Journal of the National Academy of Forensic Engineers®

NATIONAL ACADEMY OF FORENSIC ENGINEERS

http://www.nafe.org

ISSN: 2379-3252

DOI: 10.51501/jotnafe.v40i1

Vol. 40 No. 1 June 2023

Forensic Examination of Post-Fire Damaged Electrical Conductors by Quantitative Measurement

By Mark J. Svare, PhD, PE, DFE (NAFE 851M), Neal W. Hanke, PE (NAFE 1219A), and Niamh Nic Daeid, PhD

Abstract

During their course of work, forensic engineers and electricians may apply electrical engineering and scientific principles to forensic investigations by performing electrical surveys and electrical fault evaluations. When undertaking a fire investigation, an investigator may implement a similar electrical fault methodology called "arc mapping" or more recently termed an "arc survey." The correct application of either of these methodologies is dependent, in part, on the forensic investigator's ability to distinguish features observed on damaged electrical wiring and equipment. Experiments were conducted to generate a post-fire damaged electrical artifact dataset for this engineering analysis. Generated artifacts of arc melting, fire melting, and mechanical damage features were examined, measured, and quantified by applying metallurgical analyses, such as visual examination, measurement, light microscopy, SEM/EDS, X-ray, and/or metallographic examination. The results produced a novel proof of concept method of quantifying and reliably identifying electrical conductor damage features for forensic electrical fault (short circuit) and/or arc survey evaluations.

Keywords

Arcing, electrical, forensic engineering, fault, short circuit, fire investigation, conductors, copper, arc mapping, arc survey, melting, metallography, microstructure, porosity

Introduction and Background

Electrical engineers have been researching electricity, electrical systems, arcing faults, and arc flash for more than 100 years[1,2]. Within the last 60 years, researchers have rigorously tested and published extensively on electrical distribution faults and arc flash analysis[3-14]. Power electrical engineers are aware of the hazards and risks associated with electrical arcing. They conduct electrical analyses as well as analytical and experimental studies to ensure proper overcurrent protection and coordination for safeguarding person(s) and property. Currently, both the electrical and fire investigation industries rely upon subjective observations to distinguish features of electrical damage in the form of arc melting, fire melting, or mechanical damage.

Low-Voltage Electrical Faults (<600VAC)

Location of a fault in the system/circuit, voltage, current, impedance, and duration of the event determines the electric arc plasma energy. These electrical variables can be derived from short-circuit calculations and evaluations[15-18] (**Figure 1**). Unlike a low-energy spark generated from static discharge, such as the capacitive discharge by touching a doorknob, the electrical energy released from a low-impedance electrical distribution system fault can lead to an arcing event that transfers significant amounts of electrical energy to surrounding materials. Additionally, variables (such as arc gap, arc location, impacted material properties, and exposure time) all factor into the resultant melting, burning, or vaporizing of the impacted material(s) within the area of origin of the electrical arcing fault.

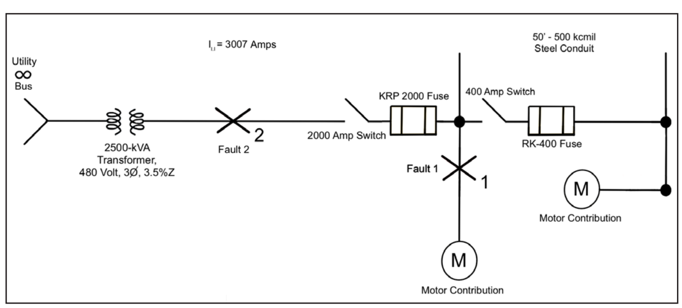

Figure 1
Example: one-line electrical diagram
utilized for short-circuit (fault) evaluations.

Mark J. Svare, PhD, PE, PO Box 517, Anoka, MN, (763) 238-6980, mark@msd2010.com

Generally, low-voltage (<600VAC) arcs can result from a direct short circuit. Below 350VAC, an electric arc at one atmosphere will not jump an air gap greater than 50 μm[19]. Additionally, "below 350VAC, single-phase, sinusoidal electrical circuits will generally self-extinguish an arc at the 0VAC crossing point"[7]. Therefore, "the time dependent arcing event only generates a finite amount of energy to cause localized damage to electrical equipment and wiring"[20].

Electrical Distribution and Fire Investigation

Low-voltage (<600VAC) electrical distribution conductor damage is often observable. For example, storm-damaged electrical conductors resulting in an electrical arcing fault on an electrical distribution system are commonly located, identified, and repaired by qualified and competent electrical workers.

According to NFPA 921 and NFPA 1033, qualified and trained fire investigators should (as part of their fire investigation practice) be able to recognize and distinguish the differences between fire damage patterns, electrical damage patterns, and mechanical damage features at the fire scene by applying arc mapping (arc survey) for fire origin and cause determinations[21,22]. The observable electrical artifact of the arcing fault (arc melt site) is in the form of physical evidence of localized melting of the electrical equipment or wiring.

Characteristic features of arcing damage include beading, notching, welding, or severing of the conductors. There may also be molten spatter or residue of vaporized metal immediately adjacent to the area of the arcing event. This may pose an effect on adjacent conductors or surfaces of other materials in close proximity[23-26]. A recent survey conducted of 317 participants revealed that investigators could reliably identify and characterize mechanical damage. However, survey participants had low probability overall (45.61%) of visually distinguishing the differences between arc-melting and fire-melting features[27].

Electrical Arcing and Metallurgy

From the time of initiation of the electrical arc until extinguishment, the arc transfers electrical energy to surrounding materials. The transfer of energy may include all three heat transfer mechanisms of radiation, convection, and conduction. The transfer of energy in the form of heat causes impacted materials to increase in temperature, which, in turn, may lead to melting, burning, or vaporization of the materials.

Depending on the thermal energy generated by the electric arc, impacted materials (including metals such as steel, copper, aluminum, zinc, silver, gold, and tin) may undergo phase changes from a solid to a liquid, gas (vapor), and/or plasma. The phase change will depend upon the specific physical properties of the material. After the arc is extinguished, vaporized and melted materials will be quenched by the surrounding material and revert to a solid form. The solidification of the melted materials provides characteristic physical evidence (morphology) of the electrical event. The arc-melting data can provide important physical evidence related to how and where the electrical artifact was generated.

Phase Transition Properties of Copper

Copper materials are commonly utilized for electrical equipment and wiring. The heat required to raise the temperature of one gram of copper by one degree Celsius (known as the specific heat) is 0.386 J/g °C[19]. Additional phase transition properties of copper are listed in **Figure 2**.

Where: T(C°) = 5/9 x [T(F°) - 32]

1 kJ/kg = 0.4299 Btu/lb = 0.23884 kcal/kg

Copper has loosely bound electrons that are able to easily transfer or conduct heat and electricity compared to other materials[3]. Alexander and Street described how the "pure copper metal is ductile and can be easily worked, rolled, and pressed into a variety of shapes"[28]. "Copper is easily alloyed with other metals, such as tin, aluminium, or zinc, affecting the electrical conductivity. For example, the addition of 10% aluminium doubles copper's physical strength but reduces the electrical conductivity of copper by one sixth"[28].

