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Forensic Examination of Post-Fire Damaged Electrical Conductors by Using X-Ray Radiographs

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Abstract

Structural fires globally have a catastrophic impact on loss of life, property damage, and socioeconomic factors. Forensic scientists, engineers, and/or fire investigators — often working together as fire investigation practitioners — are commonly tasked with determining both the area of fire origin and its cause. During the course of a fire investigation, a fire investigation practitioner may implement an origin determination methodology termed "arc mapping" or an "arc survey." The correct application of an arc survey as a fire origin determination method is dependent on the fire investigation practitioner's ability to distinguish and characterize features observed on post-fire damage electrical wiring and equipment. Experiments were conducted to generate a dataset of post-fire damaged electrical conductor artifacts. Generated artifacts were visually examined, compared, and characterized by X-ray examination. The research results produced a validated, novel, non-destructive methodology for utilizing X-ray imagery to reliably distinguish and characterize electrical conductor damage features for forensic investigations.

Keywords

Arc mapping, arc survey, arc, artifact, bead, conductors, electrical, fire, fire investigation, forensic engineering, science, origin and cause investigation, microstructure, porosity, X-ray, radiograph, computed tomography, NDT

Introduction and Background

Structural fires globally have a catastrophic impact on loss of life, personal injury, property damage, and socioeconomic factors (**Figure 1**). Forensic scientists, forensic engineers, and fire investigators (fire investigation practitioners), often working together as a team, are commonly tasked with determining both the area of fire origin and its cause. The National Fire Protection Association (NFPA) 921, "Guide for Fire and Explosion Investigations," 2021 edition[1] is currently recognized as an industry guide for fire and explosion investigations.

According to NFPA 921, the cause of a fire is identified after the fire origin has been determined by utilizing data collected from one or more of the recognized origin determination methods. During the course of a fire investigation, fire investigation practitioners may implement an electrical origin determination methodology called "arc mapping," which is a term defined by NFPA 921 as "Identifying and documenting a fire pattern derived from the identification of arc sites used to aid in determining the area of fire origin or spread"[1]. The proper application of arc mapping — or more recently called an "arc survey" — requires the qualified fire investigation practitioner to conduct an electrical system survey, identify features of electrical fault damage, and evaluate the derived electrical data.

Figure 1
Structure fire.

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Currently, the fire investigation practitioner utilizes subjective observations to attempt to identify features of damage observed on electrical conductors and conducting surfaces. X-ray imagery, a non-destructive testing (NDT) method, has been reliably utilized within manufacturing and medical industries for more than a century. X-ray imagery utilized in fire investigations can assist the fire investigation practitioner in characterizing features of post-fire damaged electrical wiring and equipment, thereby further assisting the fire investigation practitioner to more reliably analyze post-fire damaged artifacts and provide further underpinning evidence supporting an electrical system-based origin determination methodology.

Fire Investigation and Arc Mapping (Arc Survey)

Examination of post-fire damage to electrical wiring and equipment within buildings provides fire investigation practitioners with data that can assist in both fire origin and cause determination. NFPA 921 describes the origin of a fire as one of the most important hypotheses that a fire investigation practitioner develops and tests during the investigation[1]. It further outlines the means of coordinating data gathered from one or more of the three recognized origin determination methods: witness information, fire patterns, and fire dynamics[1]. The data collected during the fire origin determination phase of the investigation becomes the foundation of the fire investigation, which leads to understanding a fire, its sequence of events, origin determination, hypothesis development and testing, and determination of the cause of the fire. Noting the location of arc sites at the fire scene was first introduced to the fire investigation community within NFPA 921, 2001 edition[2]. Subsequently, the terms "arc surveys" and "arc mapping" were added within later editions of NFPA 921 — 2004 and 2008, respectively[3,4].

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[11].

Electrical Arcing: Cause or Victim

An effort to reliably develop a methodology to distinguish between arcing events that cause a fire versus arcing events that are a victim of a fire actually began in the 1970s. Numerous researchers conducted experiments attempting to develop methodologies to distinguish the differences between causal and victim arc damage observed on post-fire damaged electrical conductors. However, some researchers concluded that they could not find much promise with any of the methods that were proposed for distinguishing between "cause" and "victim" beads — and that reliable distinctions between "cause" and "victim" beads were yet to be discovered[5]. Therefore, it is commonly accepted within the forensic investigation community that a reliable methodology has yet to be developed to distinguish the difference between causal arc sites (fire starting) and victim (fire attacked) arc sites.

Up until the 1980s, fire investigators had attempted to answer a "cause" question before answering the critical "origin" question. A reversal of this frame of thinking was (and still is) required. Once this mindset changed, then the effectiveness of an electrically based fire investigative methodology like arc mapping (otherwise known as an arc survey) for origin determination became the focus.

Electrical Arcing and Fire Investigation

The first electrical arcing research was conducted by Davy in 1812[6]. Electrical arcing research continued through the 20th century, in part, by Ayrton, Lee, Mathews, and Gammon[7-10]. This resulted in the development of electrical safety standards such as IEEE 1584, "Guide for Performing Arc-Flash Hazard Calculations," and NFPA 70E, "Standard for Electrical Safety in the Workplace"[11]. However, electrical research related to evaluating the electrical system for fire origin determinations was not theorized until the 1950s[12] and later examined in the 1980s by Delplace & Vos[13] and Rothschild[14].

Several pioneers are recognized for empirical research, testing, and the development of training programs for utilizing the electrical system for origin determinations[15-17]. The reliability of arc mapping methodology was subsequently reviewed by both Babrauskas and Icove[18,19]. Each had questioned the application and reliability of fire investigators to perform the arc mapping methodology. McPherson also forensically examined, applied, and analyzed a systematic approach to investigating residential (domestic) fire scenes by utilizing the arc mapping (arc survey) or arc fault circuit analysis methodologies[20].

