin arcing damage	Yes	No
7	48	15	LEV287	Polypropylene	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	49	15	LEV288	Polypropylene	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	50	15	LEV289	Polypropylene	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	51	15	LEV290	Polypropylene	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	52	15	LEV291	Polypropylene	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	53	15	LEV292	Polypropylene	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	54	15	LEV293	Polypropylene	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	55	15	LEV294	Polypropylene	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	56	15	LEV295	Polypropylene	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	57	15	LEV296	Polypropylene	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	58	15	LEV297	Polypropylene	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	59	15	LEV298	Polypropylene	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	60	15	LEV299	Polypropylene	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	61	15	LEV300	Polypropylene	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	62	15	LEV301	Polypropylene	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	63	15	LEV302	Polypropylene	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	64	15	LEV303	Polypropylene	PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	65	15	LEV304	Polypropylene	PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	66	15	LEV305	Polypropylene	PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	67	15	LEV306	Polypropylene	PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	68	15	LEV307	Polypropylene	PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	69	15	LEV308	Polypropylene	PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	70	15	LEV309	Polypropylene	PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	71	15	LEV310	Polypropylene	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	72	15	LEV311	Polypropylene	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	73	15	LEV312	Polypropylene	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-

																Evidence of Overheating Screw Terminal Connections					Evidence of Overheating Plug Connections	
Test No.	Receptacle Position	Current Draw (amps)	Receptacle S/N	Recpetacle Material	Wiring Method	Terminal Torque (in-lb)	# Insertions/ Removals	Type of Plug	Nominal Plug Retention Force (kg)	Current Duty Cycle	Vibration	Time to Failure Event (days)	Total time Tested (days)	Failure Event	Tripped Circuit Breaker During Failure Event?	Welded Conductor? With Curved Striations?	Bead Type? (wire)	Bead Type? (screw)	Enlarged Screw Head?	Evidence of Arcing?	Dezincification?	Corrosion?
7	74	15	LEV313	Polypropylene	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	75	15	LEV314	Polypropylene	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	76	15	LEV315	Polypropylene	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	77	15	LEV316	Polypropylene	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	0	15	PSE273	PVC	Box - PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	1	15	PSE274	PVC	Box - PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	2	15	PSE275	PVC	Box - PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	3	15	PSE276	PVC	Box - PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	4	15	PSE277	PVC	Box - PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	10	15	PSE278	PVC	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	11	15	PSE279	PVC	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	12	15	PSE280	PVC	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	13	15	PSE281	PVC	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	14	15	PSE282	PVC	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	15	15	PSE283	PVC	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	16	15	PSE284	PVC	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	17	15	PSE285	PVC	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	110	110	Flaming Ignition	Yes	N/A	N/A	N/A	N/A	Hot Plug blade and ground strap	Yes	No
7	18	15	PSE286	PVC	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	19	15	PSE287	PVC	PLUG	-	-	Solid - Plated w/ G	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	20	15	PSE288	PVC	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	21	15	PSE289	PVC	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	22	15	PSE290	PVC	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	23	15	PSE291	PVC	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	24	15	PSE292	PVC	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	25	15	PSE293	PVC	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	26	15	PSE294	PVC	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	27	15	PSE295	PVC	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	28	15	PSE296	PVC	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	29	15	PSE297	PVC	PLUG	-	-	Folded - Brass	0.01	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	30	15	PSE298	PVC	PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	31	15	PSE299	PVC	PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	32	15	PSE300	PVC	PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	33	15	PSE301	PVC	PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	34	15	PSE302	PVC	PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	35	15	PSE303	PVC	PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	36	15	PSE304	PVC	PLUG	-	-	Solid - Plated w/ G	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	37	15	PSE305	PVC	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	38	15	PSE306	PVC	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	39	15	PSE307	PVC	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	40	15	PSE308	PVC	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	41	15	PSE309	PVC	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	42	15	PSE310	PVC	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
7	43	15	PSE311	PVC	PLUG	-	-	Folded - Brass	0.1	Yes	No	DNF	382	-	-	-	-	-	-	-	-	-
1A	3	15	LEV001	Polypropylene	SW	1	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	2	15	LEV002	Polypropylene	SW	1	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	1	15	LEV003	Polypropylene	SW	1	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	0	15	LEV004	Polypropylene	SW	1	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	13	15	LEV005	Polypropylene	SW	1	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	14	15	LEV006	Polypropylene	SW	1	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	15	15	LEV007	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	16	15	LEV008	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	14	14	Shorted, Neutral to Ground	No	No	N/A	N/A	No	Yes	-	-
1A	17	15	LEV009	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	21	21	Shorted, Neutral to Ground	No	No	N/A	N/A	No	Yes	-	-
1A	22	15	LEV010	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	36	36	Shorted, Hot to Ground	Yes	No	N/A	N/A	No	Between top hot contact and ground strap	-	-
1A	21	15	LEV011	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	46	46	Shorted, Hot to Ground	Yes	No	N/A	N/A	No	Yes	-	-
1A	20	15	LEV012	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	21	21	Conductor Severed, Arc Unknown	No	Yes/Yes	Round	Round	No	No	-	-
1A	19	15	LEV013	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	161	161	Conductor Severed, With Arc	Yes	Yes/Yes	Flat	Irregular	No	Yes	-	-
1A	18	15	LEV014	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	5	5	Shorted, Hot to Ground	Yes	No	N/A	N/A	No	Between top hot contact and ground strap	-	-
1A	33	15	LEV015	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	158	158	Shorted, Hot to Ground	Yes	No	N/A	N/A	No	Between top hot contact and ground strap	-	-