Substance	Melting Point °C	Latent Heat of Melting (kJ/kg)	Heat Capacity $C_{p,m}$(J/mol C°)	Boiling Point — Vaporization Temperature °C	Latent Heat of Evaporation (kJ/kg)
Copper	1083	207	24.7	2595	4730

Figure 2
Phase transition properties of copper[19].

Within a fire scene, post-fire damaged electrical conductors may have characteristic damage features in the form of mechanical, fire melting, or arc melting. These have different morphology characteristics and are generally observable visually or with low magnification. There are instances where damage features may require specialized equipment and/or techniques to evaluate. The following damage types are generally recognized to describe observable damage features observed on post-fire damaged electrical wires[21,26,29, 30].

Mechanical Damage Sites

Mechanical damage sites are generally recognized by fracture, impact, cracks, cuts, shearing, stretching, or other damage from a mechanical action at the damage site. Mechanical damage can occur prior to the incident event, during the progression of the event or due to the excavation process involved in a scene investigation. Examples include gouging/scraping of wires during installation or subsequent construction tasks, structural collapse (causing conductors to stretch or break), or cutting by a tool.

Fire Melt Sites

Fire melt sites generally occur during heat or fire attack that exceeds the melting temperature of conductor materials, such as aluminum, zinc, or copper. Conductor melt sites identified as fire-melting damage features are recognized in the form of gross melting, globules, and/or balls. They may exhibit, in part, a non-uniform surface and shape, no clear lines of demarcation at the damage site, irregular melting in and around the damage site, and multiple or widespread areas of damage. Conductor manufactured tool markings (i.e., drawing lines) are generally melted at and away from the damage site, and no porosity or non-uniform porosity will be within the damage site.

Alloying Sites

Alloying sites, a subset of fire melting, are generally recognized by the mixing or alloying of dissimilar materials from elevated temperatures at the damage site. Electrical equipment uses many different materials that may alloy together, such as copper, aluminum, lead, tin, and zinc. Buc reported that alloying is a fire-melt feature that may exhibit features similar to an arc site; however, it is generally accepted that alloying of copper with other common materials, such as aluminum and zinc, exhibit visible features that are, respectively, silver and bronze in color and visually distinguishable from arc melt sites consisting of only copper materials[31].

This type of damage site has been inaccurately broadly identified as eutectic melting; however, "eutectic" is a specific metallurgical term that commonly applies to specific alloy systems and concentrations where the melting point of the mixture is lower than either of the involved materials individually. Thus, some mixtures (e.g., Cu-Al) exhibit eutectic behavior, but others (e.g., Cu-Zn) do not. "Alloying" encompasses any mixture of dissimilar metallic materials; therefore, it is a more appropriate general term.

Arc Melt Sites

When the heat of the fire is sufficient to compromise the electrical insulation of electrically energized (with sufficient available fault current) conductors, a fault or short circuit (arcing melting event) often occurs between the energized and/or earth (grounded or grounding) conductors.

The arcing event generates an arc-melt site(s) that can be identified by localized electrical arcing damage features that are generally identified on electrical wiring and equipment in the form of beads and/or notches. They may exhibit (in part) a smooth surface appearance, distinct lines of demarcation, internal uniform porosity between the different surface textures as well as obliteration of manufactured tool markings within the damage site. Conductor manufactured tool markings may be observed outside the damage site in some cases, but can also be obscured by post-event oxidation or damage. Furthermore, arc-melt sites are generated by electricity — not by fire.

Carbon Tracking

Carbon tracking, also known as arcing through char, is a subset of arc melting wherein electrical current can flow through a carbonized semi-conductive path. Sufficient electrical voltage and available current across the carbonized path may cause electrical current to flow between the carbonized materials and conductors. The carbon is formed from otherwise insulating materials by

Safety Note:

Electricity can be a dangerous occupational hazard. Forensic investigation practitioners may work in areas where this hazard exists. Prior to work, determine site-specific or foreseeable safety hazards, understand your employer's health and safety program, and review safety documents related to workplace hazards. National Fire Protection Association's NFPA 70E, "Standard for Electrical Safety in the Workplace," which addresses safety-related work practices, can help reduce the risk of electrically related workplace injuries[20].

impinged heat and flame.

Notable Fire Investigation Related Arc Melting and Fire Melting Research

Carey and Nic Daeid were able to visibly differentiate between arcing damage as a result of short circuit and arcing through char. They conducted 39 full-scale, electrically energized compartment fire test experiments. These tests enabled them to characterize nine types of post-fire, conductor arc-melt damage features that included combinations of arcing through char, severed ends, beading, notches and welding. No samples of fire melt were generated during their experiments[29].

Murray advanced metallurgical techniques for fire investigation. Murray's findings were, in part: "Electrical damage due to arcing revealed distinct characteristics. More precisely, macroscopically, damage was confined to a localized area, where the surrounding material showed the same condition than initially. Due to the fact that short-circuit phenomenon transfers to the metal an important amount of energy very quickly, liquification and thus re-solidification are state changing that occurred very fast"[32].

In 2012, Hussain's research called into question whether arc melt sites and fire melt sites could be reliably distinguished from one another. Hussain (as well as Roby and McCallister) reported that in their view, "it is not possible to distinguish between the beads formed on energized and non-energized wires exposed to various thermal insults"[33,34]. Note: Hussain's research (and that of Roby and McCallister) present the same research/data but under different authorship.

In contrast to other researchers, Buc researched and developed a laboratory examination method to characterize the damage site[31,35], distinguishing the difference between arc melt and fire melt sites by examining the interior of the damage site for microstructure, porosity, and internal lines of demarcation. However, no quantifiable (measurable) research has been undertaken to distinguish between arc-melt and fire-melt features observed on post-fire damaged electrical copper conductors of 1.0 mm² to 2.5 mm². Thus, the following experiments were undertaken to generate electrical artifacts for study.

Methodology:
Part 1 – Generation of Datasets of Known Damage Full-Scale and Scaled Experiments

Post-fire electrical conductor arc melting, fire melting, mechanical damage, and non-damaged site specimens were generated within both laboratory and field experiment settings. North American copper #14 AWG (1.6 mm) non-metallic (NM) cabling and United Kingdom (UK) "Twin & Earth" type copper, 1.0 mm² and 2.5 mm², NM (where CD is the electrical conductor diameter) were used. Each cable type was used for repeated experiments as follows:

Series One Experiments

A total of 63 full-scale compartment fires were conducted at the United States Federal Law Enforcement (FLETC) ATF fire training center in Brunswick, Georgia (**Figure 3**).

The electrical distribution system under these tests, represented in a one-line diagram (**Figure 4**), included 120/240VAC, single-phase, 15A electrical circuits. The available fault current at the point of fire impingement was calculated to be 210.9A. Six #14 AWG (1.6 mm), NM, copper electrical circuits (four energized at 120VAC, overcurrent protected at 15A and two non-energized electrical circuits) were installed at the ceiling level of each compartment.

Figure 3
(A) Full-scale compartment fire testing at FLETC, (B) interior view of fire, and (C) post-flashover fire extending outside of compartment.

FLETC Experiments — One-Line Diagram and Calculated Fault Current

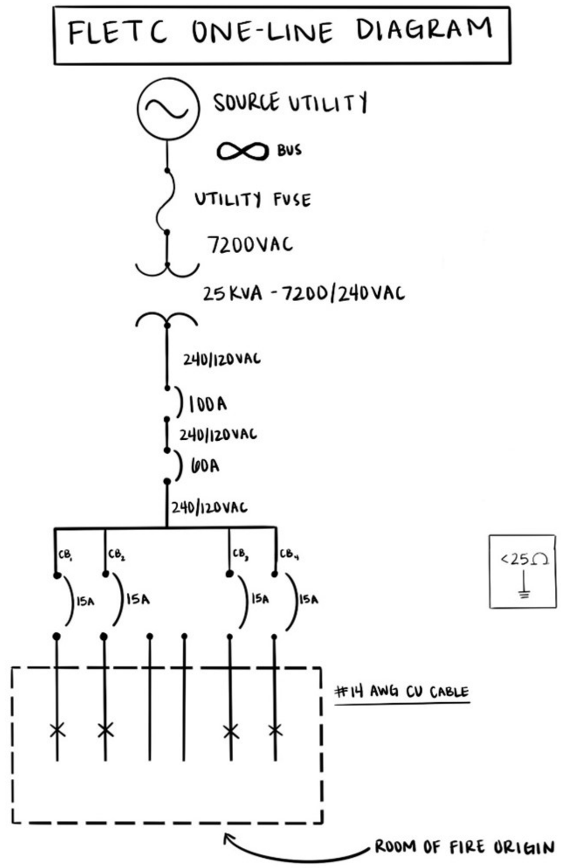

Figure 4
Electrical one-line diagram for FLETC experiments.

A fire was independently initiated by ATF personnel within each compartment. Each fire was allowed to develop based on controlled compartment fuel and ventilation characteristics that were determined by the ATF training parameters. A total of 87.3% of the full-scale experiments went to post-flashover conditions. Electrical data in the form of voltage and short-circuit fault currents were recorded for future analysis. Although fires had reached post flashover conditions, only artifacts of arc melting were generated during the full-scale, FLETC burn cell experiments. However, additional arc melting, fire melting, and mechanical damaged artifacts were generated during a series of scaled fire impingement and non-fire experiments.

Series Two Experiments

No artifacts of fire melting were generated during the full-scale, FLETC burn cell experiments. As a result, two full-scale wooden compartments were constructed in Covington, Louisiana. Both Gulf Coast Fire Investigation and Fire Investigation Group personnel assisted with the construction, ignition, and collection of artifacts generated within these compartments.

Non-energized electrical circuits were installed within the two burn cells. North American copper #14 AWG (1.6 mm) non-metallic (NM) copper cabling and United Kingdom (UK) copper, 1.0 mm² (1.1 mm) and 2.5 mm² (1.7 mm), "Twin & Earth" cabling were installed. Each compartment fire was allowed to burn until complete destruction of the compartment. Since no melting in these experiments could have been due to arc melting, 60 non-energized electrical conductor artifacts with melting were selected from the resultant dataset to be representative of fire melt sites.

Series Three Experiments

The third set of experiments was conducted at MSD Engineering laboratory in Crystal Lake, Illinois. The purpose of these experiments was to perform scaled tests to generate electrical artifacts using a newly developed electrical testing apparatus, which was designed and constructed to facilitate testing of electrical equipment and wiring under varying electrical, fire, and installation configurations. This newly designed test platform, called the Mark I – Arc Research Chamber (MARC – USPTO patent pending), included onboard flame/heat sources and instrumentation that can record voltage, current, temperature, heat flux data, and electrical fault current data.

In total, 42 scaled tests were undertaken. In each case, UK 1.0 mm^2 (1.1 mm), UK 2.5 mm^2 (1.7 mm) "Twin & Earth" and North American #14 AWG (1.6 mm) NM copper cables were electrically connected to appropriately sized single-pole, overcurrent protection devices (6A, 20A, and 15A, respectively) and energized using an associated system voltage (UK "Twin & Earth" 230VAC and North American - 120VAC) that had sufficient electrical fault current to generate an arcing fault. The arc artifacts generated using the MARC test platform were validated in terms of their characteristics and morphology against the artifacts generated under known conditions in the full-scale series one (arc melt) and series two (fire melt) tests. These experiments provided the opportunity to repetitively generate the arc and fire melt artifacts required for practitioner surveys and human factor research[27].

Carey Experiments

In total, 106 arc melting artifacts generated through Carey's research[28] were also provided for incorporation into the overall project dataset. These samples were generated using UK cables installed within full-scale compartments under real fire conditions. The inclusion of these samples enabled a direct comparison between the UK and North American samples to be made in terms of characterization of damage[29].

Part 2 — Examination and Analysis of Electrical Artifacts

The artifacts generated through the three series of experiments were examined and analyzed in multiple stages by several forensic engineers/technicians employed by both Materials Evaluation and Engineering (MEE) and MSD Engineering (MSD). Each artifact was documented based on the location, date of generation, and date of recovery. All artifacts were independently coded. Samples were initially examined and cleaned, removing loose debris. When required, melted and charred insulation material was carefully removed. (**Figure 5**).

Each artifact was sectioned from the lengths of electrical cabling and examined using low power light microscopy where various visible features were characterized and compared to arc melt and fire melt images found within both ATF technical bulletin and NFPA 921[30,36]. While visual examination revealed a difference in features between arc melt and fire melt, no protocol for the morphological examination of arc and melt damage has been published to date. The authors have developed a systematic methodology for the comparisons of post-fire features observed on fire-damaged electrical wiring[37]:

Arc-melted and fire-melted artifacts were examined. Measurements were made using calibrated or validated handheld calipers, magnifying instrument(s), or light microscopy utilizing optical or digital Keyence microscope(s), as noted in **Figure 6**.

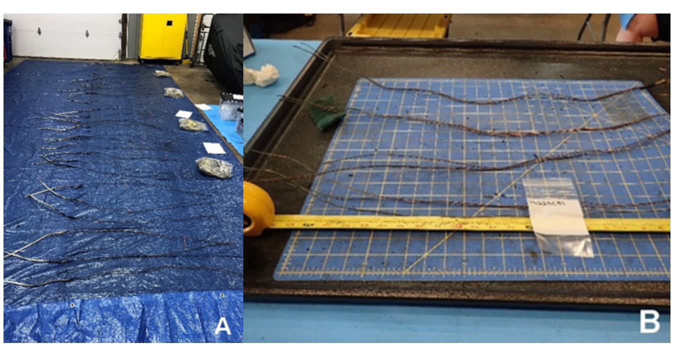

Figure 5
Post experiment examination of electrical artifacts.
(A) post-fire damaged cable examination; (B) post-fire damaged collection and packaging of damage sites[27].