Reliability of any methodology as an origin determination method is dependent on the skill, knowledge, education, training, and experience of the person applying it. To successfully undertake any electrical fault analysis, one must be qualified and competent in the areas of electrical safety and electrical systems that are under investigation (residential, commercial, industrial, agricultural, and transportation vehicles). Additionally, one must be able to perform a systematic and scientific approach to accurately analyze data related to damage observed on electrical wiring and equipment. These damage sites are generally identified in the form of arc melting (arc melt site), fire melting (fire melt site), alloy melting (alloying site), and mechanical damage (mechanical damage site).

Electrical Investigations

Fundamentally, the electrical investigation begins with an electrical survey, which can be defined as a systematic approach of examining, documenting, and analyzing the electrical distribution system, wiring, and equipment. Electrical fault evaluations, in their fundamental form, consist of identifying how electrical circuits were installed and protected at the scene as well. Subsequently, this method involves identifying boundaries of faulted and non-faulted electrical circuits/equipment and analyzing the electrical system/electrical faults to determine or define a spatial relationship, sequence of events, and/or conduct hypothesis testing.

Power electrical engineers have been reliably evaluating and performing electrical transmission and distribution fault evaluations for more than a century[21]. Today, skilled and trained power electrical engineers and electricians perform short-circuit evaluations and analysis based on accepted electrical industry methods[22-24].

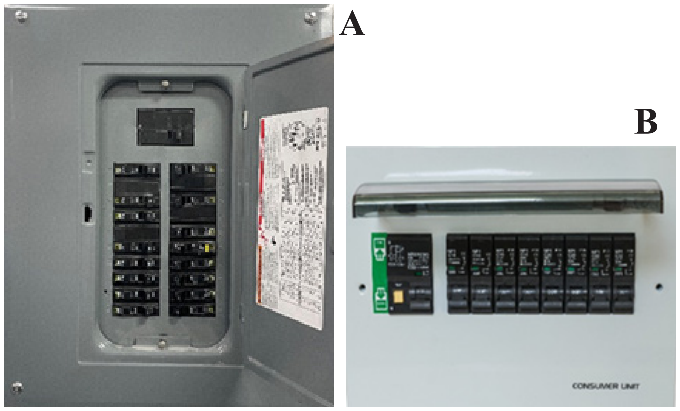

Figure 2
(A) North American electrical panel
and (B) UK electrical consumer unit.

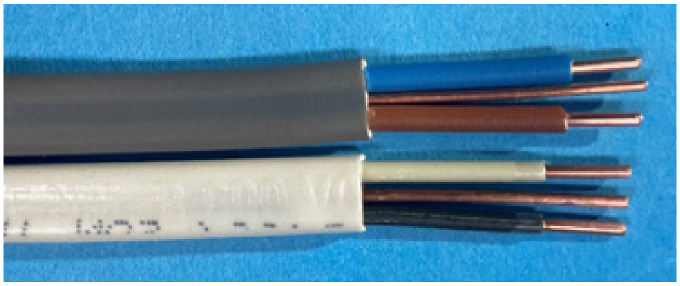

Figure 3
Non-metallic electrical cabling (UK and North America).

Examples of electrical equipment examined during an electrical survey and arcing fault evaluation may include (in part): electrical service equipment, electrical distribution panels (**Figure 2**), overcurrent protective devices, electrical feeders, branch circuits, appliances, luminaires, wiring, cables (**Figure 3**), and cords.

Therefore, the identification of electrical damage (or lack thereof) generated from a fire can lead the fire investigation practitioner to determine a bounded area(s). Independent of the constantly changing or time unstable generation of fire patterns, the area of fire origin defined by physical electrical evidence is time stable. The electrical system, an unbiased witness to the fire, responds to the event. For example, heat and flames of a fire impinging on an electrically energized 120VAC, electrical code compliant electrical circuit will respond and provide physical evidence for the fire investigation practitioner to discover and evaluate — thereby, generating a timeline or sequence of events(s) data, based on the electrical system response. It is paramount that the fire investigation practitioner is able to systematically and reliably distinguish characteristic features observed on post-fire electrical conductor damage.

Post-Fire Electrical Conductor Damage Characteristics

Arc Melt Site

When the heat of the fire is sufficient to compromise the electrical insulation of an electrically energized (with sufficient available fault current) non-metallic cable, a fault or short circuit (arcing melting event) often occurs between the energized and/or earth (grounded or grounding) conductors. The arc melt site features are formed from an electrical arcing event and subjectively identified by localized electrical arcing damage, generally identified on electrical conductors and equipment in the form of beads and/or notches (**Figure 4**).

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 should be observed outside the damage site. However, they can be obscured by post-event oxidation and/or damage. In his research, Carey classified nine different categories of electrical arc melt site damage[17,25]. Furthermore, arc melt sites are generated by electricity — not by fire.

Fire Melt Site

Fire melt site features will generally form during fire and heat attack that exceeds the melting temperature of electrically conductive materials, such as aluminum, zinc, copper, or steel. Conductor melt sites (recognized as fire-melting damage) are generally identified in the form of gross melting and/or globule features (**Figure 5**). They may exhibit, in part, a non-uniform surface and shape, no clear lines of demarcation at the damage site, irregular melting features in and around the damage site, manufactured tool markings melted away from the damage site, and non-uniform porosity within the damage site.