1A	34	15	LEV016	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	21	21	Shorted, Neutral to Ground	No	No	N/A	N/A	No	No	-	-
1A	35	15	LEV017	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	36	15	LEV018	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	88	88	Conductor Severed, Without Arc	No	Yes (2)/Yes (2)	Flat	Round	No	No	-	-
1A	37	15	LEV019	Polypropylene	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	7	15	PSE001	PVC	SW	1	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	6	15	PSE002	PVC	SW	1	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-

																Evidence of Overheating Screw Terminal Connections					Evidence of Overheating Plug Connections	
Test No.	Receptacle Position	Current Draw (amps)	Receptacle S/N	Recpetacle Material	Wiring Method	Terminal Torque (in-lb)	# Insertions/ Removals	Type of Plug	Nominal Plug Retention Force (kg)	Current Duty Cycle	Vibration	Time to Failure Event (days)	Total time Tested (days)	Failure Event	Tripped Circuit Breaker During Failure Event?	Welded Conductor? With Curved Striations?	Bead Type? (wire)	Bead Type? (screw)	Enlarged Screw Head?	Evidence of Arcing?	Dezincification?	Corrosion?
1A	5	15	PSE003	PVC	SW	1	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	4	15	PSE004	PVC	SW	1	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	8	15	PSE005	PVC	SW	1	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	9	15	PSE006	PVC	SW	1	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	10	15	PSE007	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	11	15	PSE008	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	12	15	PSE009	PVC	SW	1	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	27	15	PSE010	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	26	15	PSE011	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	25	15	PSE012	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	285	285	Conductor Severed, Arc Unknown	No	Yes/No	LOST-N/A	Round	Yes	No	-	-
1A	24	15	PSE013	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	244	244	Conductor Severed, Without Arc	No	Yes/No	LOST-N/A	Round	Yes	No	-	-
1A	23	15	PSE014	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	28	15	PSE015	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	29	15	PSE016	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	30	15	PSE017	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	31	15	PSE018	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-
1A	32	15	PSE019	PVC	SW	1/4 Turn Loose	-	-	-	Yes	No	DNF	307	-	-	-	-	-	-	-	-	-

APPENDIX G – SUMMARY OF RECEPTACLES TESTED (FIRE EXPOSURES)

Test No.	Location	Receptacle Serial No.	Energized State	Receptacle Material	Prior Evidence of OH?	Type of Plug	Outlet Box Material	Face Plate Material	Receptacle Damage Category	Outlet Box Damage Category	Faceplate Damage Category	Maximum Exposure Temperature (°C)	Tripped Circuit Breaker?	Time to Tripping (sec)	Maximum Temperature at Trip Time (°C)	Used Power Meter?	Selected for Arcing/ Melting Examination	Primary Arc Location	Secondary Arc Location	Confidence
1	C-1	LEV065	Non-energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	757	-	-	-	-		-	-	-
1	C-2	LEV066	Non-energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	757	-	-	-	-		-	-	-
1	C-3	LEV067	Non-energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	757	-	-	-	-		-	-	-
1	A-1	LEV068	Non-energized	Polypropylene	-	-	Steel	Nylon	TC	SO	TC	757	-	-	-	-		-	-	-
1	A-2	LEV069	Non-energized	Polypropylene	-	-	Steel	Nylon	TC	SO	TC	757	-	-	-	-		-	-	-
1	A-3	LEV070	Non-energized	Polypropylene	-	-	Steel	Nylon	TC	SO	TC	757	-	-	-	-		-	-	-
1	H-1	LEV071	Energized	Polypropylene	-	-	PVC	Steel	MM	PM	BP	711	No	-	-	-		-	-	-
1	H-2	LEV072	Energized	Polypropylene	-	-	PVC	Steel	MM	PM	BP	711	No	-	-	-		-	-	-
1	H-3	LEV073	Energized	Polypropylene	-	-	PVC	Steel	MM	PM	BP	711	No	-	-	-		-	-	-
1	J-1	LEV074	Energized w/ Current Draw	Polypropylene	-	-	PVC	Steel	MM	PM	SO	615	No	-	-	-		-	-	-
1	J-2	LEV075	Energized w/ Current Draw	Polypropylene	-	-	PVC	Steel	MM	PM	SO	615	Yes	236	585	-		Female Plug Contact	Ground Strap	Possible
1	E-1	LEV076	Energized	Polypropylene	-	-	Steel	Nylon	TC	SO	TC	711	No	-	-	-		-	-	-
1	E-2	LEV077	Energized	Polypropylene	-	-	Steel	Nylon	TC	SO	TC	711	Yes	225	665	-		Unknown	-	-
1	E-3	LEV078	Energized	Polypropylene	-	-	Steel	Nylon	TC	SO	TC	711	Yes	193	631	-		Female Plug Contact	Outlet Box	Confirmed
1	J-3	LEV079	Energized w/ Current Draw	Polypropylene	-	-	PVC	Steel	MM	PM	SO	615	No	-	-	-		-	-	-
1	L-1	LEV086	Energized w/ Current Draw	Polypropylene	-	-	PVC	Nylon	MM	PM	TC	615	No	-	-	-		-	-	-
1	L-2	LEV087	Energized w/ Current Draw	Polypropylene	-	-	PVC	Nylon	MM	PM	TC	615	No	-	-	-		-	-	-
1	L-3	LEV088	Energized w/ Current Draw	Polypropylene	-	-	PVC	Nylon	MM	PM	TC	615	No	-	-	-		-	-	-
1	D-1	PSE064	Non-energized	PVC	-	-	PVC	Steel	TC	MM	BP	757	-	-	-	-		-	-	-
1	D-2	PSE065	Non-energized	PVC	-	-	PVC	Steel	MC	MM	BP	757	-	-	-	-		-	-	-
1	D-3	PSE066	Non-energized	PVC	-	-	PVC	Steel	TC	MM	BP	757	-	-	-	-		-	-	-
1	B-1	PSE067	Non-energized	PVC	-	-	PVC	Nylon	PC	MM	TC	757	-	-	-	-		-	-	-
1	B-2	PSE068	Non-energized	PVC	-	-	PVC	Nylon	TC	PC	TC	757	-	-	-	-		-	-	-
1	B-3	PSE069	Non-energized	PVC	-	-	PVC	Nylon	TC	PC	TC	757	-	-	-	-		-	-	-
1	F-1	PSE070	Energized	PVC	-	-	PVC	Nylon	MC	PM	TC	711	Yes	242	670	-		Unknown	-	-
1	F-2	PSE071	Energized	PVC	-	-	PVC	Nylon	TC	PM	TC	711	Yes	174	631	-		Unknown	-	-
1	F-3	PSE072	Energized	PVC	-	-	PVC	Nylon	MC	MM	TC	711	No	-	-	-		-	-	-
1	I-1	PSE073	Energized w/ Current Draw	PVC	-	-	Steel	Steel	PM	SO	SO	615	No	-	-	-		-	-	-
1	I-2	PSE074	Energized w/ Current Draw	PVC	-	-	Steel	Steel	PM	SO	SO	615	No	-	-	-		-	-	-
1	I-3	PSE075	Energized w/ Current Draw	PVC	-	-	Steel	Steel	PM	SO	SO	615	No	-	-	-		-	-	-
1	G-1	PSE076	Energized	PVC	-	-	Steel	Steel	MC	SO	BP	711	No	-	-	-		-	-	-
1	G-2	PSE077	Energized	PVC	-	-	Steel	Steel	MC	SO	BP	711	Yes	197	631	-		Break off tab	Faceplate	Confirmed
1	G-3	PSE078	Energized	PVC	-	-	Steel	Steel	MC	SO	BP	711	Yes	174	631	-		Break off tab	Faceplate	Confirmed
1	K-1	PSE082	Energized w/ Current Draw	PVC	-	-	Steel	Nylon	PC	SO	TC	615	No	-	-	-		-	-	-
1	K-2	PSE083	Energized w/ Current Draw	PVC	-	-	Steel	Nylon	PC	SO	TC	615	No	-	-	-		-	-	-
1	K-3	PSE084	Energized w/ Current Draw	PVC	-	-	Steel	Nylon	PC	SO	TC	615	No	-	-	-		-	-	-
2	A-1	LEV080	Energized	Polypropylene	-	-	PVC	Nylon	TC	PC	TC	559	Yes	289	537	-		Receptacle Wiring	Other Wire	Confirmed
2	C-1	LEV081	Energized	Polypropylene	-	-	PVC	Steel	TC	MM	SO	559	Yes	252	537	-	Yes	Female Plug Contact	Faceplate	Confirmed
2	C-2	LEV082	Energized	Polypropylene	-	-	PVC	Steel	TC	MM	SO	559	Yes	360	537	-		Receptacle Wiring	Other Wire	Confirmed
2	C-3	LEV083	Energized	Polypropylene	-	-	PVC	Steel	TC	PM	SO	559	Yes	436	537	-		Female Plug Contact	Ground Strap	Confirmed
2	F-1	LEV084	Energized w/ Current Draw	Polypropylene	-	-	Steel	Steel	MM	SO	SO	515	No	-	-	-		-	-	-
2	F-2	LEV085	Energized w/ Current Draw	Polypropylene	-	-	Steel	Steel	MM	SO	SO	515	No	-	-	-		-	-	-
2	A-2	LEV089	Energized	Polypropylene	-	-	PVC	Nylon	TC	MM	TC	559	Yes	321	537	-		Female Plug Contact	Ground Strap	Confirmed
2	A-3	LEV090	Energized	Polypropylene	-	-	PVC	Nylon	TC	MM	TC	559	Yes	310	537	-		Unknown	-	-
2	F-3	LEV091	Energized w/ Current Draw	Polypropylene	-	-	Steel	Steel	MM	SO	SO	515	Yes	389	455	-		Female Plug Contact	Faceplate	Confirmed
2	H-1	LEV092	Energized w/ Current Draw	Polypropylene	-	-	Steel	Nylon	MM	SO	TC	515	No	-	-	-		-	-	-

Test No.	Location	Receptacle Serial No.	Energized State	Receptacle Material	Prior Evidence of OH?	Type of Plug	Outlet Box Material	Face Plate Material	Receptacle Damage Category	Outlet Box Damage Category	Faceplate Damage Category	Maximum Exposure Temperature (°C)	Tripped Circuit Breaker?	Time to Tripping (sec)	Maximum Temperature at Trip Time (°C)	Used Power Meter?	Selected for Arcing/ Melting Examination	Primary Arc Location	Secondary Arc Location	Confidence