Each artifact was examined visually and/or with a microscope, and images were collected. The length of each area of displaced copper (in the form of beads, notches, globules, or other features indicating melting of the copper conductor) was documented. The maximum displacement was measured and recorded (**Figure 7** and **Figure 8**). In cases where melted copper artifacts were grossly melted, melted open or discontinuous, a displaced material measurement of 50 mm was recorded for each artifact. Artifacts that exhibited multiple melt sites separated by greater than 100 mm were considered separate independent melting events.

Results and Discussion

In total, 721 artifacts were generated and categorized into 476 samples of electrical arc melting, 102 samples of fire melting, and 143 samples of fire-impinged, mechanical damage, or non-melted electrical conductors. Normalized diameter measurements of the displaced melted copper for both arc melt and fire melt artifacts were determined. The data revealed quantifiable and statistically significant Chi-squared, ($p = <0.00001$) differences between the measurable damage features and their comparison to the conductor diameters for arc melt sites and fire melt sites for all three cable types studied.

Arc Melt Sites

Localized melting features, clear lines of demarcation, and uniform porosity were observed within arc melt sites. Electrical arc-melt features generated had melted copper

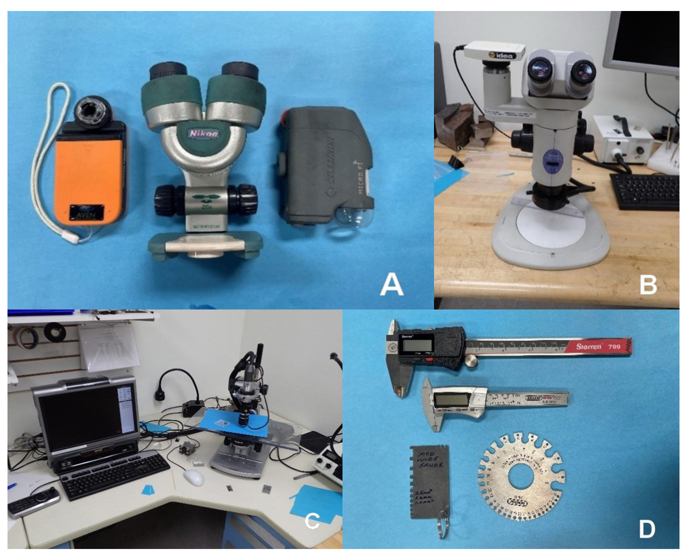

Figure 6
Examination equipment utilized for artifact examination.
(A) portable microscopes for field light microscopy; (B) laboratory or bench optical light microscope; (C) digital light microscope for microscopy and measurements (calibrated); (D) digital caliper (top) and measurement gauges (bottom)[27].

displacement of less than or equal to four times the subject conductor diameter (0<AM≤4CD). Arc melting scatter plots and normalized graphs for solid North American (NM) 1.6 mm, (UK) 1.0 mm² and (UK) 2.5 mm² copper conductors are presented in **Figures 9** through **12**.

Artifact ID	Wire ID	Conductor Diameter (mm)	Max Arc Melt Size (mm)	Artifact
FLETC 150515	Cell 5 Wire 2	1.6	4.01	
FLETC 150515	Cell 3 Wire 1	1.6	2.53	
FLETC 150515	Cell 1 Wire 3	1.6	2.37	

Figure 7
Representative samples of series one – FLETC arc-melted artifacts[27].

Fire Melt Sites

In all cases, the generated fire melt sites had measurable melting features greater than four times the conductor diameter (FM>4CD). The sites exhibited melting, spherical balls (globules). Non-uniform or non-persistent porosity was observed within the mixed gas flame generated globules and/or spherical ball fire melt sites.

Fire melt scatter plots and normalized graphs for 1.6 mm conductors are presented in **Figures 13** and **14**. The data analysis and findings for both 1.0 mm² and 2.5 mm² (UK) copper conductors were similar to the NM 1.6 mm

Artifact ID	Wire ID	Conductor Diameter (mm)	Max Fire Melt Size (mm)	Artifact
Louisiana 2	2	1.6	17	
Louisiana 2	3	1.6	32	
Louisiana 2	4	1.6	>50	

Figure 8
Representative sample of series two - Louisiana (LA) fire melt artifacts[27].

copper conductor results.

Additional Metallurgical Examination Techniques

The previously discussed methodology of quantifying displacement of melting observed on a post-fire damaged electrical conductor provided high confidence in characterizing conductor melt sites by visual examination and quantitative measurement. This provides investigators with the ability to field deploy the methodology for characterizing electrical conductor melt sites. However, in instances of uncertainty with respect to whether an artifact is an arc melt or fire melt, further examination utilizing non-destructive X-ray examination[35] or destructive metallurgical techniques (such as metallography) can provide

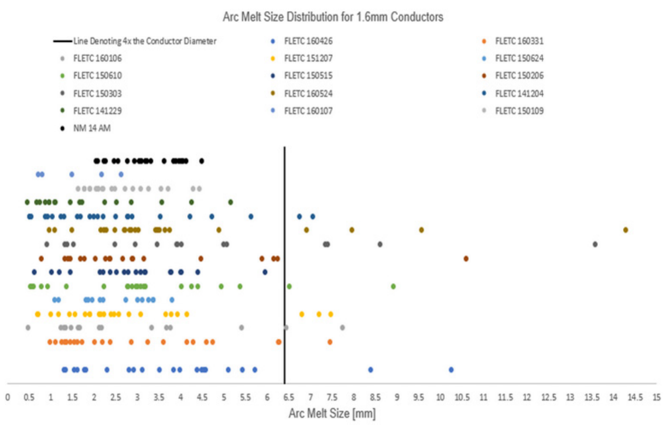

Figure 9
Scatter plot for Series One 1.6 mm arc melt size distribution. The vertical line represents the location of 4X the conductor diameter[27].

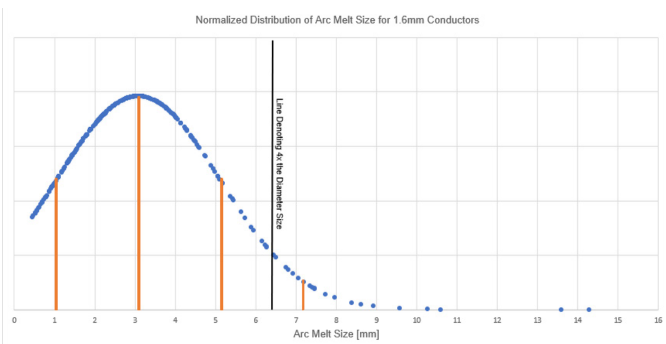

Figure 10
Distribution of the Series One arc melt size generated on 1.6 mm conductors. The vertical line represents the location of 4X the 1.6 mm conductor diameter[27].

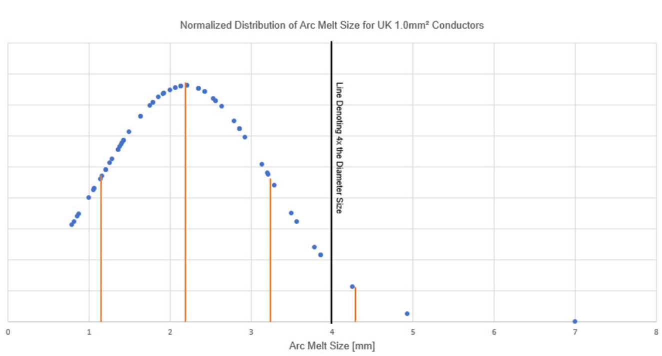

Figure 11
Distribution of the arc melt size generated on 1.0 mm² and the Carey samples (NC UK fire arc) size distribution. The vertical line represents the location of 4X the 1.0 mm² conductor diameter[27].