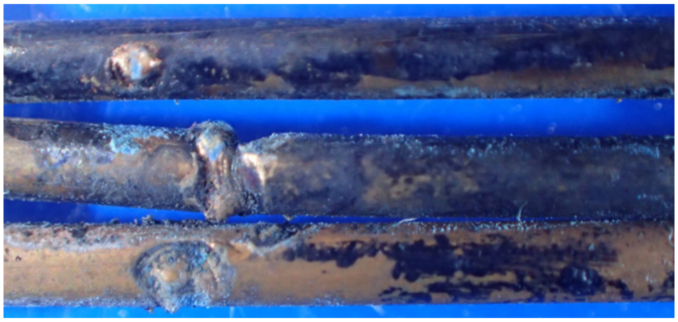

Figure 4
Example of electrical conductor arc melting damage[26].

Figure 5
Example of electrical conductor fire melting damage[26].

Alloying Site (Subset of Fire Melting)

Alloying sites (mixed metal) are generally recognized as a fire-melting feature that occurs by the mixing or alloying of dissimilar materials at elevated temperatures, causing melting at the damage site. The effect may occur due to electrical equipment, components, and wiring of different materials (such as copper, aluminum, lead, tin, and zinc) coming in contact during the course of a fire. Alloying sites may exhibit features similar in appearance to fire melt sites. The alloying site may have a brass and/or silver color appearance (**Figure 6**). Alloying sites are commonly mischaracterized as eutectic melting.

Mechanical Damage Site

Mechanical damage sites are generally recognized by fractured, impact, cracked, cut, sheared, stretched, or other damage from a mechanical action at the damage site (**Figure 7**). Mechanical damage can occur prior to the incident event or due to the excavation process involved in a scene investigation. Examples of this type of damage include: gouging/scraping of wires during installation or subsequent construction tasks; structural collapse causing conductors to stretch or break; or cutting by a tool.

Figure 6
Examples of electrical conductor fire melting damage (alloying). Fire melting copper and aluminum (A) and fire melting copper and zinc fire (B)[26].

Figure 7
Example of electrical conductor mechanical damage[26].

Subjective Methods of Characterizing Damage

Traditional methods of identifying electrical conductor or equipment damage sites at the fire scene have included, in part, visual and/or light microscopy surface analysis examination. NFPA 921 provides classic examples of the above types of damage sites that may be observed while performing the arc mapping methodology at the fire scene[1]. The Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory issued a technical bulletin in 2012, describing visual characteristics of arc melting and fire melting on copper conductors that may visually assist the forensic fire investigation practitioner in identifying damage sites while performing an electrical survey and arc mapping methodology[27]. Novak, together with nine other subject matter consultants, published "A Review of the Long-Standing Science Behind Arc Melting Identification"[28].

Skilled, trained, qualified, and competent forensic fire practitioners should be able to reliably recognize and distinguish the difference between electrical arc melting and fire melting at the fire scene. If the damage site is visually examined — and the damage type identification is disputed or otherwise identified as undetermined — additional examination and analysis can be performed by implementing advanced methods. Additional examinations may involve laboratory analysis utilizing a scanning electron microscope (SEM) and/or by dissecting and examining the interior of the damage site to perform internal microstructure analysis (**Figure 8** and **Figure 9**).

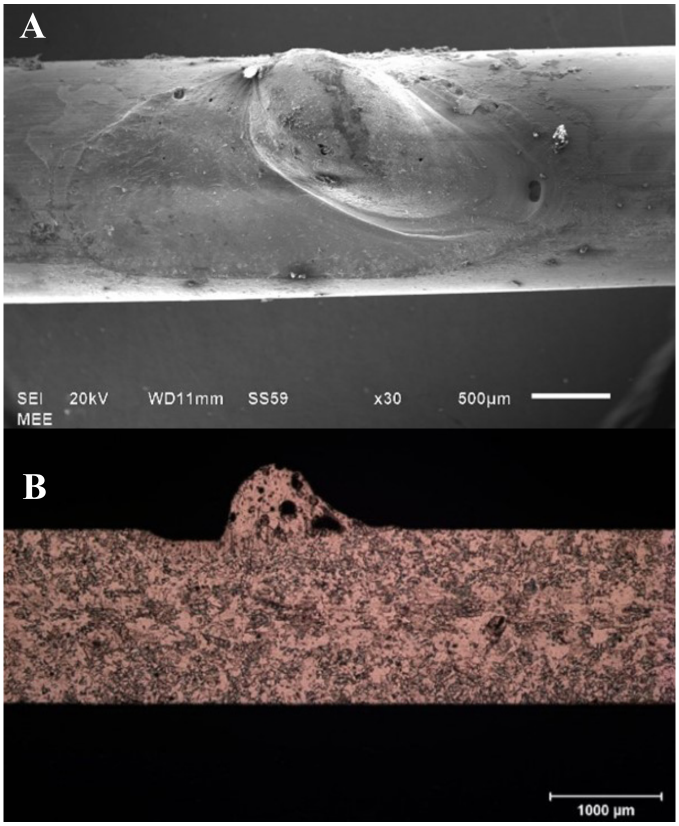

Figure 8
(A) Example of SEM arc melt surface features
and (B) internal arc melt microstructure[29].