2	H-2	LEV093	Energized w/ Current Draw	Polypropylene	-	-	Steel	Nylon	MM	SO	TC	515	No	-	-	-		-	-	-
2	H-3	LEV094	Energized w/ Current Draw	Polypropylene	-	-	Steel	Nylon	MM	SO	TC	515	Yes	385	453	-		Receptacle Wiring	Other Wire	Confirmed
2	I-1	LEV095	Non-energized	Polypropylene	-	-	PVC	Steel	PM	CL	SO	454	-	-	-	-		-	-	-
2	I-2	LEV096	Non-energized	Polypropylene	-	-	PVC	Steel	PM	CL	SO	454	-	-	-	-		-	-	-
2	I-3	LEV097	Non-energized	Polypropylene	-	-	PVC	Steel	PM	CL	SO	454	-	-	-	-		-	-	-
2	K-1	LEV098	Non-energized	Polypropylene	-	-	PVC	Nylon	PM	CL	BL	454	-	-	-	-		-	-	-
2	K-2	LEV099	Non-energized	Polypropylene	-	-	PVC	Nylon	PM	CL	BL	454	-	-	-	-		-	-	-
2	K-3	LEV100	Non-energized	Polypropylene	-	-	PVC	Nylon	PM	CL	BL	454	-	-	-	-		-	-	-
2	B-1	PSE079	Energized	PVC	-	-	Steel	Nylon	MC	SO	TC	559	Yes	408	537	-		Receptacle Wiring	Other Wire	Confirmed
2	B-2	PSE080	Energized	PVC	-	-	Steel	Nylon	MC	SO	TC	559	No	-	-	-		-	-	-
2	B-3	PSE081	Energized	PVC	-	-	Steel	Nylon	TC	SO	TC	559	Yes	229	537	-		Receptacle Wiring	Other Wire	Confirmed
2	D-1	PSE085	Energized	PVC	-	-	Steel	Steel	MC	SO	SO	559	Yes	172	537	-		Break off tab	Faceplate	Confirmed
2	D-2	PSE086	Energized	PVC	-	-	Steel	Steel	MC	SO	SO	559	Yes	209	537	-	Yes	Break off tab	Faceplate	Confirmed
2	D-3	PSE087	Energized	PVC	-	-	Steel	Steel	MC	SO	SO	559	Yes	185	537	-		Break off tab	Faceplate	Confirmed
2	E-1	PSE088	Energized w/ Current Draw	PVC	-	-	PVC	Nylon	MC	MM	TC	515	Yes	457	475	-	Yes	Receptacle Wiring	Other Wire	Confirmed
2	J-1	PSE089	Non-energized	PVC	-	-	Steel	Steel	PM	CL	SO	454	-	-	-	-		-	-	-
2	J-2	PSE090	Non-energized	PVC	-	-	Steel	Steel	PM	CL	SO	454	-	-	-	-		-	-	-
2	J-3	PSE091	Non-energized	PVC	-	-	Steel	Steel	PM	CL	SO	454	-	-	-	-		-	-	-
2	L-1	PSE092	Non-energized	PVC	-	-	Steel	Nylon	PM	CL	BL	454	-	-	-	-		-	-	-
2	L-2	PSE093	Non-energized	PVC	-	-	Steel	Nylon	PM	CL	BL	454	-	-	-	-		-	-	-
2	L-3	PSE094	Non-energized	PVC	-	-	Steel	Nylon	PM	CL	BL	454	-	-	-	-		-	-	-
2	E-2	PSE099	Energized w/ Current Draw	PVC	-	-	PVC	Nylon	MC	MM	TC	515	No	-	-	-		-	-	-
2	E-3	PSE100	Energized w/ Current Draw	PVC	-	-	PVC	Nylon	PC	MM	TC	515	No	-	-	-		-	-	-
2	G-1	PSE101	Energized w/ Current Draw	PVC	-	-	PVC	Steel	MC	MM	BP	515	Yes	424	465	-		Receptacle Wiring	Other Wire	Confirmed
2	G-2	PSE102	Energized w/ Current Draw	PVC	-	-	PVC	Steel	MC	PM	BP	515	No	-	-	-		-	-	-
2	G-3	PSE103	Energized w/ Current Draw	PVC	-	-	PVC	Steel	PC	PM	BP	515	No	-	-	-		-	-	-
3	G-1	LEV130	Non-energized	Polypropylene	-	-	Steel	Nylon	TC	LP	TC	883	-	-	-	-		-	-	-
3	G-2	LEV131	Non-energized	Polypropylene	-	-	Steel	Nylon	TC	LP	TC	883	-	-	-	-		-	-	-
3	G-3	LEV132	Non-energized	Polypropylene	-	-	Steel	Nylon	TC	LP	TC	883	-	-	-	-		-	-	-
3	E-1	LEV133	Non-energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	883	-	-	-	-		-	-	-
3	E-2	LEV134	Non-energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	883	-	-	-	-		-	-	-
3	E-3	LEV135	Non-energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	883	-	-	-	-		-	-	-
3	A-1	LEV136	Energized w/ Current Draw	Polypropylene	-	-	Steel	Steel	TC	SO	BP	840	Yes	150	634	-	Yes	Female Plug Contact	Faceplate	Confirmed
3	A-2	LEV137	Energized w/ Current Draw	Polypropylene	-	-	Steel	Steel	TC	SO	BP	840	Yes	173	695	-		Female Plug Contact	Faceplate	Confirmed
3	A-3	LEV138	Energized w/ Current Draw	Polypropylene	-	-	Steel	Steel	TC	SO	BP	840	Yes	154	634	-		Female Plug Contact	Faceplate	Confirmed
3	C-1	LEV139	Energized w/ Current Draw	Polypropylene	-	-	Steel	Steel	TC	SO	BP	840	Yes	157	634	-		Female Plug Contact	Faceplate	Confirmed
3	C-2	LEV140	Energized w/ Current Draw	Polypropylene	-	-	Steel	Steel	TC	SO	BP	840	Yes	138	593	-	Yes	Female Plug Contact	Faceplate	Confirmed
3	C-3	LEV141	Energized w/ Current Draw	Polypropylene	-	-	Steel	Steel	TC	SO	BP	840	Yes	192	759	-		Female Plug Contact	Faceplate	Confirmed
3	K-1	LEV142	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	886	Yes	201	704	-		Female Plug Contact	Faceplate	Confirmed
3	K-2	LEV143	Energized	Polypropylene	-	-	Steel	Steel	TC	CL	BP	886	Yes	183	663	-		Female Plug Contact	Faceplate	Confirmed
3	K-3	LEV144	Energized	Polypropylene	-	-	Steel	Steel	TC	CL	BP	886	Yes	216	731	-	Yes	Female Plug Contact	Faceplate	Confirmed
3	I-1	LEV145	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	886	Yes	179	655	-		Female Plug Contact	Faceplate	Confirmed
3	I-2	LEV146	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	886	Yes	186	676	-		Female Plug Contact	Faceplate	Confirmed
3	I-3	LEV147	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	886	No	-	-	-		-	-	-
3	H-1	PSE095	Non-energized	PVC	-	-	PVC	Nylon	TC	MM	TC	883	-	-	-	-		-	-	-
3	H-2	PSE097	Non-energized	PVC	-	-	PVC	Nylon	TC	MM	TC	883	-	-	-	-		-	-	-
3	H-3	PSE104	Non-energized	PVC	-	-	PVC	Nylon	TC	MM	TC	883	-	-	-	-		-	-	-
3	F-1	PSE105	Non-energized	PVC	-	-	PVC	Steel	TC	MM	BP	883	-	-	-	-		-	-	-
3	F-2	PSE106	Non-energized	PVC	-	-	PVC	Steel	TC	MM	BP	883	-	-	-	-		-	-	-

Test No.	Location	Receptacle Serial No.	Energized State	Receptacle Material	Prior Evidence of OH?	Type of Plug	Outlet Box Material	Face Plate Material	Receptacle Damage Category	Outlet Box Damage Category	Faceplate Damage Category	Maximum Exposure Temperature (°C)	Tripped Circuit Breaker?	Time to Tripping (sec)	Maximum Temperature at Trip Time (°C)	Used Power Meter?	Selected for Arcing/ Melting Examination	Primary Arc Location	Secondary Arc Location	Confidence
3	F-3	PSE136	Non-energized	PVC	-	-	PVC	Steel	TC	MM	BP	883	-	-	-	-		-	-	-
3	B-1	PSE137	Energized w/ Current Draw	PVC	-	-	PVC	Steel	TC	MM	BP	840	Yes	140	602	-		Break off tab	Faceplate	Confirmed
3	B-2	PSE138	Energized w/ Current Draw	PVC	-	-	PVC	Steel	TC	MM	BP	840	Yes	148	634	-		Break off tab	Faceplate	Confirmed
3	B-3	PSE139	Energized w/ Current Draw	PVC	-	-	PVC	Steel	TC	PC	BP	840	Yes	142	608	-	Yes	Break off tab	Faceplate	Confirmed
3	D-1	PSE140	Energized w/ Current Draw	PVC	-	-	PVC	Nylon	TC	MM	TC	840	Yes	202	759	-		Receptacle Wiring	Other Wire	Confirmed
3	D-2	PSE141	Energized w/ Current Draw	PVC	-	-	PVC	Nylon	TC	MM	TC	840	No	-	-	-		-	-	-
3	D-3	PSE142	Energized w/ Current Draw	PVC	-	-	PVC	Nylon	TC	MM	TC	840	Yes	158	634	-	Yes	Female Plug Contact	Ground Strap	Confirmed
3	J-1	PSE143	Energized	PVC	-	-	PVC	Steel	MC	PM	BP	886	No	-	-	-		-	-	-
3	J-2	PSE144	Energized	PVC	-	-	PVC	Steel	MC	PM	BP	886	Yes	196	704	-		Break off tab	Faceplate	Confirmed
3	J-3	PSE145	Energized	PVC	-	-	PVC	Steel	MC	PM	BP	886	Yes	215	731	-		Break off tab	Faceplate	Confirmed
3	L-1	PSE146	Energized	PVC	-	-	PVC	Nylon	TC	PM	TC	886	Yes	244	838	-		Unknown	-	-
3	L-2	PSE147	Energized	PVC	-	-	PVC	Nylon	MC	PM	TC	886	Yes	252	858	-		Female Plug Contact	Ground Strap	Confirmed
3	L-3	PSE148	Energized	PVC	-	-	PVC	Nylon	MC	PM	TC	886	No	-	-	-		-	-	-
4	A-1	LEV148	Energized	Polypropylene	-	-	PVC	Nylon	TC	PC	TC	648	Yes	425	597	-	Yes	Receptacle Wiring	Other Wire	Confirmed
4	A-2	LEV149	Energized	Polypropylene	-	-	PVC	Nylon	TC	PC	TC	648	Yes	366	484	-		Female Plug Contact	Ground Strap	Confirmed
4	A-3	LEV150	Energized	Polypropylene	-	-	PVC	Nylon	TC	PC	TC	648	Yes	393	546	-		Unknown	-	-
4	B-1	LEV151	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	648	Yes	388	580	-	Yes	Female Plug Contact	Faceplate	Confirmed
4	B-2	LEV152	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	648	Yes	414	578	-		Female Plug Contact	Faceplate	Confirmed
4	B-3	LEV153	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	648	Yes	360	457	-		Receptacle Wiring	Faceplate	Confirmed
4	C-1	LEV154	Energized w/ Current Draw	Polypropylene	-	-	PVC	Nylon	TC	PC	TC	648	Yes	470	609	-		Unknown	-	-
4	C-2	LEV155	Energized w/ Current Draw	Polypropylene	-	-	PVC	Nylon	TC	MM	TC	648	Yes	393	546	-		Female Plug Contact	Ground Strap	Confirmed