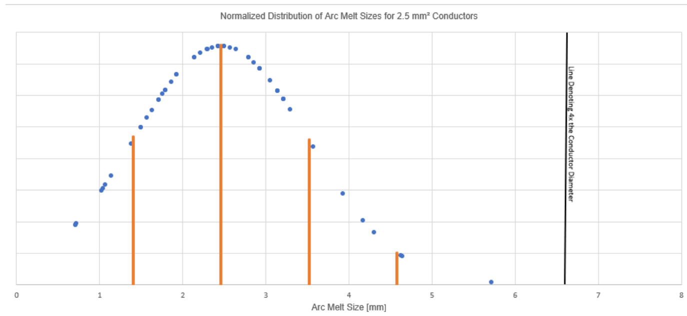

Figure 12
Distribution of the Series Two arc melt size generated on 2.5 mm² and the Carey samples (NC UK fire arc) size distribution. The vertical line represents the location of 4X the 2.5 mm² conductor diameter[27].

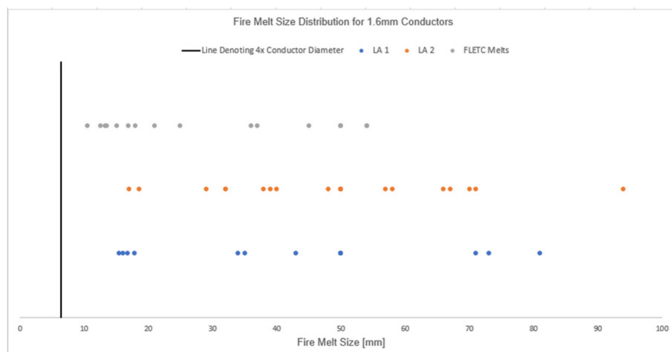

Figure 13
Scatter plot for 1.6 mm fire melt size distribution. The vertical line represents the location of 4X the conductor diameter[27].

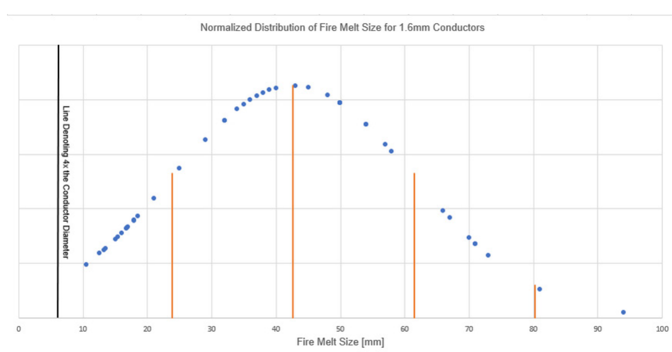

Figure 14
Normalized curve of 1.6 mm fire melt size distribution. The vertical line represents the location of 4X the 1.6 mm conductor diameter[27].

increased confidence and additional data to assist in the damage feature characterization.

To better understand the usefulness of many metallurgical techniques like metallography, a fundamental understanding of the structural configuration (grain structure) of metallic materials (in this case, specifically focusing on copper) is required.

The atoms in a solid copper material are arranged in an orderly structure, known as a face-centered cubic (FCC) lattice. Most commercial applications of copper (conductor) wire are polycrystalline materials. This means that the bulk wire material is comprised by discrete zones of the FCC lattice structure in various orientations (**Figure 15**). These zones are called grains, and their size/shape collectively constitute the material's "grain structure." Grain structure is one of the most useful aspects of characterizing melted conductors because the grain structure can change drastically due to the effects of various types of thermal exposure.

As copper materials cool from a liquid state (randomized atomic structure), the material will begin solidifying at many nucleation sites simultaneously[37]. Each nucleation site is the origination point of a single grain; these grains continue to grow until they either run into another grain, or all of the liquid material is solidified[37]. These solidified grains have a characteristic dendritic morphology, but become altered through further processing of the wire during subsequent manufacturing. The room-temperature grain structure of a typical copper conductor consists of very small grains. Levinson reported that the grains of copper become elongated during the manufacturing process of drawing copper into wire[38]. Copper wire for electrical purposes is commonly supplied in the annealed condition, which has a fine, equiaxed (i.e., non-elongated) grain structure. A representative example of the typical microstructure for a commercially available copper wire is shown in **Figure 16**.

Thus, through fundamental principles of metallurgy and direct observation of the specimens created during the course of the research presented herein, differences from this baseline structure observed in field specimens can be correlated to the thermal exposure condition for the subject conductor(s).

Conductor Characterization by Scanning Electron Microscopy

Characterization of a conductor surface by scanning electron microscopy (SEM) is typically non-destructive and a simple first step in a more comprehensive evaluation of a suspected arc site (**Figure 17**). As discussed previously, since an electrical arc is an extremely short-

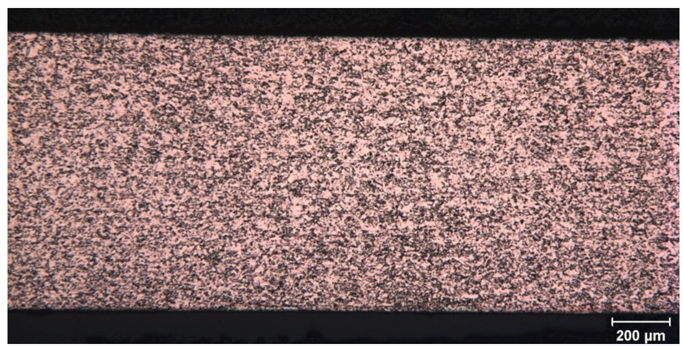

Figure 16
Typical material microstructure for a copper conductor as-manufactured (longitudinal section view)[27].

