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State of the Arc (Mapping)

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Abstract

NFPA 921 Guide for Fire and Explosion Investigations *considers the technique arc mapping to be one of the methodologies used in isolating a fire's origin and spread. Provided the technique is used properly and understanding its limitations, it is a tool for investigators. Synthesized here is the latest peer-reviewed research and discussions on the implications of increased use of ground- and arc-fault circuit interrupters on arc mapping analysis. Incorporated are case studies and evaluations of recent legal decisions. The goal is to arm investigators with what's needed to maximize the arc mapping's efficacy and best present its use and results.*

Keywords

Fire investigation, arc mapping, *Daubert*, fire origin, metallurgy, computed tomography, forensic engineering

Introduction

The standard of care for fire investigations is the National Fire Protection Association's NFPA 921 — *Guide for Fire and Explosion Investigations*, currently in its 2021 Edition[1]. If possible, fire investigators are tasked to reliably establish a room or area of origin for subsequent cause determination. When conducting a thorough fire scene examination, the fire investigator examines the structure, specific parts of the structure, and the geographic location within a fire scene to determine and identify the three-dimensional area of fire origin where it is reasonably believed to be located. NFPA 921 Par. 3.3.13 defines the area of origin as "[a] structure, part of a structure, or general geographic location within a fire scene, in which the 'point of origin' of a fire or explosion is reasonably believed to be located[1]."

This process is of paramount importance and must precede efforts to determine the fire cause, as defined by NFPA 921 Par. 3.3.27 as "[t] circumstances, conditions, or agencies that brought about or resulted in the fire or explosion incident, damage to property, bodily injury, or loss of life[1]." If the area of origin cannot be established, it is difficult to identify the fire's cause. Basic fire science, experience, surveillance camera footage, witness statements, and other tools or techniques, such as burn pattern analysis, are used to identify as small as possible an area wherein a fuel encounters a competent ignition source. Par. 18.1.2 of NFPA 921 states that the determination of a fire's origin relies on the interpretation of one or more of the following[1]:

(1) <u>Witness Accounts and/or Electronic Data</u>. The analysis of observations reported by persons who witnessed the fire or were aware of conditions present at the time of the fire as well as the analysis of electronic data including but not limited to security camera footage, alarm system activation, or other such data recorded in and around the time of the fire event.

(2) <u>Fire Patterns</u>. The analysis of effects and patterns left by the fire, which may include patterns involving electrical conductors.

(3) <u>Fire Dynamics</u>. The analysis of the fire dynamics [i.e., the physics and chemistry of fire initiation and growth and the interaction between the fire and the building's systems].

Fire origin determination can be complex when considering one, many, or all of these factors. In some cases, credible witness information may not be available. (Of course, witness information must be corroborated.) In other cases, fire patterns may be obscured or not useful, especially after full-room involvement. The weight of arc mapping to establish an area of origin must be based on data, including agreement or verification of each arc site, and include a survey and documentation of the room of origin and nearby circuits and devices.

Reliability of Arc Mapping

The definition of arc mapping according NFPA 921 Par. 3.3.9 is[1]:

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"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**." (emphasis added)

This process utilizes the evaluation of electrical arc sites' spatial location found during a systematic examination of the electrical circuit configuration, including devices. The investigative technique continues to be taught as one of the factors used to establish a fire's area origin per NFPA 921[1].

The principle of arc mapping has seen widespread utilization within the fire investigation community, but the quality of arc mapping varies. The presumed basis for mapping is that it correlates with the area of origin of an emerging fire as it damages the insulation on electrical wiring in its path. The developing fire creates short circuits and visible arcs in that damaged wiring, often before circuit breakers and other protection equipment shut down the electrical circuits in those areas. However, the presence of ground-fault and arc-fault current interrupters (AFCIs and GFCIs) may de-energize circuits and therefore prevent arcing conditions. Where this occurs, the absence of arcs does not always mean that the origin area of the fire is elsewhere.

Fire investigators have used arc mapping for decades. A succession of scientific and engineering articles as far back as that of Delplace and Vos in 1983[2] to a doctoral dissertation by Carey in 2009[3] and his follow-up study in 2010[4] described the usefulness of arc mapping to identify the fire origin and trace the fire's development. In Carey's 42 fully furnished repetitive room configurations, he determined through the analysis of the post-fire three-dimensional data that a high probability exists that arcing damage observed on electrical conductors occurred in close proximity to the fire's origin area.

Whether arc mapping can be considered a pillar of origin determination or merely a tool (such as burn pattern analysis) is the subject of recent debate. Assuming confirmation of arc sites, the ability of the fire investigator or engineer to properly infer an area of origin from the available data was identified as an important factor in the arc mapping process. In other words, it is crucial that the investigator have skill in performing and interpreting arc damage patterns. The skillset is a combination of background, training, and experience. Although an electrical engineer may not be required to perform arc mapping, electrical engineers are keenly qualified to calculate and evaluate the levels of available short-circuit current or circuit tracing activities that produce an arc. Metallurgists may be consulted to confirm or differentiate between fire melting, arc sites, and eutectic melting, though additional testing may be needed to verify and validate these observations.