4	C-3	LEV156	Energized w/ Current Draw	Polypropylene	-	-	PVC	Nylon	TC	MM	TC	648	Yes	288	430	-		Female Plug Contact	Ground Strap	Confirmed
4	D-1	LEV157	Energized w/ Current Draw	Polypropylene	-	-	Steel	Nylon	TC	SO	TC	648	Yes	359	457	-	Yes	Female Plug Contact	Ground Strap	Confirmed
4	D-2	LEV158	Energized w/ Current Draw	Polypropylene	-	-	Steel	Nylon	TC	SO	TC	648	Yes	458	609	-		Receptacle Wiring	Other Wire	Confirmed
4	D-3	LEV159	Energized w/ Current Draw	Polypropylene	-	-	Steel	Nylon	TC	SO	TC	648	Yes	380	527	-		Female Plug Contact	Ground Strap	Confirmed
4	E-1	LEV160	Non-energized	Polypropylene	-	-	PVC	Steel	TC	MM	BP	680	-	-	-	-		-	-	-
4	E-2	LEV161	Non-energized	Polypropylene	-	-	PVC	Steel	TC	MM	BP	680	-	-	-	-		-	-	-
4	E-3	LEV162	Non-energized	Polypropylene	-	-	PVC	Steel	TC	MM	BP	680	-	-	-	-		-	-	-
4	G-1	LEV163	Non-energized	Polypropylene	-	-	PVC	Nylon	TC	MM	TC	680	-	-	-	-		-	-	-
4	G-2	LEV164	Non-energized	Polypropylene	-	-	PVC	Nylon	TC	MM	TC	680	-	-	-	-		-	-	-
4	G-3	LEV165	Non-energized	Polypropylene	-	-	PVC	Nylon	TC	MM	TC	680	-	-	-	-		-	-	-
4	J-1	LEV166	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	728	Yes	455	598	-		Female Plug Contact	Faceplate	Confirmed
4	J-2	LEV167	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	728	Yes	395	497	-		Female Plug Contact	Faceplate	Confirmed
4	J-3	LEV168	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	728	Yes	512	621	-	Yes	Female Plug Contact	Faceplate	Confirmed
4	F-3	PSE149	Non-energized	PVC	-	-	Steel	Steel	MC	SO	BP	680	-	-	-	-		-	-	-
4	H-1	PSE150	Non-energized	PVC	-	-	Steel	Nylon	TC	SO	TC	680	-	-	-	-		-	-	-
4	H-2	PSE151	Non-energized	PVC	-	-	Steel	Nylon	TC	SO	TC	680	-	-	-	-		-	-	-
4	H-3	PSE152	Non-energized	PVC	-	-	Steel	Nylon	TC	SO	TC	680	-	-	-	-		-	-	-
4	I-1	PSE153	Energized w/ Current Draw	PVC	-	-	PVC	Steel	MC	PM	BP	728	No	-	-	-		-	-	-
4	I-2	PSE154	Energized w/ Current Draw	PVC	-	-	PVC	Steel	MC	PM	BP	728	Yes	556	640	-		Female Plug Contact	Ground Strap	Confirmed
4	I-3	PSE155	Energized w/ Current Draw	PVC	-	-	PVC	Steel	TC	MM	BP	728	Yes	565	640	-		Unknown	-	-
4	K-1	PSE156	Energized	PVC	-	-	PVC	Steel	MC	PM	BP	728	No	-	-	-		-	-	-
4	K-2	PSE157	Energized	PVC	-	-	PVC	Steel	MC	PM	BP	728	No	-	-	-		-	-	-
4	K-3	PSE158	Energized	PVC	-	-	PVC	Steel	MC	PM	BP	728	No	-	-	-		-	-	-
4	L-1	PSE159	Energized w/ Current Draw	PVC	-	-	Steel	Steel	MC	CL	BP	728	Yes	458.0	598	-		Break off tab	Faceplate	Confirmed
4	L-2	PSE160	Energized w/ Current Draw	PVC	-	-	Steel	Steel	PC	SO	BP	728	Yes	655.0	702	-		Receptacle Wiring	Other Wire	Confirmed

Test No.	Location	Receptacle Serial No.	Energized State	Receptacle Material	Prior Evidence of OH?	Type of Plug	Outlet Box Material	Face Plate Material	Receptacle Damage Category	Outlet Box Damage Category	Faceplate Damage Category	Maximum Exposure Temperature (°C)	Tripped Circuit Breaker?	Time to Tripping (sec)	Maximum Temperature at Trip Time (°C)	Used Power Meter?	Selected for Arcing/ Melting Examination	Primary Arc Location	Secondary Arc Location	Confidence
4	L-3	PSE161	Energized w/ Current Draw	PVC	-	-	Steel	Steel	PC	SO	BP	728	No	-	-	-		-	-	-
4	F-1	PSE162	Non-energized	PVC	-	-	Steel	Steel	MC	SO	BP	680	-	-	-	-		-	-	-
4	F-2	PSE163	Non-energized	PVC	-	-	Steel	Steel	MC	SO	BP	680	-	-	-	-		-	-	-
5	A-1	LEV247	Non-energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	798	-	-	-	-		-	-	-
5	A-2	LEV248	Non-energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	798	-	-	-	-		-	-	-
5	A-3	LEV249	Non-energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	798	-	-	-	-		-	-	-
5	C-1	LEV250	Non-energized	Polypropylene	-	-	Steel	Nylon	TC	SO	TC	798	-	-	-	-		-	-	-
5	C-2	LEV251	Non-energized	Polypropylene	-	-	Steel	Nylon	TC	SO	TC	798	-	-	-	-		-	-	-
5	C-3	LEV252	Non-energized	Polypropylene	-	-	Steel	Nylon	TC	SO	TC	798	-	-	-	-		-	-	-
5	F-1	LEV253	Energized	Polypropylene	-	-	PVC	Steel	TC	MM	BP	903	Yes	138	785	Yes, Ch3		Female Plug Contact	Ground Strap	Confirmed
5	F-2	LEV254	Energized	Polypropylene	-	-	PVC	Steel	TC	MM	BP	903	Yes	140	785	Yes, Ch4		Female Plug Contact	Ground Strap	Confirmed
5	F-3	LEV255	Energized	Polypropylene	-	-	PVC	Steel	TC	MM	BP	903	Yes	152	839	-		Female Plug Contact	Faceplate	Confirmed
5	G-1	LEV256	Energized w/ Current Draw	Polypropylene	-	-	PVC	Nylon	TC	PC	TC	903	Yes	100	729	-		Receptacle Wiring	Other Wire	Confirmed
5	G-2	LEV257	Energized w/ Current Draw	Polypropylene	-	-	PVC	Nylon	TC	PC	TC	903	Yes	117	761	-	Yes	Female Plug Contact	Ground Strap	Confirmed
5	G-3	LEV258	Energized w/ Current Draw	Polypropylene	-	-	PVC	Nylon	TC	PC	TC	903	Yes	101	729	-		Female Plug Contact	Ground Strap	Confirmed
5	H-1	LEV259	Energized	Polypropylene	-	-	PVC	Nylon	TC	MM	TC	903	Yes	130	781	-		Unknown	-	-
5	H-2	LEV260	Energized	Polypropylene	-	-	PVC	Nylon	TC	MM	TC	903	Yes	135	785	-		Female Plug Contact	Ground Strap	Confirmed
5	H-3	LEV261	Energized	Polypropylene	-	-	PVC	Nylon	TC	MM	TC	903	Yes	121	781	-	Yes	Receptacle Wiring	Other Wire	Confirmed
5	J-1	LEV262	Energized w/ Current Draw	Polypropylene	-	-	PVC	Steel	TC	PM	BP	859	Yes	115	738	-		Female Plug Contact	Faceplate	Confirmed
5	J-2	LEV263	Energized w/ Current Draw	Polypropylene	-	-	PVC	Steel	TC	PM	BP	859	Yes	140	736	-	Yes	Female Plug Contact	Faceplate	Confirmed
5	J-3	LEV264	Energized w/ Current Draw	Polypropylene	-	-	PVC	Steel	TC	PM	BP	859	Yes	133	730	-		Female Plug Contact	Faceplate	Confirmed
5	B-1	PSE242	Non-energized	PVC	-	-	PVC	Steel	TC	PC	BP	798	-	-	-	-		-	-	-
5	B-2	PSE243	Non-energized	PVC	-	-	PVC	Steel	MC	MM	BP	798	-	-	-	-		-	-	-
5	B-3	PSE244	Non-energized	PVC	-	-	PVC	Steel	TC	PC	BP	798	-	-	-	-		-	-	-
5	D-1	PSE245	Non-energized	PVC	-	-	PVC	Nylon	MC	MM	TC	798	-	-	-	-		-	-	-
5	D-2	PSE246	Non-energized	PVC	-	-	PVC	Nylon	TC	MM	TC	798	-	-	-	-		-	-	-
5	D-3	PSE247	Non-energized	PVC	-	-	PVC	Nylon	TC	MM	TC	798	-	-	-	-		-	-	-
5	E-1	PSE248	Energized	PVC	-	-	Steel	Steel	TC	SO	BP	903	Yes	127	705	Yes, Ch1		Female Plug Contact	Ground Strap	Confirmed
5	E-2	PSE249	Energized	PVC	-	-	Steel	Steel	TC	SO	BP	903	Yes	127	705	Yes, Ch2	Yes	Female Plug Contact	Ground Strap	Confirmed
5	E-3	PSE250	Energized	PVC	-	-	Steel	Steel	TC	SO	BP	903	Yes	141	785	-		Female Plug Contact	Ground Strap	Confirmed
5	I-1	PSE251	Energized w/ Current Draw	PVC	-	-	Steel	Steel	MC	CL	BP	859	Yes	133	730	-	Yes	Break off tab	Faceplate	Possible
5	I-2	PSE252	Energized w/ Current Draw	PVC	-	-	Steel	Steel	PC	SO	BP	859	No	-	-	-		-	-	-
5	I-3	PSE253	Energized w/ Current Draw	PVC	-	-	Steel	Steel	PC	SO	BP	859	Yes	145	747	-		Female Plug Contact	Ground Strap	Confirmed
5	K-1	PSE254	Energized	PVC	-	-	Steel	Nylon	TC	CL	TC	859	Yes	168	805	-		Female Plug Contact	Ground Strap	Confirmed
5	K-2	PSE255	Energized	PVC	-	-	Steel	Nylon	MC	SO	TC	859	Yes	176	837	-	Yes	Female Plug Contact	Ground Strap	Confirmed
5	K-3	PSE256	Energized	PVC	-	-	Steel	Nylon	PC	SO	TC	859	Yes	172	812	-		Female Plug Contact	Ground Strap	Confirmed
5	L-1	PSE257	Energized w/ Current Draw	PVC	-	-	Steel	Nylon	PC	SO	TC	859	Yes	159	774	-		Unknown	-	-
5	L-2	PSE258	Energized w/ Current Draw	PVC	-	-	Steel	Nylon	MC	SO	TC	859	No	-	-	-		-	-	-
5	L-3	PSE259	Energized w/ Current Draw	PVC	-	-	Steel	Nylon	MC	SO	TC	859	No	-	-	-		-	-	-
6	A-1	B007	Energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	585	Yes	347	497	-	Yes	Receptacle Wiring	Other Wire	Confirmed
6	A-2	B008	Energized	Phenolic	-	-	Steel	Nylon	LM	SO	TC	585	Yes	358	497	-		Receptacle Wiring	Other Wire	Confirmed
6	A-3	B009	Energized	Phenolic	-	-	Steel	Nylon	LM	SO	TC	585	Yes	316	491	-		Receptacle Wiring	Other Wire	Confirmed
6	B-1	B010	Energized	Phenolic	-	-	Steel	Steel	CR	SO	BP	585	Yes	272	491	Yes, Ch1		Receptacle Wiring	Unknown	Confirmed
6	B-2	B011	Energized	Phenolic	-	-	Steel	Steel	CH	SO	BP	585	No	-	-	Yes, Ch2		-	-	-
6	B-3	B012	Energized	Phenolic	-	-	Steel	Steel	CH	SO	BP	585	No	-	-	Yes, Ch3		-	-	-