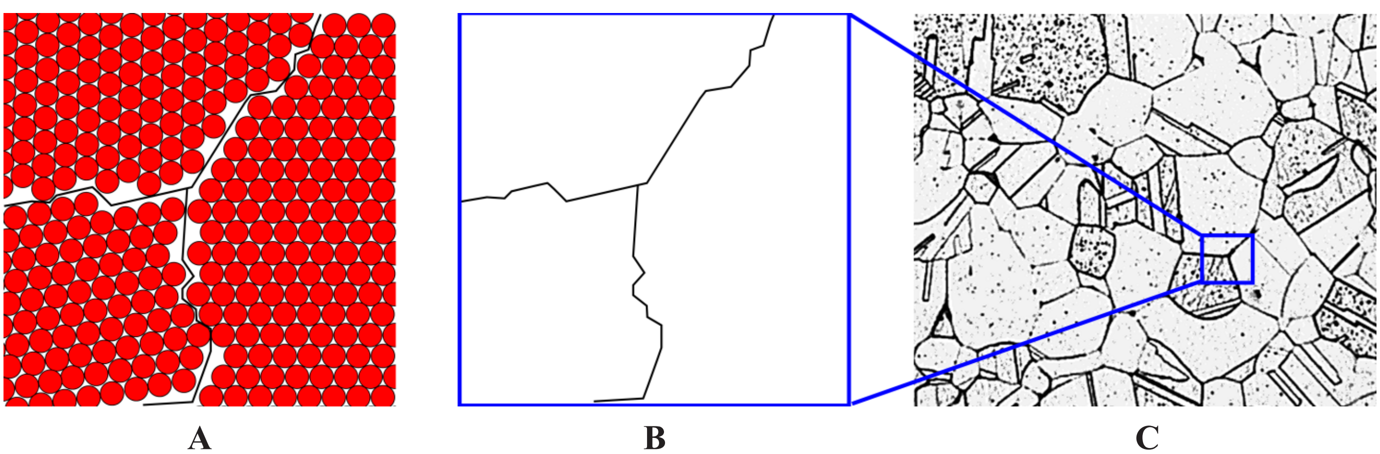

Figure 15
(A and B) schematic representation of a copper grain structure and (C) a typical micrograph of an actual grain structure for a copper material.

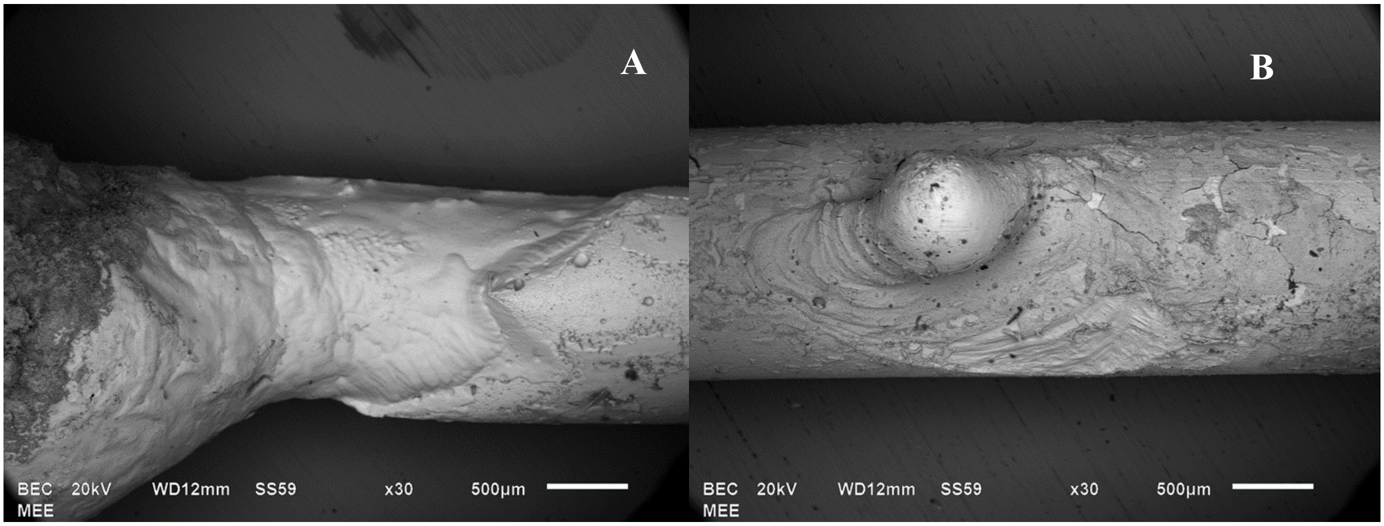

Figure 17
(A) and (B) SEM images of conductors showing boundaries between melted and non-melted regions.

duration but very high-temperature event[32], the bulk wire material adjacent to the melted material does not experience sufficient heating to alter the grain structure, and the boundary between melted and resolidified material will be very sharply delineated. Examination by SEM can aid in characterizing the transition between resolidified material and the original conductor surface in very small regions that may not be as easily resolved by light microscopy.

In some cases — particularly after a fire and subsequent artifact extraction — the surface features in a suspected arc site may be more adequately characterized as mechanical damage or corrosion/oxidation. SEM examination is also useful in characterizing these features and can aid in distinguishing between the microscopic surface features that result from melting and re-solidification and surface features that result from mechanical damage, corrosion, or foreign material contamination.

A common companion technique to SEM is a method for elemental analysis known as energy dispersive x-ray spectroscopy (EDS), which is capable of identifying the elements comprising specimen surface features as small as a few microns.

As an example, one condition that can result in localized melting of copper conductors is alloying with lower-melting-point materials. As discussed previously, an alloy is a mixture of different metallic elements, and the melting point of alloys can be vastly different from the melting point of either material individually[39]. For some metals, such as aluminum, lead, or tin, the melting point of a mixture with copper can be well below the temperatures sustained during a fire event[36,39]. Thus, melting can occur at conditions where the copper would normally be expected to be intact. EDS analysis is very useful for identifying elements (or the lack of elements) that could be responsible for melting due to alloying or the source of arcing to materials other than copper.

If surface level evaluations by SEM/EDS are still inconclusive, additional metallographic examination can be conducted to aid in further characterizing the damage.

Conductor Characterization by Metallographic Examination

Metallographic examination is a widely accepted and standardized method for characterizing the grain structure

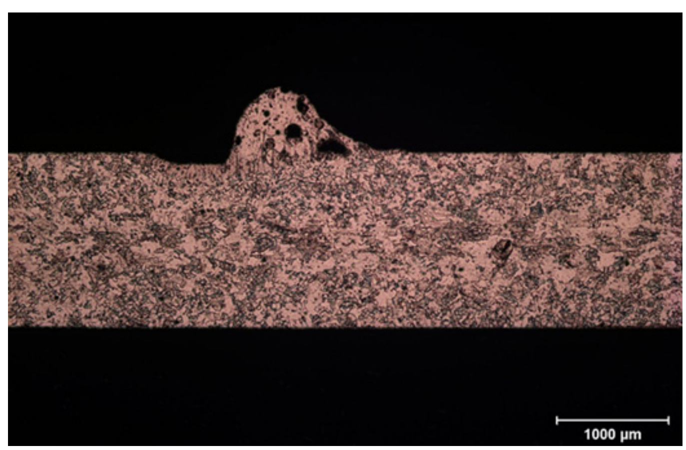

Figure 18
Light micrograph of a metallographically prepared specimen showing localized columnar grains, internal porosity, and a sharp boundary between the resolidified material and unaffected bulk material grain structure[27].

of a material[40]. However, due to its destructive nature, it should be the last step in the characterization process. Since metallographic specimen preparation involves preparing a cross section through the conductor material to be studied, a primary benefit is that the internal structure of the material can be characterized. Once a metallographic section is prepared, the surface is chemically etched to reveal the grain structure and examined by light microscopy and/or SEM/EDS (**Figure 18**).

As discussed previously, melted and resolidified material will typically have a dendritic or columnar structure (unless there has been sufficient subsequent heating to recrystallize the material). Again, a clearly delineated boundary between the resolidified material and the bulk material and/or a lack of other indications of high temperature exposure for the damaged conductor is strong evidence of an extremely localized and rapid heating event (e.g., an electrical arc).