Like fire test methods, investigation tools such as arc mapping have limitations. **Figure 1** provides lists of circumstances where arc mapping might or might not be useful.

The question is whether an arc site identified by an investigator can be scientifically relied upon in conjunction with other available information in confirming the area of fire origin. For that question to be answered, the fire investigator must have sufficient knowledge, training, and experience in correctly recognizing, collecting, and preserving this evidence and be able to demonstrate to meet or exceed the standards of care in performing these tasks.

For example, the following is a hypothetical situation involving the documentation of an arc site during a routine fire investigation:

A woman was in the basement doing laundry when she reported a light bulb above a table of stored goods failed. She cleaned up glass remains and went upstairs. Moments later, she was alerted to smoke and fire in the basement and vacated the structure. A v-pattern originated from table of stored goods. A severing arc site was found on the exposed Romex wiring directly above the location of the broken bulb; glass fragments were found in the basement trash receptacle.

The methodology assumes that the fire attacks an energized wire causing degradation of the insulation and that a fault occurs between the hot conductor and one at

When arc mapping is useful	When arc mapping is not useful
• Incipient stage fires • Limited damage • Clearly defined arc site • On power cords to devices and appliances • Open fuses • Notches in metal appliance housing • Exposed Romex (e.g., basements) • Older structures • Vehicles with limited fire damage	• Copper thieving • Explosions (ignition of fugitive gasses) • Extensive, widespread fire damage • Fires with temperatures exceeding the melting temperature of copper • Circuits with AFCIs, GFCIs, other forms of RCDs • Aluminum conductors • New construction (due to the wide presence of RCDs) • Motor vehicles with extensive fire damage

Figure 1
When arc mapping is and is not useful.

a different potential. The arcing that occurs damages the conductor. Ideally, the circuit breaker will trip, and the arcing will cease. Arc site damage is not limited to conductors; it can also affect other elements in a circuit, including fuses.

This paper considers other scenarios that are not ideal. In some room configurations, arc sites may be more prolific adjacent to exposed areas of heavy fuel concentration or significant ventilation patterns. Such areas do not always correspond to the area of fire origin.

In some cases, wires may be completely transected or a partial collapse of part of a structure has occurred. In other instances, a breaker may trip before the arcing has severed the wiring. Other times, the breaker never trips, but bare wires fly apart, stopping the arcing. However, in any event, the arc damage indicates the first-place heat flux was sufficient to damage the insulation of energized cabling. As such, the arc site may tell something about the development of the fire's progression or origin area. The weight placed on one or more arc sites in establishing an origin area rests with the practitioner.

This paper assumes an investigator has the minimum NFPA 1033 (*Standard for Professional Qualifications for Fire Investigators*)[5] understanding of electricity and is capable of distinguishing arc sites from other forms of conductor damage. Any question regarding the cause of damage to conductors should be resolved, or the area of origin expanded.

A recent paper by Babrauskas, *Arc Mapping: A Critical Review*[6], has shown that arc mapping may not be as instructive as previously believed. In his article, Dr. Babrauskas shows that the published research does not support the notion that arc mapping can reliably indicate an area of origin under most circumstances. Also, there seems to be a basic misunderstanding as to what arc mapping shows. Fire investigators can be unaware that arcing artifacts more often correspond to areas of heavy fuel or areas of significant ventilation than a fire's origin area. Coupled with this misunderstanding is a lack of basic electrical knowledge by some practitioners. Finally, a series of electrical components that is being used in new construction such that arc mapping (and the resultant lab work and analysis) will look very different in newer structures than in older ones that lack these devices.

So, the questions emerge as to whether arc mapping is dead, and how useful is it as an investigative tool? The authors are resolute in stating that arc mapping can be a viable technique if used in the right circumstances and with an understanding of its limitations.

For directional patterns, this requires a severing arc and another arc downstream of that, in which case the local direction of fire propagation may be inferred. For intensity patterns, it requires that effects of local fuel load concentrations and local ventilation patterns be correctly accounted for. The latter task may be difficult or impossible in many cases.

Only if the work is done by a competent professional who has analyzed the fire scene from this point of view — and has been able to demonstrate that ventilation or fuel load would not have dominated the arcing propensity — will the data gathered be useful. But it has been the authors' experience that too often investigators have not shown such care. When this happens, arc mapping is likely to be misused, and misleading conclusions are likely to be drawn. The misuse of arc mapping can result in the wrong area of origin and, therefore, the wrong cause. Fire investigation reports should address arc mapping's reliability and limitations, and the author(s) must be prepared to explain both.

Electrical faults can also act as ignition sources. It is generally accepted that arcs can ignite low-density lightweight combustible fuels, dust, gases, and vapors, but an arc in a 120V branch circuit may not ignite solid fuels such as wood 2×4s. Also, there are no valid laboratory techniques to distinguish between an arc site that caused a fire or was the victim of a fire. Furthermore, absent video recordings, no one can say when a particular arc occurred.

For the investigator, the question becomes whether arc mapping can, or cannot, be validly used in a given fire.

Arc Mapping at the Site

Site processing techniques and data collection applied post-fire event should follow NFPA 921 Chapter 9, Electricity and Fire[1]. The process involves systematically examining circuits and wire remains for localized damage to conductors or plug blades. Colored tape or a flag is used to mark arc site locations. Damage requiring additional examination may be flagged with a different color. The arc sites are typically indicated on a map or plan drawing or annotated photograph. The entire length or sections of wiring with arc sites may be preserved. At a minimum, the arc site damage should be photographed using some form of magnification (e.g., macro lens, cameras with microscope feature, portable microscopes). Fire investigators must be capable of distinguishing arc sites from other forms of damage (e.g., mechanical damage, eutectic melting).

To demonstrate proficiency, the fire investigator or engineer needs to confirm and defend the arc site(s) and understand factors influencing the response of circuit breakers and residual current devices at those sites. The following summarizes the significance of laboratory data and the inferences that can be made based on the circuits and their protection devices to support or negate fire origin and spread hypotheses. It is recommended that the fire investigator or electrical engineer examine electrical wiring and devices in rooms adjacent to the area of origin until they are satisfied that their analysis is sufficient to support their findings.

Applicable Laboratory Techniques to Confirm Arc Sites

Damage mechanisms to conductors from fire scenes may be mechanical, chemical, thermal, or electrical. The appearance of melting distinguishes electrical and thermal from mechanical damage. Examples of mechanical damage include gouging from twist-on wire connectors and fractured ends. The only form of chemical damage with physical evidence of melt is eutectic melting, typically aluminum or solder contacting a conductor, which can occur even if the conductors are not energized. Questionable damage to conductors should be subject to additional examination, if not confirmation in a laboratory.

Most arc sites have characteristic, macroscopic physical indicators on the exterior of the wire: that is, smooth melt in the shape of a round globule(s) with a distinct area of demarcation between the arc damage and conductor and notches. Buc and Reiter et al pointed out that not all arc sites are discernible with the naked eye; some sites are so small that the area requires magnification[8].

In the laboratory, there are four techniques used to further study localized damage to conductors and other electronic devices and appliance subcomponents. These analytical techniques include: 1) cleaning by ultrasonic and/or plasma etching; 2) imaging by stereomicroscopy and/or radiography; 3) chemical analysis by Energy Dispersive X-ray Spectroscopy; and 4) examination of microstructure by metallography[8]. The various techniques and their ability to distinguish between the various causes of damage to conductors is illustrated in **Figure 2**.

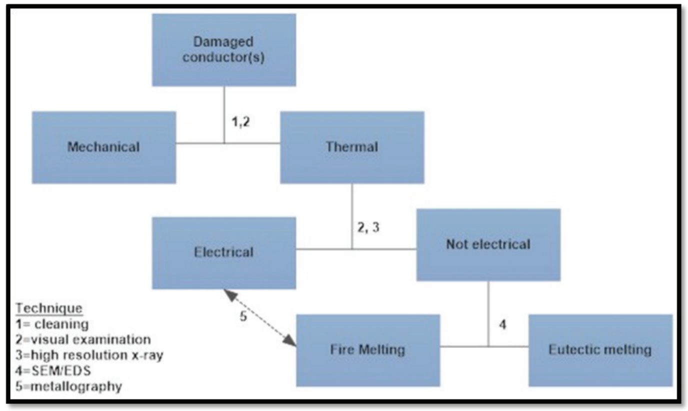

Figure 2
Protocol for the examination of damage to copper conductors from fire scenes.

Cleaning with an abrasive, such as glass fiber pens, can damage finer features on the surface. The best method for examining arc damage is an ultrasonic cleaner and mild detergent in hot water. For this, more time may be required to remove stubborn surface debris. Microscopy, using a stereomicroscope or equipped camera, preserves the arc site's appearance and should include the area of clear demarcation and the condition of the conductor away from the arc site. A second distinguishing feature of an arc site is internal porosity. High resolution, two-dimensional radiography is capable of distinguishing voids in the otherwise solid melt. X-ray is a non-destructive option to confirm the presence or absence of porosity compared to metallography.

A number of authors have investigated arc sites in detail using one or more of the above techniques. Laboratory-created arc sites are analyzed and compared with arc sites and fire melting from the field to establish the list of arc site characteristic attributes. Photographs of arc sites and fire melting are contained in NFPA 921 Chapter 9, Pt. 9.10, entitled *Interpreting Damage to Electrical Systems*[1]. Additional examples of arc sites are shown in **Figure 3**.

Fire investigators must be aware that arc sites to or involving brass and other alloys may have different characteristic physical attributes.

Circuit Breaker Basics

Identifying beads, marks, and other indicators of electrical arc activity is only one-half of the task. Information that is also needed is the determination of circuit breaker status, circuit breaker characteristics, how that would affect the arc fault duration, and (given the indications and duration) was the arc activity in close proximity to combustible material(s).

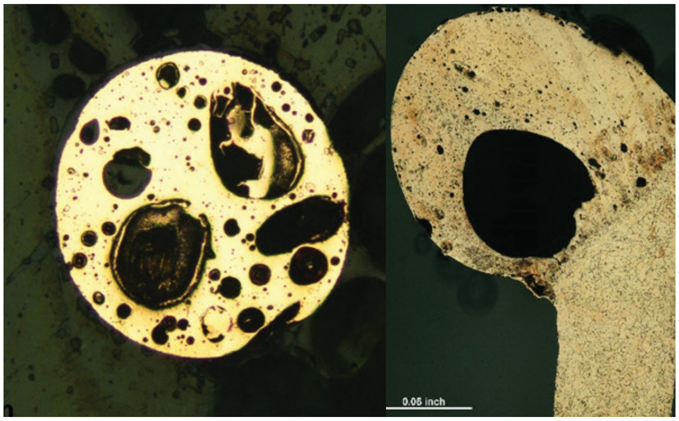

Figure 3
Arc sites to copper conductors.

What causes an arc event to stop? One scenario is the tripping of a breaker or the opening of a fuse. A circuit protected by a ground fault circuit interrupter (GFCI) or similar type device may also activate, causing the cessation of current flow. Moreover, finally, the magnetic forces associated with arcing (as well as expansive thermal forces associated with spatter) may cause the conductors to repel and current flow to stop. These interruptions of current are key to arc mapping. If the current flow does not timely cease, the sharp melt transition lines viewed microscopically become blurred; arc sites start to appear as melt sites.

UL 489 *Standard for Molded Case Circuit Breakers* (MCCBs) is often referenced[9]. OCP (overcurrent protection) is normally in the form of an MCCB or a fuse. An OCP is designed to protect house wiring and permanently installed appliances only. **Figure 4** shows the ratings of MCCBs and their design load:

1. MCCBs follow an inverse time-current relationship: the larger the overcurrent, the shorter the time allowed to trip.

2. There are two salient trip points – 135% of handle and 200 % of handle. At 135%, a 20-ampere breaker must trip in less than 1 hour at a load of 27 amperes. At 40 amperes, the same breaker must trip in less than 120 seconds. At breaker sizes of 40 and 50 amperes, 240 seconds are allowed for a trip time at 200% handle rating.

3. Overcurrent or overload situations cause heat to generate in a breaker, causing the tripping. This is referred to as the "thermal" mechanism of the breaker.

4. The thermal part of the breaker is also affected by ambient temperature. It will trip faster in hot weather and be slow to trip (or may not trip at all) in cold temperatures.

5. Short circuits cause the magnetic portion of the breaker to trip. While this depends upon the breaker size and manufacturer, typical short circuit trip-levels are from 5X to 12X the handle rating. A 20-ampere breaker would instantaneously trip at levels between 100 and 240 amperes, depending on how the manufacturer has designed and made the breaker.

6. Magnetic trip times are not affected by heat.

MCCB Ampere	AWG
15	14
20	12
30	10
40	8
50	6

Figure 4
MCCB ampere-AWG ratings.

Some forensic engineers and investigators neglect the notation from above regarding OCP being designed for protecting permanent wiring and appliances. For example, assume that an 18 AWG line cord is connected to an appliance and is plugged into an outlet with a 20-amp breaker protecting the circuit. The appliance malfunctions and starts to draw 25 amperes. A 20-ampere breaker is not required to trip until a sustained current of 27 amperes (135%) exists for an hour. The appliance can overheat and cause a fire, and the breaker is of little use in preventing the problem. Similarly, the 18 AWG line cord will overheat and could well catch fire.

Residual Current Devices

On occasion, the investigator may encounter a true Residual Current Device (RCD) as utilized in Europe. This original RCD trips at a fault current of ~30 mA. This device, unlike its American counterparts, is strictly a mechanical device. The 30 mA level is the "trip" level, unlike the 6 mA sensitivity used in the United States.

This difference in operation is brought in by the fact that 30 mA is deemed (by the IEC) not to cause electrical deaths; obviously, there are differing opinions on this. This European model uses a magnetic field to cause a mechanical relay to open and stay latched. The 30 mA trip level is instantaneous; there is no delay time in the breaker tripping. On the other hand, at 30 mA, the GFCI is allowed up to 56 seconds to trip.

In Europe, a common type name for one type of circuit protection is the RCD. In general, these are the GFCIs and their various permutations. One type of device that is truly not an RCD is an AFCI. This device looks for the signature of a repetitive arc (such as with a loose connection). In many devices sold in the U.S., the AFCI also contains ground fault protection. For this paper, the AFCI will be considered an RCD.

The common forms of RCDs include:

- Ground fault circuit interrupter breaker
- Ground fault circuit interrupter receptacle
- Ground fault equipment protector
- Leakage current detection interrupter
- Appliance leakage circuit interrupter
- Immersion detection circuit interrupter
- Arc fault circuit interrupter

These devices affect the conclusions that can be drawn from arc mapping. For example:

> *A fire breaks out in a bathroom. Arc mapping of the structure reveals that there was bare type NM wiring, but no arc beads on any of the bathroom wiring; similarly, the circuit breaker serving the bathroom wiring was not tripped. Arc mapping would lead one to state that the fire did NOT start in the bathroom. Continued work processing the scene showed that there was a GFCI in another bathroom but protecting this bathroom. This GFCI was tripped. During the fire, the Hot and Ground leaked to one another at a level of 6 mA or more, or the neutral and ground faulted to each other during the fire. Either condition would be brought on by invasive thermal heat, degrading the type NM insulation. Similarly, these conditions cause the GFCI to trip, taking away power from the downstream bathroom.*

Goodson brought the impact of RCD devices to the fire investigation community in 1999[10]. He addressed the issue again at ISFI in 2016. Nevertheless, the authors collectively run into many fire investigators who are unable to see why the RCDs and their properties are important.

GFCI Breaker — GFCI breakers reside in a breaker panel. The breaker portion of the device is a conventional 15- or 20-amp T-M (thermal magnetic), per UL 489. In addition, this MCCB contains ground fault protection. The output hot and neutral is run in opposing directions through an internal toroid. Should the currents differ from the other by about 6 mA, the circuit is interrupted — BOTH poles are removed from the load. It is further noted that this device does not need a working ground to cause tripping when the ~ 6 mA differential is exceeded. The allowed time to trip follows (per UL 943)[11]:

$$T = \left(\frac{20}{I}\right)^{1.43}$$

Where I is the current in mA, and T is the time in seconds allowed for the device to respond. However, the actual response time is much less. Testing by Goodson of several GFCIs (not GFCI breakers) made by Cooper Industries showed an average trip time of 31 mS when a 10 mA fault is created between the line and ground. Per the formula, 2.7 seconds is allowed.

This device also responds to a downstream ground to neutral fault; should they touch — both output poles (hot and neutral) are removed from the load. Testing of several GFCI breakers made by Square D showed that with a 2-ohm resistor placed between the load side neutral and the ground of the GFCI, the GFCI would never trip. At a 1 ohm short between output neutral and ground, the N G fault was immediately detected, and the GFCI shut down in less than 100 mS.

GFCI Receptacle — This has the same operation as the GFCI portion of the GFCI breaker, only it is mounted and installed as part of a duplex outlet receptacle. The GFCI protects loads plugged in the receptacle and downstream loads. It does not respond to overloads. It will sense a hot to ground fault (short circuit) but will not respond to a hot to neutral fault (short circuit).

Ground Fault Equipment Protector — This device works like a GFCI, but trips at higher levels, such as a 30 or 50 mA differential. It is not reliable in protecting against electric shock injury, because of its higher trip level (relative to the 6 mA GFCI trip level). Rather, it is designed to protect equipment from catastrophic destruction.

Leakage Current Detection Interrupter — LCDIs are permitted as an alternative to AFCIs in accordance with Section 440.65 of the *National Electrical Code* (NEC)[12]. LCDI power supply cord assemblies use a special cord employing a shield around the individual conductors and are designed to interrupt the circuit when a leakage current occurs between a conductor and the shield. The LCDI is often found on cord sets for window air conditioning units and contains the male blades.

> ***440.65*** *— Single-phase cord- and plug-connected air conditioners shall be provided with one the of the following factory-installed devices:*
>
> 1. Leakage current detector-interrupter (LCDI)
>
> 2. Arc-fault circuit interrupter (AFCI)
>
> 3. Heat detecting circuit interrupter (HDCI).

Appliance Leakage Current Interrupter — ALCI is an appliance leakage current interrupter. The main difference between the GFCI and ALCI is that GFCI not only senses current imbalance, but it also has the ability to identify improper wiring. The ALCI does not have that feature. Having either an open neutral or a neutral-ground short will trip GFCI right away, whereas an ALCI will not detect these hazards. ALCIs are used as components on appliances, where these wiring conditions can be guaranteed. Typical applications for ALCI are portable appliances such as bathroom heaters, carpet cleaners, power washers, and hair dryers. ALCI devices are used to protect customers from immersion electrocution. The ALCI will trip if the portable appliance is immersed in grounded water (i.e., sink, tub, etc.).

Immersion Detection Circuit Interrupter — An IDCI is a component device that interrupts the supply circuit to an immersed appliance. When a conductive liquid enters the appliance and contacts both a live part and an internal sensor, the device trips when current flow between the live part and the sensor exceeds the trip current value. The trip current may be any value below 6 mA sufficient to detect immersion of the connected appliance. The function of an IDCI is not dependent on the presence of a grounded object, in applications in accordance with Section 422.41 of the NEC.

422.41 — Cord- and plug-connected, free-standing appliances subject to immersion. Cord- and plug-connected, free-standing appliances and hand-held hair dryers shall be constructed to protect personnel against electrocution when immersed while in the "on" or "off" position.

Arc Fault Circuit Interrupter — An arc fault circuit interrupter is a device that analyzes current flow to a load and determines whether or not abnormal arcing is taking place. We first define "normal" arcing, the kind of arcing that occurs during the usual operation of a load or appliance. For example: arcing at a switch when a light is turned off or on; arcing between brushes and a commutator in a drill motor or small appliance; and arcing internally to a fluorescent light bulb. These are examples of normal arcing that do not start fires (we specifically exclude fires caused by spark ignition of fugitive vapors here).

An example of abnormal occurring is that associated with a loose connection. Current increases and decreases are analyzed by the AFCI, and a "signature" is developed; i.e., what do the changes in current look like? The signature is then classified as to its mode — normal or abnormal. The AFCI then removes power from the load. The AFCI is mentioned with the RCD devices because some AFCIs installed in the United States also have GFCI protection built in.

Field Case Studies

Below are representative field case studies that have relied on some of the principles of arc mapping. It is worth noting that absence of arcing is sometimes just as important as finding arc beads.

Field Case Study No. 1

A 6-foot length of bare 16 AWG 2 SJT (Junior Service) cable was found on an outdoor porch, plugged into an exterior GFCI receptacle mounted on the wall of a residence. The SJT was found with both conductors fractured distally. The GFCI had not tripped. The upstream OCP was provided by a 20-amp T/M breaker found in the tripped position. The temperature in the utility closet where the load center was located had not singed or discolored the paper calibration tags on the circuit breaker body. The NM cable from the circuit breaker to the GFCI had no arc damage; the NM cable was examined both grossly and microscopically. Downstream type NM wiring protected by the GFCI was found to be completely bare in places but without arc damage. No loads were present on the circuit, except for whatever the Junior Service cord was feeding.

The question is why something tripped the breaker. No physical cause, however, was noted; there were no indications of arcing or overloading on the type NM on this branch circuit. Breakers can trip from heat, but the breaker was not abnormally hot. This would indicate that the SJT was not all recovered (also indicated by fractured ends), and one would expect that the additional missing wiring (and possibly load) would explain why the breaker would have tripped.

Field Case Study No. 2

A large (30,000-square-foot) three-story mansion caught fire. The fire department responded twice to the fire, having to receive alarms from the smoke detection system. Seeing no smoke or flame, the firefighters twice departed the house. On the third visit of the fire department, the house was seen to be well engulfed in flame. The mansion was a total loss.

Many of the fire investigators determined the area of origin to be in a utility closet. This was the area of lowest burn, and the area immediately outside the closet had no fire damage. Examination of a type NM cable in this room showed that it was bare but with no arcing. The cable fed a set of lighting sconces located at the front door.

During the investigation, the interview of a neighbor showed that the neighbor had taken numerous photos of the mansion during the fire. One of the photos showed that the sconces were illuminated well into the fire. This illumination (obviously) could not have happened if the fire began in the utility closet.

Field Case Study No. 3

A fairly new window AC unit was seen catching on fire in a security video. Examination of the window unit showed a motor with good windings, wiring that in no instance had arcing, a good capacitor, and an intact line cord with an intact LCDI. We could not tell whether the LCDI had tripped, as the unit had been handled after the fire.

A product's liability lawsuit was undertaken. The video was clear as to both the fire's cause and origin. The defense position was that any AC unit that caught fire would have to arc internally on the wiring — a very valid point, in that most of the wiring inside the AC unit was bare.

Testing of the same brand LCDI showed that when a fire starts in the AC unit, the generated plasma causes the LCDI to trip. More particularly, the line cord terminates in the AC unit such that an internal fire will be detected and cause the plasma to bridge between the conducive pieces on the LCDI triggering circuit, causing a cessation of power. The cause of the fire was a leaked refrigerant line. The refrigerant oil, dispersed as an atomized mist, caught fire, and the ion-rich plasma tripped the LCDI.

Field Case Study No. 4

A decorated soldier from the Iraq war lived with his family in an apartment complex in Kentucky. The family paid increased rent such that they had access to a private locking "closet" to store bicycles, sporting goods, and the like. A fire occurred at the apartment complex, and its origin was determined to be the unlocked storage closet rented by the family. The soldier was charged with arson.

Several lengths of type NM cable passed through the closet. They were never made available for examination, but the pictures showed them to be bare secondary to heat damage. The prosecution maintained that because the cables were protected upstream by AFCIs, the cables could never arc.

AFCIs detect arcing by developing a signature. This signature takes several cycles of data (minimum) to be analyzed. During that time, a hot to ground fault (arc) can occur and ignite combustibles. The point of this case scenario is that AFCIs detect and respond to repetitive arcs — a single arc event will not cause the AFCI to trip. Likewise, the single arc event can occur without the AFCI tripping.

Field Case Study No. 5

The fire involved an older residence. Wiring was of type NM, and (as best as could be traced out) every circuit had one or more instances of arcing present. Some of the conductors were severed by arcing, and some did not sever the wiring. The unusual feature of this fire was that the load center had a large number of breakers, but only a few of that number tripped.

This fire demonstrates one of the underlying assumptions of arc mapping — arc events are short-lived because a breaker trips or wires repel (or sever), and continuity is lost; these short lives of the arc events result in the rapid

Figure 5
Federal Pacific Electric (FPE) panel.

transition in the copper from the melt to non-melt regions. When a breaker is slow to trip, this can result in multiple arc sites being present or in the wiring having the appearance of the melt. A typical FPE breaker panel is shown in **Figure 5**.

Field Case Study No. 6

A fire occurred in a large room. The local authorities first thought it was an incendiary fire. However, they could not rule out a fire of electrical origin. An engineer was hired. He examined the evidence, with his report reading as follows:

> *No signs of electrical overheating were found in the evidence analyzed, based upon the scene examination, within a degree of scientific probability. Damage to the circuits found to date is consistent with fire attack to the circuits.*

Based on the engineering report, the fire was ruled arson. There was a suspect, and he was convicted and sent to prison. The defendant was later exonerated of the crime and filed suit against the electrical engineer for generation of a misleading report.

At one end of the large room, there was an open load center. At least five instances of arcing were found in the load center. These instances of arcing were all attributed to external fire attack (the word consistent was used). The problem with the word consistent is that the investigators are not looking for facts that are consistent; they are looking for uniqueness. It is well known that an arc site that started a fire cannot, in and of itself, be distinguished from an arc site that resulted from an external heat attack of an energized conductor.

In this case, a wrongful arson conviction occurred and demonstrated the issue of *reliability*. Arc mapping was utilized and was deemed to have eliminated electricity as a cause of the fire. In this case, the origin and cause personnel examined a report. The report eliminated electrical causes. With the elimination of electrical, the arson case could be filed. The problem, though, was a lack of communication between the engineer and the investigator. For the engineering opinion to be reliable, the engineer had to be aware of the circumstances associated with the fire; that is, the fire originated within, attacked, and caused arcing within the load center. Without the two investigators talking to one another, reliability was sacrificed.

Discussion

Arc mapping is a scientific tool. Its use is based on scientific and engineering principles. The underlying premise is sound: *An energized cable will allow arcing to develop between two conductors carrying different potentials when then the insulation is sufficiently damaged (compromised), and further, that the arc damage will occur where the breech of insulation was sufficient to allow conduction between conductors at two different potentials.*

In considering the reliability of arc mapping, guidance can be sought from NFPA 921[1], which includes laboratory verification, similar to confirming canine hits for possible ignitable liquids.

With arc mapping, the location of the arc sites is just as important as the lack of arcing in other areas. The Buc and Reiter paper et al, noted earlier, clarifies that some arc sites could only be found microscopically. With this being the case, one has to ask if it's necessary to retain all wiring for a laboratory exam and confirm every arc site with lab work. If one cannot see all arcs without using a microscope, is it possible that arcs in the field may be missed? This answer is, obviously, "yes." This factor alone immediately indicates that arc mapping has reliability issues unless *all* wiring is examined in the laboratory.

The 16 areas of competency of NFPA 1033[5] dictate that the fire investigator should have an understanding of electrical systems in a building, and the introduction of new wiring devices requires the investigator remain current in their knowledge and training. NFPA 921[1] also indicates that a fire investigator should be able to perform arc mapping. The quality of the work performed is highly dependent upon the skills and training of the person who is carrying out the task. This is where the authors have concerns with the use of arc mapping when carried out by someone other than a forensic engineer, especially if other circuit devices are not considered, or the absence of arcing directs a fire investigator to another area that is not the true area of origin. The fire investigator may be able to map out and locate arc damage on an older structure but may have difficulty on a newer structure fire. The various nuances of how each device operates are likely beyond the training of many investigators. Moreover, there are times when a laboratory examination will yield details contrary to what was deduced at the fire site. To wit,

> *A residential fire occurs. In the area of origin, there is found a "home run" length of type NM (14/2 AWG w/ ground). The type NM is bare for about 6 feet in this area of origin. The breaker serving the NM has tripped. Examination of the bare conductors by way of palpation revealed no nodules or discontinuities (i.e., no arc damage). The load center is in a closet which did not suffer elevated temperatures. There are no downstream loads present.*

How does one analyze this situation? Possible explanations are:

1. The circuit breaker had tripped for some other reason before the fire.

2. The cable was unpowered during the fire.

3. The area of origin is wrong.

However, there is also a fourth explanation: the research by Reiter et al has shown that some instances of arcing were so small in his testing that they could only be identified with microscopy[8]. Another possibility is an arcing event may occur that leaves no identifiable marks, even to the microscopist. The lesson to be learned here is that the absence of arcing (as noted in the field) should be at least verified by microscopy in the lab.

Finally, fire investigators and electrical engineers benefit from open communication and working together in the field when arc mapping is performed. Coordination of efforts and understanding circuits, circuit breakers, and residual current devices is best performed on-site.

Legal Cases and Expert Testimony Involving the Use of Arc Mapping

For arc mapping evidence and testimony to be admissible, the data must meet the Daubert and a federal rule of evidence governing admission of expert testimony. *Daubert v. Merrell Dow Pharm., Inc.*, 509 U.S. 579, 113 S. Ct. 2786 (1993). Factors that may be considered in determining the soundness of the scientific methodology include, but are not limited to:

1. <u>Testing</u> — Whether the theory or technique can be and has been tested;

2. <u>Peer Review and Publication</u> — Whether the theory or technique has been subjected to peer review and publication;

3. <u>Error Rates and Standards</u> — What is the known or potential rate of error and the existence and maintenance of standards; and

4. <u>General Acceptance</u> — Whether the theory or technique used has been generally accepted.

Rule 702 simply requires that: (1) the expert be qualified; (2) the testimony address a subject matter on which the fact finder can be assisted by an expert; (3) the testimony be reliable; and (4) the testimony "fit" the facts of the case (quoting Fed.R.Evid. 702 advisory committee's note).

The advantages and limitations of arc mapping as a principal indicator of fire origin are well known by forensic fire investigative expert practitioners. Nevertheless, an increase in criticisms concerning the limitations of arc mapping methodology as a fire investigation tool for the accurate inference of area of fire origin conclusions are on the rise in the relevant scientific community. Several of the criticisms cited in court cases that fire investigators should be prepared to both address and include:

1. Overpromises on the technique's precision,

2. Exaggerated inferences from the available data,

3. Failure to adequately account for potential methodological flaws,

4. Deficient scientific rigor in establishing evidentiary fire origin-related reliability,

5. Errors due to deficient practitioner training and experience, and

6. Indeterminate findings based upon subjective visual analysis.

In *Glassman v. Home Depot USA, Inc.*, 2018 WL 3569344 (C.D. Cal.), an experienced electrical engineer performed an arc map survey and thereafter confirmed the fire investigator's area of origin was "on the top of a workbench in the garage." The arc mapping expert then surveyed the designated area of fire origin for ignition sources and formed an "initial hypothesis was that a [defendant] Ryobi charger or battery sitting in the charger [on the workbench] was the cause of the fire." After a laboratory CT scan of the benchtop battery revealed that it was not manufactured by defendant Ryobi and was not the hypothesized ignition source, the expert's ignition scenario and area of origin morphed into a "Ryobi batter[y] that investigators recovered *from the floor of the garage*." (emphasis added). The court subsequently stated: "[t]o say this raises an eyebrow is an understatement," but irrespective of the arc mapping expert's "serendipitous changes of heart," ultimately ruled that his "opinions were shaky but admissible."

In P*owell v. State Farm Fire & Casualty*, Case No. 2:15-cv-13342 (E.D. MI 2016), after a basement fire occurred, the fire investigator initially determined that "[a]n electrical issue caused the fire. It started above the circuit breaker panel involving the service conductor where it comes into the house." The defendant insurance company thereafter transferred the fire claim to its large loss team and retained an electrical engineer to perform an arc mapping analysis to "rule out electrical." The arc mapping expert performed a single visual on-scene examination and determined that "the branch circuit conductors and associated electrical components located in the area of interest were not causal elements of the fire." Armed with this conclusion, the fire investigator's area of origin mutated into "in the ceiling space, ["on top of a suspended ceiling tile in the basement bathroom"] approximately 21 inches east of the west wall and east of the circuit breaker panel." The fire expert's rehabilitated fire classification opinion metamorphosed into incendiary due to "the introduction of combustible material on top of a lay-in-ceiling and ignited with an open flame."

Clearly, the fluctuating hypotheses in the above cases resulted from the misapplication of validated methods or deficiencies in qualitative analysis. Fire investigators continue to be reminded that in *Gen. Elec. Co. v. Joiner*, 522 U.S. 136, 146, 118 S. Ct. 512, 519 (1997), the Court noted that:

> *conclusions and methodology are not entirely distinct from one another. Trained experts commonly extrapolate from existing data. But nothing in either Daubert or the Federal Rules of Evidence requires a district court to admit opinion evidence that is connected to existing data only by the ipse dixit of the expert. A court may conclude that there is simply too great an analytical gap between the data and the opinion proffered.*

The above cases exemplify potentials for analytical gaps between the available data and the opinions reached.

The jury is still out where arc mapping methodologies are concerned. According to Novak "[A]rc mapping is a continuing topic of debate within the fire investigation community[14]." "The (ATF) Fire Research Laboratory (FRL) also recommends further training and research on the principles and use of arc mapping in fire investigation[15]."

Additional legal cases involving arc mapping are listed under References.

Conclusions

Arc sites have to be carefully identified, characterized. They should be laboratory verified where questionable, and their location in a compartment and within a circuit documented and described, including the type, presence, and absence of various circuit and appliance protection devices. Because arc mapping may support an area of origin — the most essential first step of fire investigation — the results should be based on a transparent and scientific methodology with careful consideration of its limitations[16]. The weight or reliability of the arc mapping depends on a thorough investigation and understanding of electrical and circuit protection basics. Fire investigators should be aware of and prepared to address limitations, current criticisms, and legal issues, including the *Daubert* criterion[17].

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