Buc researched and developed a laboratory examination methodology to characterize the damage site by grinding or cutting the arc site open and examining the internal structure[30]. Buc's research further distinguished the difference between arc melt and fire melt sites by examining the interior features of the damage site for microstructure, porosity, and internal lines of demarcation. Murray advanced metallurgical techniques for fire investigation. Murray's findings were, in part: "As to the electrical damage, they 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

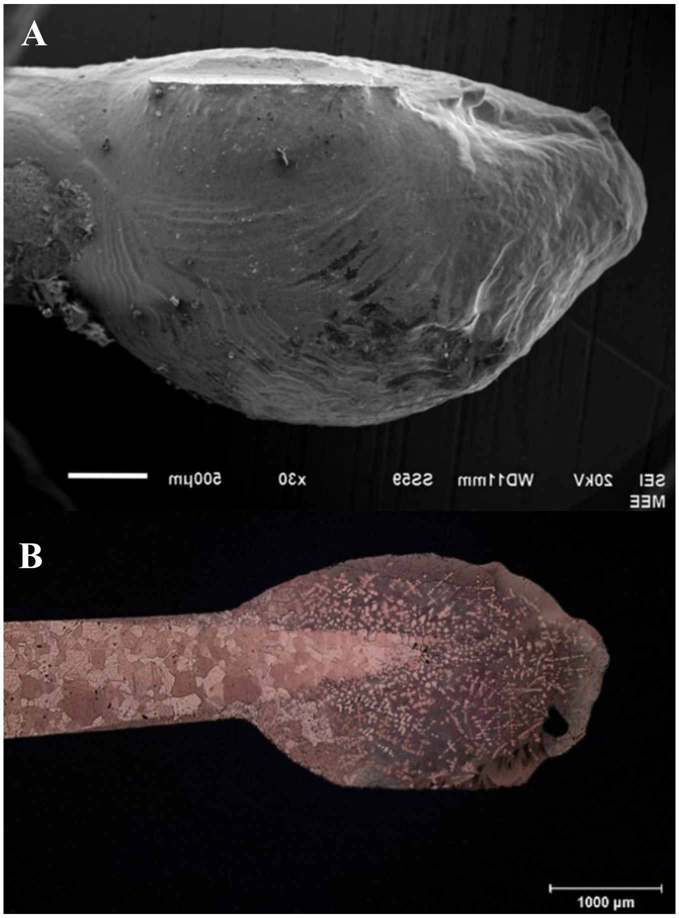

Figure 9
(A) Example of SEM fire melt surface features
and (B) internal fire melt microstructure[29].

quickly, liquification and thus re-solidification are state changings that occurred very fast”[31].

If, during the electrical survey and fault evaluation, the fire investigation practitioners question the reliability of a damage site identification, they should identify the damage site as undetermined. Doing so will allow for expanding the size of the fire origin boundary as defined by the electrical system, thus leading to a fire origin hypothesis that is better defined and leads to a more reliable result.

Arc Mapping and X-Ray Techniques

Errors in fire origin determination may occur if the data collected is determined to be unreliable. Examples of unreliable eyewitness information, misinterpretation of fire patterns, and misapplication of fire dynamic principles can lead the fire investigation practitioner to inaccurately determine the area of fire origin and cause. Arc mapping has been challenged as an unreliable fire origin determination methodology[18]. Recent research has called into question whether arc melt sites or fire melt sites observed on post-fire damaged electrical conductors can be reliably distinguished from one another[32].

It was reported that “it is not possible to distinguish between the beads formed on energized and non-energized wiring exposed to various thermal insults”[32]. There are instances where visual, non-destructive examinations of the damage sites may limit the ability of the forensic fire practitioner to accurately identify the type of damage found on the electrical wiring or equipment. Subsequent blind testing had revealed that experienced metallurgists can reliably distinguish between an arc melt site and fire melt site features by utilizing destructive means[33]. However, neither NDT method nor protocol exists for distinguishing damage features observed on post-fire damaged electrical conductors.

X-Ray Radiographs and Computed Tomography (CT)

X-ray radiographs have been generally accepted and utilized by the professional welding industry for NDT examinations for almost 100 years. The American Society of Mechanical Engineers (ASME) provides guidelines for employers to establish certification programs for the qualification of NDT personnel.

The X-ray system is generally made up of a radiation source and imaging film or digital plate. Radiation from the source passes through an object or specimen, resulting in a captured two-dimensional image, known as a radiograph. Most objects have an X-ray density, which will determine the ability of X-rays to pass through the material to the film or imaging plate.

Examination of radiographs taken for forensic examinations may reveal wiring, components, and parts that are not visible to the naked eye. For instance, by examining a radiograph of an electrical appliance, the forensic fire practitioner may determine if the device was “ON” or “OFF” or if wiring or component parts were damaged, out of place, or missing (**Figure 10**). Hansen agreed that X-ray analysis of electrical conduits can be helpful when attempting to document where electric arcs have occurred in relation to the fire origin area[34]. However, Goodson reported that X-ray radiographs may have limitations (e.g., if an object has multiple components overlapping and/or at different levels of depth, the radiograph may not reveal a clear image)[35]. Partial or complete disassembly of the object may be required to acquire a clear X-ray radiograph image.

X-ray imagery can be performed with either portable or fixed equipment (**Figure 11**). The resultant X-ray radiograph imagery is determined by the density of materials under examination.

X-ray radiographs can reveal internal features and structure (such as porosity) that are represented by varying gray scale values. For example, 10-bit grayscale, commonly utilized in digital radiograph (DR), ranges from one

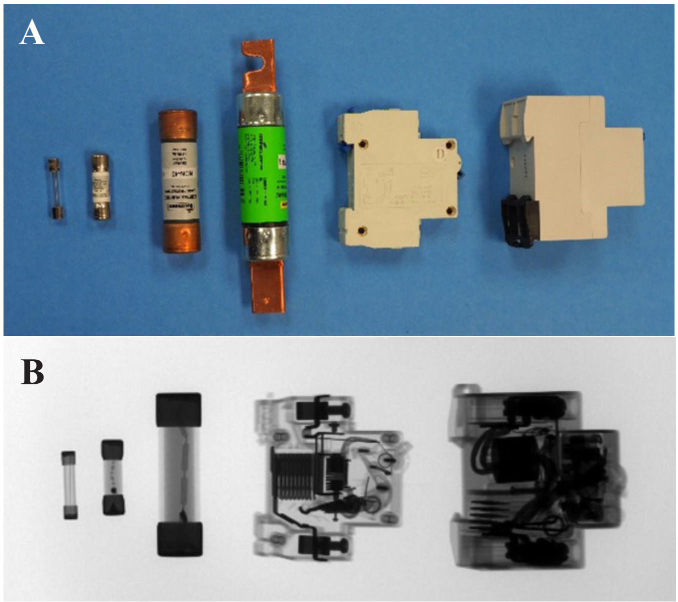

Figure 10
(A) Fuses and circuit breakers and (B) X-ray digital radiograph of fuses and circuit breakers[26].

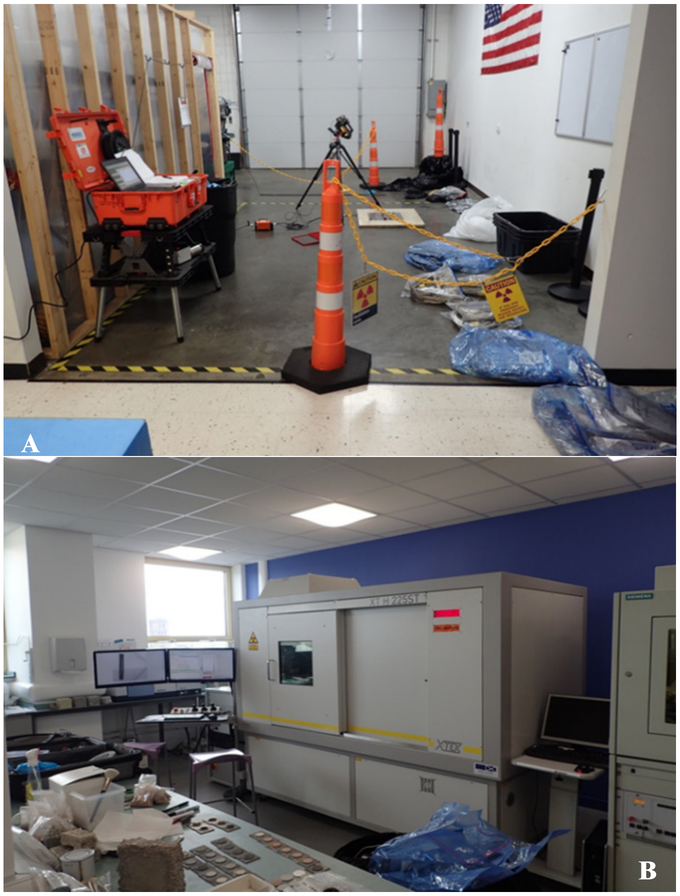

Figure 11
(A) Portable X-ray digital system and
(B) fixed X-ray micro-focus CT[26].

to 1,024 different shades of gray/pixels. The human eye can detect 900 varying shades of gray/pixels. Generally, monochrome monitors only support 256 different shades of gray/pixels[36].

The shades of gray tests were developed to evaluate the ability to differentiate between shades of gray as required by American Society of Mechanical Engineers ASME V/SNT-TC-1A. **Figure 12** is a graphic example of 255 different shades of gray/pixels. Grayscale charts for visual comparisons are commonly available between 0 and 10 — where 0 is black and 10 is equal to white.

Advanced adaption of the two-dimensional X-ray radiograph was in the modern invention of CT, commonly utilizing a micro-focus, X-ray radiation source, rotating pedestal or stand and radiation detector, and generating a computerized three-dimensional representation of a scanned object. A 16-bit grayscale (commonly utilized in CT) ranges from 1 to 65,535 different shades of gray/pixels.

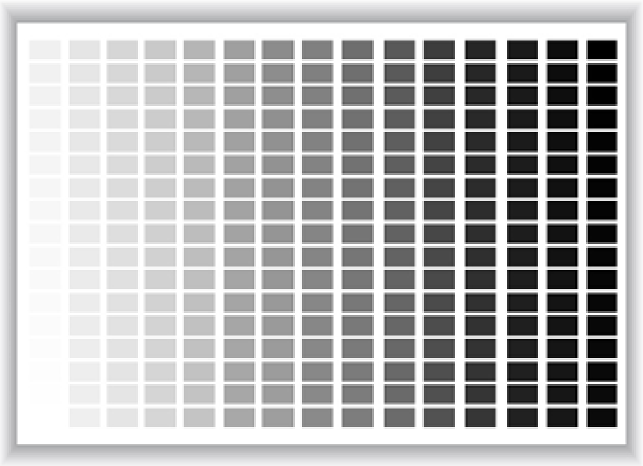

Figure 12
Graphic example of 255 shades of gray/pixels.

During the operation of a CT, the radiation source or object is rotated, thereby allowing each incremental image to be recorded by the detector. The data elements collected can be reconstructed to provide a three-dimensional image. The constructed image can be examined in all three dimensions externally and internally by stepping through or slicing through the object image. Goodson discussed additional history and theory of CT for fire investigation purposes in his research paper titled "The Application of CT X-Ray Analysis of Electrical Components"[35]. Therefore, can X-ray technology be utilized for distinguishing damage features observed on post-fire damaged electrical conductors?

Methodology:

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

This empirical research represents a novel method of utilizing X-ray imagery to distinguish electrical conductor damage features. Post-fire electrical specimen samples were generated by field and laboratory experiments. North American copper #14 AWG (1.6 mm) non-metallic (NM) cabling and United Kingdom (UK) copper, 1.0 mm^2 and 2.5 mm^2, NM "Twin & Earth" cabling were utilized. Each cable type was utilized for repeated experiments. Specimens were generated by impinging heat and flame on energized and non-energized cabling as well as generating mechanical damage specimens. Both full-scale and scaled field experiments were performed as follows.

Series One Experiments

A total of 63 full-scale compartment fires were conducted at the United States' Federal Law Enforcement, ATF fire training center (FLETC) located in Brunswick, Georgia (**Figure 13**). The electrical distribution system under these tests was a 120/240VAC, single-phase, 15A electrical circuit. The available fault current at the point of fire impingement was calculated to be 210.9A.

Six #14 AWG (1.6 mm) diameter, 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. 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.

In total, 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 fire 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, a total of 60 non-energized electrical conductor artifacts 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 located 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 that 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.

A total of 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 (OCPD) (6, 20 and 15A, respectively) and energized using an associated system voltage (UK "Twin & Earth" - 230VAC and North American NM 1.6 mm - 120VAC) that had sufficient electrical fault current to generate an arcing fault.

Figure 13
(A) Full-scale compartment fire testing at FLETC, (B) interior view of fire, and
(C) post-flashover fire extending outside of compartment[26].

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 melting) and series two (fire melting) fire tests. These experiments provided the opportunity to repetitively generate the arc and fire melt artifacts required for practitioner surveys and human factor research[26].

Carey Experiments

A total of 106 arc melting artifacts generated through Carey's research[17] were also incorporated 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.

Part 2 — Examination and Analysis of Electrical Artifacts

The artifacts generated through the three series of experiments were examined and analyzed in several stages by numerous forensic engineers and 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. A Nikon, X-Tek XT H 225 DR & CT scanner was used for examining specimens. Key features of the X-ray machine included (in part): a 225 KV, micro focus X-ray source with 3µm focal spot size and a Varian Amorphous Si detector array that had 3 X 10^6 individual pixels. This detector allows for high-performance image acquisition and volume processing. The CT had the capability of performing 3,600 scans per 360 degrees of specimen rotation. The Nikon micro focus X-ray source and movable turntable was able to provide an X-ray image in real time. This allowed for in-motion imaging as well as specimen magnification. The micro focus radiation source and stage also allowed it to be operated as an X-ray microscope. Specimens (in part) were examined, measured, compared, and contrasted between known electrical conductor damage at the University of Dundee, Scotland, United Kingdom and Avonix Imaging, Maple Grove, Minnesota.

Samples were mounted on the turntable located within the enclosure of the CT. Specimens could then be rotated 360 degrees about the axis of the turntable. Based, in part, on specimen size and density, DR & CT imagery was collected at 190KV. CT was conducted at 1,200 scans per 360 degrees of revolution. Additionally, DR real time imagery was captured utilizing varying levels of magnification.

NDT — X-Ray Examination

Thermal imagery, ultrasonic testing, and X-ray methodologies were considered. Initial X-ray examination revealed the most promise for damage site identification. X-ray examination of North American #14 AWG (1.6 mm) and United Kingdom (UK) copper, 1.0 mm² (1.1 mm) and 2.5 mm² (1.7 mm), "Twin and Earth" cabling revealed distinguishable features when compared to known artifacts or phantoms. Localized melting features, clear lines of demarcation, and uniform porosity were observed within an arc melt site (**Figure 14**).

In Buc's analysis of arc melt sites, Buc described this feature as a persistent porosity within the arc site[30]. In contrast, fire melt sites revealed irregular melted globules or balls with non-uniform or non-persistent porosity (**Figure 15**). Mechanical damage sites revealed sharp lines of mechanical damage demarcation and no porosity (**Figure 16**). These experiments were repeated with the same identifiable, distinguishing features.

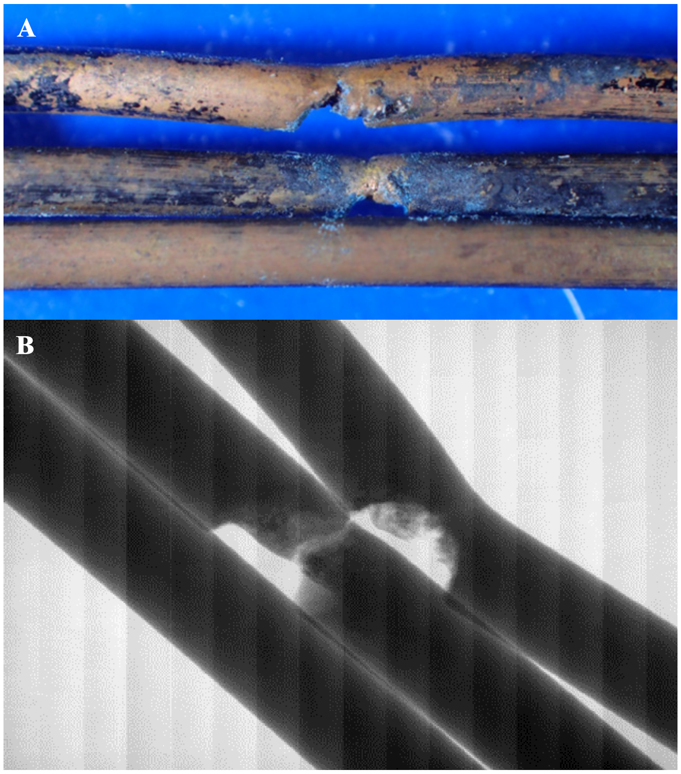

Figure 14
(A) Arc melting surface features and (B) X-ray digital radiograph[26].

Examination of the imagery acquired by NDT, utilizing both DR and CT for different types of damage sites, revealed distinguishable and measurable external and internal features. Currently, metallurgists use destructive methods to cut open and examine internal features to distinguish the difference between arc melting and fire melting. X-ray examination of damage sites along electrical conductors revealed measurable features from localized or non-localized melting along a specimen length. Internal features (in the form of porosity) were also clearly definable. Porosity was uniformly observed at arc melt sites (beads). However, porosity (if present) within the displaced mass was non-persistent and non-uniform within fire melt sites (globules).

Arc melting, fire melting, and mechanical damaged post-fire damaged electrical conductor's artifacts were examined and compared to a 0 to 10 grayscale chart. Comparison analysis revealed observable and measurable grayscale features within damaged areas of subject electrical conductors. Based on the collected data on a grayscale index of 0 to 10 (where 0 is black and 10 is white), arc melt sites had a mean grayscale index of 5.948 with a standard deviation of 0.793; fire melt sites had a mean grayscale index of 2.25 with a standard deviation of 0.439; and mechanical damaged or non-damaged electrical conductors had a grayscale index of 2 with a standard deviation of 0 (**Figure 17**).

Characterization of Sample Artifacts

The following dataset table and figures (**Figure 18** and **Figure 19**) represent an example of post-fire damaged electrical conductors with X-ray radiographs. X-ray imagery and grayscale analysis assisted in validating characteristic features of arc melting, fire melting, and mechanical damage sites observed on the tested post-fire damaged electrical conductors.

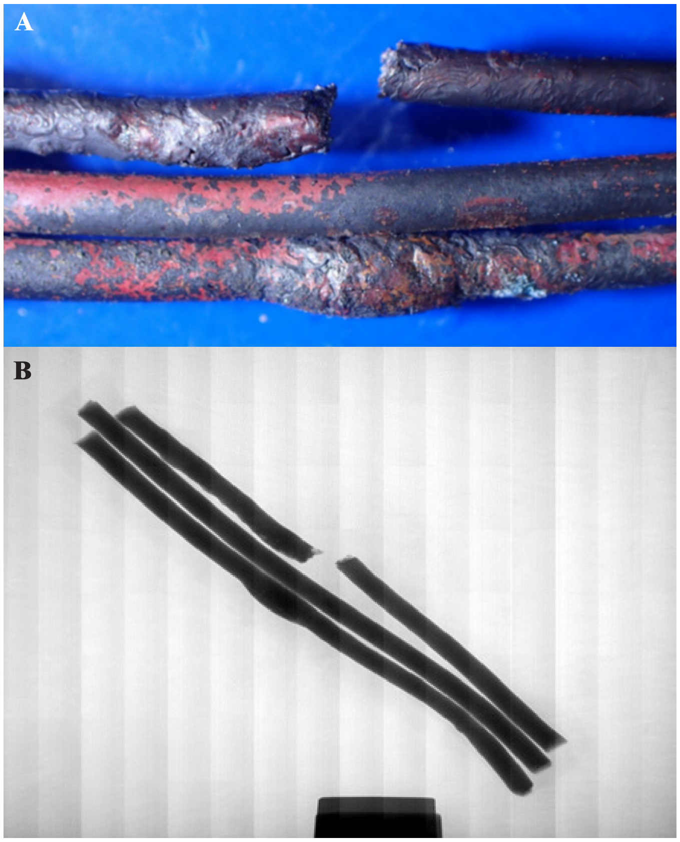

Figure 15
(A) Fire melting surface features and (B) X-ray digital radiograph[26].

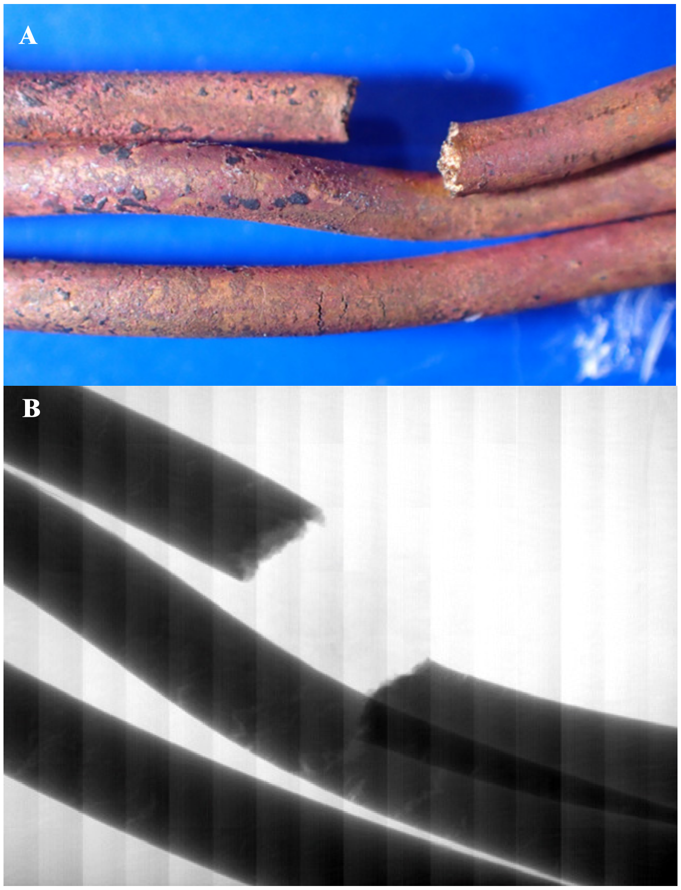

Figure 16
(A) Mechanical damage surface features and (B) X-ray digital radiograph[26].

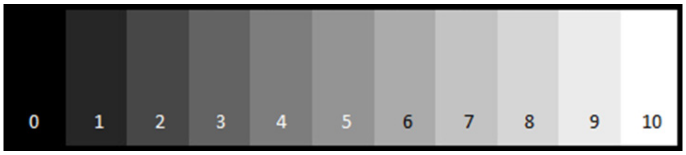

Figure 17
Grayscale chart (0-10), courtesy of MJ Svare.

Survey Sample Identifier	Wire Type	Damage Type	Damage Size (mm)	Notes on Damage	Gray Scale Identifier	Corresponding Wire Identifier
C-1	UK 1.0 mm^2	ND	—	No damage	2	NC 54
C-2	UK 1.0 mm^2	MD	—	Mechanical	2	NC 19
C-3	UK 2.5 mm^2	AM	3.44	Arc melt	5	NC 21
C-4	UK 1.0 mm^2	FM	*>4.44	Fire melt	2	MS 12
C-5	UK 1.0 mm^2	AM	2.76	Arc melt	7	NC 54
C-6	UK 2.5 mm^2	MD	—	Mechanical	2	MS 13
C-7	UK 1.0 mm^2	FM	*>10.37	Fire melt	2	MS 14
C-8	UK 2.5 mm^2	AM	2.84	Arc melt	7	NC 48
C-9	UK 2.5 mm^2	AM	2.70	Arc melt	7	NC 98
C-10	UK 2.5 mm^2	FM	*>6.96	Fire melt	2	MS 15

Figure 18
Example grayscale dataset (* = melted open)[26].

Surveys and Human Factors

Quantitative data was collected by surveying 912 participants within the fire investigation community to assess their ability to correctly identify arc-melting, fire-melting, and mechanical artifacts by applying arc fault data in a scenario-based context. Two surveys testing the participants' observations were administered.

Survey one participants were provided with post-fire damaged electrical conductor samples for visual observation without any additional data. The overall results revealed a mean examination score of 57% of distinguishing features observed on post-fire damaged conductors.

The ability to accurately identify conductor damage is a key step in any electrical evaluation, including the arc mapping methodology. The inability of participants to correctly identify damage on post-fire damaged electrical conductors indicated a knowledge gap within the fire investigation profession.

Survey two participants were provided with an additional one-hour training session on how to visibly identify and distinguish the different damage features of arc melted, fire melted, and mechanical damaged post-fire damaged electrical conductors, including through the interpretation of X-ray radiographs of the artifacts. Their ability to correctly identify the damage features observed on post-fire damaged conductors increased from an initial mean examination score of 45.6% to a mean score of 78.6% as a result of the training. Statistical evaluation further correlated that additional training had a significant positive effect in the participants' abilities to correctly attribute the damage observed.

Summary and Conclusions

When undertaking a fire investigation, 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 an electrical system-based origin determination methodology is dependent, in part, on the forensic investigation practitioner's ability to distinguish features observed on damaged electrical wiring and equipment.

Currently, fire investigation practitioners rely upon subjective visual observations to distinguish the difference between arc melting, fire melting, and mechanical features on post-fire damaged electrical conductors.

This empirical research represents a validated, novel, non-destructive methodology

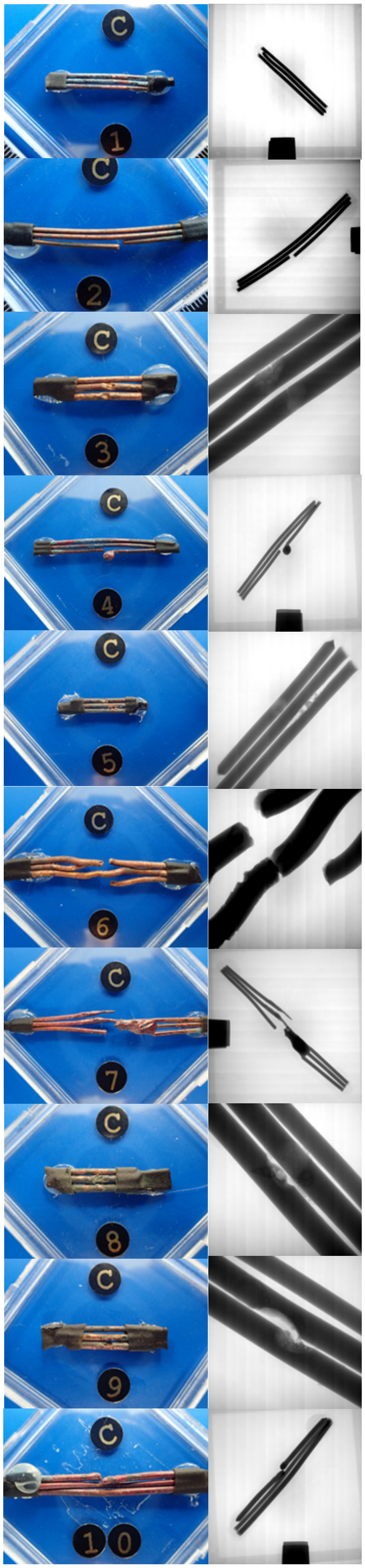

Figure 18
Sample set C1-C10 with corresponding X-ray radiograph[26].

for utilizing X-ray imagery and grayscale analysis to reliably distinguish characteristic conductor damage features observed on the tested post-fire damaged electrical conductors of the same size. Application of quantitative measurement of characteristic conductor damage features would further increase characterization reliability. However, additional testing may be required for different conductor sizes, materials, and fault current conditions.

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