Resolidified material from an electrical arcing event is also characterized by a high concentration of porosity[31]. Levinson described how the "grain structure in copper changes when copper wire is heated through the melting point as well as the subsequent formation of copper oxide and the development of porosity"[38]. Therefore, localized electrical arcing affects copper grain structure, the formation of copper oxide, and the formation of porosity.

Levinson[38] and Gray[41] both reported that porosity was present, creating a "Swiss cheese" effect on the copper wire surface due to arc melting. However, surface-level examinations, such as those conducted by light microscopy or SEM, may not reveal internal porosity that is easily observed in a properly prepared metallographic section. Levinson theorized that "the porosity effect would be found if the wire was melted by the fire, the resistance effect of a gross overcurrent, or by arcing"[38]. Levinson further theorized that this "porosity was a result of partial entrapment of gas pockets liberated from the copper wire"[38]. Gray observed the effects of porosity within electrically arced conductor samples by utilizing an SEM[41]. Present empirical research continues to corroborate the findings of porosity within the resolidified material of an electrical arc melt site.

Converse to the characteristics of electrical arcing, conditions can also be observed that indicate more widespread, longer-term degradation due to high-temperature exposure. A gradual transition from a melted and resolidified zone to the bulk wire material grain structure indicates

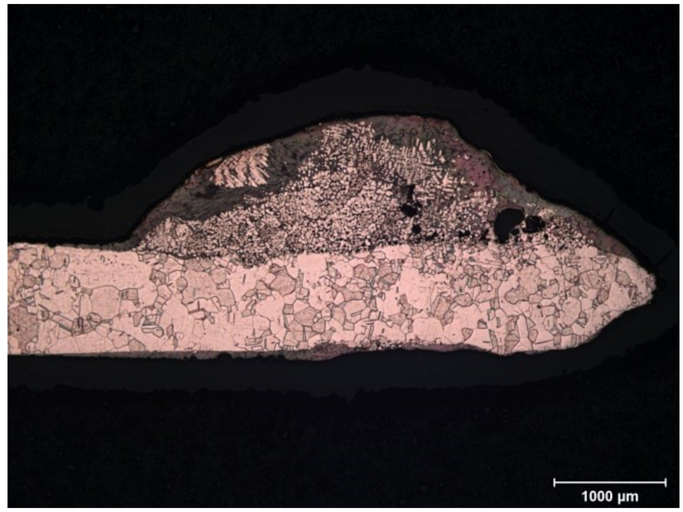

Figure 19
Light micrograph of a metallographically prepared specimen showing an irregular conductor profile, non-uniform melting, a more gradual transition between melted material and the bulk structure as well as a widespread enlarged grain structure[27].

non-localized heating that can be expected from the heat of a fire. Somewhat localized or gross changes in the fine-grained texture of the bulk material (e.g., grain growth) indicate prolonged exposure to elevated temperatures (**Figure 19**). The specific features observed, as well as their location, orientation, and/or coincidence with other artifacts, can be used to make a more conclusive determination of the conditions that resulted in the damage to the conductor.

Summary and Conclusions

During the course of their work, forensic electrical power engineers and electrician practitioners may apply electrical engineering and scientific principles to forensic investigations by performing electrical surveys and electrical fault evaluations. A fire investigation practitioner may implement a similar electrical investigation methodology called "arc mapping" or more recently termed an "arc survey." The correct application of either of these methodologies is dependent, in part, on the forensic investigation practitioner's ability to distinguish features observed on damaged electrical wiring and equipment.

Currently, practitioners rely upon subjective visual observations to distinguish the difference between arc melting, fire melting, and mechanical features on post-fire damaged electrical conductors. The experiments undertaken as part of this research generated an underpinning dataset of electrical conductors that exhibit arc melt, fire melt, and mechanical damage features. Examination and analysis of the data generated from this research resulted in findings for tested conductors, in part:

- Post-fire damaged electrical conductor melting features in the form of arc melting and fire melting can be reliably distinguished from each other.

- Under fire conditions, arc melt sites were only observed on electrically energized electrical circuits, and arc melt sites were only located within the area of origin.

- Physical evidence in the form of both fire patterns from the effects of fire and electrical patterns in the form of arc melt sites were observable, distinguishable, and quantifiable throughout these experiments.

- Electrical arc melting features generated from these experiments had melted copper displacement of less than or equal to four times the subject conductor diameter (0<AM≤4CD). Fire melt features had a copper displacement greater than four times the subject conductor diameter (FM>4CD). This was a validated and repeatable characteristic across the dataset at 95% for both full-scaled and scaled experiments.

- The experiments revealed, in part, that NM 1.6 mm (#14 AWG) North American (U.S.) cables responded to fire in a similar manner as experiments conducted on UK 1.0 mm^2 and UK 2.5 mm^2 cabling experiments[27].

- Electrical experiments did not result in malfunction, damage upstream, or uncoordinated operation of overcurrent protective device(s) (OCPDs) that were electrically upstream from the OCPD protecting the circuit under test.

- Power electrical engineers and electricians can apply short-circuit/electrical fault analysis procedures during a fire investigation(s) whereby an electrical analysis of a one-line diagram in conjunction with arc fault analysis or arc survey may define a region of investigation interest, area of origin, and point of origin.

- Examination of non-energized electrical cabling recovered from the FLETC experiments had no observable melting.

- Adaptation of metallurgical techniques and methods, such as SEM, EDS, and microstructure analysis, further underpinned the ability to distinguish the different features of arc melting and fire melting.

This empirical research represents a validated novel methodology using quantified measurement to reliably distinguish the difference between arc melt and fire melt sites observed on the tested post-fire damaged electrical conductors of the same size. However, additional testing may be required for different conductor sizes, materials, and fault current conditions.

Acknowledgements

The authors wish to thank, in part, the Leverhulme Research Centre for Forensic Science; University of Dundee (UK), Special Agents of the Department of Justice; Bureau of Alcohol, Tobacco, Firearms and Explosives (US), MSD Engineering (US), Gulf Coast Fire, LLC (US), Investigative Loss Services (US) and Materials Evaluation and Engineering (US) for their continued support. The authors also wish to acknowledge the following for their invaluable support. – Prof. Susan Black, Dr. Nick Carey IAAI-CFI, Jeff Washinger Sr. IAAI-CFI, Robert Schaal ATF (retired) and IAAI-CFI, Larry Hanke, PE, Albert Bartolome i Regue Engineer & IAAI-CFI, Lester Rich ATF (former) & IAAI-CFI, Kerry Svare ATF (retired) and IAAI-CFI, Roberta Svare, Carol Severson EIT, and Erik Severson EIT.

These experiments were conducted and assisted by numerous companies and personnel further acknowledged. Additionally, all FLETC experiments were performed in conjunction with ongoing ATF training programs. All research expenses for FLETC, Louisiana, Minnesota, Illinois and United Kingdom locations were funded by researcher Dr. Mark J. Svare, PE.

References

1. H. Davy, Elements of Chemical Philosophy: Part 1, Vol. 1. Bradford and Inskeep, 1812.

2. C. L. Fortescue, “Method of Symmetrical Co-Ordinates Appllied to the Solution of Polyphase Networks,” Transactions of the American Institute of Electrical Engineers, vol. 37, no. 2, pp. 1027-1140, 1918.

3. R. Kaufmann and J. Page, “Arcing Fault Protection for Low-Voltage Power Distribution Sys-

tems -Nature of the Problem," Transactions of the American Institute of Electrical Engineers. Part III: Power Apparatus and Systems, vol. 79, no. 3, pp. 160-167, 1960.

4. R. Lee, "The Other Electrical Hazard: Electric Arc Blast Burns," IEEE Transactions on Industry Applications, vol. IA-18, no. 3, pp. 246-251, 1982.

5. R. Lee, "Pressures Developed by Arcs," IEEE Transactions on Industry Applications, vol. IA-23, no. 4, pp. 760-764, 1987.

6. T. Gammon and J. Matthews, "The Historical Evolution of Arcing-Fault Models for Low-Voltage Systems," IEEE Industrial and Commercial Power Systems Technical Conference, pp. 1-6, 1999.

7. T. Gammon and J. Matthews, "Arcing-fault models for low-voltage power systems," in 2000 IEEE Industrial and Commercial Power Systems Technical Conference. Conference Record (Cat. No. 00CH37053), 2000: IEEE, pp. 119-126.

8. T. Gammon and J. Matthews, "Instantaneous Arcing-Fault Models Developed for Building System Analysis," IEEE Transactions on Industry Applications, vol. 37, no. 1, pp. 197-203, 2001.

9. T. Crnko and S. Dyrnes, "Arcing Fault Hazards and Safety Suggestions for Design and Maintenance," IEE Industry Applications Magazine, vol. 7, no. 3, pp. 23-32, 2001.

10. T. Gammon and J. Matthews, "The application of a current-dependent arc model to arcing at a main distribution panel, a sub-panel and a branch circuit," in Proceedings. IEEE SoutheastCon 2001 (Cat. No. 01CH37208), 2001: IEEE, pp. 72-78.

11. T. Gammon and J. Matthews, "IEEE 1584-2002," IEEE Industry Applications Magazine, vol. 11, no. 1, pp. 24-31, 2005

12. T. Gammon and J. Matthews, "Conventional and Recommended Arc Power and Energy Calculations and Arc Damage Assessment," IEEE Transactions on Industry Applications, vol. 39, no. 3, pp. 594-599, 2003.

13. H. Land, "The Behavior of Arcing Faults in Low-Voltage Switchboards," IEEE Transactions on Industry Applications, vol. 44, no. 2, pp. 437-444, 2008. [Online]. Available: vb.

14. H. Land and T. Gammon, "Addressing Arc-Flash Problems in Low-Voltage Switchboards: A Case Study in Arc Fault Protection," IEEE Transactions on Industry Applications, vol. 51, no. 2, pp. 1897-1908, 2015.

15. Bulletin EDP-2 - Selective Coordination of Overcurrent Protective Devices For Low Voltage Systems, 1969, pp. 1-31.

16. Bulletin EDP- 1-3 - A Simple Approach to Short Circuit Calculations - Part 1, 2004, pp. 1-104.

17. Short Circuit Current Calculations, Cooper Bussmann, 2005, pp. 192 - 198.

18. C. Miller, Ugly's Electrical References. Jones & Bartlett Learning, 2023.

19. D. Lide, CRC Handbook of Chemistry and Physics, 79th ed. (Handbook of Chemistry and Physics). New York: CRC Press, 1998.

20. National Fire Protection Association, 70E Standard for Electrical Safety in the Workplace. NFPA, Quincy, MA, USA, 2021.

21. National Fire Protection Association, 921 Guide for Fire and Explosion Investigations. NFPA, Quincy, MA, USA, 2021.

22. National Fire Protection Association, 1033 Standard for Professional Qualifications for Fire Investigator. NFPA, Quincy, MA, USA 2014.

23. B. Beland, "Examination of Electrical Conductors Following a Fire," Fire Technology, vol. 16, no. 4, pp. 252-258, 1980.

24. B. Ettling, "Arc Marks and Gouges in Wires and Heating at Gouges," Fire Technology, vol. 17, no. 1, pp. 61-68, 1981.

25. B. Ettling, "Problems with Surface Analysis of Copper Beads Applied to the Time of Arcing," International Association of Arson Investigators,

pp. 23-26, 1998.

26. R. Svare, "Using the electrical system to help reconstruct the fire scene," in Proceedings of International Symposium on the Forensic Aspects of Arson Investigations, Federal Bureau of Investigation, Washington, 1995, pp. 103-116.

27. M. Svare, "A reliable systematic methodology for reconstructing the fire scene using the electrical system: analysing human factors," Ph.D. Dissertation, Science and Engineering, University of Dundee, Dundee, UK, 2022.

28. W. Alexander and A. Street, Metals in the Service of Man, 8th ed. Pelican Technology, 1982.

29. N. Carey, "Developing a reliable systematic analysis for arc fault mapping," Ph.D. Dissertation, Pure and Applied Chemistry, University of Strathclyde, Glasgow, UK, 2009.

30. ATF Fire Research Laboratory, "Visual Characteristics of Fire Melting on Copper Conductors," ATF Fire Research Laboratory Technical Bulletin, no. Technical Bulletin 001, pp. 1-8, 2012.

31. E. Buc, D. Reiter, J. Battley, T. Sing, and T. Sing, "Method to Characterize Damage to Conductors from Fire Scenes," Fire and Materials, pp. 657-666, 2013.

32. I. Murray and F. Ajersch, "New Metallurgical Techniques Applied to Fire Investigation," Fire and Materials, pp. 857-870, 2009.

33. R. Roby and J. McAllister, "Forensic Investigation Techniques for Inspecting Electrical Conductors Involved in Fire," Journal National Institute of Justice, pp. 1-105, 2012.

34. N. Hussain, "Forensic Investigation for Inspecting Electrical Conductors Involved in Fire for Arc and Melt Beads," Thesis for Master of Science, Department of Fire Protection Engineering, University of Maryland, 2012.

35. E. Buc, "Metallurgy and Fire Investigation," International Symposium on Fire Investigation Science and Technology, pp. 137-148, 2012.

36. National Fire Protection Association, 921 Guide for Fire and Explosion Investigations. NFPA, Quincy, MA, USA, 2017.

37. J. Davis, Ed. Metals Handbook Desk Edition. ASM International, 1998.

38. D. Levinson, "Copper Metallurgy as a Diagnostic Tool for Analysis of the Origin of Building Fires," Fire Technology, vol. 13, no. 3, pp. 211-222, 1977.

39. ASM International, Alloy Phase Diagrams (ASM Handbook). ASM International, 2016.

40. Standard Guide for Preparation of Metallographic Specimens, E3-11 (Reapproved 2017), ASTM, 2017.

41. D. Gray, "Investigation of Electrical Fires," MSc in Fire Engineering Dissertation, University of Edinburgh, 1982.