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Interim Report on the Status of the Analysis of Electrical Components Installed in Homes with Chinese Drywall*

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November 23, 2009

*This report uses the terms "Chinese drywall" and "imported drywall" interchangeably but CPSC staff cautions that until completion of its investigation it is premature to consider that all Chinese or imported drywall exhibits the reported health or corrosive characteristics; nor is it correct to assume that all domestic brands are entirely void of any reported health or corrosive characteristics.

This interim technical report is being released as a draft until the full study has been completed, and all of the results are available for interpretation. This CPSC staff report has not been reviewed or approved by, and may not necessarily reflect the views of, the Commission.

Executive Summary

This report is intended to provide a preliminary view of how electrical components have been affected by allegedly corrosive drywall. This information is preliminary because the bulk of the analysis is still in process, and conclusions drawn from the results at this point would be premature. This ongoing assessment of fire and electric shock safety issues is a two-part test program. The first involves the metallurgical analysis of various components harvested from affected homes to characterize the type and extent of damage by corrosion to the components in homes. The second part includes accelerated corrosion testing of new components in an effort to understand long-term exposure implications to these components.

A total of 169 electrical components were harvested by U.S. Consumer Product Safety Commission (CPSC) staff from six homes in Florida and Virginia which were being remediated by the home builders due to the believed presence of corrosive drywall. A preliminary, visual inspection by CPSC electrical engineering staff of all of the electrical components harvested revealed significant corrosion of copper wiring, and lesser degrees of corrosion to other parts of the electrical components (e.g., screws, metal alloy conductors, etc.). There were no indications of significant overheating of conductors or conductive parts due to the corrosion events, which would have been exemplified by discoloration of various insulating materials, or the formation of metallic beads from the melting of copper or other metal alloys. CPSC staff selected 73 components for analysis.

The scientific staff of the Sandia National Laboratories' (SNL) Material Science and Engineering Center investigated six severely corroded receptacles (one receptacle from each of the six different homes) in advance of the full study of the remaining 67 components provided by CPSC staff. The characterization by SNL included optical and scanning electron microscopy examinations and imaging, and chemical analysis of corrosion products observed on the surfaces of the metal conductor sub-components (wires, screws and contact plates) from the partial group of receptacles. SNL's examination of wires attached to the six receptacles revealed several morphologies, or forms of copper corrosion products, but due to time constraints, only two morphologies were able to be analyzed from one wire in time for this interim report: cauliflower-shaped nodules and spongiform (sponge-like) texture. The corrosion nodules are readily found on the surface of the exposed copper wires, while the spongiform texture appears in micro-cavities that underlie the corrosion nodules. The sequence of events understood at this time

suggests that as the corrosion nodules grow, micro-cavities form under the corrosion nodules as copper is transported from the unaltered, underlying copper wire to the overlying nodules. After the micro-cavities form, corrosive gases may then penetrate into the cavities, creating the spongiform texture. The overall thickness of the corrosion layer varies from nearly zero to twenty thousandths of a millimeter.

Elemental analyses of both forms of corrosion indicate the presence of copper, sulfur, and small amounts of oxygen, strongly suggesting the presence of a variety of copper sulfide and copper oxide. One sample of corroded copper wire was examined via X-ray Diffraction (XRD) and was found to contain copper sulfide in the variety known as digenite (Cu_9S_5) and copper oxide in the variety known as cuprite (Cu_2O).

Corrosion of copper wiring was most extensive where bare copper was exposed. Intact electrical insulation (e.g., thermoplastic) on copper wiring protects the underlying copper conductor from corrosion.

Introduction

The following report documents the status of the U.S. Consumer Product Safety Commission (CPSC) Directorate for Engineering Sciences (ES) staff assessment of the effects of corrosive gases reportedly emanating from Chinese-manufactured drywall on electrical components. This component study is part of a multi-track program that also includes research into the health effects associated with the emission of gases from the suspect drywall. This report is intended to provide a preliminary glimpse into how electrical components have been affected by allegedly corrosive drywall, so that the report may be considered in conjunction with the release of reports on health concerns. This information is preliminary because the bulk of the analysis is still in process, and any conclusions drawn from the results at this point would be premature.

The assessment of fire and electric shock safety issues is a two-part test program. The first involves the metallurgical analysis of various components harvested from affected homes to characterize the type and extent of damage by corrosion to the components in homes. The second part includes accelerated corrosion testing of new components in an effort to understand long-term exposure implications to these components. Sandia National Laboratories' (SNL) Material Science and Engineering Center is analyzing electrical distribution components under an interagency agreement between the CPSC and the Department of Energy (CPSC-I-09-0020/SNL 018090709), while the National Institute of Standards and Technology (NIST) is analyzing smoke alarms, sprinklers and fuel gas components under two interagency agreements (NIST analysis results will be reported separately from the SNL analysis results).

Accelerated corrosion testing will be based on gases identified in the drywall chamber studies conducted at Lawrence Berkeley National Laboratory in combination with Environmental Health and Engineering's results on indoor-air measurements in 51 homes. New electrical components will be exposed to elevated concentrations of selected gases in test chambers at Sandia National Laboratories, for an exposure duration yet to be determined, in order to better understand long-term exposure risks. A metallurgical analysis will be conducted on the components undergoing accelerated corrosion testing (while electrically powered), and compared with the affected-house harvested samples. The intent is to attempt to understand whether the long-term exposure results in unacceptable degradation of the performance that could present either a risk of fire or electric shock. Although the duration of the accelerated corrosion testing is not known at this time, the testing and analysis is expected to be completed in spring or summer 2010.

It is hoped that through these analyses the risks that corroded electrical components may present to the consumer will be understood. However, the ability to reach an absolute conclusion may be difficult to accomplish due to a number of highly varying factors (some possibly yet to be determined) that could affect the production of corrosion products on electrical components, such as local outdoor temperature and humidity, consumer preferences for indoor temperature and humidity levels, size and layout of homes, proportion and location of affected and unaffected drywall used in a home, rates and quantities of corrosion-producing gases in differing drywall lots, and local indoor and outdoor air quality.

Background

In late 2008, CPSC staff began to receive reports that homes in Florida constructed in 2006 and 2007 were exhibiting common characteristic problems including noxious odors, sickened occupants, air conditioning failures and visible corrosion of metals including electrical wiring in the walls. Florida Department of Health (FL DOH) officials began to assess the situation based on health complaints of irritated and itchy eyes and skin, difficulty in breathing, persistent cough, bloody noses, runny noses, recurrent headaches, sinus infection, and asthma attacks. Many consumers reported that their symptoms lessened or went away when they were away from their homes, but returned upon re-entry, suggesting that these symptoms were short-term and related to something within the home. Reports of similar problems from other states gradually began to accumulate. By the end of October 2009, the CPSC had received about 1,897 reports from residents in 30 states, the District of Columbia, and Puerto Rico who reported that their health symptoms and/or the corrosion of certain metal components in their homes are related to the presence of drywall produced in China, with most reports coming from Florida, Louisiana, Mississippi, Virginia and Alabama. State and local authorities have also received similar reports.

After conducting a preliminary inspection of four affected homes on the west coast of Florida in March 2009 and assimilating other data presented by FL DOH officials, homebuilders, and a drywall manufacturer, CPSC staff believed that drywall was creating an odor in the houses and blackening copper parts like air conditioning evaporator coils and electrical wires. CPSC technical staff proceeded in developing plans to determine if the drywall was defective. This multi-track program included sub-programs to assess potential health effects, trace the importation of potentially-affected drywall through the chain of commerce (from source to distribution), and study the corrosion effects of electrical components with respect to risks of fire and electric shock. The CPSC is partnering with the U.S. Environmental Protection Agency (EPA), U.S. Department of Housing and Urban Development (HUD), Centers for Disease Control and Prevention (CDC), Agency for Toxic Substance and Disease Registry (ATSDR), and numerous state departments of health, working together to investigate and analyze how Chinese-made drywall entered into the country, where it was used, what mechanism(s) and substance(s) are creating the noxious and corrosive gases emanating from the drywall, and what impact it may have on human health and corrosion of electrical and fire safety components.

The CPSC Directorate for Engineering Sciences staff drafted plans to assess immediate and long-term effects of allegedly corrosive drywall on electrical components, fuel gas components and fire safety devices by examining components harvested from affected homes and conducting accelerated corrosion tests on new exemplar components to study long-term effects of the corroding gases. Electrical distribution components of interest include residential wiring, receptacles, switches, circuit breakers, panel boards, ground fault circuit interrupters

(GFCIs), and arc fault circuit interrupters (AFCIs). The objective is to determine to what extent the electrical and fire safety components are being corroded and what effect the corrosion could have on their safe operation. Excessive corrosion could create hazards in the following areas:

Fire

- Deterioration of wiring connections, such as to the terminals of a receptacle, could cause overheating.
- Significant reduction of the cross-sectional area of wiring that would eventually result in loss of capacity to carry current, leading to overheating, or, become physically weak and break. Compromised or broken ground wires could present a risk of fire because ground faults could occur in the distribution system without facilitating tripping of a branch circuit overcurrent protection device.
- Damage to circuit traces or electronic components on printed circuit boards in protective devices such as AFCIs, causing functional failures of the protective devices, leading to a loss of protection that these devices provide.

Electric Shock

- Deterioration of connections could diminish the effectiveness of grounding connections.
- Significant reduction of the cross-sectional area of grounding wires that could become physically weak and break or increase in resistance to the point of providing an inadequate grounding protection.
- Damage to circuit traces or electronic components on printed circuit boards in GFCIs, causing failure of GFCIs and the loss of protection they provide.

Component Harvesting

The primary objective of the harvesting effort was to obtain samples of electrical components of interest in order to evaluate any damaging effects from allegedly corrosive drywall. The team elected to harvest the components of interest from homes that were in the process of being remediated by the homebuilder. There were two primary reasons for this. First, homes being remediated were verified by the builder as having been constructed with at least some Chinese drywall. Components collected from these homes would be in scope in terms of potential exposure. Second, the highly invasive nature of removing electrical and fire safety components made it much easier to collect electrical wiring and wiring devices without concern for creating an unsafe condition within the system. While all builder remediation efforts differed in some aspects, complete removal of the drywall was being performed in the homes available for sampling. Most remediation efforts included removal/replacement of all wiring devices (receptacles, GFCIs and switches) along with all electrical wires (signal/communication as well as power conductors). Appendix A includes descriptions of the electrical components of interest and the areas where the corrosion analysis will focus for each component.

Logistics and scheduling presented four single-family homes and two townhomes for harvesting in the collection timeframe from June through August 2009. The two townhomes were from the tidewater area of Virginia. One of the single-family homes was from eastern Florida while three were on Florida's southwest coast. Table 1 summarizes the electrical components taken from each house. Five of the six houses were occupied until shortly before the component harvesting. Not too long before harvesting was scheduled, the occupants moved from their houses so that the remediation could occur. The one exception is the house in North Venice, FL, which had been purchased by a relocation company and was already vacant when CPSC staff first visited this home in March. The relocation firm sold the home to a real estate developer just before the harvesting in June. The developer intended to remove and replace the drywall in order to place the property on the market for resale. This limited the number of components available for harvesting. Because of this arrangement, an electrician was hired to replace extracted components from the North Venice house. For all six houses, the component harvesting preceded drywall demolition.

Table 1. Summary of Harvested Electrical Components

Location	Collection Date	Receptacles	GFCIs	Switches	Standard Circuit Breakers	AFCIs	Chinese Drywall
North Venice, FL	6/15/09	10	3	2	2	1	Unknown
Chesapeake, VA 1	7/7/09	26	3	6	0	0	Brand A
Chesapeake, VA 2	7/7/09	25	3	5	0	0	Brand A
Boynton Beach, FL	7/23/09	16	5	6	0	0	Brand B
Port Charlotte, FL	8/24/09	14	3	4	1	1	Brand C
Ft. Myers, FL	8/25/09	16	5	8	0	0	Brand B

A procedure was developed for harvesting components, with the first house serving as a pilot. Refinements were made to the procedure after completing the sample extraction from the two Virginia homes. During the Virginia harvesting effort, CPSC staff was accompanied by Environmental Health & Engineering (EH&E) scientists, who were conducting their own pilot analyses for use in the 51-home study. Personnel from EH&E performed in-situ Fourier transform infrared (FTIR) spectroscopy and x-ray fluorescence (XRF) scans of the drywall as part of a sub-task to identify markers in Chinese drywall (in Chesapeake, VA, EH&E personnel removed drywall for later FTIR and XRF scanning). Receptacle sampling by the CPSC staff was performed wherever EH&E conducted a scan. Four receptacles per room were extracted (two from interior walls and two from exterior walls) as well as switches and GFCIs, where available. Drywall samples adjacent to every collected electrical component sample were added to the collection procedures before sampling of the final three houses had been initiated; during previous harvesting efforts, only a visual validation of the presence of imported drywall somewhere in the house was made. The procedure followed for harvesting electrical components is detailed in Appendix B. While the baseline harvesting plan for each home was to extract two receptacles per room (one interior/one exterior), switches, all GFCIs, an AFCI, and two circuit breakers, the scheduling for remediation and general availability of homes dictated the ultimate selection of components that were harvested.

The receptacle/switch/GFCI extraction method used on the first three homes was to remove the cover plate, extend the device from the box and cut the wires at a point closest to the electrical box. For the last three houses, the cover plate was removed so that the entry of the cable into the box could be determined. Then a piece of drywall was cut out above and/or below the receptacle to allow the cable to be cut in order to also allow retrieval of several inches of cable that were connected to the wiring device. Each device was placed into a polyethylene locking-type bag, with a label affixed to the bag and then inserted into another polyethylene bag.

Metallurgical Analysis of Components

Engineering staff sorted through all of the harvested electrical components to select those that would provide the best information on corrosion. The samples were then packaged and shipped to SNL. Table 2 lists the parts that were selected from each house.

In order to get some preliminary results for inclusion in their initial report, CPSC staff requested that SNL staff first examine a receptacle from each of the six homes that were part of the harvesting program.

Table 2. Components sent to Sandia National Laboratories for analysis.

Home Location	Receptacles	Switches	GFCIs	Breakers	AFCIs
North Venice, FL	7	2	2	2	1
Chesapeake, VA 1	7	3	2		
Chesapeake, VA 2	6	3	3		
Boynton Beach, FL	6	2	2		
Port Charlotte, FL	7	2	2	1	
Ft. Myers, FL	5	5	3		
Totals	38	17	14	3	1

Discussion

For the purposes of being able to convey some initial level of understanding of the corrosion of electrical components noted by CPSC staff on samples harvested from the field, the scientific staff of the Sandia National Laboratories' (SNL) Material Science and Engineering Center investigated six severely corroded receptacles (one receptacle from each of the six different homes) in advance of the full study of the remaining 67 components provided by CPSC staff. Their analyses to date, documented in their interim report attached as Tab A, provide an interim understanding of the corrosion events that are currently occurring in homes. A more thorough understanding of the corrosion events may only be possible with the completion of additional analyses of corroded field samples, as well as analyses of corrosion products after accelerated corrosion testing has been completed on exemplar samples of the various electrical components.

A preliminary, visual inspection by CPSC electrical engineering staff of all of the electrical components harvested revealed significant corrosion of copper wiring, and lesser degrees of corrosion to parts of the electrical components (e.g., screws, metal alloy conductors, etc.). There were no indications of significant overheating of conductors or conductive parts due to the corrosion events, which would have been exemplified by discoloration of various insulating materials, or the formation of metallic beads from the melting of copper or other metal alloys.

It should be noted that the collection of samples was difficult due to issues involving scheduling as well as legal barriers due to pending lawsuits. A statistically valid sampling plan would be necessary in order to obtain a larger variety of samples for evaluation, and prevent the injection of statistical bias into the sample collection process. Therefore, the observation of a lack of overheating effects should not be broadly interpreted as a refutation to reports by some consumers of electrical component and appliance failures. Although the six homes from which samples were collected by the CPSC staff were scheduled for remediation, this does not imply that other homes could not have experienced more or less severe corrosion effects.

A review of the interim report by SNL (Tab A) and conversations with SNL staff suggest that copper wiring is the most susceptible electrical component to the effects of the corrosive gases. Other metallic structures, the failure of which could lead to risks of electric shock or fire, appeared to be far less sensitive to the effects of the corroding gases. The composition of the corrosive gases that are suspected of being released by the allegedly corrosive drywall is being investigated under different tracks of the overall multi-track investigation.

Examination of wires attached to the six receptacles revealed several morphologies, or forms of copper corrosion products, but due to time constraints only two morphologies were able to be analyzed from one wire in time for this interim report: cauliflower-shaped nodules and spongiform (sponge-like) texture. Figure 1 shows a scanning electron microscope (SEM) image of the surface corrosion including a cross-sectional view created by removing a section of the corrosion and wire with a focused ion beam. The corrosion nodules are readily found on the surface of the exposed copper wires, while the spongiform texture appears in micro-cavities that underlie the corrosion nodules. The sequence of events understood at this time suggests that as the corrosion nodules grow, micro-cavities form under the corrosion nodules as copper is transported from the unaltered, underlying copper wire to the overlying nodules. After the micro-cavities form, corrosive gases may then penetrate into the cavities, creating the spongiform texture. The overall thickness of the corrosion layer varies from nearly zero to twenty thousandths of a millimeter. The micro-cavities also show depths of a similar magnitude. Analyses of other samples could reveal greater thicknesses of corrosion product and cavity depths.

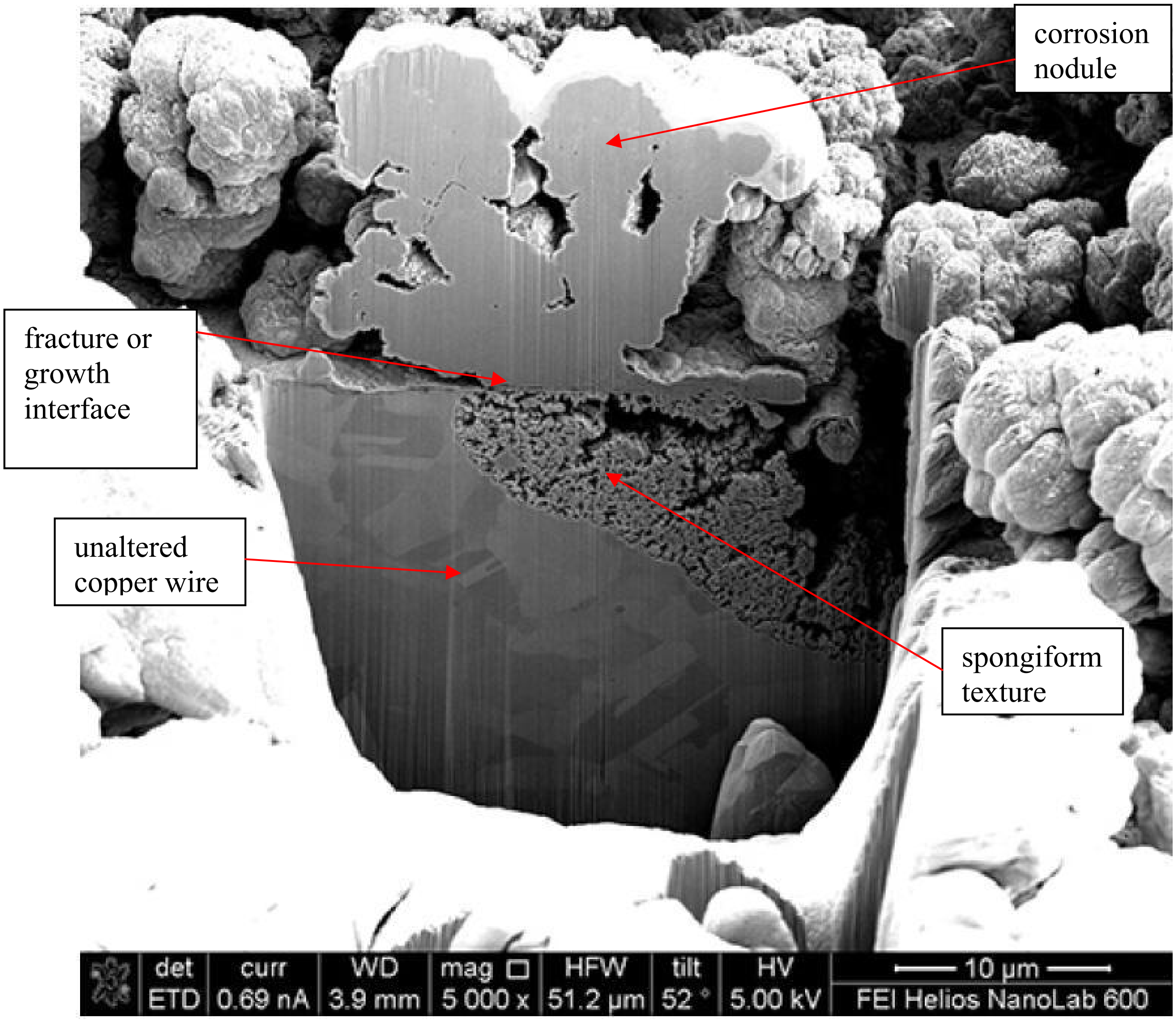

Figure 1. SEM-magnified view of surface corrosion on a ground wire.

The rate of copper corrosion is believed to be initially high until a corrosion surface layer covers the exposed surface of the copper wire. At that point, penetration of the corrosive gases to the underlying copper is more restricted, and the corrosion rate therefore slows. However, as long as the corrosive gases are present, the process of corrosion will continue. The growth process may lead to a poorly adhered layer of corrosion product. Fractures could occur at the base of the corrosion nodules, due to a combination of the expansion and contraction of the underlying copper wire as it experiences heating from a cooler state, and cooling from a warmer state, along with the presence of micro-cavities, which together undermine the base of the nodules. This could lead to the separation of the corrosion nodule from the surface of the copper wire, enhancing the penetration of the corrosive gases to the layer below, which for a period of time would result in an increase in the rate of corrosion until a new, thick layer of corrosion products is formed. In the continuous presence of corrosive gases, this process would be cyclical, continuing to consume the copper wire.

Elemental analyses, i.e., identifying the chemical elements, of both forms of corrosion indicate the presence of copper, sulfur, and small amounts of oxygen, strongly suggesting the presence of a variety of copper sulfide and copper oxide. One sample of corroded copper wire was examined via X-ray Diffraction (XRD) and was found to contain copper sulfide in the variety known as digenite (Cu_9S_5) and copper oxide in the variety known as cuprite (Cu_2O). Other varieties of copper sulfide and copper oxide may also exist, but were either not present on the one sample of copper wire that was analyzed, or were present in such low quantities that identification via XRD was not possible. Additional XRD analyses are planned on the remaining harvested components provided to SNL for analysis.

Corrosion of copper wiring was most extensive where bare copper was exposed. Intact electrical insulation (e.g., thermoplastic) on copper wiring protects the underlying copper conductor from corrosion. In the examination of one insulated wire, it was noted that on a wire that was originally covered by insulation, in a location immediately adjacent to where insulation had been stripped away, the corrosive gases were able to penetrate between the copper wire and the overlying insulation up to a distance of 0.2 cm under the insulation, creating slight levels of corrosion on the copper surface. For distances beyond 0.3 cm the copper wire appeared bright and uncorroded. Additionally, where the insulation of the wire had been removed, but the bare copper was shielded or covered in such a way as to prevent the free flow of gases to the exposed areas, the exposed areas typically exhibited minor corrosion.

Battelle Labs' mixed flowing gas specifications define four classes of corrosive environments for the operation of equipment, ranging from Class I (least corrosive) to Class IV (most corrosive). For copper, Battelle assigns the following definitions to these four classes[1]:

Class I	No significant corrosion observed.
Class II	Corrosion product on unprotected copper contains oxide and chloride.
Class III	Corrosion product on unprotected copper is rich in sulfide and oxide.
Class IV	Corrosion product on copper is primarily a sulfide film with some oxide.

[1] Robert Baboian, *Corrosion tests and standards: application and interpretation*, *Edition 2*, (ASTM International, Pennsylvania, 2005), p. 360.

Based on the degree of corrosion observed on all of the samples provided to SNL, as well as the presence of corrosion products that are creeping onto inert surfaces (e.g., dried droplets of paint on the copper conductors), SNL staff believe the Battelle corrosive environments that the copper wiring has been exposed to could be as severe as either Class III or Class IV. Electrical equipment that is intended to operate in such environments needs to be designed in such a way, through choice of materials and overall device construction, to reduce the impact of the corrosive gases. Further research will be conducted by SNL in order to attempt to arrive at the appropriate corrosive environment classification. The corrosion classification will additionally be used to select corrosive gas concentration levels for the accelerated corrosion testing yet to be performed. To date, the mechanism(s) and rate(s) of creation of the corrosive gas(es) from the allegedly corrosive drywall are not yet known.

Appendix A
Description of Components of Interest

Wire and Cable

In residential distribution systems, general purpose circuits are rated for 15 amperes (A) and use AWG 14 for copper conductors (nominally 4110 circular mils), or circuits are rated 20 A, necessitating the use of AWG 12 for copper conductors (nominally 6530 circular mils). Other specialty circuits include those supplying higher power loads such as electric clothes dryers, electric water heaters and electric ranges, requiring AWG 10 or larger conductors (nominally 10,380 circular mils). In the harvesting effort, all of the conductors in a cable that were smaller than AWG 8 were solid conductors, and all larger conductors were stranded. The harvesting effort primarily yielded three sizes of wire and cable (based on the rating of the circuit) attached to receptacles/GFCIs/ switches. The main type of power cable that was found in the harvested homes was Type NM or nonmetallic sheathed cable, consisting of two or more insulated conductors with a bare grounding conductor, all enclosed in a nonmetallic jacket. All of the harvested power cable conductors were copper. One of the main questions related to the Type NM cables is whether the insulation on the individual conductors and/or the plastic outer sheath of the cable assembly forms a sufficient vapor barrier to prevent corrosion along the unexposed length of the cable. This is an important question for remediation efforts.

Receptacles

The most common wiring device in a residential distribution system is the standard receptacle used for connection of cord-and-plug connected appliances to the electrical distribution system. Receptacles are often found in the common, duplex arrangement (permitting the connection of two power cords to the receptacle), but occasionally found as a single outlet; both types were collected. Unless the receptacle is the only outlet on a branch circuit intended for dedicated load, it is one in a series of receptacles connected sequentially, often wired in a configuration know as daisy-chaining (see Figure A1). In a typical daisy-chaining set-up, a cable is routed from the main panelboard and connected to one set of terminals on the first receptacle in the circuit. A cable attached to the second set of terminals on the first receptacle is routed to the next receptacle, from which a cable connects to the next receptacle in line. Therefore, a receptacle’s terminals may be carrying current (to an appliance plugged into a downstream receptacle) even when nothing is plugged into that receptacle's outlets. The safety implication is that there is an interdependence between the daisy-chained components of the circuit, i.e., severe corrosion at a critical point in the chain can have an impact on remaining parts of the daisy-chained circuit, or operation of the remaining points within the daisy-chained circuit may affect a corroded component within the circuit.

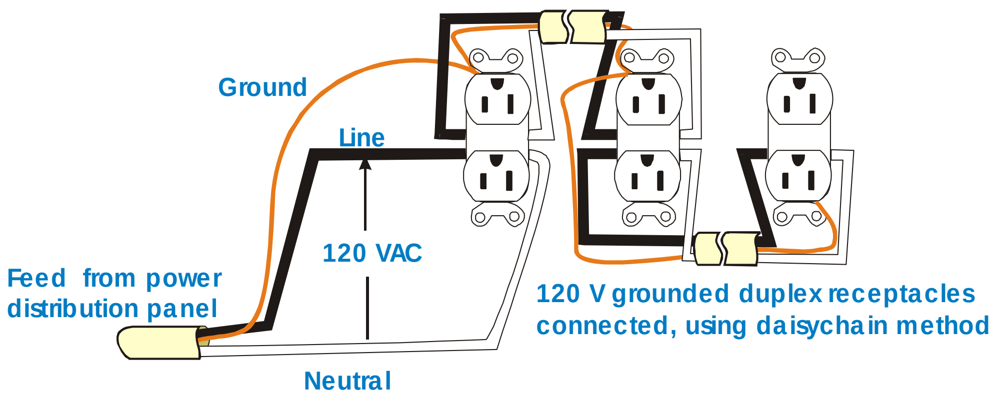

Figure A1. Typical 120 V branch circuit wired using daisy-chain method.

Current-carrying conductors, i.e., the line and neutral wires, may be attached to a receptacle by any of three methods: by the back-wire push-in (BWPI) terminals through the back of the receptacle, by the wire-binding screws (WBS) on the sides of the receptacle, or by a pressure-plate connection through the back of the receptacle (this connection means supplants the BWPI type of connection and is often found on receptacle-type GFCIs). In all cases, the grounding conductor is connected to the receptacle by a WBS.

Figure A2 shows the back of a standard receptacle with line and neutral conductors attached by BWPI connection; the unused, fully-extended wire-binding screws can also be seen in the photo. Two sets of terminals facilitate daisy-chaining of the receptacle as well as permitting one outlet to be switched while the other is continuously powered. A BWPI connection can only be made with AWG 14 wires, limited by the diameter of the opening on the back of the receptacle. A BWPI connection is made by inserting the wire into the back of the receptacle where it is captured by a brass clip that holds it in place and forms part of the connection by cutting into the surface of the wire. This is shown in Figure A3, which is a photo of the terminal removed from the receptacle. Figure A3 illustrates how the BWPI connection is created by a preset force and exerted primarily at the contact point on the spring clip. Therefore, areas of concern for corrosion of a BWPI connection are from the wire to the spring clip and along the surface of the wire between the wire and the side of the terminal in contact with the wire.

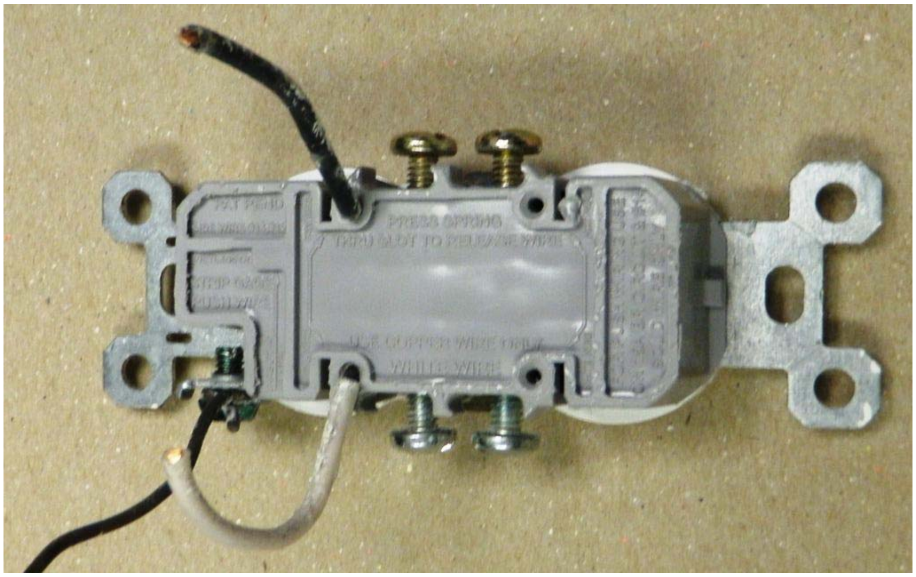

Figure A2. The back of a standard receptacle with wires connected via BWPI terminals.

Figure A3. Receptacle terminal removed to show how a BWPI connection is formed.

A WBS connection is made by tightening a loop of wire under the head of the screw as seen in Figure A4. Electrical contact is made between the wire loop surface and the contact plate on the side of the receptacle. The screw is not intended to be a primary current-carrying path. The tightness of the connection is dictated by the installer. Workmanship plays a large role in the tightness of the connection and how well the loop is captured under the head of the screw. Areas of concern for corrosion of a WBS connection are from the wire to the contact plate and exposed surfaces of the stripped-back wire lead. A connection in which the wire is tightly looped around the screw, has been tightened with the proper torque and has an optimal amount of insulation stripped back will have less surface area exposed to the air than in a BWPI connection. However, one of the objectives of the detailed metallurgical analysis is to study the wire/contact plate interface to see if corrosion intrusion is present.

Figure A4. Receptacle wired via WBS terminals.

Wire-splicing Connectors

While not identified as a specific component of interest, twist-on wire-splicing connectors were collected during the harvesting efforts wherever they were part of the wiring to a receptacle or switch. Twist-on splicing connectors are conical-shaped plastic caps, usually enclosing a metal spring, used to join two or more wires together. The metal spring exerts mechanical pressure on the conductors to improve the tightness of the connection but is not intended to be part of the current-carrying circuit. Despite not being a targeted component, twist-on type connectors are

Figure A5. Twist-on splicing connectors.

an important part of the system to consider because a corrosion-related failure could result in the same fire and shock hazards as any other wiring device. Twist-on type connectors that were collected included both current-carrying connections and grounding connections. Areas of concern where corrosion may have an effect are between the wires within the twist-on connector. If the wire-to-wire connection degrades and results in the spring becoming the main current-carrying path, overheating of the spring could result.

The pressure plate connection means will be discussed under the GFCI section.

Switches

Rocker switches are common throughout homes for controlling power to luminaires and switched receptacles. They are often wired with AWG 14 conductors. Back-wire push-in and wire-binding screw terminals are available as a means for connecting circuit conductors just as with receptacles. Figure A6 shows a switch that is backwired. The areas of concern for corrosion include the same connections points as the BWPI and WBS connections to receptacles. Another area of concern for switches is the internal switch contacts. Switch contacts are the specially-designed metal pads inside the switch intended for withstanding the repetitive arcing caused by the interruption of current when the contacts are opened. The contacts are separated when the switch is in the off position and therefore exposed to air. The objective of the metallurgical analysis will include examination of the contact surfaces to determine if they are affected by the corroding gases.

Figure A6. Back-wired switch.

Ground Fault Circuit Interrupters

Ground-fault circuit interrupters are electrical safety devices that are located in select circuits in the distribution system to rapidly sense ground faults and to open the circuit before an individual may be exposed to lethal shock currents. The requirement for a GFCI is dictated by the location of a receptacle, but the GFCI function may be incorporated into a receptacle or into a circuit breaker. All six of the houses had GFCI receptacles rather than GFCI circuit breakers. Some receptacle locations that require GFCI protection include bathrooms, kitchens, garages and outdoors. Receptacle GFCIs located in bathrooms and kitchens often provide protection to other downstream receptacles besides itself. Receptacle GFCIs include WBS connection means as well as a back-wire pressure-plate connection, which is a hybrid of the BWPI and the WBS types of connections. A GFCI that is back-wired is shown in Figure A7. For the pressure-plate connection, the stripped wire lead is inserted into an opening on the back of the receptacle like the BWPI, but the connection is formed by tightening the wire-binding screw on the side of the device. The pressure plate is threaded onto the end of the wire-binding screw and clamps the wire as the screw is tightened. This compressive force exerts pressure along a wider section of wire than a BWPI. However as with any of the other means for receptacle connections, the

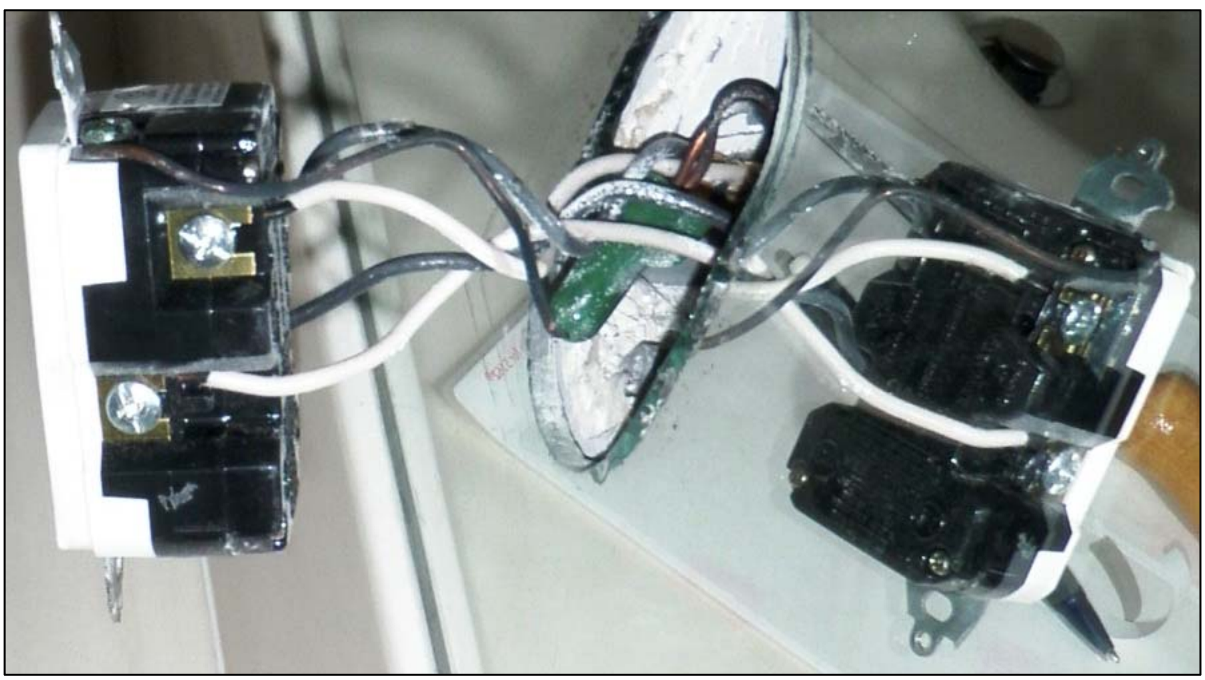

Figure A7. Photo showing a GFCI, connected by the back-wire pressure connector, and its image in a mirror.

contact surfaces are one of the areas of concern with respect to corrosion.

In addition to their basic electrical distribution system function, receptacle GFCIs are electronic devices that include a printed circuit board for monitoring and detecting ground leakage currents and a circuit interruption mechanism (with contacts much like that of a switch). Deleterious effects of the corroding gases on either of these subcomponents could result in improper functioning of a GFCI. The analysis will attempt to determine the effects of the corroding gases on these parts. GFCIs play an important role in preventing severe electric shock or electrocution from faulty equipment. Loss of this function due to damage incurred from corrosion could be interpreted as a shock hazard.

Circuit Breakers

Circuit breakers are a vital part of a residential electrical distribution system, intended to protect the electrical cables from overheating due to short circuits and overloads in the system. In most cases, all of the circuit breakers are installed in a central location in a panelboard. Figure A8 shows a panelboard with its cover removed to show the layout. In the photo, the feed from the utility enters at the bottom through three aluminum conductors. A main circuit breaker controls the power to the two lines of circuit breakers.

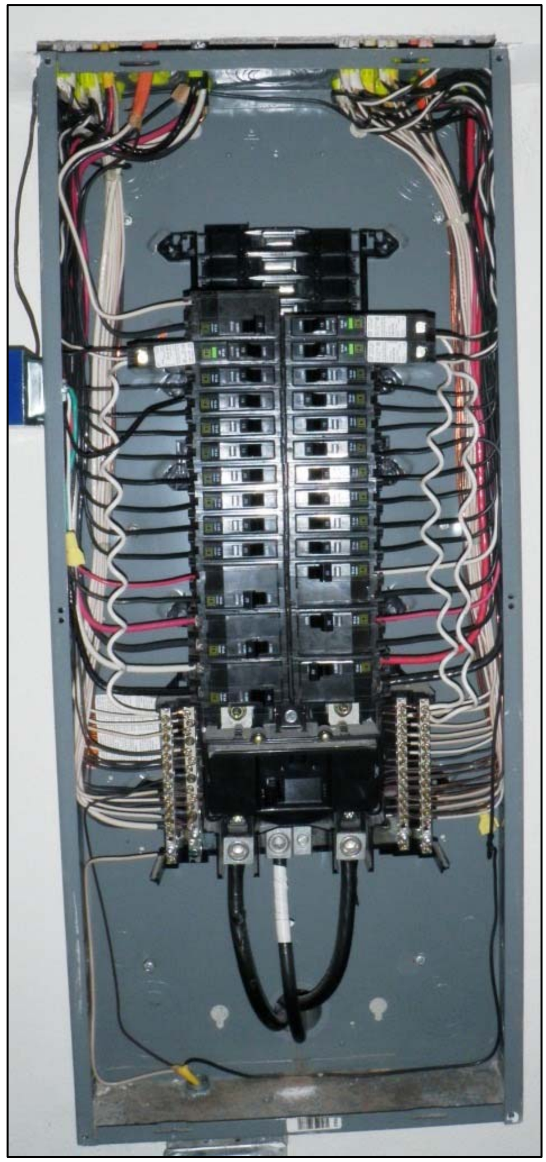

Figure A8. Panelboard with cover removed.

A circuit breaker has a spring-loaded metal clip, which connects it to a bus or metal bar within the panelboard through which power from the utility meter is distributed to the various circuits throughout the house. The output terminal of a circuit breaker is a set-screw, which is tightened by the installer, to connect the line conductor to the breaker. Internally, a circuit breaker incorporates circuit-breaking contacts similarly to switches and GFCIs as well as electromechanical elements to actuate the tripping. Areas of concern for corrosion for circuit breakers are the input and output connections and the contacts, which could overheat if compromised, and damage to the trip mechanism linkages that could result in failure of the circuit breaker to operate under a short circuit or overload and allow the circuit conductors to overheat. Not all builders were replacing circuit breakers so they were only available on a limited basis.

Arc-fault circuit interrupters (AFCIs). AFCIs are a specialized type of circuit breaker incorporating an electronic monitoring circuit to detect arc currents and trip the circuit breaker when the arcing current exceeds preset limits. AFCIs were first introduced into electrical systems in January 2002 as an enhanced means of reducing the likelihood of electrical distribution system fires. An AFCI circuit breaker also incorporates all of the overcurrent features of a conventional circuit breaker. Areas of concern for corrosion include the same as for a conventional circuit breaker as well as any damage to the electronic components that are part of the fault detection circuitry and whose failure would result in loss of operation and lack of protection to the branch circuit.

Appendix B

Draft Procedure for Collection of Electrical/Gas/HVAC Components and Fire Safety Equipment from Homes with Corrosion Symptoms Attributed to the Presence of Imported Drywall

The CPSC technical staff is studying the long-term effects from gasses reportedly emitted by drywall on the creation of corrosion products on copper and other metals, and on the operation of electrical, gas and fire safety equipment with respect to fire and shock hazards. The testing will consist of two major phases: examination of various components harvested from affected homes, and the reaction of new components (one set of components in a powered state, another set of components in an unpowered state) to elevated levels of gases (to be identified in chamber studies of Chinese drywall samples) as part of an accelerated aging test program. The following is a draft procedure for the harvesting of electrical/gas/HVAC samples from homes with imported drywall.

The selected homes will primarily consist of those which are scheduled for drywall removal as part of a repair/remediation program being conducted by several homebuilders. Since repair/remediation programs may differ from builder to builder, some components may not be available for collection.

1. Components of interest
    a. Standard receptacles from interior and exterior walls
    b. Light switches
    c. GFCI receptacles
    d. Standard circuit breakers
    e. AFCI circuit breakers
    f. Flexible gas connectors
    g. HVAC evaporator coils and tubing
    h. Smoke alarms
    i. Fire Sprinklers
    j. Drywall

2. Recommended equipment
    a. Drywall saw
    b. Utility knife
    c. Screwdrivers or Drill/driver
    d. Side, diagonal and cable cutters
    e. Copper pipe cutter for up to 1" pipe
    f. Hacksaw
    g. Digital camera
    h. Flashlight
    i. Plastic locking-type bags
    j. Self-adhesive labels
    k. Tape

l. Electrical tape
m. Twist-on wire connectors
n. Laser rangefinder
o. Digital multimeter

No electric power may be available in the house. Be sure that rechargeable batteries are fully charged and spares are available, if possible.

3. Removal Procedures

What can actually be collected will largely be dictated by the builder's repair plan and the schedule. Discuss with builder liaison staff what can and cannot be removed and if there are any specific removal instructions. Find out if circuits will be re-energized in the future so that wires cut during the removal are properly covered (with electrical tape or twist-on connector) to prevent accidental contact. Be very careful not to damage parts of the house not scheduled for removal (floors, countertops, vanities, sinks, tubs, etc.). A floor plan from the builder is ideal for annotating the location of removed components. It is advisable to first walk through the house and develop a plan for the sequence of removing components.

1. De-energize the branch circuit supplying the components of interest by opening the circuit breaker in the panel board. For removal of circuit breakers, open panel board main circuit breaker and use extreme caution while working inside panel board while the cover is removed. If any other personnel have access to the panel board during electrical component removal, tag out applicable breaker. Verify that electrical power is not present at the device-to-be-removed before proceeding with the removal.
2. For natural gas components, shut off gas centrally as well as locally. For discharging of central air conditioning refrigerant, follow all local and federal regulations for recovery.
3. For removal of receptacles, GFCIs and light switches from a room: For receptacles, arbitrarily select two from a room for removal. One should be on an interior wall (the wall behind is another piece of drywall), the other from an exterior wall (the wall behind is an outside wall of block or other material). Receptacles of particular interest include those supplying a refrigerator and 240 V receptacles (for an electric clothes dryer). Collect all GFCIs. Collect switches from at least each floor.
   a. Annotation: As you enter a room, count total number of each device and designate number from left to right in each room. For example, going into the kitchen, the third receptacle from the left will be referred to as Receptacle #3 and the second GFCI will be GFCI#2. Multiple devices within one box will be counted separately. For rooms with multiple entries, define one entry as the reference point.
   b. Photograph location of device within room. Create entry in log sheet (attached).
   c. Remove cover plate and loosen device(s) retaining screws.
   d. With drywall saw, cut approximately 4" x 4" square of drywall adjacent to outlet box; if wire is not being replaced as part of repair program, be careful not to cut into wires. If replacement program includes replacing all the wire, choose location of drywall piece to remove to facilitate cutting of

wire to remove device. Fill out a label with location and adjacent component information and affix to a bag. Insert drywall piece in bag, seal and insert the bag into another bag (to ensure that label stays with sample). An alternative method is to use s single bag and to write on the bag with an indelible marker.

e. Extend devices from outlet box and photograph.

f. If repair program does not include replacing all wire, verify with builder's liaison staff the permissible length of cut. Cut each individual conductor that is attached to the device about 1" from the termination. If wire is being replaced, cut the cable assembly with cable or side cutters so that about 6 inches of sheathing remains on the cable(s).

g. If necessary, tape or insulate cut ends with a twist-on connector; be sure to prevent any shorts between line and neutral or line and ground if circuit may be re-energized.

h. Annotate label with part designation, date, house address, room and whether it's from an interior or exterior wall and affix label to plastic bag. Insert component and seal bag. Insert sealed bag into another bag since cut ends of wire may poke through the bag and to ensure label remains with component.

4. Follow the following process for harvesting circuit breakers from houses subject to a repair program that includes circuit breaker replacement. **WARNING: Removal of circuit breakers should only be performed by qualified personnel. Uninsulated, live electrical are exposed and accessible within a panel board even when the main circuit breaker is off. Proper safety precautions should be taken.**
   a. Photograph panel board with and without cover. Photograph enclosure door indicating load/breaker assignments.
   b. If panel board is surrounded by drywall that is scheduled to be removed, cut approximately 4" x 4" square of drywall adjacent to panel board using drywall saw. Fill out a label with location and adjacent component information and affix to a bag. Insert drywall piece in bag, seal and insert the bag into another bag (to ensure that label stays with sample). An alternative method is to use a single bag and to write on the bag with an indelible marker.
   c. Turn main breakers off and remove panel board cover.
   d. For AFCI removal: arbitrarily select an AFCI circuit breaker and switch circuit breaker to off. Loosen set screw on neutral bus that is retaining the neutral pigtail wire that is affixed to AFCI. If repair program does not include wire replacement, use diagonal cutters to cut black and white wires approximately one inch back from connection to breaker. If repair program includes complete wire replacement, use cable cutters to cut cable at entrance to panel board enclosure; loosen set screw on ground bus to remove grounding conductor for this cable assembly. Pivot breaker and remove from panel board bus with cable still attached to AFCI.
   e. For standard circuit breaker removal, arbitrarily select a breaker for removal and switch circuit breaker to off. If repair program does not include wire replacement, use diagonal cutters to cut black wire approximately one inch back from connection to breaker. If repair program includes complete wire

replacement, use cable cutters to cut cable at entrance to panel board enclosure; loosen set screws on neutral and ground buses for the neutral and grounding wires from this breaker's cable assembly. Pivot breaker and remove from panel board bus with circuit breaker attached to hot (black) conductor.

f. Annotate self-adhesive label with part designation, location within panel board, load (from panel board chart), date, house address, and room and affix label to plastic bag. Insert breaker and seal bag. Insert sealed bag into another bag since cut ends of wire may poke through the bag and to ensure label remains with component.

Page:
_____ **of**
_____

Date: ______________________________
Location: ____
Attendees: ____

Seq #	Sample #	Item Description	Location	Adj. Wall (Int/Ext)	Comments	Photo #s

Tab A

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Nov. 2009

Interim Report on the Analysis of Corrosion Products on Harvested Electrical Components

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National Nuclear Security Administration under Contract DE-AC04-94AL85000.

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Unlimited Release
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Interim Report on the Analysis of Corrosion Products on Harvested Electrical Components

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Abstract

Sandia National Labs (SNL) was tasked by the Consumer Product Safety Commission (CPSC) with identifying the extent and nature of corrosion that is present on electrical components harvested from homes in several states. This interim report documents the imaging and analyses conducted to date on the wires, screws, and contact plates from one receptacle from each of six homes.

EXECUTIVE SUMMARY

Sandia National Labs (SNL) was tasked by the Consumer Product Safety Commission (CPSC) with identifying the extent and nature of corrosion that might be present on conductor subcomponents of residential electrical components harvested from homes in several states. Questions to be answered in the overall study include:

1. What is the corrosion product or products?
2. Does the corrosion vary with the origin of the component, the composition of the metal component (e.g., copper vs. zinc vs. steel) or with the presence of metal plating?
3. Does wire insulation provide protection against corrosion?
4. Is the corrosion process likely to continue to propagate in the absence of the atmospheric gases that cause it?

Residential electrical components including receptacles, switches, GFCI's, AFCI's, and circuit breakers were provided to SNL for corrosion analyses. Six receptacles out of forty provided were selected as the initial target for Sandia's analyses. The group selected represents receptacles with screw type terminals, receptacles from two (of two) manufacturers, and receptacles with different degrees of corrosion damage.

This interim report documents the imaging and analyses conducted to date on the wires, screws, and contact plates from one receptacle from each of six homes, with some additional data from two additional receptacles. The information in this document is a starting point in providing answers to questions 1, 2, and 3 for receptacles.

Optical and scanning electron microscope (SEM) images were collected to document the extent and nature of corrosion products observed on the surfaces of the metal conductors. A suite of characterization techniques including SEM, X-ray diffraction (XRD), and Focused Ion Beam (FIB) were used to start to determine the morphology, thickness, and chemical identity of the observed corrosion layers.

Optical examination showed discoloration of all the examined metal surfaces relative to un-corroded metals, and for wires the presence of an obvious black surface layer. The extent of the corrosion was assessed using a scale of 1-5, with 1 representing minimal (or no) corrosion and 5 representing the most severe attack.

Corrosion was observed on all of the examined copper wires (ground, neutral and hot). At higher magnification in the SEM, the surface corrosion layer was rough with features that were on the scale of microns. In the plan views these features appear to be particles or clusters of particles that have varying degrees of continuity or adherence to each other, and appear to cover a substantial area of the wires' surfaces. The elemental composition of the corrosion layer is primarily copper and sulfur as determined with Energy Dispersive Spectroscopy (EDS) in the SEM and confirmed with both X-ray Photoelectron Spectroscopy (XPS) and Auger Electron Spectroscopy (AES).

A focused ion beam (FIB) was used to generate a local cross-section through the corrosion product and into the base copper of a corroded hot wire. This technique can be likened to archeology on the microscopic scale. Material was removed in very thin (~ 0.5 microns) slices, each slice showing a cross section of the corrosion layer and underlying copper. SEM images taken of the trench after each thin slice was completed clearly show the thickness (up to 20 microns) of the corrosion layer in the analyzed region and its cauliflower-like morphology. Corrosion of the base copper is also observed and this results in a spongy (porous) region or pit. Energy dispersive spectroscopy (EDS) was performed to obtain a qualitative identification of the elemental composition of the various regions seen in the FIB cross section. The major elements in the corrosion product layer are Cu (copper) and S (sulfur), with minor amounts of O (oxygen). The spongy region in the underlying copper is primarily Cu, S, and O.

Using the FIB technique a thin slice was removed from the trench and placed on a metal grid for subsequent analysis. This view of the slice allowed observation of the details of the corrosion product. Subtle contrast differences suggest a layer structure. Preliminary compositional analysis suggests a gradient in the Cu/S ratio. This layered morphology could indicate that corrosion product growth occurred over a range of conditions (humidity, temperature, concentration of atmospheric pollutants, etc.).

Examination of one insulated hot wire showed that corrosion was present on the bare copper where the insulation had been removed prior to installation. Some corrosion products were also observed on the copper in a region that was stripped of insulation by Sandia. At a distance of approximately 0.7 cm from the as-received edge of the insulation, no corrosion was observed on the copper. Stripping insulation from wire during installation of a receptacle may cause separation to occur between the wire and the insulation, thereby allowing subsequent access to the copper by the atmosphere.

Some of the examined receptacle wires showed light spots or specks of what was suspected to be paint or drywall dust. Elemental analysis of a cross sectioned wires by Energy Dispersive Spectroscopy (EDS) in the SEM showed the presence of a Ti, Al, and Si containing region that was clearly distinguishable from the Cu and S containing corrosion product. Ti, Al, and Si are elements often found in paint pigment. Observations and images also showed that corrosion product grew into and over the paint layers, suggesting that wire corrosion occurred after installation.

X-ray Diffraction (XRD) analysis of one copper ground wire shows that its corrosion product contains Cu_9S_5 (digenite) and Cu_2O (cuprite). The ratio of the identified corrosion compounds and their presence on all wires will be evaluated in ongoing tests.

SEM/EDS analyses to date of cross sectioned screws (hot, neutral, ground) from six receptacles show that the screws consist of iron (Fe) that is plated with thin layers of metals including nickel (Ni), chromium (Cr), and zinc (Zn). The corrosion product observed on screws to date is suspected to be very thin because its presence was not detected in the SEM analyses of cross sections. EDS analyses of screws in plan view show copper and sulfur peaks that are not seen in the EDS analyses for the bulk metal of the screw.

CONTENTS

FIGURES

TABLES

NOMENCLATURE

AES	Auger–Electron Spectroscopy
AFCI	arc-fault circuit interrupter
Al	aluminum
Au	gold
CCD	charge-coupled device
CPSC	Consumer Product Safety Commission
ct	contact tab
Cr	chromium
Cu	copper
Cu_2O	cuprite, copper oxide
Cu_9S_5	digenite, copper sulfide
EDS	energy dispersive spectroscopy
Fe	iron
FIB	focused ion beam
GFCI	Ground Fault Circuit Interrupter
GS	ground screw
GW	ground wire
HS	hot screw
HW	hot wire
l	left
lcp	left contact plate
LIBS	Laser Induced Breakdown Spectroscopy
mm	millimeter
m-ohm	milli-ohm or one thousandth of an ohm
Ni	nickel
NS	neutral screw
O	oxygen
Pd	palladium
Pt	platinum
ppm	parts per million
R	receptacle
r	right
rcp	right contact plate
S	sulfur
SEM	scanning electron microscopy
SNL	Sandia National Laboratories
Ti	titanium
XPS	X-ray Photoelectron Spectroscopy
XRD	X-ray Diffraction
Z	atomic number of element from the periodic table (e.g., Z for copper is 29)
Zn	zinc
micron (μm)	1 millionth of a meter or $1x10^{-6}$ meters
micrometer	1 millionth of a meter or $1x10^{-6}$ meters

1 INTRODUCTION

Sandia National Laboratories' Materials Science and Engineering Center was tasked by the Consumer Product Safety Commission with evaluating the nature and extent of conductor metal corrosion that may have occurred in residential electrical components. The components provided to Sandia had been removed from homes in several states by the CPSC. They included standard duplex NEMA Type 5-15R receptacles, single pole switches, circuit breakers, ground-fault circuit interrupter (GFCI) receptacles, standard thermal/magnetic circuit breakers and arc-fault circuit interrupter (AFCI) circuit breakers. This document is an interim report that describes the initial characterization conducted to date by Sandia on six of the eight receptacles provided by the CPSC. The characterization included optical and scanning electron microscopy examinations and imaging, and chemical analysis of corrosion product observed on the surfaces of the metal conductor sub-components (wires, screws and contact plates) from the partial group of receptacles. The analyses conducted to date also include a determination of the nominal compositions of the metal subcomponents to help in the assessment and understanding of the different degrees of sensitivity to corrosion.

2 EXPERIMENTAL DETAILS

2.1. Sample Identification and Labeling

Labeled components received from the CPSC were checked against the CPSC inventory and their numbers were entered into a Sandia parts inventory. Random numbers were assigned by Sandia to each component and subcomponent parts (wires, screws, etc) were identified with that random number along with the part type. Figure 1 shows an example of a receptacle (R) identified as 01. The subcomponents of the receptacle were labeled as ground wires (gw), hot wires (hw), neutral wires (nw), hot screws (hs), ground screws (gs) and neutral screws (ns). In the case of duplex receptacles the neutral and hot wires and screws were labeled as left (L) or right (R) according to a standard orientation used in the low magnification optical pictures that were taken of four sides of the receptacles (See Figure 4). Contact plates (hot and neutral) were separated into three subcomponents: contact tab (ct); left (lcp); and right (rcp) contact plates.

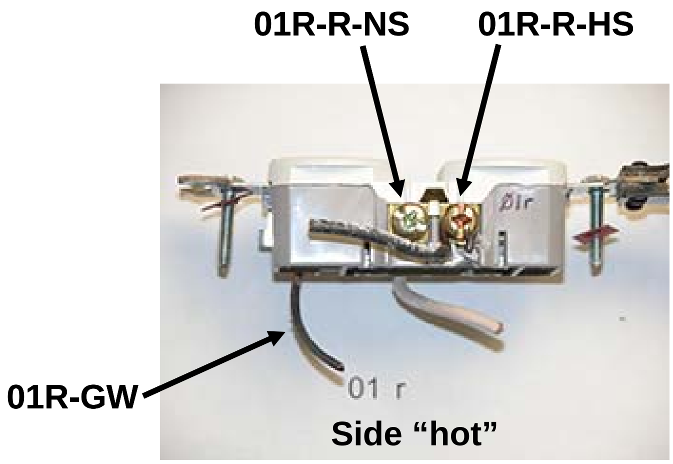


Figure 1: Example of subcomponent labeling scheme. The part number is designated as 01R (component 01, receptacle). 01R-GW designates the ground wire subcomponent from receptacle 01. 01R-L-HS designates left side hot screw from component 01.

2.2. Preliminary Assessment and Sample Preparation

Visual examination of all components (receptacles, switches, AFCI, GFCI, circuit breakers) was conducted to establish the qualitative level of corrosion (scale of 1-5 with 1 representing little or no corrosion and 5 representing the most severe corrosion). The assessment rating procedure is shown in Table 1. No components received were judged as category 1 on this scale.

Table 1: Corrosion level ratings and their selection basis

Corrosion Level	Observations that were used as the basis for the corrosion level ratings
1	pristine copper or just light tarnish ground wire
2	light tarnish on ground wire, some clean wire
3	heavy tarnish on ground wire, little or none on terminal screws or tabs
4	heavy tarnish on ground wire, light tarnish on one or more terminal screws or tabs
5	heavy tarnish on ground wire, heavy tarnish on one or more terminal screws or tabs

Excess wire was trimmed from all components, and groups (multiple outlets/switches) were separated to allow for positioning during optical examination and imaging. Optical images were taken of four views (front, rear, side hot, side neutral) of all components.

Six out of the forty received receptacles were selected for the first round of inspection and analyses. The group of six receptacles described in this report represents two (of two) receptacle manufacturers, receptacles with screw type terminals, and the range of observed corrosion levels (2-5). Following optical imaging, contact resistance measurements were made on the hot and neutral wires of the first group of six receptacles using a Keithly four-point probe ohmmeter. Resistance was measured on the wire between a freshly removed portion of insulation at the free end of the wire and the corresponding contact plate as shown schematically in Figure 2**.**

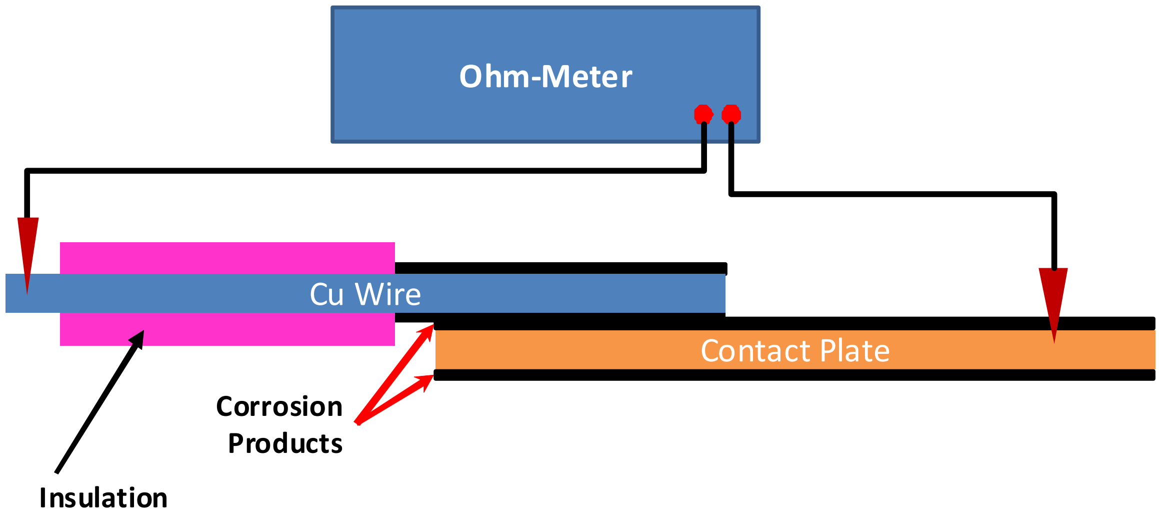


Figure 2: Schematic showing contact resistance measurement configuration.

Copper wires were carefully removed from screw-type terminals, and after removal, handled in such a manner so as to minimize the accidental removal of corrosion products. Contact with skin was avoided to prevent introducing biological corroding compounds onto the samples. As paint appeared to be present on many surfaces, care was taken to avoid analyzing this substance and mistakenly including its composition in the analysis of corrosion product. Parts were retained in labeled plastic containers.

2.3 Materials Characterization Instrumentation and Methods

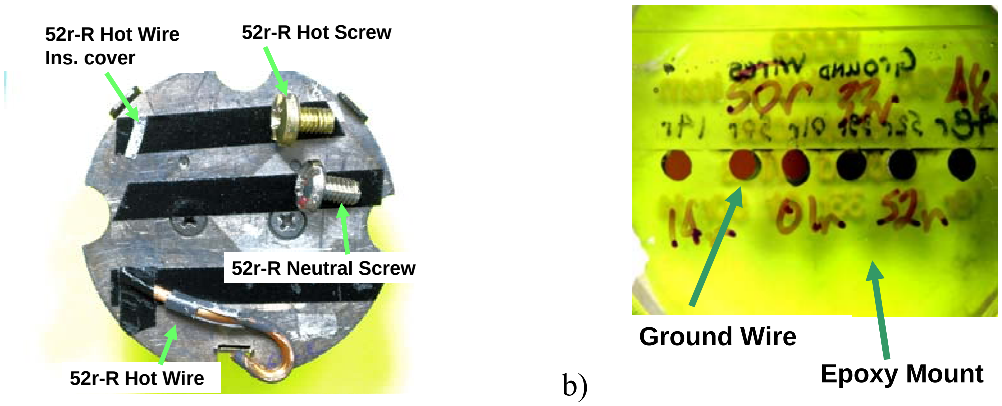
Table 2 summarizes the analytical work performed on components to date, not including photos and disassembly. Although the focus of this interim report has been on analyses of the subcomponents from six of the forty 125 Volt receptacles, some analyses have also been conducted on the other receptacles.

Table 2: Summary of work performed to date on receptacles. Empty squares indicate analyses still to be done. SEM Plan=plan view SEM imaging and analysis, SEM x-sec=cross section view SEM imaging.

	B	C	P	Q	R	S	T	U	W
1	**SNL random i.d.**	**1st inspection category (1,2,3,4,5)**	**ground wire GW**	**ground screw GS**	**right hot screw RHS**	**left hot screw LHS**	**right neutral screw RNS**	**left neutral screw LNS**	**left hot wire LHW**
2	01	3	SEM plan SEM x-sec	x-sec prep		SEM x-sec		x-sec prep	
3	14	2	SEM plan SEM x-sec	x-sec prep		SEM x-sec		x-sec prep	
4	33	5	SEM plan SEM x-sec XRD	x-sec prep		SEM x-sec		x-sec prep	
5	48	5	SEM plan SEM x-sec	x-sec prep		SEM x-sec		x-sec prep	
6	50	5	SEM plan SEM x-sec	SEM x-sec		SEM x-sec		x-sec prep	
7	52	4	SEM plan	x-sec prep	SEM plan	SEM x-sec	SEM plan	SEM x-sec	SEM plan FIB slices
8	23	5	FIB FIB EDS FIB-Auger						
9	60	5	Auger SEM plan XPS		SEM plan				

2.3.1. Scanning Electron Microscopy (SEM), Focused Ion Beam (FIB), and Hyperspectral Imaging Analyses

Two scanning electron microscopes (SEM) (Hitachi S4500 and Zeiss Supra 55VP) with X-Ray energy dispersive spectroscopy (EDS) capabilities were utilized. SEM allows images to be made of an object or material at high magnification. Prior to analysis samples were sometimes coated with a thin layer of platinum (Pt), gold-palladium (Au-Pd) or carbon (C) to enhance imaging and prevent charging. EDS data as collected here give information about which elements are present at or near the surface. Qualitative information about differences in the relative amounts of various elements can also be obtained. Samples used for plan view imaging and analysis were affixed to an aluminum stub with conductive carbon tape (Figure 3a) Sub-components submitted for SEM cross sectional imaging and analysis were mounted in epoxy, and then cut, ground, and polished to provide a smooth surface including a cutaway of the subcomponent (Figure 3b).



a) b)

Figure 3: Photograph of (a) ground wire and screws prepared for SEM plan view analyses and (b) six ground wires mounted in epoxy (wire is perpendicular to the plane of the paper) for cross sectional analysis.

A focused ion beam (FIB) instrument (FEI Helios Nanolab) was utilized to generate local cross sections as well as remove material from the surface of interest in order to measure corrosion layer thickness. A platinum coating was used to protect the top surface of the sample during the sectioning process. The exposed surfaces are then analyzed using SEM techniques including analysis by Hyperspectral Imaging, which allows the entire elemental spectrum measured at each point to be deconvoluted.

2.3.2. X-Ray Diffraction (XRD)

The XRD technique allows the chemical identification to be made for the material in a region of interest. XRD data were collected using a Bruker D8 system with GADDS. Cu K alpha radiation was employed from a sealed tube source. The X-ray beam was conditioned via an incident beam mirror for removal of K beta radiation. A 300 micron pinhole snout was used for beam collimation. The detector used was a Hi-Star area detector. Sample to detector distance was 15 cm. Data reduction was performed using GADDS software. Phase identification was performed using Jade v 9.0 and the ICDD (International Centre for Diffraction Data) database. Two locations on a single wire were investigated, each with a spot diameter of approximately 300 μm.

2.3.3. Auger Electron Spectroscopy (AES)

Auger spectroscopy was performed using a Physical Electronics (Minneapolis, MN) scanning Auger spectrometer model 690 (nanoprobe). A field emission electron source provides an electron beam with a diameter of less than 10 nm for secondary electron imaging of the surface. A sputter ion gun, motorized five axis sample stage, and analyzer provide a sputter depth profiling capability that allows the composition to be analyzed for different depths into the surface. Sputter depth profiling provides the elemental composition of new surface as it is being exposed by sputtering. The Auger nanoprobe is capable of producing elemental composition spectra, surface images, selective elemental line scans and maps, and depth profiles. Imaging is achieved through detection of secondary, backscattered and Auger electrons. Samples are mounted for Auger examination by attaching them to a sample stub with conductive carbon tape.

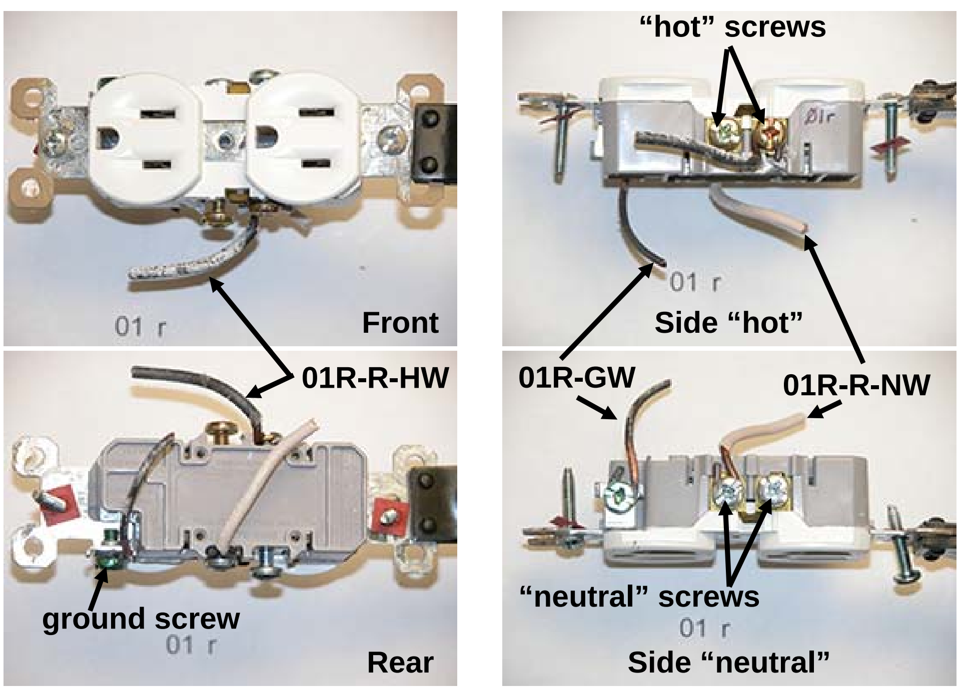
2.3.4. *X-ray Photoelectron Spectroscopy (XPS)*

XPS was performed using a Kratos Axis Ultra DLD (Kratos Analytical, Inc., Manchester, U.K.) XPS spectrometer with a monochromatic (500 mm Rowland circle monochromator) source of Al Kα (1486.6 eV) X-rays and a Delay Line Detector (DLD). The analysis volume consisted of an elliptical 300 x 700 micron spot size. XPS is a surface sensitive technique with the sampling depth generally between 5 and 15 nm. A photo-emission spectrum collected in a survey scan provides information about which elements are present and their oxidation state. This information can often be used to identify the chemistry of a surface. Samples are anchored to a steel bar and electrical contact is made through copper contacts. The analysis chamber is at UHV conditions (typically around 5 x10^{-9} Torr).

3 RESULTS AND DISCUSSION

3.1. Low Magnification Optical Examination and Imaging

Optical photographs were taken of all parts from each view (front, rear, both sides), after trimming and separation of groups, with the assigned sample identification number on a placard in the photo. An example is shown in Figure 4 for a duplex receptacle. For groups, a photo was taken in its "as received" state and then the conductors were trimmed to approximately one inch for further processing and analysis.



HW = "hot" wire, GW = ground wire, NW = "neutral" wire

Figure 4: Example optical photographs showing four views of a duplex receptacle. The neutral and hot wires have electrical insulation on the part of the wire away from the attachment screws. The ground wire has no electrical insulation, but could appear to due to it being blackened over much of its area.

3.2. Higher Magnification Optical Examination and Imaging

Each of the six 110V rated, screw-type connection receptacles (5 duplex, 1 single pole) had paint or plaster splatter on various surfaces including the wires. There was visible corrosion on the ground, neutral, and hot wire surfaces as well as on the contact plate surfaces for the neutral and hot wire connections. Figure 5 shows the corrosion (blackened regions) that is observed on both sides of ground wires from the six receptacles examined to date. Each of these wires was originally fastened to the receptacle with a screw at the curved section of the wire. The areas where the wire made contact with its screw or contact plate show less blackening or no blackening compared to other regions of the wire where it was not in contact with another material. The lack of corrosion in these areas is likely due to this region being somewhat shielded from any corrosive gasses that are present. Some of the wires also show a white material (likely paint, texturing material, or drywall debris). Some of this appears to have been introduced prior to it being fastened to the receptacle as it is located in a region that was under the screw when it was fastened to the receptacle. Blackening was observed on neutral and hot wires as shown in the examples in Figure 6**.**

 01r – side 1	 01r – side 2	 14r- side 1	 14 r – side 2
 33 r – side 1	 33r – side 2	 48 r – side 1	 48 r – side 2
 50 r – side 1	 50 r – side 2	 52r- side 1	 52r – side 2

Figure 5: Optical images showing ground wire corrosion as evidenced by black layer. The looped section of the wire, which had been in contact with the screw or contact plate, has little or no blackening in some cases (for example, see 33r – side 2).

			
14 r – hot wire – top view	14 r – hot wire – side view	14 r – neutral wire – top view	14 r – neutral wire – side view

Figure 6: Optical images showing corrosion of hot and neutral wires. Corrosion is most obvious on surfaces that were not in contact with a screw or contact plate.

For the group of six examined receptacles some tarnishing and/or corrosion products was observed on the (1) ground screws, (2) neutral screws, and (4) hot screws as shown in Figure 7**.** Hot and neutral screws have a yellow and silver appearance respectively to distinguish them from each other, and the ground screws are green in appearance. The extent of corrosion of the screws examined to date was significantly less than that observed on the various wires examined to date.

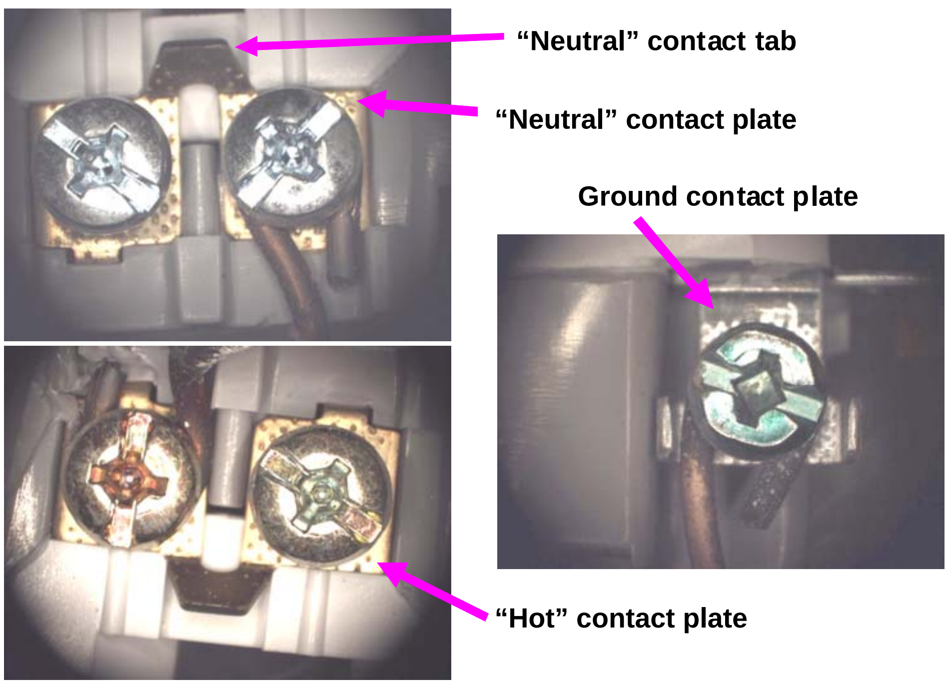
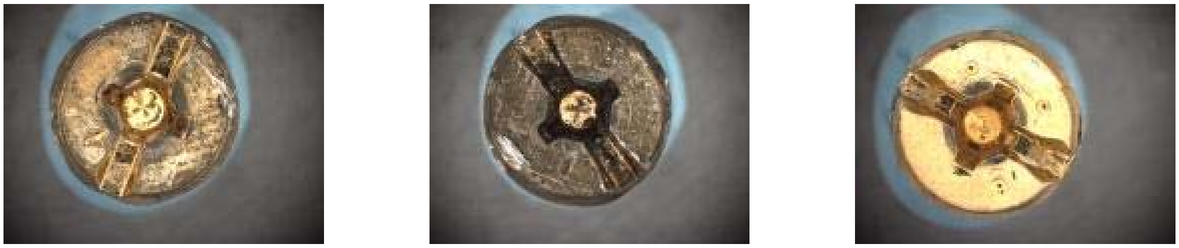


Figure 7: Optical photographs of connection terminals including the contact plate, screws, and wires before disassembly. Ground screws have a green appearance, hot screws appear yellow, and neutral screws appear silver.

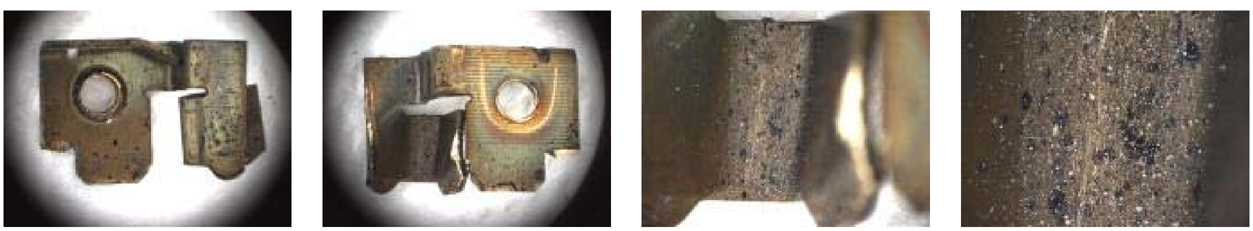
Optical images of tarnished hot screws are shown in Figure 8 in comparison to a shiny reference screw (never installed in a home). The degree of darkening of the surface and the loss of the shiny luster indicate that the screw surfaces have changed in some manner, likely due to corrosion.



33r hot screw | 50r hot screw | Reference hot screw

Figure 8: Comparison of the appearance of hot screws from receptacles harvested from components 33 and 50 to the appearance of a reference hot screw (never installed in a home).

The appearance of a tarnished contact plate from receptacle number 50 is shown in Figure 9. The top and bottom surfaces of the contact plate and a close-up of the plug contact surface are all shown to demonstrate how corrosion has changed the appearance of the surface. Black specks (mounds of corrosion products) can be seen on the surface of the contact plate especially in the region shown in Figure 9d) at higher magnification. It is important to note that these surfaces are interior to the receptacle, and suggest that the corrosive gasses penetrated the receptacle in this case.



a) 50r contact plate – back view | b) 50r contact plate – top view | c) 50r contact plate – plug contact surface | d) 50r contact plate – higher mag view

Figure 9: Optical image showing corrosion on side 1 (a) and side 2 (b) of a 50r hot wire contact plate. b) The shiny U-shaped region is the location of a wire that was originally in contact with the contact plate. Images c) and d) show higher magnification views of corrosion in the plug contact surface

3.3. Electrical Contact Resistance Measurements

The electrical contact resistance between two conductors depends on the contact area between them and on any corrosion species at the interface. Because corrosion product layers typically have a much higher electrical resistivity than metals their presence can dramatically degrade the quality of the electrical contact between two surfaces. An increase in resistance is often a sign that conductive surface to surface contact is being lost or degraded.

Resistance measurements were made for all six receptacles for the circuit containing the hot and neutral wires. None of the measurements shown in Table 3 suggest that the electrical interface between the wire and contact plate has degraded at this time. The maintenance of low contact resistance is consistent with observations that sections of wire sandwiched between the contact plate and the screws exhibited little or no blackening (and corrosion) compared to wire that is not covered with a screw.

Table 3: Contact resistance values measured between wires and their contact plate. The number in the part no. represents the component; R=receptacle. The letter in parentheses designates left or right in the pairs of wires for duplex receptacles. 48-R is a single receptacle.

Part No.	Neutral Wire (m-ohm)	Hot Wire (m-ohm)
01-R	0.35 (r)	0.30 (r)
14-R	0.20 (r)	0.19 (r)
33-R	0.14 (l) 0.14 (r)	0.16 (l) 0.18 (r)
48-R	0.20	0.33
50-R	0.33 (l)	0.21 (r)
52-R	0.19 (l) 0.18 (r)	0.18 (l) 0.18 (r)
Control	To be measured	To be measured

3.4. Ground Wire Analyses

3.4.1. SEM/EDS Plan View and FIB Analyses of Wire Corrosion

Figure 10 shows the plan view Scanning Electron Microscope (SEM) images of the corroded copper ground wires from six receptacles. The corrosion product layers are similar for the six receptacles. The layers have a nodular appearance with varying degrees of coverage of the Cu wire, and differences in the apparent corrosion product thickness. In some regions small cracks are observed in the layer. Further analysis of each wire and analysis of additional wires would be needed to determine whether there are real differences in the corrosion product coverage on wires from different locations, or between locations within a home. The residence time of the receptacle in a home would also need to be considered to be able to determine that the corrosive environment in one home was more severe than in another.

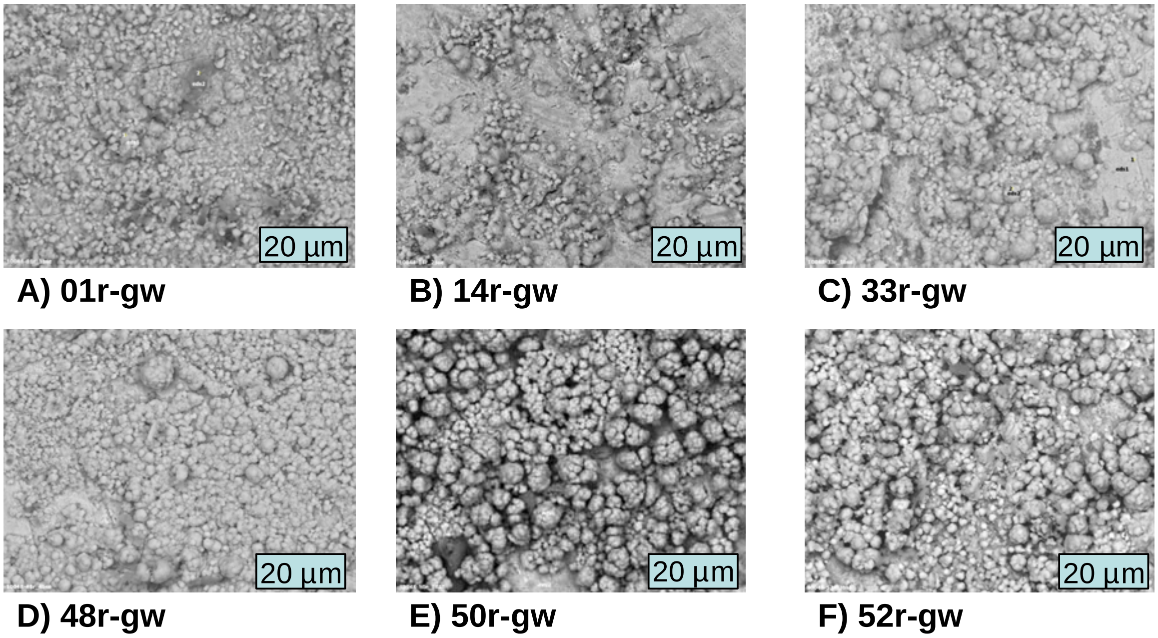


Figure 10: SEM plan view images of six corroded ground wires. All samples show the growth of a layer on the copper wire. The morphology in these images shows what appear to be individual particles or clusters of particles.

The elemental composition of the corrosion product layer on ground wires observed to date is primarily copper and sulfur (indicating a copper sulfide rather than a copper sulfate) as shown in the Energy Dispersive Spectrum in Figure 11**.** The presence of Cu and S was confirmed with both X-ray Photoelectron Spectroscopy (XPS) and Auger Electron Spectroscopy (AES) analyses.

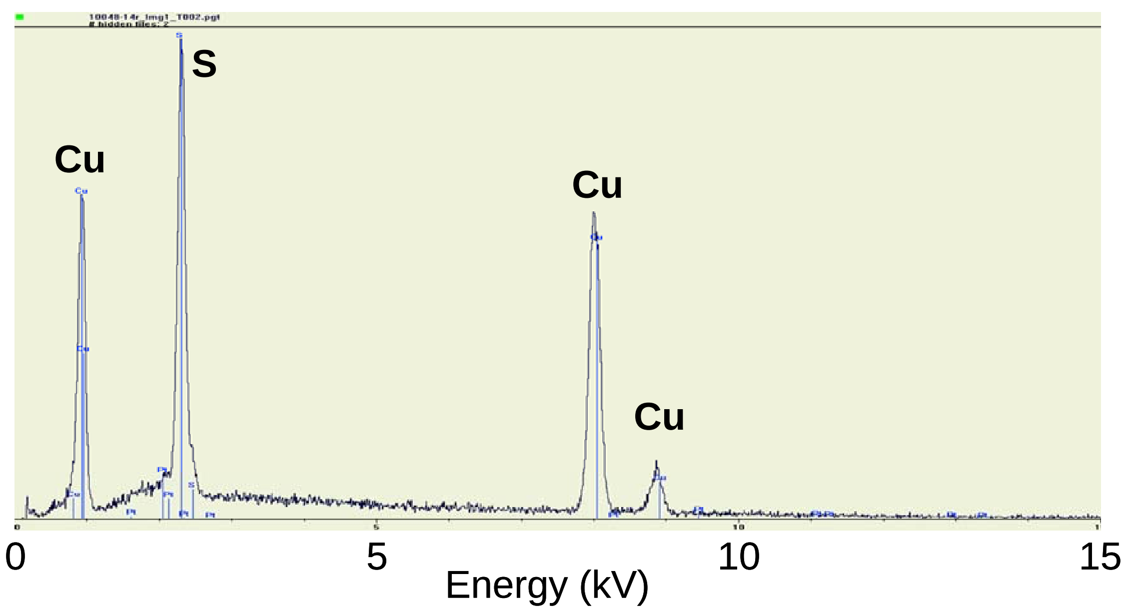


Figure 11: EDS spectrum showing elemental composition of the ground wire corrosion product shown in Figure 10. (From component 14)

To assess the ability of the wire insulation to prevent corrosion of the copper wire, the insulator was carefully cut from one sample and the wire surface was analyzed. Figure 12 shows a comparison of three regions of a single hot wire near the edge of the electrical insulation. Location 1 is the boldly exposed copper surface near the edge of the insulation. Location 2 was originally under the insulation (after a strip of insulation was removed) at a distance of approximately 0.2 cm from the edge. Location 3 was originally under the insulation at a distance of approximately 0.7 cm from the edge. There is a clear difference in the extent of the surface corrosion with the boldly exposed region showing a substantial layer, the middle region showing the start of a surface layer (which seems to begin along surface features on the underlying copper), and the region under the tight insulation showing no corrosion, only bare copper. There is no corrosion product on the wire at a distance of approximately 0.3 cm away from the interface between the originally bare and covered regions of the wire. The act of stripping the insulation from the wire may produce a separation between the wire and the insulation, allowing access to the copper by the atmosphere. These observations indicate that the electrical insulation acts as a barrier to the corrosive gasses and protects the underlying copper.

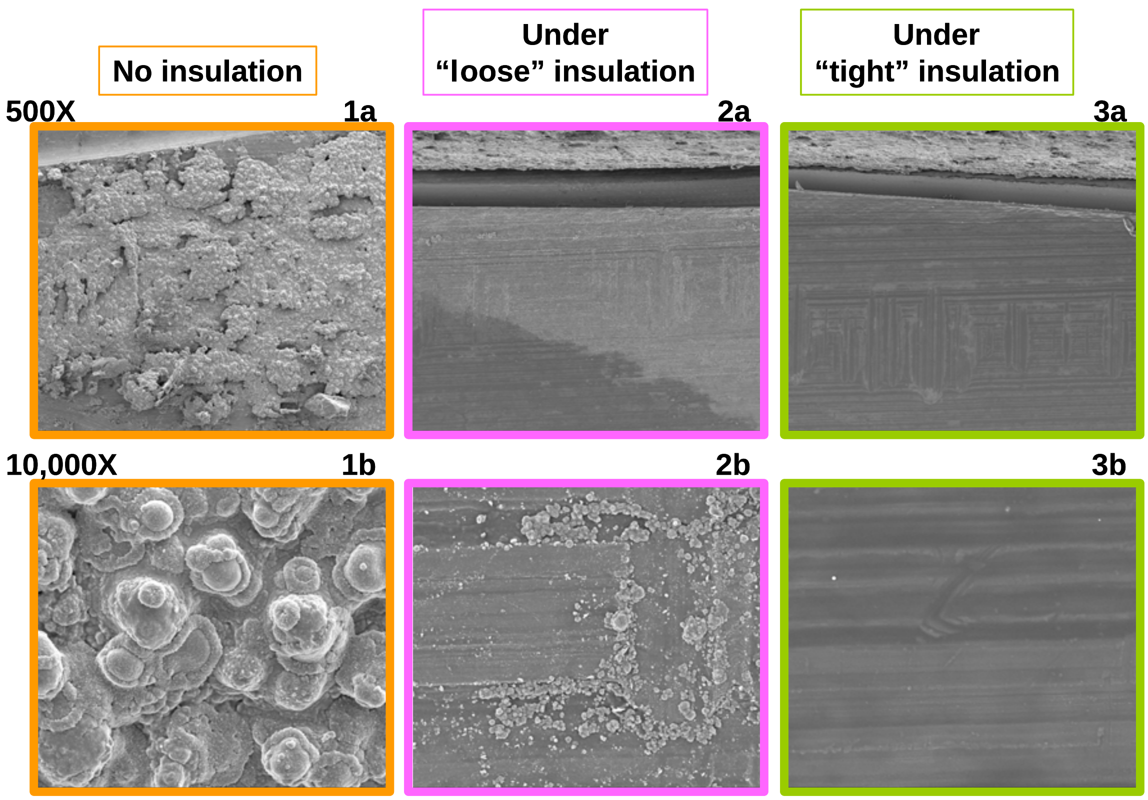


Figure 12: Comparison of SEM images at 500X and 10,000X magnification showing a hot wire in (1) an area that was not covered by electrical insulation (2) an area originally covered by “loose” electrical insulation prior to Sandia’s analysis (3) and an area tightly covered by the electrical insulation prior to Sandia’s analysis. The copper in this area exhibits no corrosion.

A focused ion beam (FIB) process was used to mill a small trench through the corrosion product and into the base copper of a corroded hot wire. This technique can be likened to archeology on the microscopic scale. Material was removed creating a precisely located local cross section. Both the corrosion product layer and underlying copper substrate are visible. Scanning electron microscope images were taken of the cross section and EDS spectra were collected to determine the elemental composition. Figure 13 shows the FIB cut at increasing magnifications. The sample is tilted at an angle of 52 degrees to allow viewing of both the top surface and one of the side walls of the FIB cut. The images clearly show a 20 micron thick sulfide with a cauliflower-like morphology. This thickness exceeds that expected for a Class II corrosion environment and suggests that the actual environment is likely Class III or higher.[1] The very bright area on the top of the cauliflower is a layer of platinum (Pt) that is deliberately deposited to protect the underlying materials during the FIB cutting process. Corrosion of the base copper is also observed and this produces a pit with a spongy (porous) morphology. The pits observed to date are up to twenty microns in depth. There is a very thin layer observed between the base copper and the thicker cauliflower like corrosion layer. Further analyses are required to identify whether this layer is a corrosion product or an artifact of the FIB cutting process. Additionally it appears that there is a separation or a fracture between the corrosion product layer and the underlying material. At this time it is not known whether this is intrinsic to the corrosion process, a separation that occurred because of differences in expansion between the copper and corrosion product, or an artifact of the FIB cutting process.

EDS indicated that the major elements in the cauliflower layer are Cu (copper) and S (sulfur). There are minor amounts of O (oxygen). The spongy region in the underlying copper is Cu, S and O. The grain (or crystal) structure of the copper can be seen because of channeling contrast (darker or lighter) that different copper grain orientations produce. This kind of contrast is normal and expected for SEM imaging of the copper.

[1] W. H. Abbott, The Development and Performance Characteristics of Mixed Flowing Gast Test Environment, IEEE Transactions on Components, Hybrids, and Manufacturing Technology, pp. 22- 35, Vol. 11, No. 1, March 1988.

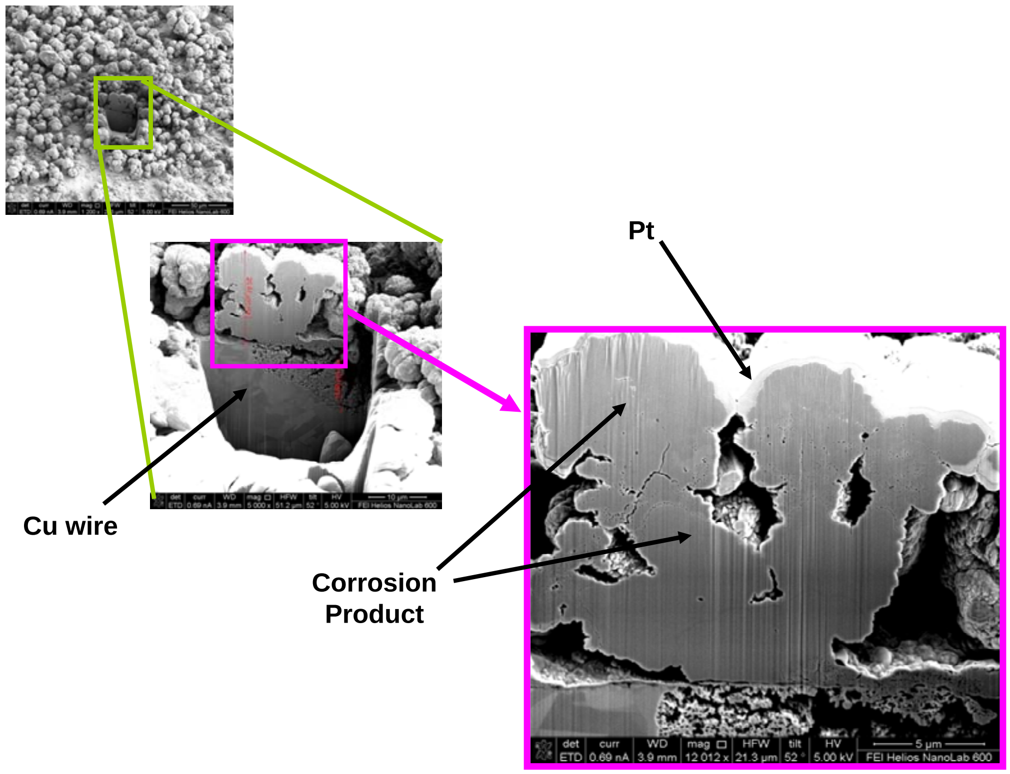


Figure 13: SEM images at increasing magnification of FIB cut into a corroded ground wire showing “cauliflower” morphology of corrosion product and porous region in the base copper. The cauliflower feature is approximately 20 microns in height. The very bright region seen on top of the cauliflower feature is platinum used to coat and protect the sample during the FIB cutting process.

Spectral imaging was performed on the FIB cross section shown in Figure 13. In essence, spectral imaging uses EDS techniques to identify “phases” or “components” present in a sample. Figure 14 shows the hyperspectral image and spectrum for the FIB cross section of the corroded ground wire shown in Figure 13. For this region three components were identified: a Cu-S component, a Cu-S-O-C component, and Cu. Colors are used in the figure to identify the location of the components. Individual representative spectra for the components are also shown. Note that the tree-like nodule (red) is basically a copper sulfide. The copper substrate shows up as the blue area. The spongy material below the copper sulfide appears to be a mixture of copper sulfide and something containing Cu, S, O, and C. While these results represent only a single sample and cannot therefore be used to arrive at a general conclusion, they do provide insight into the nature of the corrosion product and possible corrosion mechanism.

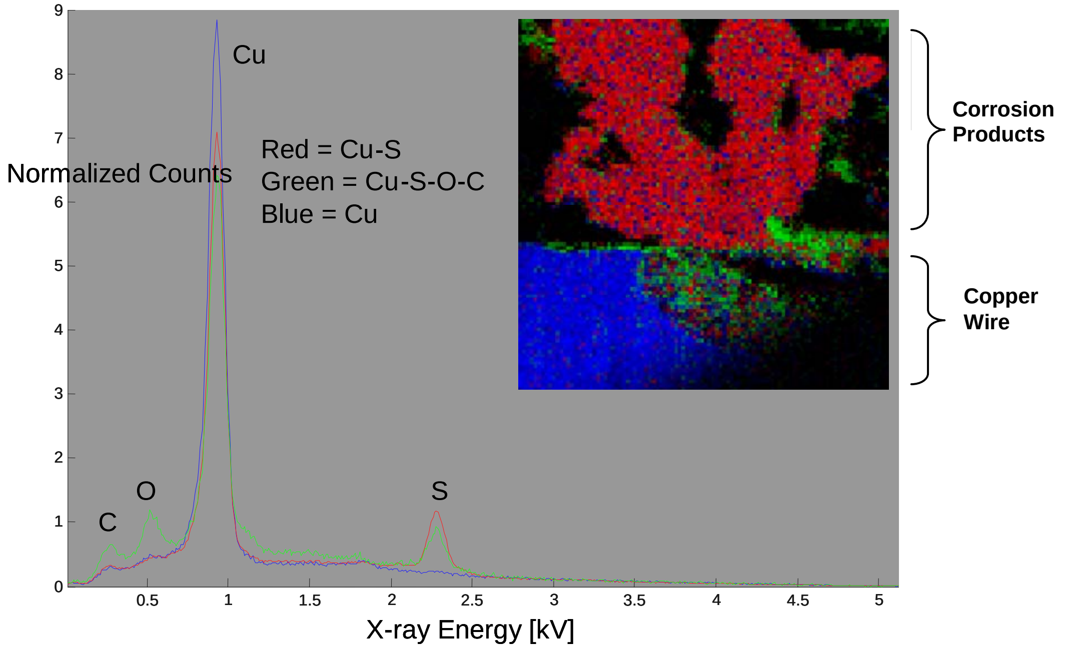


Figure 14: Hyperspectral image and spectrum showing the elemental make-up of various regions of the FIB cross-section of the corroded ground wire shown in Figure 13.

The FIB technique also allows a slice of the corrosion layer and underlying copper to be cut and lifted off the surface. This allowed the slice to be placed horizontally on a sample stub, whereby enhanced imaging and analyses of the cauliflower-like corrosion product and underlying materials could be performed. Regions of the cauliflower like corrosion products show subtle contrast differences (lighter and darker) indicating variations in structure, density or composition. This layer morphology suggests that the growth of the corrosion product layers may have occurred under varying conditions (humidity, temperature, concentration of atmospheric elements, etc.). In additional images of the region shown in Figure 15 it appears that there may be three areas with little or no contrast, separated by what look like darker and lighter bands. The vertical lines in Figure 15 are the result of the FIB process and do not represent variations in the product layer.

The grain (or crystal) structure of the underlying copper can be seen by slight contrast differences (darker or lighter) that are produced by different grain orientations. This kind of contrast is normal and expected for imaging of the copper.

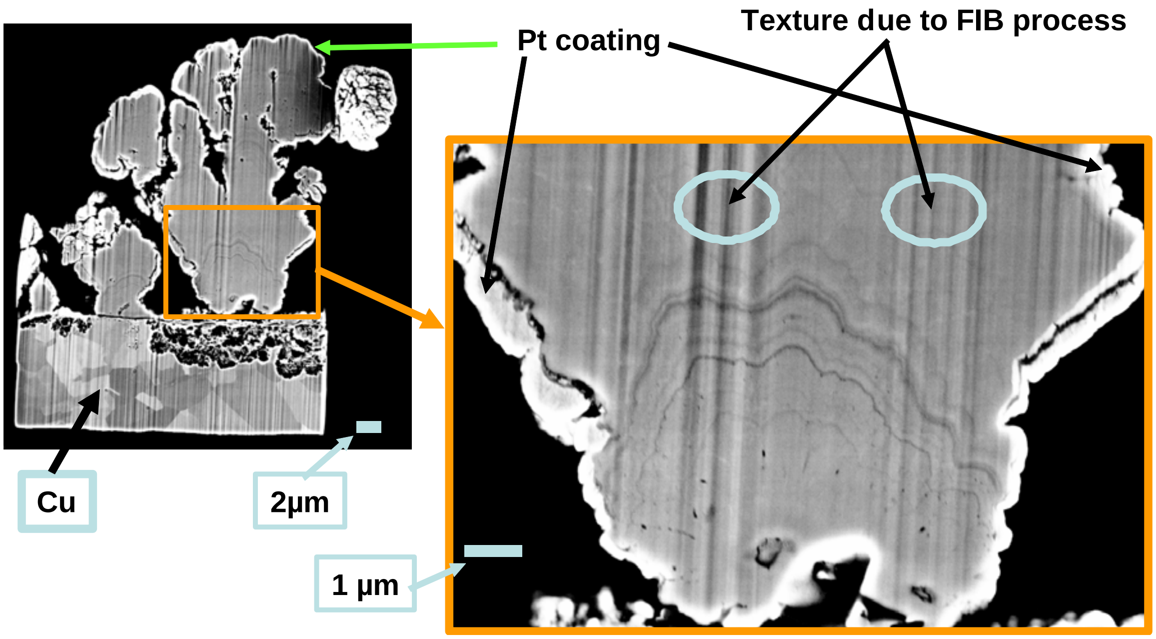


Figure 15: SEM images of section cut from corroded ground wire showing "tree-ring" morphology in the cauliflower-like corrosion product. The underlying copper shows regions of light and dark contrast that are produced by different orientations of the copper grains. Vertical lines seen in the images and highlighted with blue oval are artifacts of the FIB cutting process.

A series of FIB slices were made through the corrosion product on a copper hot wire. Two of the slices are shown on the right in Figure 16 along with the corresponding plan view SEM images (left) showing the region from which they were taken. The bright layers on top of the corrosion product are platinum used to protect the underlying material during the FIB cutting process.

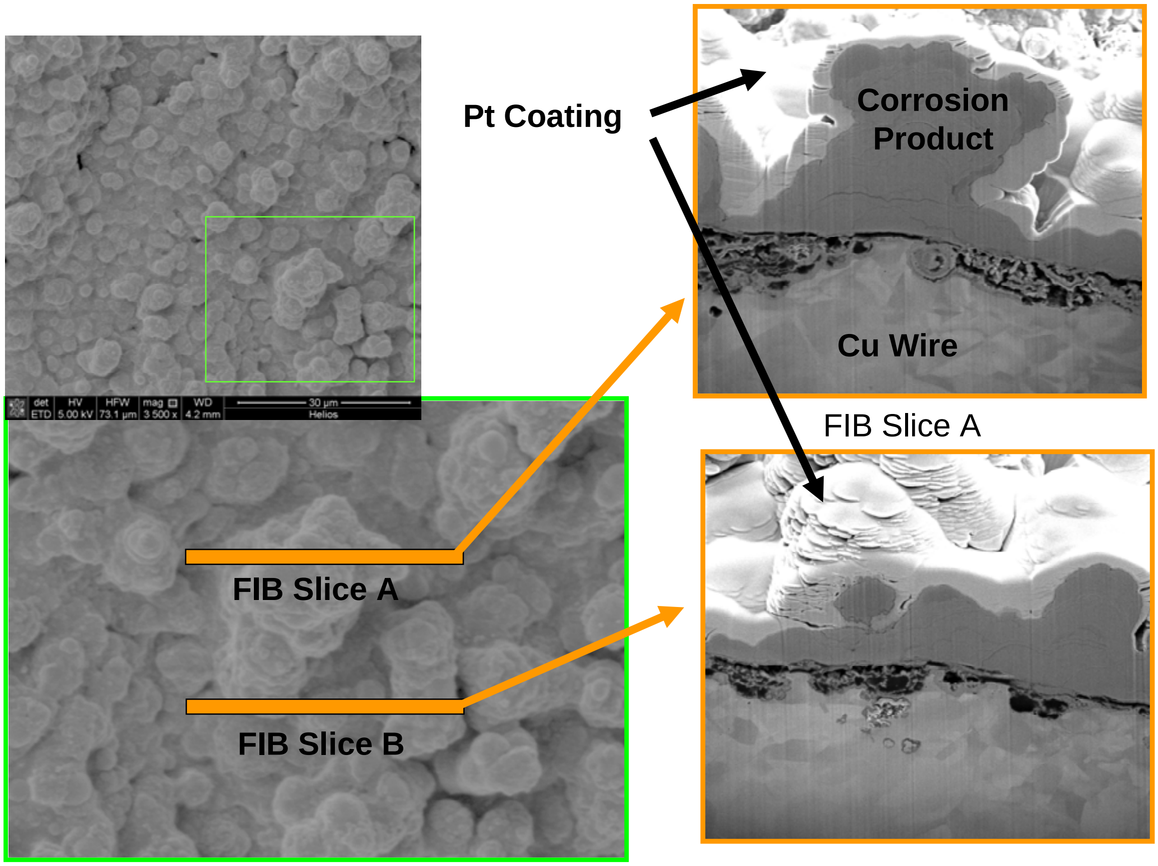


Figure 16: SEM images (left) and two FIB slices (right) of a corroded copper hot wire.

3.4.2. SEM Cross Sectional Analyses of Wire Corrosion

Figure 17 shows an optical micrograph and two SEM images of a cross sectioned ground wire used to identify the thickness and elemental composition of the corrosion layer or layers. Consistent with previous images, this sample exhibits a layered structure. The difference in contrast seen in the highest magnification SEM image could be due to changes in density or elemental composition. These differences suggest that there may have been periods of growth of the corrosion product during which conditions varied. The corrosion product layer was not of a consistent thickness over the circumference of the wire. The range of corrosion layer thicknesses observed on cross sectioned ground wires from six homes are shown in Table 4. The values range from 0-18 microns, the highest values being consistent with the observations made on FIB slices. The purpose of the layer thickness measurement was only to obtain an estimate of the corrosion product layer – it is not a statistically valid measurement from which inferences can be made about the entire population.

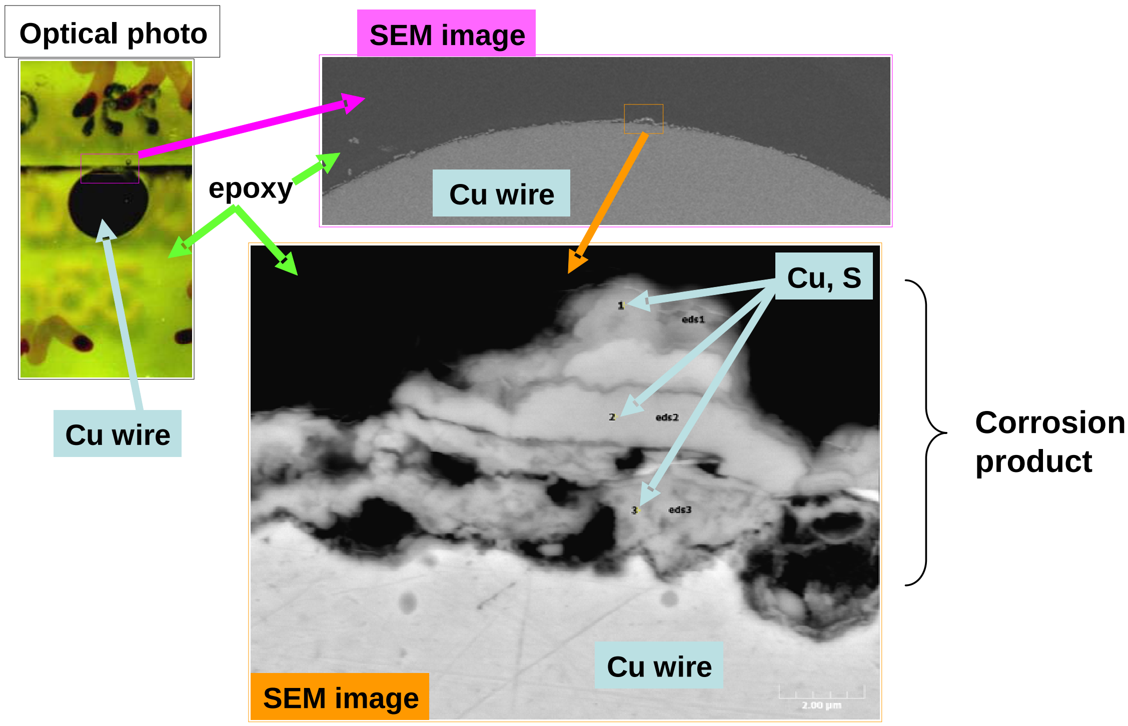


Figure 17: Optical (left) and SEM images (right) of the cross section of receptacle ground wire at increasing magnification used to estimate corrosion layer thickness and determine elemental composition. EDS was used to identify the primary elements (Cu, S) in the regions shown in the highest magnification image (bottom right).

Individual spectra were obtained for several of the layers shown in Figure 17. The spectra were normalized to the Cu peak and are plotted in Figure 18. Only sulfur and copper were identified by EDS, indicating that the corrosion product is a form of copper sulfide. The difference in Cu/S ratio for the various layers suggests that the corrosion products are not a single sulfide (for example Cu_9S_5), but are likely a mixture of sulfides.

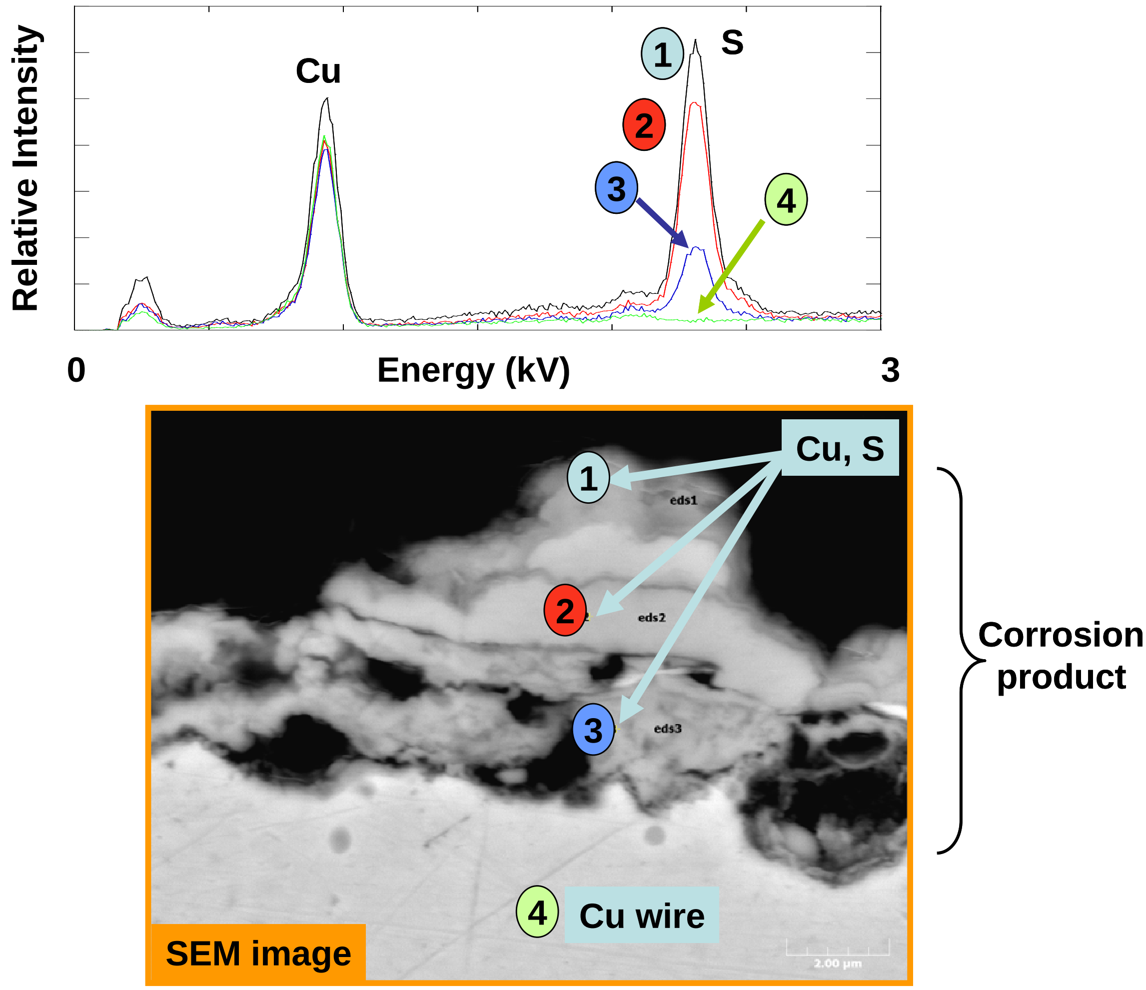


Figure 18: Qualitative comparison of changes in the sulfur content relative to the copper across the corrosion layer thickness as measured by EDS (normalized to Cu peak at 8 kV) for a corroded ground wire.

Table 4: Observed range of corrosion layer thicknesses observed by SEM on cross sectioned ground wires from receptacles.

Part No. (no. is component, R=receptacle)	Observed Thickness (microns)
01-R	1 - 7
14-R	0 - 2
33-R	2 - 18
48-R	2 - 6
50-R	0 - 8
52-R	3 - 18

Ground wires and other subcomponents from the set of analyzed receptacles often showed white particles or paint on their surfaces during optical examination. Cross sections of the ground wires often cut through these particles on the surfaces of wires. EDS analyses were used to identify the elemental composition of these materials and to distinguish them from areas of corrosion product. Figure 19 shows the SEM image of a cross section that cut through a region of the wire that appears to be covered by paint. The EDS spectra in Figure 20 show the differences in composition between the darker and lighter regions that are located above (on top of) the copper wire in Figure 19. The spectrum in Figure 20 **a)** shows that the elemental composition of the darker contrast region consists of aluminum (Al), silicon (Si) and titanium (Ti), typical constituents of pigments or pigment extenders in paint. Figure 20 **b)** shows the spectrum for the light region, which consists of Cu and S, on top of the paint layer. This observation of corrosion product on top of paint indicates that the corrosion product formed after the paint was spattered on the wire surface and that it occurred after installation of the receptacle. In addition, the observation of creep corrosion supports the claim that the actual corrosion conditions were more aggressive than Battelle Class II, and likely Class III, IV or higher.

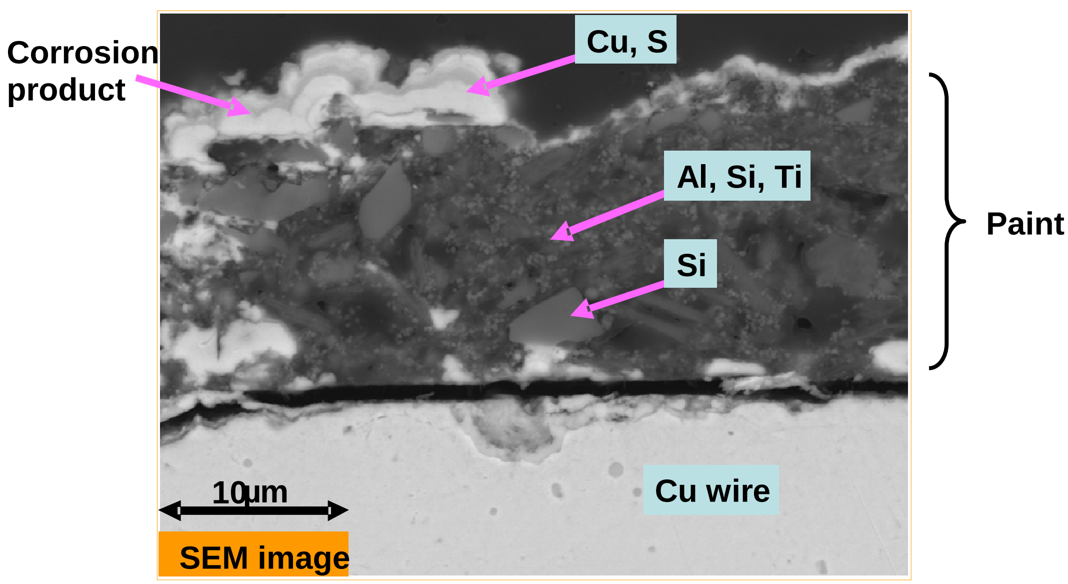


Figure 19: SEM cross sectional image of corroded copper ground wire, showing corrosion product growth on top of paint layer. Elements detected by EDS are shown at particular spots.

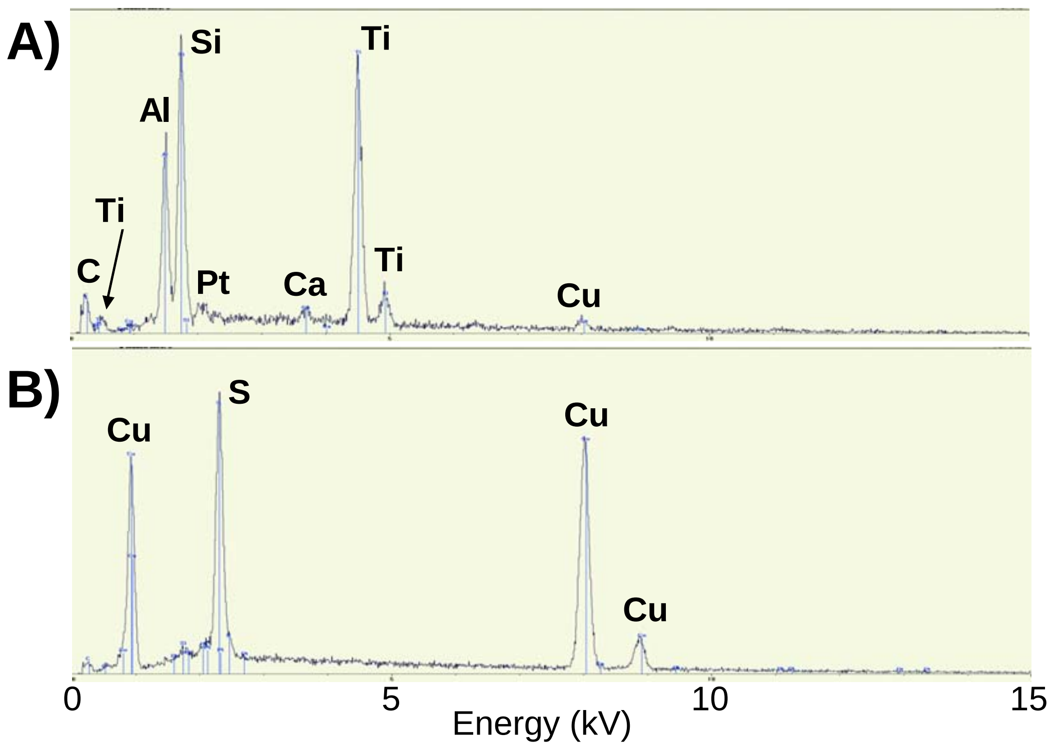


Figure 20: EDS spectrum (signal intensity versus energy in kV) showing major elements detected in areas attributed as A) paint and B) corrosion product shown in Figure 19.

3.4.3. X-ray Diffraction (XRD) Analysis of Ground Wire Corrosion Product

X-ray diffraction (XRD) analysis was conducted on two spots on a single corroded ground wire to gain an initial understanding of the chemical compound (or compounds) present in the corrosion layer. The analysis used a spot on the sample that was approximately 300 microns (0.3 mm) in size and was located on a region of interest as shown by the cross hairs in Figure 21. The XRD spectrum (Figure 22) showed peaks identified as Cu, Cu_2O (cuprite), and Cu_9S_5 (digenite). Other elements or compounds may be present, but at small concentrations relative to the species identified above. A 300 micron diameter X-ray spot provides information about an area that is large relative to the size of the particles (or clusters of particles) in the corrosion product layers shown in the SEM images in Figure 10. The XRD analysis cannot be used to identify the chemical identity of individual particles, but provides information averaged over the entire spot. The analysis provides chemical information from a 10-20 micron depth, but most of the X-ray signal comes from the top 5 microns. The large Cu peak in the spectrum suggests that there is incomplete coverage of the surface or that the corrosion product depth is not large on this sample. To enhance the identification of other minor phases and to increase the relative peak heights of the cuprite and digenite additional XRD analyses will be performed on material scraped from the surface of the wire and collected for analyses.

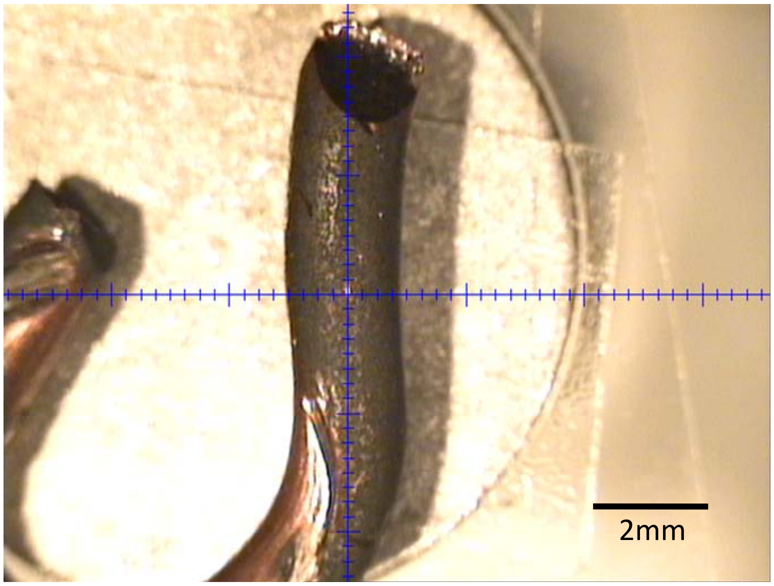


Figure 21: Optical photographs of corroded ground wire used for XRD analysis. The intersection of the blue cross hairs indicates the region of the wire that was analyzed.

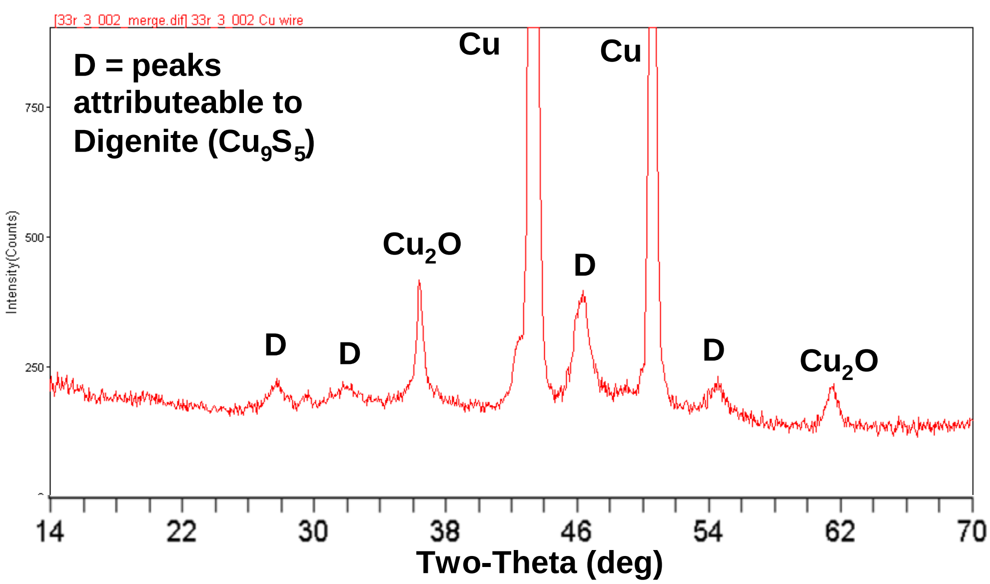


Figure 22: XRD data (signal intensity versus diffraction angle) showing peaks attributable to copper (Cu), cuprite (Cu_2O) and digenite (Cu_9S_5).

3.4.4. Auger Electron Spectroscopy and X-Ray Photoelectron Spectroscopy Analyses of Ground Wires

A segment of a copper ground wire (60-r-gw) was cut from the loose end of the ground wire on electrical receptacle (60-r). The wire segment was mounted to an Auger sample mount via carbon tape attached at the cut end of the wire. Elemental analysis was performed at nine spots on the corroded area of the wire and a sputtering depth profile was performed on three spots. An SEM image was taken of the area that was to be sputtered, and the three spots subsequently analyzed are indicated in Figure 23. These three spots illustrate the three different surface morphologies observed: “nodular”, “smooth”, and “smeared”. The smeared area was likely generated in prior handling of the component as extra care was taken during disassembly to leave corrosion undisturbed.

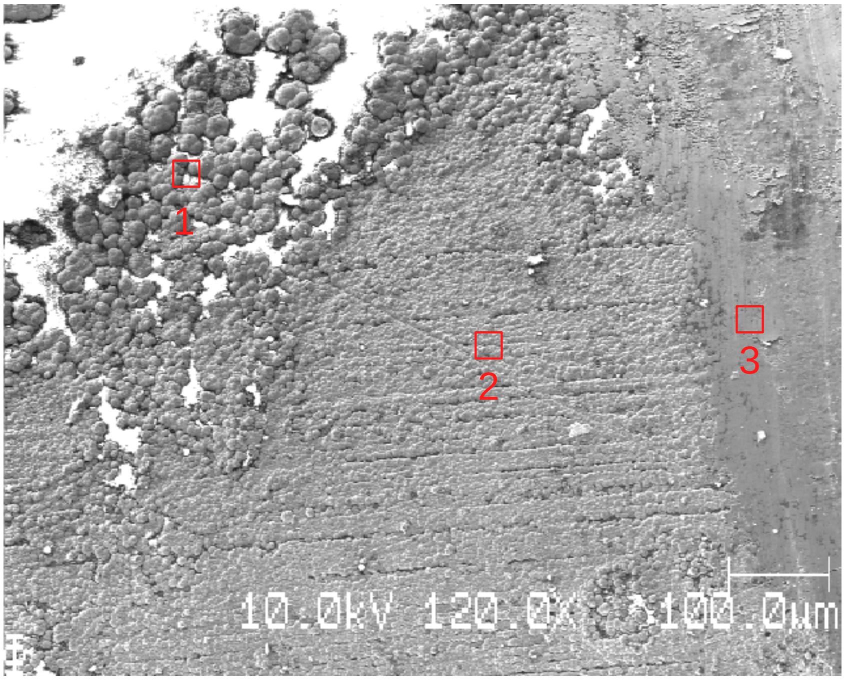


Figure 23: SEM image of ground wire showing three different morphologies and three spots indicating where Auger sputtering was performed.

Auger depth profiles were performed in each of the three spots shown in Figure 23 to obtain a preliminary indication of whether there are differences in the elemental make-up of corrosion product for corroded regions of the same wire, with different morphologies. The depth profiles for spots 1 and 2 are shown in Figure 24. Carbon, which is detected at high levels at the surface but rapidly decreases with depth, is believed to be surface contamination from transport, handling, etc. Both spots show high levels of Cu and S, and lower levels of Ca and O. Spot 1 shows higher levels of Ca and O than Spot 2, not surprising since this spot clearly include a non-conductive substance (white in the image), possibly gypsum ($CaSO_4 \cdot 2H_2O$) dust. These results demonstrate that on this particular wire, despite clear morphological differences, the corrosion product is similar in elemental composition.

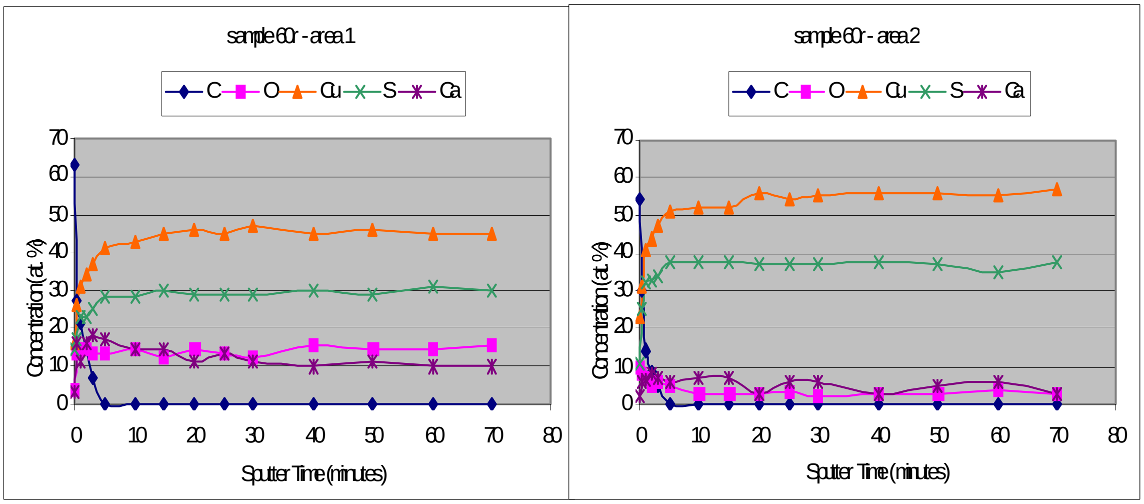


Figure 24: Comparison of Auger elemental analysis results versus sputter time for spot locations 1 and 2 shown in Figure 23.

XPS analysis of one corroded ground wire (results not shown) in several spots confirms the presence of copper sulfide and calcium sulfate (from gypsum) chemistry, but was unable to distinguish between CuS and Cu_2S because of overlap of the peaks of interest for these two species.

3.5. Receptacle Screw Analyses

Receptacle screws were mounted for plan and cross section analyses by SEM and EDS. An example image of a cross sectioned hot screw is shown in Figure 25. The elemental compositions of the screw (Fe) and its plating (Zn, Fe, and Cr) are shown in the image. If there is corrosion product on this particular screw it is too thin to be detected in the cross section. The cross sectioning and polishing process appears to have caused some loss of material from the surface of the screw as there is a gap between the screw surface and the epoxy it is mounted in, and some debris can be seen in this gap.

Table 5 shows the major elemental constituents of the hot, neutral and ground screws (note that these analyses are not complete and will be filled in as data become available). The bulk composition of receptacle hot screws is Fe. All of the hot screws are plated (to prevent rusting) with other metals or combinations of metals including Zn, Cr, Fe and Ni. The plating composition for the analyzed screws depends on the component that each originated from.

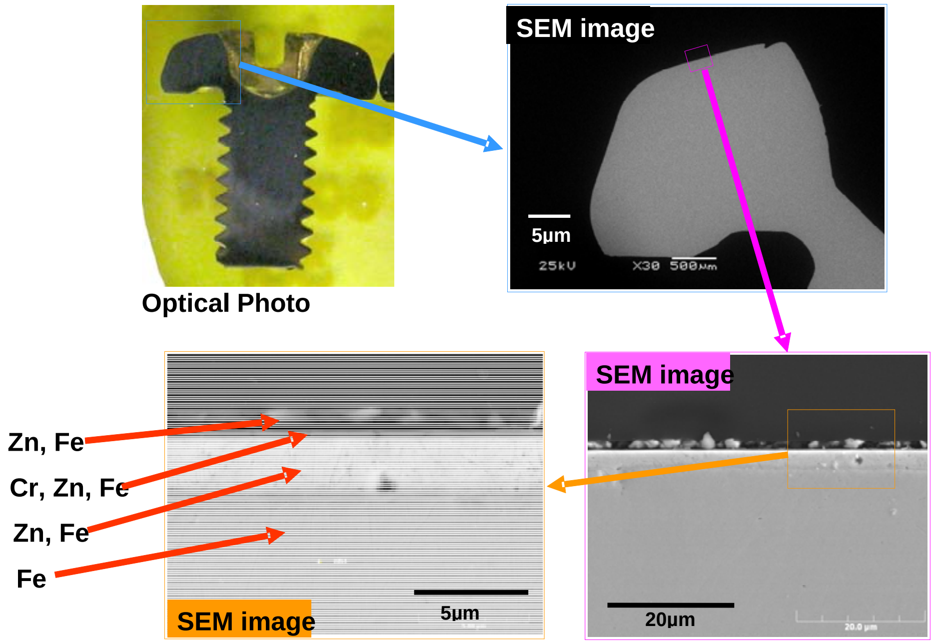


Figure 25: Optical and SEM images of a cross sectioned hot screw. Elemental analyses results are shown in the bottom left image for the bulk metal (Fe) and the plating layer (Zn, Fe, and Cr).

Table 5: Constituent elements observed in plating and bulk metal of receptacle screws

Component no.	Hot screw plating	Hot screw bulk metal	Neutral screw	Ground screw
01-R	Zn	Fe	ongoing	ongoing
14-R	Zn, Cr, Fe	Fe	ongoing	ongoing
33-R	Ni, Fe	Fe	ongoing	ongoing
48-R	Ni, Fe	Fe	ongoing	ongoing
50-R	Ni, Fe	Fe	ongoing	Zn plating Fe bulk
52-R	Ni, Fe	Fe	Ni plating Fe bulk	ongoing

Optical images of harvested receptacle screws shown in Figure 8 show discoloration relative to a reference screw. SEM/EDS elemental analyses of corrosion product observed on screws will be conducted.

3.6. Contact Plate Analyses

Analyses have not been done as of the submission of this interim report.

4. SUMMARY AND CONCLUSIONS

A set of six receptacles has been the focus of Sandia's observations and analyses to date for the corrosion study of harvested electrical components. Corrosion has been observed on electrical conductors (wires, screws, and contact plates) from receptacles harvested from six homes. Evidence of corrosion can be seen in both optical and SEM images. Wires show the greatest degree of corrosion with some areas showing a continuous layer of corrosion product. SEM/EDS elemental analyses show that the corrosion product, which is up to twenty microns thick in samples analyzed to date, consists primarily of copper and sulfur. In some regions of a corroded ground wire the corrosion product appears to consist of layers that vary in composition, suggesting differences in the conditions that produced the corrosion product. SEM analyses of FIB cross-sectioned ground wires also show that there is localized corrosion of the base copper that produces pits containing a spongy looking material. The pits observed to date are up to twenty microns in depth. Additional observations could reveal both greater corrosion product layer thicknesses and pit depths. X-ray Diffraction analyses identified Cu_9S_5 (digenite) and Cu_2O (cuprite) as the two major constituents of the surface corrosion layer on a ground wire. One cross sectional analysis showed growth of corrosion product on top of paint that partially covered a wire surface, suggesting that the corrosion occurred after installation of the receptacle. Screws and contact plates also show evidence of corrosion, but examination to date suggests that it is a thinner layer than what is observed on wires. SEM/EDS analyses of the corrosion product observed on two hot screws showed sulfur and copper. Wire insulation and coverage by other metallic surfaces provide some degree of protection against corrosion. Copper under the wire insulation (at a distance of ~ 0.3 cm away from the original cut in the insulation) shows no corrosion in one instance, therefore suggesting that the insulation protects the conductor from the corrosion source. Screw and contact plate surfaces that were in contact with other conductors also show minimal or no corrosion compared to exposed conductor surfaces.

5. FUTURE WORK

Although corrosion has been observed on the conductor metals of all receptacles examined to date, additional analyses are needed to provide a more complete picture of the extent and nature of the corrosion, and to understand its relationships to the part type and the conductor composition. The work to date provides guidance for further analyses with respect to techniques more and less useful to characterizing the corrosion. Further observation and analyses of receptacles and of the other harvested components could provide results that vary from the results obtained to date.

Future work is expected to include:

a) SEM/EDS analyses of contact plates and wire surfaces that appear to be free of corrosion to verify that corrosion or pitting is not occurring at the microscopic scale,
b) SEM analysis of receiving contact surfaces,
c) Additional XRD analyses of corrosion on wires and other receptacle components
d) Analyses of switches and other hardware.

6. ACKNOWLEDGMENTS

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

The following personnel are gratefully acknowledged for their contributions to this study and to the interim report: Michael T. Brumbach, Carly S. George, Terry R. Guilinger, Alice C. Kilgo, Paul G. Kotula, Samuel J. Lucero, Joseph R. Michael, Kirsten Norman, Mark A. Rodriquez, Michael J. Rye, Bonnie B. McKenzie, and Gary L. Zender.

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