6	C-1	C016	Energized	Phenolic	-	-	Steel	Nylon	LM	SO	TC	585	Yes	351	497	-		Receptacle Wiring	Outlet Box	Confirmed
6	C-2	C017	Energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	585	Yes	228	491	-		Receptacle Wiring	Other Wire	Confirmed
6	C-3	C018	Energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	585	Yes	355	497	-		Unknown	-	-
6	D-1	C019	Energized	Phenolic	-	-	Steel	Steel	LM	SO	BP	585	Yes	432	550	Yes, Ch4		Unknown	-	-
6	D-2	C025	Energized	Phenolic	-	-	Steel	Steel	LM	SO	BP	585	Yes	468	549	-		Receptacle Wiring	Other Wire	Confirmed

Test No.	Location	Receptacle Serial No.	Energized State	Receptacle Material	Prior Evidence of OH?	Type of Plug	Outlet Box Material	Face Plate Material	Receptacle Damage Category	Outlet Box Damage Category	Faceplate Damage Category	Maximum Exposure Temperature (°C)	Tripped Circuit Breaker?	Time to Tripping (sec)	Maximum Temperature at Trip Time (°C)	Used Power Meter?	Selected for Arcing/ Melting Examination	Primary Arc Location	Secondary Arc Location	Confidence
6	D-3	C026	Energized	Phenolic	-	-	Steel	Steel	LM	SO	BP	585	No	-	-	-		-	-	-
6	E-2	D012	Energized	Phenolic	-	-	Steel	Nylon	LM	SO	TC	590	Yes	472	549	-		Receptacle Wiring	Outlet Box	Confirmed
6	E-3	D013	Energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	590	No	-	-	-		-	-	-
6	F-1	D014	Energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	590	Yes	381	526	-		Unknown	-	-
6	F-2	D015	Energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	590	Yes	313	499	-		Receptacle Wiring	Outlet Box	Confirmed
6	F-3	D016	Energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	590	Yes	363	514	-	Yes	Receptacle Wiring	Outlet Box	Confirmed
6	E-1	D017	Energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	590	Yes	394	533	-		Unknown	-	-
6	I-1	E020	Energized	Phenolic	-	-	Steel	Steel	CH	SO	SO	559	No	-	-	-		-	-	-
6	I-2	E021	Energized	Phenolic	-	-	Steel	Steel	CH	CL	SO	559	No	-	-	-		-	-	-
6	I-3	E022	Energized	Phenolic	-	-	Steel	Steel	CH	CL	SO	559	No	-	-	-		-	-	-
6	J-1	E023	Energized	Phenolic	-	-	Steel	Steel	CH	SO	BP	559	No	-	-	-		-	-	-
6	J-2	E024	Energized	Phenolic	-	-	Steel	Steel	CH	CL	BP	559	No	-	-	-		-	-	-
6	J-3	E025	Energized	Phenolic	-	-	Steel	Steel	CH	CL	BP	559	No	-	-	-		-	-	-
6	G-1	E031	Energized	Phenolic	-	-	Steel	Nylon	CR	SO	TC	590	No	-	-	-		-	-	-
6	G-2	E032	Energized	Phenolic	-	-	Steel	Nylon	CR	SO	TC	590	Yes	450	549	-		Receptacle Wiring	Outlet Box	Confirmed
6	G-3	E033	Energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	590	Yes	341	510	-		Receptacle Wiring	Other Wire	Confirmed
6	H-1	E034	Energized	Phenolic	-	-	Steel	Nylon	LM	SO	TC	590	No	-	-	-		-	-	-
6	H-2	E035	Energized	Phenolic	-	-	Steel	Nylon	LM	SO	TC	590	Yes	330	503	-		Unknown	-	-
6	H-3	E036	Energized	Phenolic	-	-	Steel	Nylon	CR	SO	TC	590	Yes	225	499	-		Receptacle Wiring	Other Wire	Confirmed
6	K-1	LEV317	Energized	Polypropylene	-	Folded - Brass	Steel	Steel	PM	CL	SO	559	Yes	296	443	-		Cord Wiring	-	Confirmed
6	K-2	LEV318	Energized	Polypropylene	-	Folded - Brass	Steel	Steel	PM	CL	SO	559	Yes	271	431	-	Yes	Cord Wiring	-	Confirmed
6	K-3	LEV319	Energized	Polypropylene	-	Folded - Brass	Steel	Steel	PM	CL	SO	559	Yes	266	431	-		Cord Wiring	-	Confirmed
6	L-1	LEV320	Energized	Polypropylene	-	Solid - Plated	Steel	Steel	PM	CL	SO	559	Yes	312	455	-	Yes	Cord Wiring	-	Confirmed
6	L-2	LEV321	Energized	Polypropylene	-	Solid - Plated	Steel	Steel	PM	CL	SO	559	Yes	270	431	-		Cord Wiring	-	Confirmed
6	L-3	LEV322	Energized	Polypropylene	-	Solid - Plated	Steel	Steel	PM	CL	SO	559	Yes	186	338	-	Yes	Cord Wiring	-	Confirmed
7	I-1	B013	Non-energized	Phenolic	-	-	Steel	Steel	CR	SO	BP	656	-	-	-	-		-	-	-
7	I-2	B014	Non-energized	Phenolic	-	-	Steel	Steel	CH	CL	BP	656	-	-	-	-		-	-	-
7	I-3	B015	Non-energized	Phenolic	-	-	Steel	Steel	CH	CL	BP	656	-	-	-	-		-	-	-
7	J-1	B016	Non-energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	656	-	-	-	-		-	-	-
7	J-2	B017	Non-energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	656	-	-	-	-		-	-	-
7	J-3	B018	Non-energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	656	-	-	-	-		-	-	-
7	C-1	C028	Non-energized	Phenolic	-	-	Steel	Nylon	CR	SO	TC	667	-	-	-	-		-	-	-
7	C-3	C031	Non-energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	667	-	-	-	-		-	-	-
7	B-1	C033	Non-energized	Phenolic	-	-	Steel	Steel	CR	SO	BP	667	-	-	-	-		-	-	-
7	B-2	C034	Non-energized	Phenolic	-	-	Steel	Steel	CR	SO	BP	667	-	-	-	-		-	-	-
7	C-2	C035	Non-energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	667	-	-	-	-		-	-	-
7	B-3	C036	Non-energized	Phenolic	-	-	Steel	Steel	CR	SO	BP	667	-	-	-	-		-	-	-
7	A-1	D020	Non-energized	Phenolic	-	-	Steel	Steel	CH	SO	BP	667	-	-	-	-		-	-	-
7	A-2	D021	Non-energized	Phenolic	-	-	Steel	Steel	CH	SO	BP	667	-	-	-	-		-	-	-
7	A-3	D022	Non-energized	Phenolic	-	-	Steel	Steel	CH	SO	BP	667	-	-	-	-		-	-	-
7	D-1	D023	Non-energized	Phenolic	-	-	Steel	Steel	CH	SO	BP	667	-	-	-	-		-	-	-
7	D-2	D024	Non-energized	Phenolic	-	-	Steel	Steel	CR	SO	BP	667	-	-	-	-		-	-	-
7	D-3	D025	Non-energized	Phenolic	-	-	Steel	Steel	CH	SO	BP	667	-	-	-	-		-	-	-
7	G-1	E026	Non-energized	Phenolic	-	-	Steel	Nylon	CR	SO	TC	696	-	-	-	-		-	-	-
7	G-2	E027	Non-energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	696	-	-	-	-		-	-	-
7	G-3	E028	Non-energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	696	-	-	-	-		-	-	-
7	H-1	E029	Non-energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	696	-	-	-	-		-	-	-
7	H-2	E030	Non-energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	696	-	-	-	-		-	-	-
7	E-1	E037	Non-energized	Phenolic	-	-	Steel	Steel	CR	SO	BP	696	-	-	-	-		-	-	-
7	E-2	E038	Non-energized	Phenolic	-	-	Steel	Steel	CH	SO	BP	696	-	-	-	-		-	-	-
7	E-3	E039	Non-energized	Phenolic	-	-	Steel	Steel	CR	SO	BP	696	-	-	-	-		-	-	-
7	H-3	E040	Non-energized	Phenolic	-	-	Steel	Nylon	CH	SO	TC	696	-	-	-	-		-	-	-
7	F-1	E043	Non-energized	Phenolic	-	-	Steel	Steel	CR	SO	BP	696	-	-	-	-		-	-	-
7	F-2	E044	Non-energized	Phenolic	-	-	Steel	Steel	CH	SO	BP	696	-	-	-	-		-	-	-
7	F-3	E045	Non-energized	Phenolic	-	-	Steel	Steel	CR	SO	BP	696	-	-	-	-		-	-	-
7	K-1	PSE312	Non-energized	PVC	-	Folded - Brass	Steel	Nylon	PM	SO	TC	656	-	-	-	-		-	-	-
7	K-2	PSE313	Non-energized	PVC	-	Folded - Brass	Steel	Nylon	PM	SO	TC	656	-	-	-	-		-	-	-
7	K-3	PSE314	Non-energized	PVC	-	Folded - Brass	Steel	Nylon	PM	SO	TC	656	-	-	-	-		-	-	-
7	L-1	PSE315	Non-energized	PVC	-	Solid - Plated	Steel	Nylon	PM	CL	TC	656	-	-	-	-		-	-	-
7	L-2	PSE316	Non-energized	PVC	-	Solid - Plated	Steel	Nylon	PM	CL	TC	656	-	-	-	-		-	-	-
7	L-3	PSE317	Non-energized	PVC	-	Solid - Plated	Steel	Nylon	PM	CL	TC	656	-	-	-	-		-	-	-
8	B-1	LEV323	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	546	Yes	259	429	Yes, Ch3		Female Plug Contact	Faceplate	Confirmed
8	B-2	LEV324	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	546	Yes	218	402	Yes, Ch4		Female Plug Contact	Faceplate	Confirmed

Test No.	Location	Receptacle Serial No.	Energized State	Receptacle Material	Prior Evidence of OH?	Type of Plug	Outlet Box Material	Face Plate Material	Receptacle Damage Category	Outlet Box Damage Category	Faceplate Damage Category	Maximum Exposure Temperature (°C)	Tripped Circuit Breaker?	Time to Tripping (sec)	Maximum Temperature at Trip Time (°C)	Used Power Meter?	Selected for Arcing/ Melting Examination	Primary Arc Location	Secondary Arc Location	Confidence
8	B-3	LEV325	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	546	Yes	199	402	-	Yes	Female Plug Contact	Faceplate	Confirmed
8	D-1	LEV326	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	546	Yes	271	441	-		Female Plug Contact	Faceplate	Confirmed
8	D-2	LEV327	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	546	Yes	277	447	-		Female Plug Contact	Faceplate	Confirmed
8	D-3	LEV328	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	546	Yes	304	463	-		Female Plug Contact	Faceplate	Confirmed
8	F-1	LEV329	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	551	Yes	259	436	-	Yes	Female Plug Contact	Faceplate	Confirmed
8	F-2	LEV330	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	551	Yes	297	467	-		Female Plug Contact	Faceplate	Confirmed
8	F-3	LEV331	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	551	Yes	220	414	-		Female Plug Contact	Faceplate	Confirmed
8	H-1	LEV332	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	551	Yes	248	428	-		Female Plug Contact	Faceplate	Confirmed
8	H-2	LEV333	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	551	Yes	276	454	-	Yes	Female Plug Contact	Faceplate	Confirmed
8	H-3	LEV334	Energized	Polypropylene	-	-	Steel	Steel	TC	SO	BP	551	Yes	215	414	-		Female Plug Contact	Faceplate	Confirmed
8	J-1	LEV335	Energized	Polypropylene	-	-	Steel	Steel	MM	CL	BP	531	Yes	414	479	-		Female Plug Contact	Faceplate	Confirmed
8	J-2	LEV336	Energized	Polypropylene	-	-	Steel	Steel	MM	CL	BP	531	Yes	487	479	-		Female Plug Contact	Faceplate	Confirmed
8	J-3	LEV337	Energized	Polypropylene	-	-	Steel	Steel	MM	CL	BP	531	Yes	403	479	-	Yes	Female Plug Contact	Faceplate	Confirmed
8	L-1	LEV338	Energized	Polypropylene	-	Solid - Plated	Steel	Steel	PM	CL	SO	531	Yes	319	428	-		Cord Wiring	-	Confirmed
8	L-2	LEV339	Energized	Polypropylene	-	Solid - Plated	Steel	Steel	PM	CL	SO	531	Yes	318	428	-		Cord Wiring	-	Confirmed
8	L-3	LEV340	Energized	Polypropylene	-	Solid - Plated	Steel	Steel	PM	CL	SO	531	Yes	364	458	-	Yes	Cord Wiring	-	Confirmed
8	A-1	PSE318	Energized	PVC	-	-	Steel	Steel	MC	SO	BP	546	Yes	138	394	Yes, Ch1		Break off tab	Faceplate	Confirmed
8	A-2	PSE319	Energized	PVC	-	-	Steel	Steel	MC	SO	BP	546	Yes	164	402	Yes, Ch2		Break off tab	Faceplate	Confirmed
8	A-3	PSE320	Energized	PVC	-	-	Steel	Steel	MC	SO	BP	546	Yes	166	402	-		Break off tab	Faceplate	Confirmed
8	C-1	PSE321	Energized	PVC	-	-	Steel	Steel	TC	SO	BP	546	Yes	137	394	-	Yes	Break off tab	Faceplate	Confirmed
8	C-2	PSE322	Energized	PVC	-	-	Steel	Steel	TC	SO	BP	546	Yes	174	402	-		Break off tab	Faceplate	Confirmed
8	C-3	PSE323	Energized	PVC	-	-	Steel	Steel	MC	SO	BP	546	Yes	138	394	-		Break off tab	Faceplate	Confirmed
8	E-1	PSE324	Energized	PVC	-	-	Steel	Steel	MC	SO	BP	551	Yes	175	414	-		Break off tab	Faceplate	Confirmed
8	E-2	PSE325	Energized	PVC	-	-	Steel	Steel	MC	SO	BP	551	Yes	306	463	-		Unknown	-	-
8	E-3	PSE326	Energized	PVC	-	-	Steel	Steel	MC	SO	BP	551	Yes	133	371	-	Yes	Break off tab	Faceplate	Confirmed
8	G-1	PSE327	Energized	PVC	-	-	Steel	Steel	MC	SO	BP	551	Yes	197	414	-		Break off tab	Faceplate	Confirmed
8	G-2	PSE328	Energized	PVC	-	-	Steel	Steel	MC	SO	BP	551	Yes	309	471	-		Unknown	-	-
8	G-3	PSE329	Energized	PVC	-	-	Steel	Steel	MC	SO	BP	551	Yes	274	453	-		Break off tab	Faceplate	Confirmed
8	I-1	PSE330	Energized	PVC	-	-	Steel	Steel	PM	SO	BP	531	Yes	393	479	-		Break off tab	Faceplate	Confirmed
8	I-2	PSE331	Energized	PVC	-	-	Steel	Steel	PM	SO	BP	531	Yes	374	471	-	Yes	Break off tab	Faceplate	Confirmed
8	I-3	PSE332	Energized	PVC	-	-	Steel	Steel	PM	SO	BP	531	Yes	460	479	-		Break off tab	Faceplate	Confirmed
8	K-1	PSE333	Energized	PVC	-	Solid - Plated	Steel	Steel	PM	CL	SO	531	Yes	387	479	-		Cord Wiring	-	Confirmed
8	K-2	PSE334	Energized	PVC	-	Solid - Plated	Steel	Steel	PM	CL	SO	531	Yes	283	411	-	Yes	Cord Wiring	-	Confirmed
8	K-3	PSE335	Energized	PVC	-	Solid - Plated	Steel	Steel	PM	CL	SO	531	Yes	365	459	-		Cord Wiring	-	Confirmed
Furnace 1	A-1	LEV341	Energized	Polypropylene	-	-	Steel	Steel	TC	LP	BS	998	Yes	131	700	-		Female Plug Contact	Faceplate	Confirmed
Furnace 1	A-2	LEV342	Energized	Polypropylene	-	-	Steel	Steel	TC	LP	BS	967	Yes	105	528	-		Female Plug Contact	Faceplate	Confirmed
Furnace 1	A-3	LEV343	Energized	Polypropylene	-	-	Steel	Steel	TC	LP	BS	959	Yes	115	533	-		Female Plug Contact	Faceplate	Confirmed
Furnace 1	A-4	LEV344	Non-energized	Polypropylene	-	-	Steel	Steel	TC	LP	BS	1030	-	-	-	-		-	-	-
Furnace 1	A-5	LEV345	Non-energized	Polypropylene	-	-	Steel	Steel	TC	LP	BS	1003	-	-	-	-		-	-	-
Furnace 1	A-6	LEV346	Non-energized	Polypropylene	-	-	Steel	Steel	TC	LP	BS	1018	-	-	-	-		-	-	-
Furnace 1	C-1	LEV347	Energized	Polypropylene	-	-	Steel	Nylon	BM	LP	TC	1006	Yes	128	740	-	Yes	Female Plug Contact	Ground Strap	Confirmed
Furnace 1	C-2	LEV348	Energized	Polypropylene	-	-	Steel	Nylon	BM	LP	TC	1009	Yes	163	810	-		Receptacle Wiring	Other Wire	Confirmed
Furnace 1	C-3	LEV349	Energized	Polypropylene	-	-	Steel	Nylon	BM	LP	TC	970	Yes	192	767	-		Receptacle Wiring	Other Wire	Confirmed
Furnace 1	C-4	LEV350	Non-energized	Polypropylene	-	-	Steel	Steel	TC	LP	BS	1015	-	-	-	-		-	-	-
Furnace 1	C-5	LEV351	Non-energized	Polypropylene	-	-	Steel	Steel	TC	LP	BS	1031	-	-	-	-		-	-	-
Furnace 1	C-6	LEV352	Non-energized	Polypropylene	-	-	Steel	Steel	TC	LP	BS	1030	-	-	-	-		-	-	-
Furnace 1	E-4	LEV353	Non-energized	Polypropylene	-	-	Steel	Nylon	BM	LP	TC	1043	-	-	-	-		-	-	-
Furnace 1	E-5	LEV354	Non-energized	Polypropylene	-	-	Steel	Nylon	BM	LP	TC	1019	-	-	-	-		-	-	-
Furnace 1	E-6	LEV355	Non-energized	Polypropylene	-	-	Steel	Nylon	BM	LP	TC	1055	-	-	-	-	Yes	-	-	-
Furnace 1	E-1	LEV356	Non-energized	Polypropylene	-	-	Steel	Nylon	BM	LP	TC	1002	-	-	-	-		-	-	-
Furnace 1	E-2	LEV357	Non-energized	Polypropylene	-	-	Steel	Nylon	BM	LP	TC	964	-	-	-	-		-	-	-
Furnace 1	E-3	LEV358	Non-energized	Polypropylene	-	-	Steel	Nylon	BM	LP	TC	988	-	-	-	-	Yes	-	-	-
Furnace 1	B-1	PSE336	Energized	PVC	-	-	Steel	Nylon	TC	LP	TC	952	Yes	149	629	-	Yes	Receptacle Wiring	Other Wire	Confirmed
Furnace 1	B-2	PSE337	Energized	PVC	-	-	Steel	Nylon	BM	LP	TC	1013	Yes	105	688	-		Receptacle Wiring	Other Wire	Confirmed
Furnace 1	B-3	PSE338	Energized	PVC	-	-	Steel	Nylon	BM	LP	TC	990	Yes	155	741	-		Receptacle Wiring	Other Wire	Confirmed
Furnace 1	B-4	PSE339	Non-energized	PVC	-	-	Steel	Steel	TC	LP	BS	1009	-	-	-	-		-	-	-
Furnace 1	B-5	PSE340	Non-energized	PVC	-	-	Steel	Steel	TC	LP	BS	999	-	-	-	-		-	-	-
Furnace 1	B-6	PSE341	Non-energized	PVC	-	-	Steel	Steel	TC	LP	BS	1019	-	-	-	-		-	-	-
Furnace 1	D-1	PSE342	Energized	PVC	-	-	Steel	Steel	TC	LP	BS	989	Yes	107	631	-		Break off tab	Faceplate	Confirmed
Furnace 1	D-2	PSE343	Non-energized	PVC	-	-	Steel	Steel	TC	LP	BS	1000	-	-	-	-		-	-	-
Furnace 1	D-3	PSE344	Energized	PVC	-	-	Steel	Steel	TC	LP	BS	986	Yes	119	627	-		Break off tab	Faceplate	Confirmed
Furnace 1	D-4	PSE345	Non-energized	PVC	-	-	Steel	Steel	TC	LP	BS	1036	-	-	-	-		-	-	-
Furnace 1	D-5	PSE346	Non-energized	PVC	-	-	Steel	Steel	TC	LP	BS	1024	-	-	-	-		-	-	-

Test No.	Location	Receptacle Serial No.	Energized State	Receptacle Material	Prior Evidence of OH?	Type of Plug	Outlet Box Material	Face Plate Material	Receptacle Damage Category	Outlet Box Damage Category	Faceplate Damage Category	Maximum Exposure Temperature (°C)	Tripped Circuit Breaker?	Time to Tripping (sec)	Maximum Temperature at Trip Time (°C)	Used Power Meter?	Selected for Arcing/ Melting Examination	Primary Arc Location	Secondary Arc Location	Confidence
Furnace 1	D-6	PSE347	Non-energized	PVC	-	-	Steel	Steel	TC	LP	BS	1035	-	-	-	-		-	-	-
Furnace 1	F-4	PSE348	Energized	PVC	-	-	Steel	Steel	TC	LP	BS	976	Yes	92	551	-	Yes	Break off tab	Faceplate	Confirmed
Furnace 1	F-5	PSE349	Energized	PVC	-	-	Steel	Steel	TC	LP	BS	1039	Yes	93	756	-		Break off tab	Faceplate	Confirmed
Furnace 1	F-6	PSE350	Energized	PVC	-	-	Steel	Steel	TC	LP	BS	1031	Yes	87	720	-		Break off tab	Faceplate	Confirmed
Furnace 1	F-1	PSE351	Energized	PVC	-	-	Steel	Steel	TC	LP	BS	1004	Yes	108	680	-		Break off tab	Faceplate	Confirmed
Furnace 1	F-2	PSE352	Energized	PVC	-	-	Steel	Steel	TC	LP	BS	984	Yes	110	627	-	Yes	Break off tab	Faceplate	Confirmed
Furnace 1	F-3	PSE353	Energized	PVC	-	-	Steel	Steel	TC	LP	BS	1024	Yes	121	788	-		Break off tab	Faceplate	Confirmed
Furnace 2	A-1	LEV359	Energized	Polypropylene	-	-	Steel	Steel	CM	LP	BS	1139	Yes	160	646	-		Female Plug Contact	Faceplate	Possible
Furnace 2	A-2	LEV360	Energized	Polypropylene	-	-	Steel	Steel	CM	LP	BS	1114	Yes	125	478	-		Female Plug Contact	Faceplate	Possible
Furnace 2	A-3	LEV361	Energized	Polypropylene	-	-	Steel	Steel	TC	LP	BS	1096	Yes	135	440	-		Unknown	-	-
Furnace 2	A-4	LEV362	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	BS	1176	-	-	-	-	Yes	-	-	-
Furnace 2	A-5	LEV363	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	BS	1154	-	-	-	-		-	-	-
Furnace 2	A-6	LEV364	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	BS	1169	-	-	-	-		-	-	-
Furnace 2	C-1	LEV365	Energized	Polypropylene	-	-	Steel	Nylon	CM	LP	TC	1154	Yes	145	638	-		Receptacle Wiring	Other Wire	Confirmed
Furnace 2	C-2	LEV366	Energized	Polypropylene	-	-	Steel	Nylon	BM	LP	TC	1158	Yes	196	797	-	Yes	Receptacle Wiring	Other Wire	Confirmed
Furnace 2	C-3	LEV367	Energized	Polypropylene	-	-	Steel	Nylon	TC	LP	TC	1120	Yes	174	640	-		Receptacle Wiring	Other Wire	Confirmed
Furnace 2	C-4	LEV368	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	BS	1166	-	-	-	-		-	-	-
Furnace 2	C-5	LEV369	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	BS	1182	-	-	-	-	Yes	-	-	-
Furnace 2	C-6	LEV370	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	BS	1182	-	-	-	-		-	-	-
Furnace 2	E-4	LEV371	Non-energized	Polypropylene	-	-	Steel	Nylon	CM	LP	TC	1201	-	-	-	-	Yes	-	-	-
Furnace 2	E-5	LEV372	Non-energized	Polypropylene	-	-	Steel	Nylon	CM	LP	TC	1178	-	-	-	-		-	-	-
Furnace 2	E-6	LEV373	Non-energized	Polypropylene	-	-	Steel	Nylon	BM	LP	TC	1216	-	-	-	-	Yes	-	-	-
Furnace 2	F-4	LEV374	Energized	Polypropylene	-	-	Steel	Steel	CM	LP	BS	1133	Yes	105	490	-		Female Plug Contact	Faceplate	Possible
Furnace 2	F-5	LEV375	Energized	Polypropylene	-	-	Steel	Steel	CM	LP	BS	1199	Yes	99	653	-		Unknown	-	-
Furnace 2	F-6	LEV376	Energized	Polypropylene	-	-	Steel	Steel	BM	LP	BS	1191	Yes	92	621	-	Yes	Break off tab	Faceplate	Possible
Furnace 2	B-1	PSE354	Energized	PVC	-	-	Steel	Nylon	BM	LP	TC	1090	Yes	187	630	-		Unknown	-	-
Furnace 2	B-2	PSE355	Energized	PVC	-	-	Steel	Nylon	TC	LP	TC	1160	Yes	135	633	-		Receptacle Wiring	Other Wire	Confirmed
Furnace 2	B-3	PSE356	Energized	PVC	-	-	Steel	Nylon	BM	LP	TC	1137	Yes	173	690	-		Unknown	-	-
Furnace 2	B-4	PSE357	Non-energized	PVC	-	-	Steel	Steel	TC	LP	BS	1160	-	-	-	-		-	-	-
Furnace 2	B-5	PSE358	Non-energized	PVC	-	-	Steel	Steel	BM	LP	BS	1145	-	-	-	-		-	-	-
Furnace 2	B-6	PSE359	Non-energized	PVC	-	-	Steel	Steel	BM	LP	BS	1170	-	-	-	-	Yes	-	-	-
Furnace 2	D-1	PSE360	Energized	PVC	-	-	Steel	Steel	BM	LP	BS	1142	Yes	107	525	-		Break off tab	Faceplate	Possible
Furnace 2	D-2	PSE361	Energized	PVC	-	-	Steel	Steel	MC	LP	BS	1151	Yes	134	592	-		Break off tab	Faceplate	Confirmed
Furnace 2	D-3	PSE362	Energized	PVC	-	-	Steel	Steel	MC	LP	BS	1136	Yes	145	562	-	Yes	Break off tab	Faceplate	Possible
Furnace 2	D-4	PSE363	Non-energized	PVC	-	-	Steel	Steel	MC	LP	BS	1187	-	-	-	-		-	-	-
Furnace 2	D-5	PSE364	Non-energized	PVC	-	-	Steel	Steel	BM	LP	BS	1177	-	-	-	-		-	-	-
Furnace 2	D-6	PSE365	Non-energized	PVC	-	-	Steel	Steel	BM	LP	BS	1191	-	-	-	-	Yes	-	-	-
Furnace 2	E-1	PSE366	Non-energized	PVC	-	-	Steel	Nylon	BM	LP	TC	1156	-	-	-	-		-	-	-
Furnace 2	E-2	PSE367	Non-energized	PVC	-	-	Steel	Nylon	BM	LP	TC	1114	-	-	-	-		-	-	-
Furnace 2	E-3	PSE368	Non-energized	PVC	-	-	Steel	Nylon	BM	LP	TC	1143	-	-	-	-		-	-	-
Furnace 2	F-1	PSE369	Energized	PVC	-	-	Steel	Steel	CM	LP	BS	1159	Yes	106	546	-		Unknown	-	-
Furnace 2	F-2	PSE370	Energized	PVC	-	-	Steel	Steel	CM	LP	BS	1136	Yes	156	618	-		Break off tab	Faceplate	Possible
Furnace 2	F-3	PSE371	Energized	PVC	-	-	Steel	Steel	BM	LP	BS	1182	Yes	144	686	-		Break off tab	Faceplate	Confirmed
Furnace 3	B-1	LEV377	Non-energized	Polypropylene	-	-	Steel	Nylon	CM	LP	TC	1146	-	-	-	-		-	-	-
Furnace 3	B-2	LEV378	Non-energized	Polypropylene	-	-	Steel	Nylon	CM	LP	TC	1204	-	-	-	-	Yes	-	-	-
Furnace 3	B-3	LEV379	Non-energized	Polypropylene	-	-	Steel	Nylon	CM	LP	TC	1184	-	-	-	-	Yes	-	-	-
Furnace 3	B-4	LEV380	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	BS	1205	-	-	-	-		-	-	-
Furnace 3	B-5	LEV381	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	BS	1194	-	-	-	-	Yes	-	-	-
Furnace 3	B-6	LEV382	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	BS	1213	-	-	-	-		-	-	-
Furnace 3	D-1	LEV383	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	PM	1185	-	-	-	-		-	-	-
Furnace 3	D-2	LEV384	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	BS	1195	-	-	-	-		-	-	-
Furnace 3	D-3	LEV385	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	PM	1183	-	-	-	-	Yes	-	-	-
Furnace 3	D-4	LEV386	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	BS	1228	-	-	-	-	Yes	-	-	-
Furnace 3	D-5	LEV387	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	BS	1221	-	-	-	-		-	-	-
Furnace 3	D-6	LEV388	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	BS	1231	-	-	-	-		-	-	-
Furnace 3	E-1	LEV389	Non-energized	Polypropylene	-	-	Steel	Nylon	CM	LP	TC	1199	-	-	-	-		-	-	-
Furnace 3	E-2	LEV390	Non-energized	Polypropylene	-	-	Steel	Nylon	CM	LP	TC	1165	-	-	-	-		-	-	-
Furnace 3	E-3	LEV391	Non-energized	Polypropylene	-	-	Steel	Nylon	CM	LP	TC	1190	-	-	-	-	Yes	-	-	-
Furnace 3	F-1	LEV392	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	PM	1202	-	-	-	-	Yes	-	-	-
Furnace 3	F-2	LEV393	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	BS	1183	-	-	-	-	Yes	-	-	-
Furnace 3	F-3	LEV394	Non-energized	Polypropylene	-	-	Steel	Steel	BM	LP	PM	1222	-	-	-	-		-	-	-
Furnace 3	A-1	PSE372	Non-energized	PVC	-	-	Steel	Steel	BM	LP	BS	1186	-	-	-	-	Yes	-	-	-
Furnace 3	A-2	PSE373	Non-energized	PVC	-	-	Steel	Steel	BM	LP	BS	1164	-	-	-	-	Yes	-	-	-

Test No.	Location	Receptacle Serial No.	Energized State	Receptacle Material	Prior Evidence of OH?	Type of Plug	Outlet Box Material	Face Plate Material	Receptacle Damage Category	Outlet Box Damage Category	Faceplate Damage Category	Maximum Exposure Temperature (°C)	Tripped Circuit Breaker?	Time to Tripping (sec)	Maximum Temperature at Trip Time (°C)	Used Power Meter?	Selected for Arcing/ Melting Examination	Primary Arc Location	Secondary Arc Location	Confidence
Furnace 3	A-3	PSE374	Non-energized	PVC	-	-	Steel	Steel	BM	LP	BS	1150	-	-	-	-		-	-	-
Furnace 3	A-4	PSE375	Non-energized	PVC	-	-	Steel	Steel	BM	LP	BS	1218	-	-	-	-		-	-	-
Furnace 3	A-5	PSE376	Non-energized	PVC	-	-	Steel	Steel	BM	LP	BS	1199	-	-	-	-	Yes	-	-	-
Furnace 3	A-6	PSE377	Non-energized	PVC	-	-	Steel	Steel	BM	LP	BS	1211	-	-	-	-		-	-	-
Furnace 3	C-1	PSE378	Non-energized	PVC	-	-	Steel	Nylon	CM	LP	TC	1198	-	-	-	-		-	-	-
Furnace 3	C-2	PSE379	Non-energized	PVC	-	-	Steel	Nylon	BM	LP	TC	1201	-	-	-	-		-	-	-
Furnace 3	C-3	PSE380	Non-energized	PVC	-	-	Steel	Nylon	CM	LP	TC	1168	-	-	-	-		-	-	-
Furnace 3	C-4	PSE381	Non-energized	PVC	-	-	Steel	Steel	BM	LP	BS	1209	-	-	-	-	Yes	-	-	-
Furnace 3	C-5	PSE382	Non-energized	PVC	-	-	Steel	Steel	BM	LP	PM	1223	-	-	-	-	Yes	-	-	-
Furnace 3	C-6	PSE383	Non-energized	PVC	-	-	Steel	Steel	BM	LP	BS	1224	-	-	-	-		-	-	-
Furnace 3	E-4	PSE384	Non-energized	PVC	-	-	Steel	Nylon	CM	LP	TC	1238	-	-	-	-	Yes	-	-	-
Furnace 3	E-5	PSE385	Non-energized	PVC	-	-	Steel	Nylon	CM	LP	TC	1224	-	-	-	-	Yes	-	-	-
Furnace 3	E-6	PSE386	Non-energized	PVC	-	-	Steel	Nylon	CM	LP	TC	1251	-	-	-	-		-	-	-
Furnace 3	F-4	PSE387	Non-energized	PVC	-	-	Steel	Steel	TC	LP	BS	1181	-	-	-	-		-	-	-
Furnace 3	F-5	PSE388	Non-energized	PVC	-	-	Steel	Steel	BM	LP	BS	1238	-	-	-	-		-	-	-
Furnace 3	F-6	PSE389	Non-energized	PVC	-	-	Steel	Steel	BM	LP	BS	1231	-	-	-	-		-	-	-
Furnace 4	A-1	B019	Non-energized	Phenolic	-	-	Steel	Steel	LM	LP	BS	1186	-	-	-	-		-	-	-
Furnace 4	A-2	B020	Energized	Phenolic	-	-	Steel	Steel	CM	LP	BS	1164	Yes	348	931	-	Yes	Receptacle Wiring	Other Wire	Confirmed
Furnace 4	A-3	B021	Energized	Phenolic	-	-	Steel	Steel	BM	LP	PM	1150	Yes	321	888	-		Receptacle Wiring	Other Wire	Confirmed
Furnace 4	A-6	C023	Non-energized	Phenolic	-	-	Steel	Nylon	CM	LP	TC	1211	-	-	-	-	Yes	-	-	-
Furnace 4	B-1	C037	Energized	Phenolic	-	-	Steel	Nylon	BM	LP	TC	1146	Yes	196	743	-		Receptacle Wiring	Other Wire	Confirmed
Furnace 4	B-2	C040	Non-energized	Phenolic	-	-	Steel	Nylon	CM	LP	TC	1204	-	-	-	-	Yes	-	-	-
Furnace 4	B-3	C043	Energized	Phenolic	-	-	Steel	Nylon	CM	LP	TC	1184	Yes	156	770	-		Receptacle Wiring	Other Wire	Confirmed
Furnace 4	A-4	C044	Non-energized	Phenolic	-	-	Steel	Nylon	CM	LP	TC	1218	-	-	-	-		-	-	-
Furnace 4	A-5	C045	Energized	Phenolic	-	-	Steel	Nylon	CM	LP	TC	1199	Yes	177	849	-	Yes	Receptacle Wiring	Outlet Box	Confirmed
Furnace 4	C-1	D010	Energized	Phenolic	-	-	Steel	Steel	BM	LP	BS	1198	Yes	221	909	-		Receptacle Wiring	Other Wire	Confirmed
Furnace 4	B-4	D018	Non-energized	Phenolic	-	-	Steel	Steel	BM	LP	BS	1205	-	-	-	-	Yes	-	-	-
Furnace 4	C-3	D019	Energized	Phenolic	-	-	Steel	Steel	BM	LP	BS	1168	Yes	274	890	-		Receptacle Wiring	Outlet Box	Confirmed
Furnace 4	B-6	D026	Non-energized	Phenolic	-	-	Steel	Steel	BM	LP	PM	1213	-	-	-	-		-	-	-
Furnace 4	C-2	D028	Energized	Phenolic	-	-	Steel	Steel	BM	LP	BS	1201	Yes	347	998	-		Receptacle Wiring	Other Wire	Confirmed
Furnace 4	B-5	D029	Non-energized	Phenolic	-	-	Steel	Steel	BM	LP	BS	1194	-	-	-	-		-	-	-
Furnace 4	C-4	D030	Non-energized	Phenolic	-	-	Steel	Steel	BM	LP	BS	1209	-	-	-	-	Yes	-	-	-
Furnace 4	C-5	D031	Non-energized	Phenolic	-	-	Steel	Steel	BM	LP	BS	1223	-	-	-	-		-	-	-
Furnace 4	C-6	D032	Non-energized	Phenolic	-	-	Steel	Steel	BM	LP	PM	1224	-	-	-	-		-	-	-
Furnace 4	D-1	D033	Energized	Phenolic	-	-	Steel	Steel	BM	LP	PM	1185	Yes	349	973	-	Yes	Female Plug Contact	Ground Strap	Confirmed
Furnace 4	D-2	D034	Energized	Phenolic	-	-	Steel	Steel	BM	LP	BS	1195	Yes	304	968	-		Receptacle Wiring	Other Wire	Confirmed
Furnace 4	D-3	D035	Energized	Phenolic	-	-	Steel	Steel	BM	LP	BS	1183	Yes	403	1009	-	Yes	Receptacle Wiring	Unknown	Confirmed
Furnace 4	D-4	E041	Energized	Phenolic	-	-	Steel	Nylon	CM	LP	TC	1228	Yes	175	927	-	Yes	Receptacle Wiring	Other Wire	Confirmed
Furnace 4	D-5	E042	Non-energized	Phenolic	-	-	Steel	Nylon	CM	LP	TC	1221	-	-	-	-		-	-	-
Furnace 4	E-1	E046	Non-energized	Phenolic	-	-	Steel	Steel	BM	LP	PM	1199	-	-	-	-	Yes	-	-	-
Furnace 4	D-6	E086	Non-energized	Phenolic	-	-	Steel	Steel	CM	LP	PM	1231		-	-	-	Yes	-	-	-
Furnace 4	E-2	E088	Non-energized	Phenolic	-	-	Steel	Steel	BM	LP	BS	1165	-	-	-	-	Yes	-	-	-
Furnace 4	E-3	E089	Non-energized	Phenolic	-	-	Steel	Nylon	CM	LP	TC	1190	-	-	-	-	Yes	-	-	-
Furnace 4	E-4	E090	Non-energized	Phenolic	-	-	Steel	Nylon	CM	LP	TC	1238	-	-	-	-		-	-	-
Furnace 4	E-5	E091	Non-energized	Phenolic	-	-	Steel	Nylon	CM	LP	TC	1224	-	-	-	-		-	-	-
Furnace 4	E-6	E092	Non-energized	Phenolic	-	-	Steel	Steel	CM	LP	PM	1251	-	-	-	-	Yes	-	-	-
Furnace 4	F-1	E093	Non-energized	Phenolic	-	Folded - Brass	Steel	Steel	LM	LP	BS	1202	-	-	-	-		-	-	-
Furnace 4	F-2	E094	Energized	Phenolic	-	Folded - Brass	Steel	Steel	BM	LP	PM	1183	Yes	22	278	-	Yes	Cord Wiring	Unknown	Possible
Furnace 4	F-3	E095	Non-energized	Phenolic	-	Folded - Brass	Steel	Steel	BM	LP	BS	1222	-	-	-	-	Yes	-	-	-
Furnace 4	F-4	E096	Energized	Phenolic	-	Folded - Brass	Steel	Steel	BM	LP	BS	1181	Yes	21	283	-		Cord Wiring	Unknown	Possible
Furnace 4	F-5	E097	Non-energized	Phenolic	-	Folded - Brass	Steel	Steel	BM	LP	BS	1238	-	-	-	-	Yes	-	-	-
Furnace 4	F-6	E098	Energized	Phenolic	-	Folded - Brass	Steel	Steel	CM	LP	PM	1231	Yes	20	441	-		Cord Wiring	Unknown	Possible
Furnace 5	C-2	B007	Non-energized	Phenolic	Prior Arcing	-	Steel	None	N/A	N/A	N/A	1033	-	-	-	-		-	-	-
Furnace 5	D-3	C002	Non-energized	Phenolic	Prior OH	-	Steel	Steel	TC	LP	BS	1010	-	-	-	-		-	-	-
Furnace 5	D-4	D002	Non-energized	Phenolic	Prior OH	-	Steel	Steel	LM	LP	BS	1060	-	-	-	-		-	-	-
Furnace 5	A-6	E002	Non-energized	Phenolic	Prior OH	-	Steel	Steel	BM	LP	BS	1042	-	-	-	-		-	-	-
Furnace 5	D-5	E004	Non-energized	Phenolic	Prior OH	-	Steel	Steel	LM	LP	BS	1048	-	-	-	-		-	-	-
Furnace 5	A-5	E016	Non-energized	Phenolic	Prior OH	-	Steel	Steel	TC	LP	BS	1027	-	-	-	-		-	-	-
Furnace 5	E-1	E078	Energized	Phenolic	-	-	Steel	Steel	BM	LP	BS	1026	Yes	281	917	-		Receptacle Wiring	Unknown	Confirmed
Furnace 5	E-2	E079	Energized	Phenolic	-	-	Steel	Steel	TC	LP	BS	987	Yes	236	840	-		Female Plug Contact	Faceplate	Confirmed
Furnace 5	E-3	E080	Energized	Phenolic	-	-	Steel	Steel	TC	LP	BS	1012	Yes	339	934	-		Receptacle Wiring	Other Wire	Confirmed
Furnace 5	E-4	E081	Energized	Phenolic	-	-	Steel	Nylon	BM	LP	TC	1067	Yes	178	937	-		Receptacle Wiring	Other Wire	Confirmed
Furnace 5	E-5	E082	Energized	Phenolic	-	-	Steel	Nylon	BM	LP	TC	1043	Yes	192	919	-		Unknown	-	-

Test No.	Location	Receptacle Serial No.	Energized State	Receptacle Material	Prior Evidence of OH?	Type of Plug	Outlet Box Material	Face Plate Material	Receptacle Damage Category	Outlet Box Damage Category	Faceplate Damage Category	Maximum Exposure Temperature (°C)	Tripped Circuit Breaker?	Time to Tripping (sec)	Maximum Temperature at Trip Time (°C)	Used Power Meter?	Selected for Arcing/ Melting Examination	Primary Arc Location	Secondary Arc Location	Confidence
Furnace 5	E-6	E083	Energized	Phenolic	-	-	Steel	Nylon	BM	LP	TC	1079	Yes	86	788	-	Yes	Receptacle Wiring	Unknown	Confirmed
Furnace 5	B-6	LEV008	Non-energized	Polypropylene	Prior OH	-	Steel	Steel	TC	LP	BS	1043	-	-	-	-		-	-	-
Furnace 5	B-1	LEV011	Non-energized	Polypropylene	Prior OH	-	Steel	Steel	TC	LP	BS	976	-	-	-	-		-	-	-
Furnace 5	C-5	LEV012	Non-energized	Polypropylene	Prior OH	-	Steel	Steel	BM	LP	BS	1055	-	-	-	-		-	-	-
Furnace 5	B-5	LEV016	Non-energized	Polypropylene	Prior OH	-	Steel	Steel	TC	LP	BS	1023	-	-	-	-		-	-	-
Furnace 5	B-2	LEV037	Non-energized	Polypropylene	Prior OH	-	Steel	Steel	TC	LP	BS	1037	-	-	-	-		-	-	-
Furnace 5	B-3	LEV128	Non-energized	Polypropylene	Prior OH	-	Steel	Steel	TC	LP	BS	1014	-	-	-	-		-	-	-
Furnace 5	B-4	LEV177	Non-energized	Polypropylene	Prior OH	-	Steel	Steel	TC	LP	BS	1033	-	-	-	-		-	-	-
Furnace 5	C-4	LEV272	Non-energized	Polypropylene	Prior OH	-	Steel	Steel	BM	LP	BS	1039	-	-	-	-		-	-	-
Furnace 5	C-3	LEV275	Non-energized	Polypropylene	Prior OH	-	Steel	Steel	TC	LP	BS	994	-	-	-	-		-	-	-
Furnace 5	C-1	LEV318a	Non-energized	Polypropylene	Prior Arcing	-	Steel	None	N/A	N/A	N/A	1029	-	-	-	-		-	-	-
Furnace 5	F-1	LEV395	Non-energized	Polypropylene	-	Solid - Plated	Steel	Steel	BM	LP	BS	1028	-	-	-	-		-	-	-
Furnace 5	F-2	LEV396	Energized	Polypropylene	-	Solid - Plated	Steel	Steel	BM	LP	BS	1008	Yes	47	404	-	Yes	Cord Wiring	Unknown	Possible
Furnace 5	F-3	LEV397	Non-energized	Polypropylene	-	Solid - Plated	Steel	Steel	BM	LP	BS	1047	-	-	-	-	Yes	-	-	-
Furnace 5	F-4	LEV398	Energized	Polypropylene	-	Solid - Plated	Steel	Steel	CM	LP	BS	1000	Yes	32	331	-		Cord Wiring	Unknown	Possible
Furnace 5	F-5	LEV399	Non-energized	Polypropylene	-	Solid - Plated	Steel	Steel	BM	LP	BS	1063	-	-	-	-	Yes	-	-	-
Furnace 5	F-6	LEV400	Energized	Polypropylene	-	Solid - Plated	Steel	Steel	CM	LP	BS	1055	Yes	30	492	-		Cord Wiring	Unknown	Possible
Furnace 5	A-4	PSE020	Non-energized	PVC	Prior OH	-	Steel	Steel	MC	LP	BS	1054	-	-	-	-		-	-	-
Furnace 5	D-1	PSE021	Non-energized	PVC	Prior OH	-	Steel	Steel	BM	LP	BS	1012	-	-	-	-		-	-	-
Furnace 5	C-6	PSE023	Non-energized	PVC	Prior OH	-	Steel	Steel	BM	LP	BS	1054	-	-	-	-		-	-	-
Furnace 5	D-2	PSE024	Non-energized	PVC	Prior OH	-	Steel	Steel	MC	LP	BS	1024	-	-	-	-		-	-	-
Furnace 5	A-1	PSE131	Non-energized	PVC	Prior OH	-	Steel	Steel	MC	LP	BS	1022	-	-	-	-		-	-	-
Furnace 5	A-3	PSE132	Non-energized	PVC	Prior OH	-	Steel	Steel	BM	LP	BS	982	-	-	-	-		-	-	-
Furnace 5	D-6	PSE133	Non-energized	PVC	Prior OH	-	Steel	Steel	TC	LP	BS	1058	-	-	-	-		-	-	-
Furnace 5	A-2	PSE134	Non-energized	PVC	Prior OH	-	Steel	Steel	BM	LP	BS	991	-	-	-	-	Yes	-	-	-