ARC MAPPING: NEW SCIENCE, OR NEW MYTH?

Vytenis Babrauskas
Fire Science and Technology Inc., San Diego, CA
Dept. of Mechanical and Aerospace Engineering, University of California San Diego, La Jolla, CA

ABSTRACT

Arc mapping was first introduced in the 2001 edition of NFPA 921 and was subsequently expanded so that in the recent editions it constitutes one of the four main methods for determining the origin of a fire. Careful consideration of engineering principles and large-scale experimental studies on the subject indicates that the relevance and prominence of arc mapping as a leading indicator of fire origin is greatly overstated. The technique is valid and applicable only in some very limited scenarios. Yet it has seen very extensive use in recent years by investigators preparing fire reports. In many cases, such attempted use of arc mapping is based on incorrect and invalid hypotheses, which are often implicitly assumed to be true instead of being explicitly stated. The following are myths: (i) An abundance of arc beads at a given locale means that fire originated in that area, while a paucity of arc beads indicates that it did not. (ii) When multiple arcs are present on a circuit, the direction of arcing will necessarily proceed upstream towards the power source. (iii) If an appliance is the victim of a fire, internal arcing will be primarily near the exterior of the unit, while arcing deep inside indicates a fire origin at that place. NFPA is urged to revise NFPA 921 to eliminate arc mapping as one of the four main methods for establishing fire origin, and to subsume it under the more general category of "fire patterns." In addition, it is important that NFPA 921 reduce the implied general utility of the method and provide more explicit information on its interpretation and its limitations and on the circumstances under which it may be a valid method for assisting in the determination of the fire origin.

Keywords: arc mapping; arc beads; electrical short circuits; fire investigation; metallurgical evidence; NFPA 921.

INTRODUCTION

Up until the early 1990s, fire investigation was a notably empirical profession, with very limited scientific foundations. As a consequence, various "rules" were used by practitioners, which were later learned to be myths, not valid precepts of science[1,2,3]. It was already recognized by the mid-1980s that the situation needed to improve, thus in 1985 the National Fire Protection Association (NFPA) established a Technical Committee on Fire Investigations which produced the first edition of NFPA 921—Guide for Fire and Explosion Investigations in 1992, and updated regularly since then[4]. One of the main tasks of the Committee and the Guide has been to replace myths with science-based procedures. While the early origins of arc mapping were in the 1980s, it became a technique in wide usage among fire investigators only since the 2001 edition of NFPA 921. In its recent editions, NFPA 921 progressively increased emphasis on arc mapping as a fire investigation tool. However, this was not accompanied by scientific rigor in establishing a clear understanding of its valid uses, versus its limitations and improper uses. It is the purpose of this study to examine carefully the history of arc mapping and the available experimental validation data, and especially to uncover the underlying hypotheses. It will be shown that some of these, while often tacit and not explicit, are scientifically erroneous or speculative and unsupported, and consequently lead to investigatory conclusions that are not supportable. Recommendations emerge out of this study on improvements for the NFPA 921 treatment of this topic, along with guidance for fire investigators as to what constitutes valid and correct application of arc mapping principles.

When fire engulfs energized wiring, shorting may occur (but does not necessarily have to). If shorting does occur, a detectable artifact (an "arc bead") will not necessarily be created. Laboratory experiments[5] have found that direct metallic shorting is less likely to create identifiable arc beads than is shorting where part of the path is a carbonaceous material. But the latter is often likely to happen when wire insulation gets burned due to a fire. Furthermore, if an arc bead is created, it will not necessarily be located at the point of first fire damage to the cable.

In fire investigation, arc mapping[*] is defined in NFPA 921[6] 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*

[*] Sometimes referred to as *arc surveys*, *arc fault surveys*, *arcing fault pattern analysis*, or similar terms.

identification of the area of origin and analysis of the fire's spread." NFPA 921 first referred to arc mapping in the 2001 edition, which did not provide any procedure details, but simply added arc mapping as the fourth source of information in the Origin Determination chapter. Additional material was developed in the 2004, 2008, and 2011 editions, while the 2014 edition greatly expanded the text and for the first time gave a definition of arc mapping, as indicated above. Changes for the 2017 edition have been minimal.

Note that arc mapping is not related to examining the possibility of arcing as a *cause* of fire. An electrical arc may be the initial event starting a fire, but arc mapping is a method suggested for helping identify the area of fire origin, not its cause. The fire cause is defined by NFPA 921 as: "*The circumstances, conditions, or agencies that brought about or resulted in the fire or explosion incident, damage to property resulting from the fire or explosion incident, or bodily injury or loss of life resulting from the fire or explosion incident*." In other words, determining fire cause is establishing what took place to enable the fire to occur. Laboratory examination of molten artifacts may be necessary for this purpose, but this is an undertaking different from that of conducting arc mapping and has already been covered elsewhere[7].

The present paper examines all of the experimental research published on the topic of arc mapping to date. The most important objective has been to examine the hypotheses put forth by various authors on the principles underlying arc mapping and the ways that arc mapping may be used to assist in determining the origin of a fire. The validity of these hypotheses is then examined in terms of the experimental results and in terms of basic principles of electrical and fire science.

HISTORY

The earliest mention of a concept related to arc mapping is found in a 1955 book by Straeter and Crawford[8]. The authors suggested that: "*Condition of wiring after the fire. The amount of destruction of insulation on electric wires can reveal a clear pattern for the area of intense heat. Electric shorts have their physical effects. Investigate to be sure whether the short caused the fire or the fire caused the short. The exact locations of the centers of wire damage, of char, and of other indications may well be compared to answer this question*." And: "*Sequence of shorted electric circuits. The appliances that were stopped by electrical failure may indicate the path of the fire to some degree, especially in a larger building in which there are many circuits and they were put out one at a time. The times at which the clocks stopped could tell which circuits were included first in the fire's path*." The next development was in Japan, where in 1968 Miyake discussed arc evidence at a closed meeting on forensic engineering held by the National Research Institute of Police Science. He then published it in a journal in 1975[9], stating: "*If two points of severing due to shorts are found on an electric cable burned in a fire, it means that the farther point from the power source was damaged by the fire earlier than the other one. This can be used to estimate the place of origin.*"

The obscure 1955 and 1975 references were evidently not seen by later workers and, in most literature, the first reference is to a 1983 paper by Delplace and Vos[10], who stated that they had been developing for 12 years a method that they called "systematic mapping of the locations of short circuits." The paper was brief and provided only a single diagram, but it can form the starting point of the present study, since they proposed testable hypotheses how arc mapping might be interpreted. The basic Delplace and Vos hypotheses were:

- "A close parallel exists between the patterns left by combustion and the location of short circuits."
- "A short circuit will normally take place wherever the fire first damages the cable. This gives us the point along the entire length of the circuit earliest affected by the fire."

They also noted that, when several sever-arcs[*] are found on a particular circuit, the earliest one had to be the farthest downstream from the power source, since the initial sever-arc removes power from the downstream portion, but not the upstream portion. They then offered a hypothetical example of a vehicle fire, which they also considered to be amenable to this analysis: "*If damage by electric arcs is found at the dome light and at the steering wheel, then the fire did not start in the engine compartment, nor in the dashboard*." The paper gave no details of any experiments or analyses that might have been conducted, and the method saw little use during the next two decades, apart from one other forensic paper[11] and the teachings of Robert Svare. Svare is an engineer who taught the technique to numerous individuals in classes on fire investigation, but published only brief summaries[12,13] (Figure 1). Interest within the profession resumed in the late 1990s, after which a number of papers appeared.

---

[*] A sever-arc is an arcing location where one or more conductors involved have been severed by action of electrical arcing, that is, the conductor in question is no longer continuous at that location.

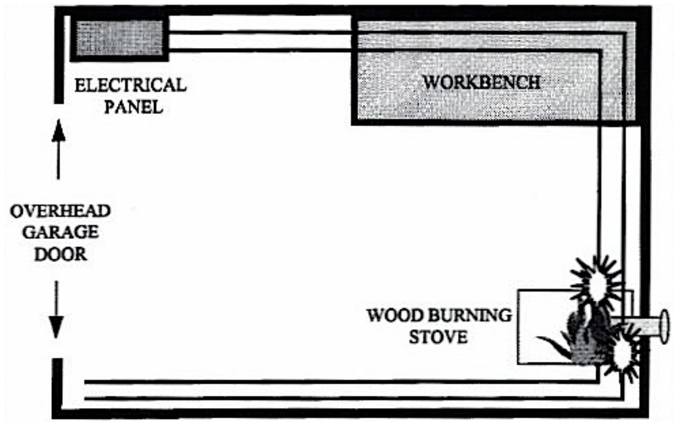

Figure 1 Teaching illustration used by Svare in a 1995 paper. According to the author, this arcing evidence signifies that fire originated at the wood-burning stove.
(Diagram: Robert Svare)

TECHNIQUE

Procedurally, arc mapping is simple. A floor plan has to be made that, if not of the whole structure, encompasses at least all areas potentially likely to be the area of origin. All circuits running through the area need to be traced[14]. The wiring then is inspected for presence of arcs, and those are recorded on the floor plan (map).

Arc mapping is likely to be a tedious process. Unless most of the structure can be excluded on the basis of other considerations, a great deal of wiring may need to be examined. But the examination is likely to be slow, since arc beads can be small and may require use of bare fingers or a sliding a cotton ball in order to detect some of them[15,16]. However, it was also learned that the cotton ball technique does not have value unless charred insulation material is first thoroughly cleaned off conductors; otherwise, cotton balls tend to get stuck on charred debris[17]. For stranded wires, this can be difficult, and ultrasonic cleaning is likely to be needed[17]. In addition, even prior to making this search, it is necessary to trace the relevant circuits[14] (back to a specific circuit breaker in the load center) and in itself this is likely to be a laborious process (and may be impossible if the conductors are broken).

Even though it is sometimes done by electrical or forensic engineers, arc mapping does not require electrical engineering expertise. The only electrical knowledge needed by the individual doing the work is to know the configuration of electrical power cables and the identification of the closed/open/tripped status of circuit breakers. Thus, arc mapping can be done by a competent fire investigator or assistant[18]. Note however that a tripped circuit breaker does not necessarily indicate tripping due to fire-caused short-circuiting. Circuit breakers may have tripped from unrelated causes, prior to the fire, or tripped due to ambient heating of the circuit breaker itself by the fire[19].

GOVERNING PRINCIPLES

The Delplace/Vos hypotheses can be usefully examined as a starting point. The first hypothesis (*A close parallel exists between the patterns left by combustion and the location of short circuits)* can be conceptualized but not readily proven by deduction from any principles of science. However, its validity may be examined by experimental study. The second hypothesis (*A short circuit will normally take place wherever the fire first damages the cable. This gives us the point along the entire length of the circuit earliest affected by the fire.*) needs some detailed scrutiny. The first sentence is either untrue, or a truism. If “first shorts out” is taken as synonymous with “first damages,” then it is a truism, making the statement superfluous. But if it is understood that “damage” can entail degrees of severity and is not identical to “shorting,” then the sentence is not a general truth. If the fire first causes mild thermal damage that does not result in shorting, then it is incorrect to state “a short circuit will normally take place.” Now, consider the second sentence, which, reworded more explicitly, would say that “On any particular circuit, a found arc bead will denote the first place where flames impinged on this circuit.” There is no principle of fire science or electrical science that would make this true (or false) for all possible fire scenarios. Potentially, it might be true in a probabilistic sense; it would then be amenable to experimental demonstration, which is considered below.

Carey et al.[25] proposed a simpler hypothesis for arc mapping theory: "*Relating the position of the beads that are formed due to arcing with the layout of the electrical system can help establish the area where the fire first attacked the energized electrical system.*" First, it may be noted that the authors take a weak position: "can help" indicates that, at best, they are anticipating some correlation, rather than describing facts provable from known science. The implied view here is that arcing will line up around some boundary of flaming at some unspecified early time of fire growth. Carey, in fact, put forth such an explicit hypothesis (beading will be "*found on the edge of the initial plumes*") in his 1999 paper[45], but his later work did not support it (nor did any other researcher's). Similarly, Churchward et al.[20] hypothesized that: "*arcing sites will pattern themselves about the area of origin*," while Johnson and Rich[21] hypothesized that "*arc mapping* [will]…*create a boundary around the area of origin*." Taken together, the above hypotheses may succinctly and clearly be worded as:

- Arc sites will be primarily found only in the area of fire origin;

and, possibly:

- Arc sites will be primarily found around the periphery of the area of early fire involvement.

In recent years, fire investigators have been perhaps most likely to adopt hypotheses such as enunciated by Karasinski et al.[22]:

- Initial stages of fire progression
  - Will cause arcing on energized circuits
  - Arcing will typically cause circuits to be de-energized by opening protective devices (breakers, fuses) or severing conductors.
- Later stages of fire progression
  - Further away from the area of origin, there will remain fewer energized circuits, and therefore less arcing.

From fundamental principles, it is useful to consider what can be accepted to be true, solely on the basis of accepted fire science or electrical science:

(1) An arc bead can only be created if the circuit is powered at the time that it gets fire engulfed and shorted*;
(2) Arc beads will not be found on circuits that were de-energized at the time of fire engulfment, irrespective of whether the loss of power was due to tripping of circuit breakers from earlier arcing, severing of conductors due to arcing elsewhere, manual disconnection, or utility outage;
(3) Arc beads are likely (but not guaranteed) to be plentiful in areas where sustained flaming occurred while power was still available; and
(4) Arc beads will not be found on circuits where fire exposure was mild.

The latter two statements stem from the well-accepted facts that applying flames onto energized conductors can burn the insulation off them (in full or in part). Then, conductors with damaged or destroyed insulation and without special means of separation and securement **<u>may</u>** make contact and thereby short out. Energized conductors with damaged insulation may also short out to non-electrical grounded objects. Note that this says nothing about the origin of the fire.

How can then the scheme be applied to fire origin determination? By making an additional hypothesis:

(5) Electric power is available in the area near the fire origin, but is no longer available once flame spread has progressed away from the origin.

There is clearly no principle of science that requires the latter to be true. So next, it must be considered how power becomes lost in structure fires. Several ways are possible:

- *Tripping of circuit breakers*. Shorting may trip a circuit breaker (or open a fuse), but the actual outcome is probabilistic and depends on voltage, available short-circuit current, characteristics of the circuit breaker, and other details of the circuit. Note: if arcing causes conductors to get *welded* together, tripping can be almost certainly assured, provided the conductor size is consistent with the circuit breaker rating and the circuit breaker is not defective. But in some cases, prolonged arcing can occur, and wires of sufficiently small diameter may undergo welding without tripping of circuit breakers.
- *Severing of conductors*. An initial arc may or may not trip a circuit breaker, and it may or may not sever an energized conductor*. But if an energized conductor does get severed, no arcing will be possible

* In some cases, the investigator also needs to be aware that power may be supplied by a flow path that is not the normal one. For example, this can entail back-feeding of a dead circuit through shorting with a still-live one, or operation of an alternate power supply (generator, UPS, etc.).

downstream, although it may remain possible upstream of the sever point. However, no methods exist for calculating if a given event will, or will not sever a conductor, nor which one will get severed if severing occurs. These are probabilistic events.

- *Manual intervention*. Building occupants generally do not respond to fires by turning off electrical circuits, although this may occasionally happen when a fire is seen to be electrical in nature. Standard operating procedures at fire departments vary widely. But fire departments may not shut down electric power unless and until a fire has become large or difficult to control. By that time, fire will have spread greatly beyond the area of origin. Thus, manual intervention is likely to occur only later in the progression of a fire, when fire has progressed greatly beyond any areas potentially to be evaluated as area of origin.
- *Utility power outage*. While this will rarely be an issue, power may simply cease to be available due to a utility outage, unrelated to any of the above actions.

Thus, apart from manual intervention (where timing may sometimes be estimated), or unrelated power outage (which would be exceptionally rare to coincide with a fire event), de-energizing of circuits in a structure fire has to be considered as probabilistic. Given that, it becomes evident that the potential of arc mapping to reveal anything about the area of fire origin is fundamentally probabilistic, and only a sufficient ensemble of experiments can establish utility of the technique. (However, certain deductions involving severed or tripped circuits may sometimes be made reliably, and these deterministic possibilities are considered later.)

The discussion to this point focused solely on establishing a fire origin area smaller than a whole room, assuming the origin is known to be in a particular room. But Carey[45] hypothesized that arc mapping can also "*be used effectively at large fire scenes to identify which compartment the fire started in*." No research exists on this point, but it is useful to consider the layout of electrical circuits in buildings. Assuming that manual intervention or power outage does not occur, the only way that circuits will be de-energized in regions remote from the area of active burning is by severing of conductors or tripping of circuit breakers. But this will be possible *only if the same circuit's wiring extends from early-burning areas to a remote area in question*. Assuming this is not ancient wiring (where circuits were typically very few), this is unlikely. Modern buildings in North America are commonly wired so that one circuit will serve only a single room, or a few closely-situated rooms or spaces[†]. If that is the case, then there is no physical reason de-energizing of circuits remote from the area of active burning should be expected.

EXPERIMENTAL VALIDATION

As seen above, no principle of science establishes that areas far away from the point of origin will be de-energized and, therefore, bereft of arc beads if fire extends into those areas. But within the general area of origin, will arc beads preferentially occur near the origin on any particular circuit, as opposed to further away? Assuming the initial fire is localized (as contrasted, say, to a vapor cloud ignition), heat fluxes might be expected to decrease monotonically with distance from the fire. Thus, with all else being the same, it might be surmised that arcing would necessarily occur first closest to the fire, and only later additional arcing might occur at farther locations. As will be shown later, the assumption of heat fluxes monotonically diminishing with distance will rarely be valid for real building fires. Apart from the dominant role of local fuel load and local ventilation effects, there are some cable-related reasons why wire shorting potential is *not* likely to bear any simple relation to distance from fire origin:

- The elevation of the cable may change along the run
- There may be more or less thermal protection at various locations along the run
- The stresses in the cable may favor shorting at some locations.

The last factor needs some explanation. Burning away plastic insulation does not, by itself, cause shorting. For shorting to occur, either conductors that are initially a few millimeters apart must move into contact, or else shorting has to involve a carbonized insulation bridge. The propensity for conductors to come into contact will be influenced, among other things, by stresses (bends, kinks, twists, etc.) of the conductors. Once plastic is burned away, conductors may stay in place, or move apart, or move closer together. None of these factors above can be calculated to predict the shorting history of a cable. Shorting may also proceed without metallic contact, due to carbonized insulation bridging the conductors; issues related to this have been discussed by Babrauskas[23]. In view of the above issues—which are not amenable to current-day theoretical or computational analysis—it is important to examine the results of experimental programs.

---

[*] Note that severing a ground or neutral conductor will not necessarily de-energize the circuit, since arcing can still potentially occur between a live conductor and another conductor that is not at the same potential as the severed conductor.
[†] In the UK, it is common to use 'ring mains.' This entails larger-size branch circuit conductors, with the cable run so as to make a loop, fed from the same circuit breaker at both ends. Such ring mains are likely to traverse sizable areas.

The earliest published studies on this topic gave no useful test data. In 1986, Rothschild[11] published a paper describing his investigation experience, but also provided no experimental results. The first report giving experimental data was published by Carey[24] in 1999. In his first room burn, he found two arc beads, one near the area of origin, the second near a window 3 m away. For a repeat burn, two arc beads were found, both in the general vicinity of fire origin. Carey also conducted another burn, but this was not for the purpose of validating arc mapping. In 2003, Carey supplemented this by another test burn[25] where he found 6 arc beads in the test compartment, 3 close to the origin and 3 at the opposite end of the room. He concluded "*the research has found that the arc mapping methodology has proven to be a reliable indicator of the fire's areas of origin*." This was not justified by the actual data, and a more accurate conclusion would be "*arcing will generally be found in the area of fire origin*." In fact, Carey provided a conclusion very similar to this in his later 2009 study, discussed below.

In 2005 West and Reiter[26], reported on three full-scale room fire tests done for arc mapping validation purposes (Figure 2 shows the detailed results for their third test). In each test, 12 to 15 branch circuits were installed using 14/2 NM cables. These were attached to the ceiling and allowed direct fire impingement. Despite the fact that the tests were run with wiring strung in the open, along the ceiling, in none of the three tests was the arcing clearly localized to the area of origin. While in all cases there was arcing near the area of origin, arcing was also found remote from the area of origin (in some cases, diametrically opposite). For test No. 3 shown in Figure 2, the remote arcing was probably influenced by doorway ventilation, but in other cases no clear reason was seen. Furthermore, in all three tests, the point of ignition was on the sofa, which was, by far, the predominant fuel load item in the test rooms. Thus, the reason for somewhat greater concentration of arc beads in the vicinity of the sofa was most likely due to fuel load, not origin, effects. The authors themselves additionally observed that electrical arcing activity was "greatly influenced by the entrained air velocity," that is, by the ventilation flow patterns.

The largest study of arc mapping was the 2009 Ph.D. dissertation by Carey[14], who conducted 39 compartment burns. This is an order of magnitude greater than presented by any other researcher. However, most of the research was focused on metallurgical studies and only limited conclusions can be drawn from the arc mapping work. The main limitations were: (a) only a single room was studied; the ability of arc mapping to identify the room of fire origin was thus not possible to address; (b) only 4 circuits were used, yet the rooms were notably large; (c) all wiring was run exposed on the ceiling; no protected or low-level circuits were studied; (d) most of the fires were exceptionally fast, flammable-liquid fires, with circuit breakers tripping in 2 – 3 min, and sometimes even around 1 min. Furthermore, 17 of the 39 tests involved scenarios with multiple points of ignition, thus there were only 22 tests where a fire with a single point of origin was configured.

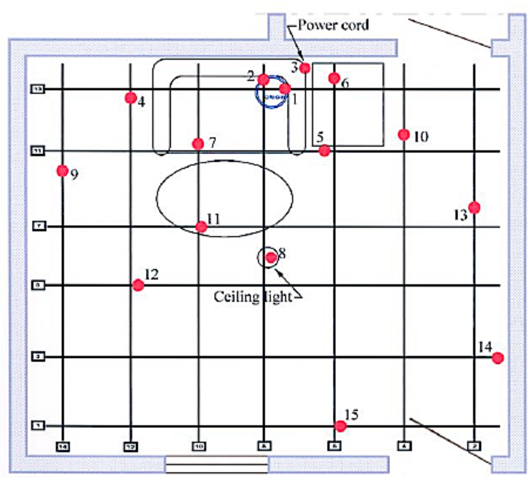

Figure 2 Arcing locations (red dots) found by West and Reiter for their test No. 3; ignition was on the seat of the two-seater couch, indicated by a blue circle
(Diagram: Larry West and David Reiter)

Carey concluded "*Analysis of the three-dimensional data recorded during the experiments and the arcing events has indicated that there is a high probability of arcing damage occurring to electrical conductors located close to the fire's area of origin*." This conclusion is supported by the results presented. However, it does not address the issue of discrimination: given that arc beads are likely to occur near the fire origin, are they rare or unlikely to occur at locales remote from the origin? In fact, an examination of his data shows that these were also plentiful.

Wood and Kimball[27] conducted four full-scale fire tests in a 3.7×4.9 m fully furnished bedroom. An array of 14 AWG NM cables was attached to ceiling on a 0.61×0.61 m grid; each cable fed by a separate 15 A circuit breaker. While such close spacing will generally not simulate real-life conditions, it does enable arcing locations to be better assessed than the coarse spacings used by Carey. No loads were fed from the cables. In each test, all circuit breakers opened before the fire reached flashover stage. Arcs found were typically between hot and ground, but there were arcs between all three conductors. In most cases, they found that the arcing artifacts were extremely small (1 – 4 mm) and required great effort to locate. The main conclusion that they drew from their work was that arcing is likely to occur in the room of fire origin, but "*no arc mapping patterns emerged from the room fire tests to clearly indicate a point of origin*." But they also added "*all conductors did arc indicating that the conductors may reliably indicate a room or area of origin even in the absence of being able to indicate a point of origin*." The latter conclusion is incorrect, since if arcing (or even copious arcing) suffices to establish the room or area of origin, then buildings with widespread, extensive arcing would necessarily have been victims of multiple areas of origin, which is an unjustifiable conclusion. It bears emphasis that the authors did not run any tests where arcing on the wiring of multiple rooms in a building was studied.

Most experimental studies involved NM cables simply fastened to the bottom of a gypsum wallboard ceiling. This may simulate wiring in unfinished basements or attics, but is not representative of normal wiring conditions in occupied spaces. In 2015, Wheeler[28] was the first researcher to explore experimentally the effect of protective barriers. He conducted three burn room tests using 14 AWG NM cables that were run up one wall, across the ceiling, and down the opposite wall. In test No. 1, the NM cables had no protection. In test No. 2, the cables on the ceiling and on one wall were protected by ½-in (12.7 mm) thick gypsum wallboard, while the cables on the other wall were protected by thin, 1/8-in (3.2 mm) thick wood paneling. In test No. 3, all cables were protected by ½-in gypsum wallboard, ignition was on the floor near a chair, and the fire went through flashover before being extinguished. The results (Figure 3) do not validate the ability of arc mapping to localize an area of origin that is smaller than room-size. Wheeler provided some moderately optimistic conclusions from his tests that were not justified by the data, and for the protected test (No. 3), the results indicate that *arcing was localized to the area of heaviest fuel concentration (the sofa), rather than the area of origin*. It should be noted that even Wheeler's protected experiment did not involve wiring compliant with the electrical code. Sec. 300.4 of the NEC[29] requires that wiring behind a wallboard inside walls have at least a 32 mm (1.25-in) air space between the cable and the back of the wallboard. By omitting this spacing, the cables in Wheeler's tests were more readily susceptible to heating from the fire, thus more likely to arc closer to the location of the dominant fuel load burning in the fire.

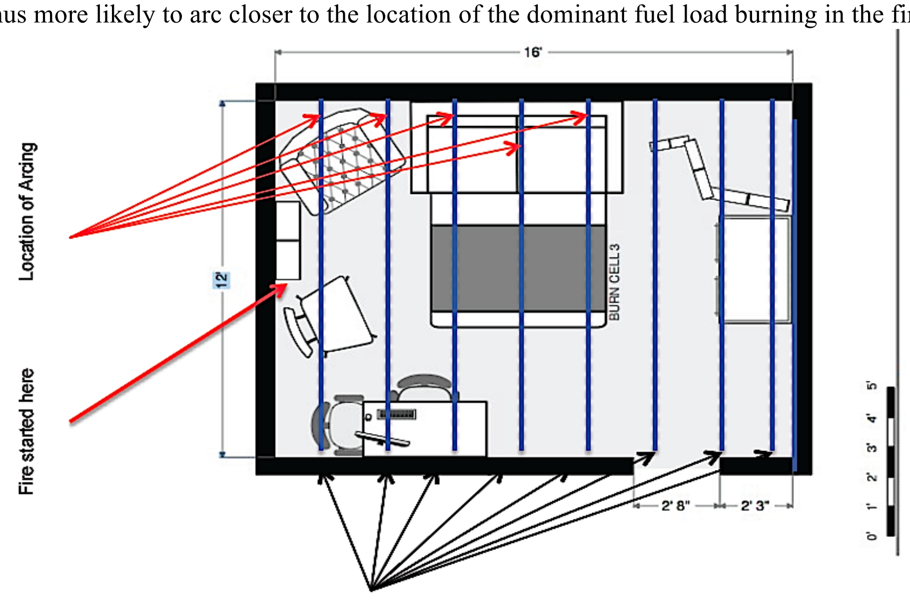

Figure 3 Results from Wheeler's Test No. 3 (all cables protected by ½-in gypsum wallboard)
(Diagram: David M. Wheeler)

MULTIPLICITY OF ARCS

Some investigators used to believe that multiple arcing will not occur on a single circuit, but well-known forensic electrical engineer Bernstein[30] already noted in 1991 that multiple arcs are possible. Rothschild[11] reported finding as many as 4 arcs on one 14 AWG branch circuit, but provided no details. West and Reiter[26] provided the first detailed experimental results on multiple arcs on a single circuit, and Table 1 shows their results; 4.8% of the circuits experienced two arcs and no instances of more than two arcs were found. Carey[14] found that 5.8% of his circuits experienced two arcs (and none three or more). These two studies gave very similar results, and it can thus be concluded that about 5% of solid-core conductor circuits can be expected to show two arcs, and an insignificant fraction may contain a larger number.

Table 1 Results from tests by West and Reiter on fire-induced arcing of 14/2 NM cables

Test No.	Test 1	Test 2	Test 3
circuits with one arc	11	14	15
circuits with two arcs	1	1	0

ARC BEAD TYPE AND SIZE

In his tests, Carey[14] found that 29% of arc sites constituted sever-arcs, while 7% were welded together. For arc sites where severing was found, however, he did not document the fraction where the hot conductor was severed.

West and Reiter[26] analyzed their data for arc bead size, and found beads ranging from very large to barely perceptible. They noted that this was an unexpected finding, since the circuit breakers were identical for all circuits, as was the available short-circuit current, I_{sc}, of 310 – 320 A. These findings indicate that arc bead size is a highly probabilistic quantity. However, there are some known effects on bead size, and Ablenas and Bodzay[5] demonstrated that lower short-circuit currents are more likely to result in large arc beads, than if the current is high and rapid circuit breaker tripping occurs. In their study, they found that, in fires, the short-circuit current is likely to be much lower than I_{sc}, due to shorting occurring with carbonaceous material in the path, not a direct metal-to-metal contact.

ARCING WITH STRANDED WIRES

Branch circuits in 15 or 20 A ratings in North America use solid-core copper wires. But power cords and wiring inside appliances and equipment are likely to use stranded wires. Stranded wires can behave differently from power cables having solid-core conductors for several reasons:

(a) Stranded-wire cords are typically used exposed in the room, not protected by any thermal barrier. Stranded appliance wiring may be protected by an appliance housing, especially if it is steel, but is unlikely to be located behind a gypsum wallboard barrier.
(b) Power cords are likely to be low, or at floor level, as opposed to being high or at ceiling level.
(c) Most stranded cords use only a single layer of insulation, rather than having both wire insulation and a jacket.
(d) Stranded-wire cords are likely to use much smaller size conductors than cords used for building wiring purposes; consequently, overcurrent protection may be much less effective, and multiple arc sites on a single circuit might be readily expected.

Thus, experimental data obtained on solid-conductor power cables may not necessarily directly apply to stranded power cords, and results specific to stranded wires should be considered. In an early paper, Rothschild described a fire where 7 arcs were found on one power cord. Hoffmann et al.[31] conducted a laboratory study on appliance power cords that had 18 AWG copper conductors. A large number of tests (713) were run under several thermal conditions—radiant heating, small gas flame, and a more realistic fire from a small wood crib. The results indicated that 100% of the power cords attacked by a wood crib fire showed arcing damage, while lesser fractions of specimens receiving radiant heat or small burner flames shorted. Johnson and Rich[32,33] ran a single compartment test where they exposed to a room fire an extension cord and three appliance cords plugged into it, arranged at heights ranging from floor to table height. The extension cord was extra-heavy duty (12 AWG) and was powered from a 20 A circuit breaker. The compartment went through flashover, and then was extinguished shortly thereafter. The extension cord showed 4 arcs, one appliance cord had 4 arcs, a second had "multiple" arc marks, while the last one had none. Presumably the extension cord shorted out and severed or tripped the circuit breaker (the authors did not state), thereby de-energizing the last appliance that showed no shorting. The authors also reported a fire case where three appliances were plugged into a circuit-breaker protected power strip. The power strip's cord showed arcing, as did one appliance, but not the other two. In this case, it was found that the power strip's circuit breaker did trip. It can be concluded from this that the likelihood of arcing on power cords is decreased if they are fed by a power strip or an extension cord, since upstream shorting or tripping may act to de-energize plugged in devices. Otherwise, the likelihood is high that energized, stranded cords will get shorted out in a serious room fire, but it should not be inferred that this is a necessary outcome.

Hoffmann et al.[34] also ran room fire tests with energized appliances and showed that fire attack on power cords will often, but not always trip circuit breakers. In some cases, arcing damage to cords occurs, but the affected circuit breaker is not tripped. Hazelwood[35] reported a case where a long extension cord was found to have not only 4 arc locations, but each location was a sever-arc. Such evidence does allow the direction of arcing damage to be established, which necessarily had to progress from the downstream to the upstream end of the cord.

Stahl and Parrott[36] discussed the application of arc mapping to motor vehicles. Vehicles utilize primarily stranded conductors, but also differ from building wiring in the power supply: DC supplied typically at 12 V for passenger vehicles, with higher voltages for heavy vehicles or electric cars. They did no tests, but did give a number of warnings against misuse of the technique for fire investigation in motor vehicles. Their main conclusion was that, given an absence of any laboratory studies applied to motor vehicles, arc mapping cannot be assumed to be a "*dependable, robust technique when translated from structures to vehicles and equipment*."

Lancaster and Meadors[17] studied arc mapping of stranded conductors using three test rooms, fueled by burning wood pallets. Fire was extinguished in the first one after all circuits tripped, while the next two rooms were allowed to burn to the ground. Each test used a number of stranded cords laid out along the floor. Trip times were typically 10 min, as contrasted to 2 – 3 min for solid-core cables stretched across the ceiling in Carey's tests. The work was unfinished, however, and the authors only presented metallurgical results, but not data obtained from the arc mapping itself.

Shanley[37] described using arc mapping as an aid in analyzing a clothes dryer fire, specifically to determine if the fire originated inside the appliance, or outside. No tests were run, and Shanley simply concluded that the fire originated inside, since the heater was energized, and since arcing locations did not correspond to places that would be most vulnerable to fire attack from the outside. Kovarsky[38] also did not perform tests, but reported investigation conclusions from several types of cases, which are generalized and expanded here:

- Arcing was found on the wiring inside an appliance at a location well away from external fire attack, and this is taken to indicate that fire originated internally, near this arcing locale. This scenario is innately questionable, since a fire originating inside an appliance is unlikely to then jump to far-off areas while leaving the near environs of the appliance unburned.
- The preceding scenario is narrowed to specify that, in addition, no arcing is found elsewhere inside the appliance, closer to the external fire. Again, this is a questionable scenario. More likely, a small, self-terminated fire occurred inside the appliance unrelated to the structure fire being investigated.
- Arcing was found inside the appliance at a location close to where an external fire would likely impinge on the device, but far from likely sources of ignition inside the appliance. Kovarsky considered that this allows one to conclude the fire originated externally. However, as discussed below, Hoffmann et al. showed that arcing inside an appliance from an external fire may more frequently be located near the externally heated area, but there is no reliable correlation. Thus, conclusions should not be drawn solely on the basis of distance between the external thermal attack and the location of internal arcing.
- Arcing is found on the cord or plug of the appliance, but no arcing is found inside. Kovarsky considers that this rules out the hypothesis of fire originating inside the appliance. However, this is not a valid deduction from general principles of science, and by itself such a condition does not preclude the origin of the fire being inside the appliance. A fire originating inside the appliance may create arcing close to the origin, inside the appliance, but this is not required. Fire may originate internally at a bad connection or an overheated component, but at a place where wiring cannot readily short out and arc. In such a case, it may well be possible for fire to emerge from the appliance and attack a nearby cord or plug outside. However, any arcing found inside an appliance warrants a detailed laboratory examination of the item.

Hoffmann et al.[39] conducted a test to examine the question whether arcing may occur inside appliances due to an external fire. They set up a single room test where three appliances—a refrigerator, a dishwasher, and a clothes dryer—were exposed to the room fire that was started in a trashcan. The dishwasher showed arc damage at several locations inside the appliance. The refrigerator showed arcing to three different internal circuits, but all close to the same general location. The dryer showed arcing on its power cord and at five different locations in its internal wiring. Two of the 5 locations were near the back of the unit, far away from the room fire that was in front of the appliance. These results indicate that an external fire can readily cause arcing inside energized appliances, but does not support the notion that arcing necessarily will be confined to portions of the interior most directly proximate to the external fire attack. In some cases, external fire attack may be close to the front of an appliance, but internal shorting may occur due to radiant heating from overhead.

The correct conclusion with regards to appliance wiring is that the same principles are obeyed as for room fires. The propensity to arc is related to the propensity for thermal damage, but the latter is controlled by fuel arrangements and ventilation patterns, and not just by time elapsed from start of flaming at a given location.

Hoffmann[40] also presented a scenario where two appliance cords are plugged into an outlet, the circuit breaker has tripped, but only one cord shows arcing (but *not* welded together). Hoffmann suggests that the appliance whose cord does not show arcing can be ruled out as being the origin of the fire. In some cases, an engineering analysis may demonstrate that this is likely to be true, but no fundamental science principles require it to be so. Burning of fuel packages commonly occurs so that, if flames are going to cause cord shorting, this will occur first to the cord of the equipment burning, rather than to a cord of neighboring equipment. But arrangements can also be such that the converse will be true. Thus, a general behavior cannot be assumed in the absence of a specific engineering analysis.

THE ROLE OF APPLIANCE FUSES

Some appliances are required by pertinent product standards to have internal or plug-mounted fuse protection (or, occasionally, circuit breaker protection). In some other cases, protection is not mandatory, but the manufacturer may provide it nonetheless. Does the blowing of the fuse, or the fact that the fuse is intact, indicate anything about the origin of the fire? Kovarsky[38] correctly explained that, in general, no conclusions can be drawn beyond the trivial one that that if a fuse blew due to overcurrent then the appliance was energized at some time prior or during a fire. Note that even the time period for this cannot be established. A fuse may have blown some time prior, and unrelated to a fire. Methods exist to distinguish fuses melted from overcurrent versus external fire heating however[41,42].

ERRONEOUS CONCEPTS

Any concepts associated with arc mapping practice can be rejected without need for considering experimental results or validation, if they are based on an incorrect understanding of electrical science. One such incorrect principle has been succinctly expressed as[43]: "*A basis for arc mapping is the idea that on any given circuit, electrical activity that is furthest from the electrical source (e.g. panel box) occurred prior to activity that is closer to the electrical source*." The concept was first enunciated by Rothschild[11], then later presented by others[12,38,44,45]. But the early researchers Miyake[9] and Delplace and Vos[10] correctly understood that this is not a general conclusion but only holds if there is a sever-arc—then any electrical activity after that must be upstream of the severing location. And Bernstein[30] explained that: "The arcing farthest from the power source probably occurred first *if arcing closer to the power source caused conductors to separate*." This follows from simple continuity, since current cannot flow beyond a severed place and therefore arcing cannot take place. There is some possibility that arcing will occur at two places simultaneously, thus a more correct version of Bernstein's statement would be: "Arcing downstream of a server point cannot have occurred later than the sever-arc location.[*]"

Recent authors have generally not explained the basis for their erroneous conception, but Rothschild made his basis clear: he did not differentiate between a bolted short and an arcing short, and thought that, once a short occurs, this means that no current is available to flow downstream of that point. In fact, arcing shorts on 120 VAC, and even 240 VAC, circuits are short-lived even when a circuit breaker is not tripped[47]. The arc may self-extinguish during the next zero-crossing of the current. But magnetic forces tend to push the conductors apart[48], aided by flow of molten material. Thus, an arcing short clears itself and, if the circuit breaker has not tripped and conductor severing has not occurred, the circuit is able to carry current further downstream. Rothschild did correctly point out that, when shorting occurs, current in the conductors upstream will necessarily increase, and this increased current may lead to

[*] An arc traveling on bare, parallel conductors (e.g., busbars) will move away from the current source (due to Lorentz force), not towards it, but this situation is not applicable to insulated conductors. It also requires that no circuit breaker tripping occur during the travel away from the power source. See Ref. 46.

arcing failures upstream. In another early paper, Sanderson[44] thought that arcing further downstream from the original arc cannot take place since all arcs will be sever-arcs, but this is also not correct.

ARC MAPPING APPLICATIONS WHICH DO NOT REQUIRE VALIDATION

Several arc mapping scenarios follow directly from accepted science principles and, therefore, do not need validation.

(1) Arc marks are found on some conductor(s). This indicates that the circuit was energized at the time of shorting. The conclusion can be reliably made, but will only rarely be of assistance in establishing the origin of a fire.

(2) Multiple arcing, including a sever-arc or a weld-arc. A conductor has multiple arc marks, but one arc location is a sever-arc. Circuit continuity demands that any arc marks downstream of the sever point had to have occurred before (or simultaneous with) the sever-arc[10,30]. Note this specifically refers to situations where the hot conductor is severed. If the neutral or ground conductors are severed, but not the hot conductor, then arcing downstream of the sever point might potentially be possible if the unsevered hot conductor comes into contact with some other grounded objected, e.g., a water pipe. Further analysis should be done to rule out such contact. In the same manner, if an arc location is found where the conductors are welded together, then no significant current can flow downstream of that location. Thus, if a downstream arc location exists, it could not have been formed later than the one at the welded-short location.

(3) Welded-short conductors. Two cords are plugged into one outlet and both cords show arcing, but the conductors on one cord are welded together, while the other cord shows arc marks, but not welded-together conductors. The circuit breaker is tripped. The cord that was welded then necessarily had to be the second event, since if it were first, the circuit breaker would have tripped due to welded-short conditions. This scenario was described by Utt[49].

RELIABILITY OF ARC MAPPING

Churchward and Ryan[15] (Churchward was the Chair of the NFPA Technical Committee on Fire Investigations when arc mapping was first introduced into NFPA 921) pointed out that "*Reliance solely on an arc survey to determine the…proposed area of fire origin places far too much importance on a technique that cannot always be reliable or validated*." They also noted that if the building is not de-energized relatively quickly, there is likely to be an abundance of arc sites and the imputed 'area of origin' is likely to be huge. They further cautioned that it is not logical to conclude that a circuit where the wire insulation burned up, yet which shows no arcing must have burned only after the power was removed, since exposure of an energized circuit to flaming *may* lead to arcing, but *not inevitably*.

Similarly, Wheeler[28] observed very recently (2015) that "*a great deal has been written about arc mapping*," however "*there are many factors that influence the reliability of arc mapping* [yet] *very little has been published that specifically addresses such factors or concerns*." This is actually an excessively optimistic assessment of the reliability of arc mapping. While more experimental studies might reveal additional information, the existing studies already suffice to indicate that, arc mapping is unreliable and unscientific if a hypothesis is made that abundance of arc beads at a given locale means that fire originated in that area, while a paucity of arc beads indicates that it did not. Only in some narrow circumstances, as discussed above, can sound, technically justified conclusions be drawn from the results of arc mapping.

Wheeler's own tests, even though not numerous, have been important for understanding the reliability of arc mapping, since he has been the only researcher to conduct experiments on the effect of wiring behind protective barriers (Novak[50] presented some theoretical modeling of this situation, but not room fire experiments). Analysis of his actual results (but not necessarily his published conclusions) indicates that:

- Significant arcing is likely to be found in areas subjected to ventilation air flows
- Significant arcing is likely to be found in areas of heavy fuel load concentration
- The above two factors tend to dominate the arcing patterns found, and arcing is not likely to be concentrated in the area of fire origin, unless this happens to be an area of heavy fuel load concentration or within the inflow region of incoming ventilation air.

While early researchers hoped that arc mapping would somehow prove to be more reliable than char-depth interpretation, experimental work has not borne this out. Instead, the experimental studies indicate that arc mapping has the same limitations as char-depth studies—local fuel load effects[51] and local ventilation effects[52] are likely to be dominant, and not the location of the fire origin. This is true of *all* the research studies that have been published to date and have been examined here. There is no basis to believe that arc beading will be found to be plentiful in the area of origin, and not present (or sparsely present) in areas away from the area of origin.

Additional considerations with regards to lack of validation are the following:

(1) In most structures, the majority of building wiring is behind protective membranes, not out in the open. Wheeler's study indicates that arcing patterns behind protective membranes do not bear a significant relationship to the area of fire origin. No other researchers have used such realistic test arrangements, but even their results, if interpreted in an unbiased way, do not suggest that arc mapping is a reliable pointer to the location of the origin of a fire. Carey[24] succinctly noted that arc mapping "*is of limited value when the cables are protected from the fire in the initial stages, for example, buried in plaster or installed behind plaster board in cavity walls*."

(2) Arcing cannot occur where there are no conductors to arc. Most of the experimental studies have been based on a tacit assumption that there is a densely-spaced grid of wiring available for potentially shorting and arcing. This will rarely be true and, in most cases, cable runs are sparsely and irregularly distributed. In other cases, a significant grouping of adjacent, parallel circuit cables may be found, often at locales near the load center[53]. Thus, presence of arc beads may indicate mainly where wiring runs were located, rather than revealing anything useful about the progress of the fire.

(3) Furthermore, runs of branch-circuit wiring are likely to be concentrated below the floor, or in the lowest portions of walls. Generally, much fewer circuits are run along ceilings or in the upper portions of walls. Thus, wiring in practice is most likely to be concentrated along the areas where there is least likely to be early fire damage to it. Consequently, experimental studies based on closely-spaced ceiling grids, when applied to such situations, will necessarily present a positive bias.

(4) Arcing and shorting may preferentially occur at places where there is a kink or bend in the cable, or a similar stress situation that facilitates shorting of heated wires. No study has explored this.

(5) Arcing may occur, but not create an artifact that can be unambiguously associated with arcing[23]. This can also include situations where an identifiable artifact was created, but was subsequently obliterated by fire melting, corrosion, or other fire effects.

(6) Few studies exist for arc mapping pertinent to stranded-wire conductors and none for wires inside conduits. However, there is no basis to believe that arc mapping in those situations would be valid under more scenarios than for branch-circuit wiring in NM cables.

(7) There have been no validation studies of arc mapping in motor vehicles, which also use stranded wires, but typically have low-voltage DC power supplies and sometimes use circuits with no overcurrent protection.

(8) In many cases, the structure will have multiple rooms, and the first task facing the investigator may be to identify the room of origin. No study exists where arc mapping was experimentally studied for a multi-room building. However, there is no basis for assuming that such application would allow valid use of arc mapping under broader circumstances than is justified for single-room scenarios.

PROBABILISTIC EVALUATION

The main scenario for which valid electrical science allows positive conclusions to be drawn from arc mapping is the severed-wire scenario. For this scenario, probabilities of occurrence can be evaluated, at least for solid-conductor branch circuits. Based on the results of West and Reiter[26] and Carey[14] given above, there is approximately a 5% probability of a second arc on any particular circuit that has arced. The probability is 29% that an arc will be a sever-arc. But conclusions can only be drawn if the non-sever arc is downstream of the sever-arc. Since, in general, there is no bias where the second arc occurs, there is a 50% probability for the downstream location. Thus, the probability is $0.05 \times 0.29 \times 0.5 = 0.0073$, which is 0.7%, that a circuit with arcing evidence will allow the direction of fire movement to be scientifically established. Limited findings suggest that the likelihood may be much higher for stranded wires, but quantitative estimates are not available.

CONCLUSIONS

Procedurally, arc mapping is a technique for plotting locations of arc marks on a floor plan (map) of a building. As such, it is non-controversial, assuming that the arcs (or absence thereof) are correctly identified and plotted. Conclusions drawn from an arc map, however, may be unreliable and inconsistent with known science, depending on the inferences being drawn.

Arc mapping is a tedious process, since it requires detailed examination of all the conductors in the relevant building area, which is likely to be a painstaking process. In addition, it requires that the circuits be traced and identified, which can be difficult to do. This requirement may also make arc mapping impossible, since there are many fires where, due to the type of damages sustained, circuits cannot be successfully traced. In case of serious fires, structural collapses may produce a jumble of wires with no means of reassembling into their original locations.

Once an arc map is prepared, in a small fraction of cases, reliable conclusions can be drawn from applying basic principles of electricity, especially the fact that arcing cannot occur without current flow, and current cannot flow in circuits beyond a sever point, or if a circuit breaker has tripped. But in the majority of cases, principles of science do not allow conclusions to be drawn from an arc map with regards to the origin of the fire. *In the cases where valid conclusions can be drawn, they only establish the local direction of fire movement at a specific locale, and do not suffice to identify the area of origin of the fire.* Reliable conclusions on the local direction of fire movement can be drawn in those cases where the branch circuit has a sever-arc or a weld-arc, and an additional arc downstream of this location. But experimental data indicate that the probability of a building's branch circuit exhibiting these conditions for allowing a valid arc-mapping conclusion is less than 1%, and is estimated to be 0.7%. This pertains to solid-core conductors; not enough research has been conducted on stranded wire arcing to be able to draw statistical conclusions.

Delplace and Vos proposed the arc mapping method on the basis of two hypotheses: (1) that patterns of arcing will be spatially similar to patterns of combustion damage; and (2) that arcing locations will tend to reflect the early boundaries of flame spread. Hypothesis #1 has been shown to be generally true, but also generally unhelpful. Hypothesis #2 is not supported by principles of science, nor by experimental studies of arc mapping.

Experimental studies have borne out the Delplace/Vos hypothesis that arcing patterns tend to correspond to patterns of combustion damage, specifically intensity of damage, e.g., as found from char-depth studies, at least in a stochastic sense. Consequently, arcing patterns can reflect:

- fuel loading configurations;
- ventilation, specifically, air inflow patterns; and
- duration of burning.

Only the last variable has any relation to the potential of an area being the area of origin for the fire. If fuel loads were uniformly distributed, and combustion air inflows also uniformly and diffusely supplied, then arcing patterns could be expected to reflect the duration of burning and, thereby, point to the area of origin. But such conditions are essentially never true in actual buildings. Thus, there is no valid basis to claim that arc patterns will identify the area of origin. But additionally, fire damage to cabling has a strong stochastic aspect. This includes both the local heat fluxes generated by the fire, and the local susceptibility of the cable to shorting and arcing. The general trends and magnitudes of heat fluxes may be modeled, but due to the turbulent nature of fire and the complexities of local geometry irregularities, precise deterministic estimates cannot be expected. The response of cables to heat is even less amenable to calculation. A limited amount of experimental data exists, but data scatter is large due to complexities such as wire stresses and cable twists.

Inside habitable buildings, wiring is occasionally placed in the open, unprotected. But in most cases, wiring is behind protective layers such as plaster, wallboard, or masonry. Such protective layers will inhibit early thermal attack on the wiring. They will also smooth out the temperature gradients, so that failure of wiring should be expected only when the fire has become widespread, instead of still being localized near the area of origin. Consequently, if the actual wiring is behind protective layers, experiments that are based on unprotected installations innately have a bias towards positive findings.

The totality of published experimental results does not support the ability of arc patterns to identify the area of fire origin. This is especially notable, since most studies have been effectively biased in favor of positive findings, due to lack of thermal protection for the circuits being fire-exposed. And even in the one study that did use thermal protection, the installation was not compliant with the electrical code, and the non-compliance was such as to bias the results towards a positive finding.

In some locales, all wiring is required to be placed in metallic conduits. There have been no experimental data on the arcing patterns in buildings using such wiring methods.

Some authors have published conclusions that are at variance with their data. The fact that some experiments show a presence, or even a copious presence, of arcing in the vicinity of the area of ignition does not logically indicate that arc mapping can distinguish between areas of fire origin and areas where fire did not originate. To be able to make such a claim would require demonstration that arcing is sparse or nil in areas where fire did not originate. However, this is impossible, since there are already sufficient data showing not only that arcing may readily be found in areas not close to the area of origin but that, in some cases, such arcing is more copious than arcing near the origin. The following are myths:

- An abundance of arc beads at a given locale means that fire originated in that area, while a paucity of arc beads indicates that it did not.
- When multiple arcs are present on a circuit, the direction of arcing will necessarily proceed upstream towards the power source.
- If an appliance is the victim of a fire, internal arcing will be primarily near the exterior of the unit, while arcing deep inside indicates a fire origin at that place.

No evidence exists that arc mapping of stranded-conductor wiring can be used to establish the origin of a fire any more so than with solid-conductor wires. However, because arcing on small-diameter stranded wires may be much less likely to trip circuit breakers, it can occasionally be useful towards establishing the *direction* of fire spread in a limited, local area, if multiple sever-arcs are encountered along the length of the same cord.

In fire investigation reports, it is not acceptable for an investigator to report that a conclusion was based simply on "arc mapping." There are a few circumstances where arc mapping may be utilized in a scientifically acceptable manner. But there are many more ways in which arc mapping may be used based on unsupported or disproven hypotheses. Thus, it is essential to identify explicitly the exact hypothesis being invoked, and how the conclusions follow from that hypothesis. A parallel to "photographic evidence" may be helpful. Photographic evidence may reliably enable some conclusion to be drawn, but if that is to happen, the exact items being illustrated in the photographs have to be clearly and explicitly identified. Simply stating that photography was done and that the investigator's conclusions are based on photography is without merit.

NFPA 921 should be revised to eliminate arc mapping as one of the four main methods for establishing fire origin, and to subsume it under the more general category of "fire patterns." In addition, it is important that NFPA 921 reduce the implied general utility of the method and provide more explicit discussion of its limitations and of those circumstances where arc mapping is a valid method for assisting in the determination of a fire origin.

REFERENCES

1. Shanley, J. H. jr., Fire Investigation Change and Evolution, Part 1: An Overview, *Fire Engineering* **147**:1, 42-46 (Jan. 1994).
2. Coleman, R. J., and LaBarbera, B. T., **Arson Investigation…a Team Approach**, California District Attorneys Association, Sacramento (1994).
3. Lentini, J. J., The Mythology of Arson Investigation, pp. 301-312 in *ISFI 2006—Proc. 2nd Intl. Symp. on Fire Investigation Science & Technology*, NAFI, Sarasota FL (2006).
4. Kennedy, P. M., Insights into Fire Investigation from Fifty Years of Professional Practice: What's Wrong? What's Right? What's the Difference, pp. 3-13 in *ISFI 2010—Proc. 4th Intl. Symp. on Fire Investigation Science & Technology*, NAFI, Sarasota FL (2010).
5. Ablenas, F. J., and Bodzay, S. J., Surface Analysis of Beaded Electrical Conductors towards the Determination of Fire Causation (Report 9018 U 810), Canadian Electrical Assn., Montréal (1994).
6. Guide for Fire and Explosion Investigations (NFPA 921), National Fire Protection Assn., Quincy MA (2017).
7. Babrauskas, V., Arc Beads from Fires: Can 'Cause' Beads Be Distinguished from 'Victim' Beads by Physical or Chemical Testing? *J. Fire Protection Engineering* **14**, 125-147 (2004).
8. Straeter, R. L., and Crawford, C. C., **Techniques of Arson Investigation**, R. L. Straeter, Los Angeles (1955).
9. Miyake, K., Fire Investigation—Article No. 5 in a Series of Articles on Scientific Investigation (in Japanese), *Sosa Kenkyu* **24**:1, 45-57 (Jan. 1975).
10. Delplace, M., and Vos, E., Electric Short Circuits Help the Investigator Determine Where the Fire Started, *Fire Technology* **19**, 185-191 (1983).
11. Rothschild, L. I., Some Fundamental Electrical Concepts in Locating the Cause and Origin of a Fire, *National Academy of Forensic Engineers J.* **3**:2, 37-44 (1986).

12. Svare, R. J., Determining Fire Point-of-Origin and Progression by Examination of Damage in the Single Phase, Alternating Current Electrical System, *Journal of People to People, International Arson Investigation Delegation to the People's Republic of China and Hong Kong* (1988).
13. Svare, R. J., Using the Electrical System to Help Reconstruct the Fire Scene, pp. 103-116 in *Proc. Intl. Symp. on the Forensic Aspects of Arson Investigations*, Federal Bureau of Investigations, Washington (1995).
14. Carey, N. J., Developing a Reliable Systematic Analysis for Arc Fault Mapping (Ph.D. dissertation), Univ. Strathclyde, Strathclyde, UK (2009).
15. Sanderson, J. L., Cotton Balls not Just for the Medicine Cabinet Anymore, *Fire Findings* **9**:2, 14 (Spring 2001).
16. Churchward, D. L., and Ryan, R. M., The 'Benefits' of Arcing, pp. 27-38 in *ISFI 2010 – Intl. Symp. on Fire Investigation Science & Technology*, Natl. Assn. of Fire Investigators, Sarasota FL (2010).
17. