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The ability for investigators to visible identify and interpret damage to electrical conductors

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DEDICATION

This thesis is dedicated to my parents
Dr. Craig and Rosemary Critchley for their
unwavering support in everything I do.

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ABSTRACT

The intent of a fire investigations is to correctly interpret the damage in order to identify the cause responsible for the fire and potentially help prevent similar incidents in the future. According to current guidelines of fire scene processing, fire investigators can implement the procedure of arc mapping as a tool to assist in the determination of the fire's progression and origin at a fire scene. To do this effectively requires the investigator to identify and correctly interpret the damage to electrical conductors as thermal melting (i.e, fire damage) or electrical activity. This study examined the ability of fire investigators to visibly identify and interpret damage to electrical conductors under two different conditions. The first condition requested fire investigators to visibly identify and interpret damage to electrical conductors based on their personal experience alone. In the second condition, fire investigators were asked to visibly identify and interpret damage with the assistance of a technical bulletin prepared by the Federal Bureau of Alcohol, Tobacco and Firearms (ATF) that characterized the visual differences between fire and electrical damage to conductors. The results of this study indicated that regardless of an investigator's level of experience, the interpretation of the damage could be misconstrued and is dependent on the individual investigator's perception. Ultimately, the application of the ATF bulletin was found to be a helpful tool for investigators in determining the electrical status of a conductor that had sustained thermal damage but not to any statistical significance. This bulletin could be considered a useful resource in the arc mapping procedure to aid in the determining of a fire's origin, but should be used in conjunction with other fire investigation techniques.

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CHAPTER 1: Introduction

When conducting an investigation into the cause of a fire, the fire's origin must first correctly be identified in order to isolate the potential ignition sources therein to be further examined in detail. There are generally four areas of information that fire investigators can use to assist in origin determination: fire patterns, witness statements, fire dynamics, and arc mapping (NFPA 921, 2017). All four areas of information have their limitations when examining a fire scene for origin determination, but when effectively used together may identify the area of origin (Gorbett & Chapdelaine, 2014). The focus of this research is to evaluate a fundamental requirement of arc mapping, which is the ability of investigators to identify and interpret damage to conductors. Specifically, this research evaluates the reliability of investigators to identify damage to electrical conductors and the accuracy of interpreting the cause of the damage.

An arc is a "high-temperature luminous electric discharge across a gap or through a medium such as charred insulation" (NFPA 921, 2017, p. 13). In other words, an arc can be the result of an electrically charged conductor encountering another conductor via a medium. This medium can consist of conductive materials such as wood, metal, carbon-based products, and air if high enough voltage is present. This event can result in a flash of sparks and heat, which may be capable of melting the conductors at the point of contact and igniting nearby combustible materials. Arcing can occur by events of outside forces that physically degrade the insulation surrounding the conductors or when the wiring is attacked by fire and compromises the insulation of the wiring.

Identification of localized damage to the conductors may indicate that those electrical conductors were energized at the time of the fire. In theory, this arcing activity would cause the overcurrent protection device to activate (i.e. circuit breaker tripping or fuse blown) de-energizing the circuit and leaving evidence of the arc. As the event of an arc is in itself still a flow of current, the over current device may not be activated. If this occurs than multiple arcs could be found on a single circuit. The investigators would then use this arc site in relationship to other arc sites as a pattern to indicate the locations where the electrical circuits were first attacked by the fire. Thus, providing the investigator with a geographical location of where the fire first impinged upon electrical conductors. This is known as arc mapping.

Arc mapping is defined as the “systematic evaluation of the electrical circuit configuration, spatial relationship of the circuit components, and identification of electrical arc sites to assist in the identification of the area of origin and analysis of the fire’s spread” (NFPA 921, 2017, p. 13). The reliability and validity of arc mapping for origin determination, therefore, relies on the premise that investigators or engineers can effectively identify and correctly interpret damage to electrical circuits after a fire, but there has been limited research performed in this area. This inquiry evaluates the effectiveness of fire investigators to differentiate arc sites, thermal melting, and mechanical damage on electrical conductors.

Chapter 2: Literature Review

The concept of arc mapping as a tool for fire investigation was developed because many times after a fire there is little evidence of the structure remaining when the fire investigators arrives. Fortunately, in these cases, some materials such as electrical wiring located throughout the structure are not consumed by the fire.

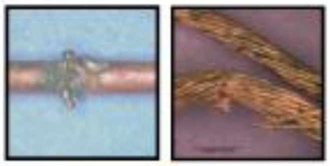
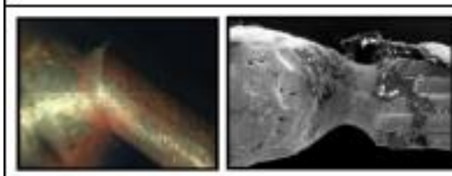
The first reference to arc mapping or the ability of a fire investigator to use damage identified on electrical conductors for origin determination was first described in the book, *Techniques of Arson Investigation* (Straeter & Crawford, 1955). This text indicated that an investigator should evaluate the condition of wiring after the fire for origin determination. These authors indicated that “electrical shorts have their physical effects” that investigators should “investigate to be sure whether the short caused the fire or the fire caused the short,” and that the “sequence of shorted electric circuits…may indicate the path of the fire to some degree” (Straeter & Crawford, 1955, p. 8, 12). No procedure or method, however, was outlined in this text to assist the investigator in what observations would be required to make a decision.

One of the first experimental studies conducted identified that the method of arc mapping could aid in identifying the area of origin as the result of a fire (Churchward, Cox, & Reiter, 2004). The concept that when electrical conductors insulated by Polyvinyl Chloride (PVC) are exposed to fire, the outer layer begins to char as well as deteriorate and eventually exposes the copper conductors within. Due to the charring and chemical change of the insulation, the PVC layering may become conductive to electricity and an arc between the conductors can occur. This is known throughout the fire investigation community as "arcing through char" (NFPA 921, 2017). By placing non-energized and electrically charged conductors along the ceiling of compartment fire tests, Churchward tried to determine if arcing would occur in geographical relation to the area of origin of the fire (Churchward et al., 2004). The findings from two of the three test burns indicated that similar arcing locations, as well as the sequence of when a particular arc would occur in a section of the room were similar. The arcing sequence followed the progression of the fire by first occurring over the area of origin and then moving outwardly in a radial pattern. It was noted that in the three test burns conducted that none of the compartments transitioned through flashover. As such, not all conductors were exposed to extreme temperatures in which melting of conductors could occur. Additionally, this meant that instances of melting damage that looked like arcing or evidence of arcing that was present prior to the fire was not exposed to conditions in which a change could occur. Regardless, this testing does indicate that arcing will occur to electrically charged conductors that are exposed to fire until the electrical current flowing through those wires is terminated.

Electrical damage can be found on conductors, contacts, terminals, conduits, or other electrical components and can occur through a variety of incidents. Due to the nature of arcing and the events experienced by the electrical conductor such as elevated temperatures and sparking, the damage is very localized. Such localization is illustrated by a line of demarcation between the melted and un-melted copper conductor. Because of this rapid heating and cooling process other identifiable indicators of an arc occurring include porous holes inside the bead, as well as splatter or indentation on adjacent conductors and nearby surfaces (NFPA 921, 2017). NFPA 921 (2017) describes the physical signs or indicators that an arc has occurred: sharp demarcation between damaged and undamaged areas, round smooth shape of artifact, localized point of contact, identifiable corresponding area of damage on the opposing conductor, locally enlarged grain size, re-solidification waves, copper drawing lines visible outside the damaged area, localized round depressions, small bead and divots over a limited area, and high internal porosity when viewed in a cross-section. These identified characteristics of an electrical arc can be the result of incidents of a short-circuit, ground fault parting arc, overheated connections, and arcing through char. It further identifies that when exposed to an environment such as a fire a variety of damages can be present on the conductor as a result of thermal melting (NFPA 921, 2017).

An arc bead is defined as "a rounded globule of re-solidified metal at the end of the remains of an electrical conductor that was caused by arcing and is characterized by a sharp line of demarcation between the melted and non-melted conductor surfaces" (NFPA 921, 2017, p. 14). Due to the nature of arcing where in electricity is discharged between two conductors through a medium, it is implied that electrical current must be flowing in order for this arcing and ultimately a bead to occur. Research conducted found that many of the visual characteristics identified by NFPA 921 as signs of arcing could be recreated on non-energized conductors through thermal heat impingement (Hussain, McAllister, & Roby, 2014). This research points out that the visual characteristics of any arc could be covered over by continued heating of the wire that results in the appearance of being melted. Throughout this research, only one physical characteristic of an arc "bead" is identified: the rounded bead shape with a clear line of demarcation found at the end of a severed conductor (Hussain, Sunderland & Roby, 2012).

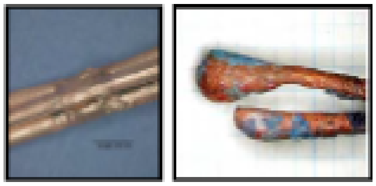
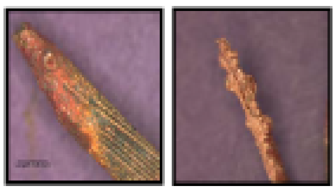
Research conducted by the ATF has found that other visual characteristics such as a notch on corresponding wires involved in an arc are one of many visual characteristics of an arc that were not addressed in the Hussain, et al. research. ATF Technical Bulletin 001 was issued in response to a report funded by the National Institute of Justice (NIJ) which concluded that the electrical status of a conductor during a fire could not be determined by the visual characteristics (Hussain, et al., 2014; Hussain, et al., 2012; Roby & McAllister, 2012). The ATF's analysis found issues not only with the analysis from the NIJ report, but also the methods by which the testing to the wires was conducted as well. The conductors in question were exposed to direct flame impingement from a propylene torch, a radiant tunnel apparatus exposing conductors to temperatures as high as 1100 degrees Celsius, a 2/5-scale compartment in which oxygen was forcibly introduced through an opening, and a full-scale compartment fire. The ATF found that only one of the tests, the full-scale burn, was representative of real world scenario that structural wiring would be exposed to. The other three tests scenarios were deemed not realistic in that the damage being sustained by the wiring was concentrated and at times even higher temperatures than are experienced in a real fire. ATF would go on to point out that even in the full-scale test that the compartment was not able to reach a temperature in which thermal melting of the conductors could even occur. In the closing sections of the ATF's bulletin it is noted that the presence of electrical arcing on a conductor should not be considered the only proof necessary to determine the origin and cause of the fire. The identification of electrical arcing should coincide with other tools used in fire investigation such as witness statements, fire patterns, and fire dynamics. The ATF bulletin then goes on to identify multiple distinct visual characteristics to differentiate an electrical arc from thermally-melted globules on a conductor. The ATF's own research established that an investigator does not need multiple identified characteristics to classify the type of damage to a particular conductor, and goes on to say that the electrical status of a damaged wire can be determined by the physical appearances remaining on a conductor after the fire at a fire scene. In the ATF bulletin, a detailed picture and description of the correctly identified characteristics of an arc compared to a globule are shown and labeled. To illustrate their findings, the ATF organized a set of visual characteristics with explanations of the characteristics related to arc beads and thermal melting. They provided this in a simple to understand chart, with images related to arc beads and melting to assist in discriminating between damage characteristics (Figures 1 and 2).

	Sharp Line of Demarcation between damaged and undamaged area (Photos by Kevin Lewis / E. C. BUC)
	Round Smooth Shape (Photos by Nick Cary / Kevin Lewis)
	Localized Point of Contact (Photos by Kevin Lewis / E.C. Buc)
	Identifiable Corresponding Area of Damage on Opposing Conductor (Photo by Kevin Lewis)
	Copper Drawing Lines Visible Outside the Damaged Area (Photos by Kevin Lewis)
	Localized Round Depressions (Photos by David Reiter / Kevin Lewis)
	Small Beads and Divots Over a Small Area (Photo by Nick Carey)

Photos and descriptions courtesy of Dr. Vytenis Babrauskas.

Figure 2: Characteristics of arc bead

Source: ATF (2012). ATF Technical Bulletin 001-Visual Characteristics of Fire Melting on Copper Conductors Technical. ATF Fire Research Laboratory.

	Extended Area of Damage Without a Sharp Line of Demarcation from Undamaged Material (Photos by Yasuki Hagimoto / E. C. Buc)
	Visible Effects of Gravity in the Artifact (Photo by Stephen Andrews)
	Blisters on the Surface (Photos by E. C. Buc)
	Gradual Necking of the Conductor (Photo by Jeremy Neagle)
	Non-Localized Loss of Integrity of Individual Strands on a Stranded Conductor (Photo by Michael Keller) (NOTE: This characteristic was not included in Dr. Babrauskas' proposal but is included here since it is part of the ATF training curriculum.)

Photos and descriptions courtesy of Dr. Vytenis Babrauskas.

Figure 2: Characteristics of melting globules

Source: ATF (2012). ATF Technical Bulletin 001-Visual Characteristics of Fire Melting on Copper Conductors Technical. ATF Fire Research Laboratory.

Only one study reviewed for this paper addressed the results of testing the effectiveness of conducting arc mapping in a full-scale compartment fire (Carey, 2010). In this particular study, six different scenarios of a room and fuel package configuration was setup for testing, and each scenario burned approximately seven times. By using the same ignition source in the same location every time, the results would be more conclusive as to identifying the progression of the fire throughout the compartment. The electrical system that ran throughout the compartment was compliant with British standards and consisted of open as well as closed circuits that were protected by circuit breakers to help identify when a particular circuit had failed and/or arcing had occurred. Thermocouples were placed throughout the compartment to assist with evaluation of any relationship between the time, temperature, and the sequence of circuit protection devices operating. Although these findings are applicable to arc mapping, as well as fire investigation, issues were identified with the positioning of the wiring throughout the compartment. In Dr. Carey's testing, wires were attached to the ceiling of the compartments using metal screws. In the analysis of the report, it was pointed out that there was a relation between the arcing location and how the wires were secured to the ceiling. The metal screws used to attach the wires to the ceiling created a concentrated point of conductive heat that would degrade the insulation of the wiring faster than other areas. This would expose the copper conductors and create an electrical arc along the wire and in several instances an arc site welded to the metal screw itself. Although this scenario of having conductors fastened to the underside of a ceiling may not be realistic, the use of metal staples to secure conductors throughout the structures void space resulting in the conductor arcing to conductive securing mechanism does occur. This type of damage, the conduction of heat and/or electricity through a foreign conductive material connecting the hot conductor to one of the other two conductors, was identified by Dr. Carey as one of the three methods of how an arc can occur. Other methods include the gradual softening of the conductor's insulation until the conductors come in physical contact or the charring of the insulation until the surrounding material becomes carbonized and allow the electrical current to pass between the three conductors.

The wires were examined on site after the fire and any potential thermal or arcing damage was marked and examined at a later date in a lab with the aid of a regular microscope, as well as a scanning electron microscope. The identified damages were compared not only to that described in NFPA 921, but also to multiple exemplar electrical conductors with arcing on them that were intentionally created by connecting an exposed live and neutral conductor together. At the conclusion of their findings, it was confirmed that one of the distinct differences between a thermally-damaged wire versus an electrically-damaged wire was the localized damage, specifically focusing on the clear line of demarcation and notch where electrical arcing occurred. Several other reoccurring damages were identified including: severed conductors with beads on one end and a notch on the other, notches across multiple conductors with a bead on one end, two conductors welded together in a localized area, demarcation between melted and un-melted conductors, raised bead on conductor visible without magnification, and arcing through char with damage over a length of 14 millimeters.

In Mr. Carey's article, a correlation was drawn between a specific event of arcing through char resulting in a common and repeatable damage present on the conductor, "This effect appears to occur when there has been electron flow through the carbonized PVC insulation during the fire's development. This type of arcing event is repeated due to a limited fault current, resulting from the resistance properties of the charred PVC cable sheath and conductor insulation. This electrical resistance effect delays the operation of the circuit breaker leading to metallic patterns on the surface of the conductor over a much larger lateral surface area than normal" (Carey 2009, p.95).

Mr. Carey then goes on to compare this damage to the other commonly seen damage to conductors in the event of an arc. The event of arcing through char resulted in damage extending over a much larger area than what is normally considered an arc yet still shared similar traits in the presence of a defined bead found throughout the damaged area but smaller in size. At the conclusion of this research Mr. Carey indicates that although damages may differ in size and shape the effects of arcing can be categorized into one of nine different types. The types of damage were described as: Arcing through charred plastic insulation "arcing through char", severed ends, bead and a notch, bead within a notch(s), two notches, one notch, bead(s) at conductor end, conductors welded together, bead on conductor surface.

According to the NFPA 921 (2017), the process of arc mapping is one of the four methods accepted to determine the origin of a fire, but as research continues evolving it appears more evident that the method of arc mapping is only effective in limited scenarios (Babrauskas, 2017). As with every fire scene, no two incidents are alike and different variables of the environment can change the progression of a fire throughout its duration. As such, the wiring within a residential structure can be exposed to a variety of situations resulting in an array of damage that may not indicate the origin of the fire, but potentially show the progression of the fire throughout the structure. Past research and arc mapping methodology indicated that identified evidence of arcing furthest from the power source (i.e., electric panel) would have occurred prior to those signs of arcing closer to the power source because the current would be disrupted by the first electrical arc and would not supply current past that point (Babrauskas, 2017). Babrauskas' research identifies this is only true when the hot wire of the electrical circuit branch is severed, otherwise current will continue to flow until the breaker associated with this circuit is tripped and power is cut off to the circuit. When the power is cut off to the circuit, further arcing will not occur, but the conductors will still be exposed to the thermal temperatures that may damage the conductors and potentially severe the conductor. All of the damage to the conductors must be examined and investigators must differentiate between thermal melting and electrical arcing in order to aid in the determination of the fire's progression throughout the structure (Babrauskas, 2017).

Research into the resulting damage of conductors after being involved in short circuits and overcurrent scenarios concluded that the patterns tended to be characteristic for each cause of damage, although there were some overlap in effects there are some guidelines for helping interpret the roles of the wiring in the fire (Ettling 1980). During Mr. Ettling's studies, conductors were electrically-and thermally-damaged, with the resulting effects cataloged. The melting temperature of copper is 1084°C whereas the ceiling temperature in the typical compartment fire reaches around 900°C. Due to the slow and gradual rise in temperature, the thermal related damage was over a much broader area. Mr. Ettling noted that thermally-damaged conductors were specifically found to have rounded severed ends, with rough surfaced beads (blisters) surrounded by thinned out areas due to the flow of the melted copper spreading over a much larger area unless protected by structural members. Conductors that sustained an overcurrent were found to have produced much larger blisters than found on strictly thermally-damaged wires. The larger blistering was found to occur in multiple areas of the length of the affected conductor, with a potential correlation based on the tension that the individual wire was under. It was also noted that during a fire investigation, the entire length of the conductor should be examined for over current related damage wherein thermally-damaged conductors could be located in unburned areas of the structure. In the event of a short circuit, a clean "cavity" or notch will be present, with no beads present on the middle conductor, but have a splatter effect on the surrounding surfaces. The heat resulting from an arc is much greater than that recorded during a compartment fire, but due to the short duration of these temperatures the copper is unable to melt/deform other than the areas that came in contact with one another.

Throughout the research for this thesis four different categories of damage were identified and described. Mechanically-damaged conductors were identified as damages from friction or pulling, resulting in broken and fractured ends. These wires could be gradually thinned until they reach a point in some instances described as a chisel point where a thin line is located across the center of the conductor when they are cut. Similar damage could also be found in areas of a partially collapsed building through the duration of a fire, wherein conductors are subjected to heat as well as the tension of baring the weight of collapsed structural members until the conductor gives breaks. Chemically-damaged conductors were caused by alloying resulting in a corroded appearance where the silver or zinc melted to the copper leaves a brass colored mark along the conductor. This type of damage could be found in multipole locations at a fire scene as several different types of melts are used for the construction of electrical distribution components. Thermally-damaged conductors caused by large fuel loads or localized ventilation effects can result in gradual sagging along the length of the conductor, with no sharp lines of differentiating damage. Sustaining temperatures through the progression of the fire that could distort the condition or even consume the conductor in an area prior to the fire. Similar to other study findings, a "bead" with a sharp line of demarcation was associated with electrical activity. Ultimately, there are a numerous damages that can be found on conductors at the conclusion of a fire. And, because no two fire scenarios are the same it is difficult to compare damages found at different fire scenes as they were exposed to different conditions. However, over the years of fire investigation several characteristics have been identified as being associated with particular types of damage.

In a study conducted by Mr. Svare, Mr. Dubbin, and Mr. Carey, four different categories of damage were identified and described. Mechanically-damaged conductors were identified as damages from friction or pulling, resulting in broken and fractured ends. These wires could be gradually thinned until they reach a point, in some instances described as a chisel point, where a thin line is located across the center of the conductor when they are cut. Chemically-damaged conductors were caused by alloying resulting in a corroded appearance where the silver or zinc melted to the copper leaves a brass colored mark along the conductor. Thermally-damaged conductors caused by large fuel loads or localized ventilation effects result in gradual sagging along the length of the conductor with no sharp lines of differentiating damage. Similar to other study findings. The bead with a sharp line of demarcation was associated with electrical activity but goes on to specify a "bullnose" effect on the end of a severed conductor as being potentially related to a short circuit event. Even with the above mentioned characteristics the document does state, "The effects of the fire itself can cause misleading damage creating gross melting or chemical reaction that can cover up or mimic arc marks, rendering them dubious or useless" (Carey, Svare, Dubbin 2006). Ultimately, there are numerous damages found on conductors after a fire incident as no two situations are the same, but there are several distinguishable identifiable characteristics that can be used to determine the type of damage sustained by the conductor in certain situations.

CHAPTER 3: Testing

Methodology

The participants in this study were volunteers from the NAFI conference being held at Eastern Kentucky University (EKU) in March of 2014. Due to the variety of participants attending the conference a self-evaluation was distributed to determine the level of expertise of the individuals. Participants were asked to indicate their status in the fire investigation field and their background, as determined by NFPA 1033 standards (Appendix A). Several different categories of groups were created as a result of these questions. One category was the type of educational backgrounds present which varied from high school diplomas to doctoral degrees. Another category was the certifications held by the individuals (CFEI, CFI, etc.). As this report deals with the examining of electrical conductors several groupings were defined around the participants experience on this topic using a five-item Likert scale with one indicating novice and fire indicating expert. For analysis, if participants responded with a one or two, they were categorized as a novice; if they responded with a three or higher they were categorized as having some expertise. One question asked using this scale was the participants ability to conduct an arc map survey. Finally, participants were then asked to rate their level of expertise in determining the difference between arc sites and thermal melting of a conductor. After completing the questionnaire participants were asked to exam the prepared set of wires.

Mechanical Damaging to Conductors

This research study attempted to create some of the more common scenarios found at fire scenes that would cause the failure of structural wiring to occur. For this research, the damage scenarios sustained by the three wire Romex conductors rated at 15-amperage (amp) included being crushed, cut, and sliced. In order to represent a crushed conductor, a metal pipe was used to crush the conductor between a hard surface until the exterior insulation was no longer present and the interior deformed conductors could be seen being in contact with one another. This simulation was done to represent when conductors are subjected to pressure and degrade the insulation over time till the conductors are exposed. To demonstrate the damage of a sliced wire, a knife was run across the insulation of the conductor until the physical damage to the conductors was witnessed. An example of this type of damage could be seen when wires are being installed and run though wooden or metal structural members. If during this process a sharp end is run across the surface of the insulation damage may occur. Finally, in order to represent a partially cut conductor, a pair of wire cutters was used to damage the conductors in a localized area but did not completely cut through the conductors. This type of damage could be seen when wires are being cut for installation or in areas where staples are used to secure the wire to a wooden structural member. In order to represent a control aspect of the damaging of the wires undamaged and unsheathed conductors were also selected. This would represent the undamaged wires that are only subjected to thermal damage through the progression of a fire.

Thermal Damage to Conductors

A portion of the conductors were electrically energized and attached to an appliance in use (e.g. desk fan, space heater, alarm clock). Other scenarios tested included being energized and connected to an appliance not being used or completely de-energized. If wires were to simulate electricity flowing through the conductors, the wires were attached to a 120-volt electric panel and protected by a 15-amp circuit breakers as would be seen in a structural dwelling. These energized wires were identified and cataloged based on the specific scenario prior to sustaining fire impingement. These wires were then exposed to various heating methods, including open flame from an acetylene torch or an electric powered radiant heating panel for an extended period of time or until an electrical arc tripped the circuit breaker stopping electrical current flowing through the conductor. After the electrical arc occurred and the original heating test was finished various wires were exposed to another round of heat impingement. This was done to simulate scenarios where arc beads are exposed to fire for an extended period of time before the fire is extinguished. During this time, the arcing damage can become deformed due to the copper conductors attaining high enough temperature that they reach their melting point and the damage is partially or completely altered. Although the wires did not sustain full-scale heat impingement, the point of this research was not to test the investigators' ability to find the evidence of arcing, but rather to distinguish the damages in a controlled manner. As such, the individual damage in question was highlighted for the test subject investigators.

Procedure

Participants were provided a sample of 16 wires that had been damaged in varying ways with different electrical load scenarios. The participants were then asked to identify whether the effects found on the wires were globules caused by thermal damage, the remains of an electrical arc, or an undetermined cause based on their personal experience. After completing this task on the first set of wires, the participants were presented with photographs and descriptions put forth by ATF Technical Bulletin 001 and recognized by NFPA 921 as being the correct identification of an electrical arc vs. a melted globule. With the bulletin in hand, the investigators were presented with a different batch of 19 wires and asked to repeat the process of examining and determining the damage to the wires. In hindsight, the same batch of wires should have been used while the participants conducted the testing with and without the bulletin aid for statistical purposes. However, during the testing preparation, the conductors' damage was randomized and the distribution of the electrically damaged conductors was evenly spread between the two batches of wires.

Analytical Strategy

A stratified analysis was conducted using a self-ranking questionnaire filled out by the participants on a variety of fire and electrical topics to categorize the individuals as novices or having some level of expertise. After the experiment was conducted a total score was calculated both with and without the use of the ATF bulletin. An independent samples t tests were used to determined mean differences between scores with and without the use of the bulletin. A summary of scores is provided and discussed in chapter 4.

CHAPTER 4: Review

Results and Discussion

A total of 32 volunteers participated in classifying the cause of damage found on each individual wire both with and without the ATF Bulletin; however, only 29 completed the demographics survey (Table 1). Of the 29 participants that completed the demographics survey, 28 (87.5%) were male with a mean age of 43 years (SD =13). A majority (62.5%) had a Bachelor's degree or higher. The mean number of years working as full-time fire investigators was 2.5 years (SD=4.6); the mean number of years as part-time investigators was 2.9 years (SD=4.2). Only three participants (9.4%) had never worked a fire in any role of an investigation team and seven (21.9%) had worked more than 100 fires. When asked how many fires they had worked as a lead investigator, nearly half (43.8%) reported zero fires, while the other half (46.9%) reported working at least one fire. Participants reported making a determination on an electrical conductor of arc site or melting an average of 13 times (SD=27.5); similarly, they reported using arc sites to assist in origin determination an average of 13.5 times (SD=25.8).

Table 1. Demographic and experience characteristics of fire investigator participants (N=29)

Variable	n (%)
Gender	
Male	28 (87.5)
Female	1 (3.4)
Education	
GED (General Education Development)	0 (0.0)
High School Diploma	1 (3.4)
Post High School	0 (0.0)

Table 1 (continued)

Variable	N (%)
Trade School	2 (6.9)
Associates Degree	6(20.7)
Bachelor's Degree	14 (48.3)
Master's Degree	5 (17.2)
Doctoral Degree (or other advanced degree)	1 (3.4)
Sector	
Private	17 (58.6)
Public	8 (27.5)

When asked to self-rate their level of expertise in determining the difference between arc sites and melting, more than half rated themselves as novice (56.3%), while the remaining (28.1%) rated themselves as having some expertise. Note that five participants (15.6%) did not self-rate their expertise. When asked to self-rate their level of expertise in determining arc mapping, more than half (62.5%) indicated they were novices, while the rest (21.9%) rated themselves as having some expertise.

The mean score without the bulletin was 52.9 (SD=12.4); the mean score after receiving the bulletin was 56.6 (SD=14.2). Although the mean scores did increase, there was not a statistically significant difference in the mean scores (t=1.27, p=.2). It is interesting to note that the standard deviation of scores among participants while using the bulletin was larger than without it, although only by 2%.

For novices at determining the difference between arc sites and melting, the mean score without the bulletin was 51.4 (SD=12.2) and the mean score with the bulletin was 57.6 (SD=12.6). There was not a statistically significant difference between scores with and without the bulletin (t=1.77, p=.1); however, the scores improved on average and the variability among scores of participants remained nearly the same. For participants with some expertise, the mean score without the bulletin was 56.3 (SD=9.9) and the mean score with the bulletin was 52.0 (SD=18.7). There was not a significant difference between mean scores with and without the bulletin (t=0.63, p=.5). The participants rating themselves with some expertise scored worse when using the bulletin and their scores have an increased variability.

Results were similar when stratifying on the self-ranking of expertise in determining arc mapping. For novices, the mean score without the bulletin was 50.9 (SD=11.0) and the mean score with the bulletin was 58.2 (SD=12.6). There was a statistically significant improvement in scores when the bulletin was introduced (t=2.34, p=.03), and again, the variance among responses for novices remained nearly the same. For participants with some expertise, the mean score without the bulletin was 58.9 (SD=11.9) and the mean score with the bulletin was 48.9 (SD=19.1). Although the difference in scores is not significant (t=1.32, p=.2), participants rating themselves with some expertise again score worse when using the bulletin and their scores have an increased variability. A summary of scores is provided in Table 2.

Table 2. Cause of damage summary scores and comparisons between novice and expert fire investigators (N=29)

	Participants self-evaluation	**Without ATF bulletin mean (SD)**	**With ATF bulletin mean (SD)**	**Group Comparison t (p-value)**
Overall	32	52.9 (12.4)	56.6 (14.2)	1.27 (.2)
Identifying Arc Sites vs Melting				
Novice (n=18)	56.3	51.4 (12.2)	57.6 (12.6)	1.77 (.1)
Experts (n=9)	28.1	56.3 (9.9)	52.0 (18.7)	0.63 (.5)
Conducting Arc Mapping Survey				
Novice (n=20)	62.5	50.9 (11.0)	58.2 (12.6)	2.34 (.03)
Experts (n=7)	29.1	58.9 (11.9)	48.9 (19.1)	1.32 (.2)

Participants were asked several questions to help identify the different certifications and educational levels represented in this sample of fire investigators to determine any potential relationship between the level of education or certifications and the effectiveness of the bulletin (Table 3). In regards to the levels of certifications represented that are held throughout the fire investigation community without CFEI (Certified Fire and Explosion Investigator), CFEI, and CFI (Certified Fire Investigator) all levels scores increased with the aid of the bulletin but still had an average score below 62%. Of the different certifications available in the fire investigation community, CFEI and CFI, the CFI is the only one that requires a period of time of working in the field before a certification can be obtained. The individuals with the CFI certification could be seen as the nonbiased experts of this study and scored a relatively low average of 61.84% with the aid of the bulletin. Several different educational disciplines were involved in this study including: Fire Science, Electrical Engineering, Mechanical

Engineering, Physical Engineering (PE), and Material Science. Of these different disciplines, Fire Science and Electrical Engineering were the only two groups whose scores decreased. Whereas the participants who had PE's and Mechanical Engineering backgrounds saw their scores increase over 15% with the aid of the ATF bulletin.

Table 3. Certifications and disciplines of education obtained by participants and their scores without and with the ATF bulletin.

Groups (# of individuals)	Score Without Bulletin % (SD)	Score With Bulletin % (SD)
Without CFEI (18)	53.27 (12.3)	57.89 (11.9)
CFEI (11)	52.27 (12.3)	54.06 (18.2)
CFI (5)	57.81 (18.0)	61.84 (12.0)
Fire Science (7)	52.68 (10.7)	48.87 (11.3)
Electrical Engineer (5)	57.50 (8.1)	51.75 (24.5)
Mechanical Engineer (5)	42.50 (6.8)	60 (10.9)
PE (4)	45.31 (6.3)	61.84 (3.0)
Material Science (1)	68.75 (0)	73.68 (0)

As another means of determining level of expertise, participants were also asked how many times they have used arc mapping in the field (Table 4). Based on the participants involved in this study the classifications were broken down to 0, 1-10,40-50, and 100+. You will note that the total number of participants in this table does not equal the total number of those that were involved in the testing, 29; this is because not all participants answered this question in the survey. As found throughout the rest of the study the majority of the disciplines' scores increased with the use of the bulletin between six and ten percent. But most notably found within this study was the 14% decrease in the score with the aid of the bulletin for those who have conducted arc mapping 40-50 times.

Several other questions in the survey were asked to identify the number of site examinations that the participants were involved in. While reviewing these results it was noted that in several instances the total number of site exams did not equal the number of site exams wherein the participant was or was not the lead investigator. As such this category of findings was not included in this report.

Table 4. Number of times arc mapping used in field scores without and with ATF bulletin.

Experience with Arc Mapping in Field (# of participants)	Score Without Bulletin (SD)	Score With Bulletin (SD)
0 (14)	52.2% (11.9)	58.3% (13.6)
1-10 (5)	45% (10.3)	55.8% (8.0)
40-50 (4)	64% (6.0)	50% (20.4)
100+ (1)	68.7% (0)	78.9% (0)

Analysis

A summary of the testing results indicates that having the ATF's bulletin of the different types of damage while examining an electrical conductor was helpful in accurately identifying the true cause of the damage to the wires. Although not of any significant value in many of the categories, the majority of average scores did increase with the aid of the bulletin. One of the most surprising findings from the analysis of the results was the decrease in the average scores of the participants that deemed themselves as having some level of expertise when using the ATF bulletin.

An interesting result from this testing was the decrease in scores of those with Fire Science and Electrical Engineering educational backgrounds. Interestingly enough, these would be two groups that would be expected to know more about arc mapping and how it is involved in fire investigation. The fact that scores decreased with the aid of the ATF bulletin for experienced investigators could indicate that the addition of the bulletin caused investigators to second guess themselves or the bulletin, whereas novice investigators may have relied more heavily on the bulletin rather than trying to decipher the bulletin and implement their own personal knowledge and experience.

Chapter 5: Closing

Conclusion

One aspect of this study that could help identify the ATF bulletin's effectiveness was the wide variety of participants attending the NAFI conference from which participants were selected. It was hoped that the variety of experience levels would be covered from beginners in undergraduate EKU fire investigation students to veterans of the fire investigation community attending the NAFI conference for recertification, although the small sample size of twenty-nine does not reflect the fire investigation community as a whole a variety of experience levels of background disciplines were accounted for. The average score with the aid of the bulletin which provided a visual and written description of the types of damages as described in NFPA 921 was 57% which is relatively low. Since the highest increase in accuracy when using the ATF bulletin was found when the novices applied the method, a potential outcome of this testing could be that ATF bulletin is an effective tool for teaching new fire investigators. It is also expected that an increase in training with the bulletin could identify improved scores.

This study had a small sample size of only 32 individuals and should not be generalized to represent the entire fire investigation community. However, it does indicate that more training and further work in the area of arc mapping is needed.

Arc mapping's effectiveness is based on the investigator's interpretation of the physical damage. The characterization of damages involved in arc mapping should not be the sole basis in determining the particular origin of a fire. Although the ATF bulletin may help in identifying electrical arcing on a conductor based on the exterior appearance, it is still recommended that all fire affected material be collected and examined in a lab to confirm the fire investigator's findings. In the growing field of fire investigation, there is no testing that can be done to an altered wire to determine the exact cause of the damage after it has been subjected to severe fire conditions. Due to a lack of objective testing, it is necessary for fire investigators to obtain continuing education to hone their craft in all aspects of fire investigation and related fields.

Future work

Through the course of this research project, a variety of variables were identified that could have been improved or addressed differently. Unfortunately, due to the time and financial restraints on this research project, not all aspects could be addressed. Some of these requiring further attention include: multiple overlying conductors, multi-strand conductors, and additional full-scale compartment fires with an eye towards realistic wiring and fire conditions.

Further research involving both the ATF's bulletin and fire investigator's ability to distinguish the different types of damage could assist in improving the reliability and validity of arc mapping in determining the origin of a fire. A larger sample size would provide a more accurate representation of the current ability of the community in recognizing and interpreting physical effects on a conductor. In addition, while continuing to ask detailed questions about the participant's education and certification background could identify an effective method of training both new and seasoned investigators. Through the analysis of the questionnaire it was identified that there was some confusion in the answering of questions involving the participants field experience. As a result more questions to clarify the background of participants involved in the study would be recommended.

References

Anderson, R. N., “Surface Analysis of Electrical Arc Residues in Fire Investigation,” *Journal of Forensic Sciences,* JFSCA, Vol. 34, No.3, May 1989, pp. 633-637.

ATF (2012). ATF Technical Bulletin 001-Visual Characteristics of Fire Melting on Copper Conductors Technical. ATF Fire Research Laboratory.

Babrauskas, V. (2017) Arc Mapping: A Critical Review. Fire and Materials Conference Proceedings.

Carey, N., PhD thesis, Developing a reliable systematic analysis for arc fault mapping. Centre for Forensic Science – Pure & Applied Chemistry. 2009, University of Strathclyde, Glasgow.

Carey, N.J., & Daeid, N.N. (2010) “The metallic damage to electrical conductors at fire scenes”, *Journal of The Chartered Society of Forensic Sciences,* 50(1), pp.29.

Carey, N., M.J. Svare, and M. Dubbin. “Arc fault mapping – a technique to assist in Identifying a fire’s origin”. In International Association of Arson Investigators Annual General Meeting. 2006. Denver, USA.

Churchward, D., Cox, R., Reiter, D. (2004). Arc Surveys as a Means to Determine Fire Origin in Residential Structures, International Symposium on Fire Investigation Proceedings.

Cunagin, S. E., (2016) “Guide to Graduate Theses,” Eastern Kentucky University, Richmond, KY

Erlandsson, R., & Strand, G. (1984/85). An Investigation of Physical Characteristics Indicating Primary or Secondary electrical Damage. *Fire Safety Journal,* 8, 97-103

Ettling, B.V., (1978) Electrical Wiring in Building Fires, *Fire Technology*, 14(4), 317-325.

Gorbett, G., & Chapdelaine, W. (2014). Scientific Method-Use, Application, and Gap Analysis for Origin Determination. International Symposium on Fire Investigation, Sarasota FL.

Hussain, N., Sunderland, P.B. & Stoliarov, I.S. Forensic Investigation Techniques for Inspecting Electrical Conductors Involved in Fires for Arc and Melt Beads. MS thesis. University of Maryland, College Park. June 2012.

Hussain, N., McAllister, J., & Roby, R. (2014) Analysis of Beads formed on energized and non-energized electrical copper conductors exposed to various thermal insults. Fire Science and Litigation, DRI conference proceedings.

Roby, R.J. & McAllister, J.L. (2012) Forensic Investigation Techniques for Inspecting Electrical Conductors Involved in Fires. *Department of Justice Publication*, 2010-DN-BX-K246.

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

Straeter, R.L. & Crawford, C.C. (1955). *Techniques of Arson Investigation*. California, (n.p.): Author

Appendixes

Appendix A: Survey Tool

Pre Survey Questions

1. In what year were you born? ____________

2. What is your gender?

   Male Female

3. How long have you worked as a full time fire investigator (years)?

   ____

4. How long have you worked as a part time fire investigator (years)?

   ____

5. How many fires have you worked as part (in any role) of an investigation team?

   0 1-25 26-50 51-75 76-100 More than 100

6. How many fires have you worked as the lead investigator?

   0 1-10 11-20 21-30 31-40 41-50

   51-60 61-70 71-80 81-90

   91-100 More than 100

7. Are you currently employed as a public or private investigator (if you are employed as both, please choose the one that is your main employer)?

   Public

   Private

8. What is your highest level of education?

   GED (General Education Development)

   High School Diploma

   Post High School

Trade School

Associates Degree

Bachelor’s Degree

Master’s Degree

Doctoral Degree (or other advanced degree)

Other: ____________________________

9. If attending/attended college, what was your primary area of study?

Fire Science

Criminal Justice

Fire Protection Engineering

Electrical Engineering

Mechanical Engineering

Other Engineering

Public Administration

Forensic Science

Other: ____

10. What certifications do you currently hold? Please select all that apply.

IAAI-FIT (Fire Investigation Technician)

IAAI-CFI (Certified Fire Investigator)

IAAI-ECT (Evidence Collection Technician)

IAAI-CI (Certified Instructor)

CFEI (Certified Fire and Explosion Investigator)

CVFI (Certified Vehicle Fire Investigator)

CFII (Certified Fire Investigation Instructor)

CFPS (Certified Fire Protection Specialist)

PE (Professional Engineer)

ATF-CFI (Certified Fire Investigator

11. How many times in your career have you made a determination on an electrical conductor of arc site or melting?

12. How many times in your career have you used arc sites to assist in origin determination?

13. How many hours of training have you had specific to identifying arc sites versus melting?

14. How many hours of training have you had specific to arc mapping?

15. How would you rate your level of expertise in determining the difference between arc sites and melting?

    1 (novice)

    2

    3

    4

    5 (expert)

16. How would you rate your level of expertise in determining arc mapping?

    1 (novice)

    2

    3

    4

    5 (expert)

17. An arc can occur even when an appliance is not energized during the fire?

True

False

Appendix B: Example of Question Form

Please mark Electrical, Thermal, or Undetermined as the cause of the damage found on each individual wire in the blank provided.

1.	Electrical Arc	Thermal Melting	Undetermined
2.	Electrical Arc	Thermal Melting	Undetermined
3.	Electrical Arc	Thermal Melting	Undetermined
4.	Electrical Arc	Thermal Melting	Undetermined
5.	Electrical Arc	Thermal Melting	Undetermined
6.	Electrical Arc	Thermal Melting	Undetermined
7.	Electrical Arc	Thermal Melting	Undetermined
8.	Electrical Arc	Thermal Melting	Undetermined
9.	Electrical Arc	Thermal Melting	Undetermined
10.	Electrical Arc	Thermal Melting	Undetermined

Appendix C: Consent Form

Consent Form

The following information is provided to make you aware of issues related to the research for which you are being asked to participate.

- The purpose of this research is to determine the validity of the ATF Fire Research Technical Bulletin concerning visual characteristics of fire melting on copper conductors.
- There will be no risks or foreseeable discomfort related to the research.
- This study will improve the current techniques for determining fire cause and origin.
- Confidentiality will be maintained within the limits allowed by law. Records related to this research will be maintained confidentially via hard copy and electronic files between the researcher and the Eastern Kentucky University academic advisor.
- Participants may contact Jacob Critchley (Graduate Thesis Student) at jacob_critchley@mymail.eku.edu. Any questions throughout the process should be directed via email.
- Participation in this research is voluntary. Refusal to participate will not result in a penalty. Participants may discontinue participation at any time without penalty.
- The finished product of this research will be a graduate thesis and a peer-reviewed journal article that will be submitted for publication.

Please indicate by signing below that you understand the information listed above and that you give consent to participate in this research.

I, _______________________, understand all aspects of this research and consent to participate.
(Print Name)

____________________________________ _____________________________

Participant Signature Date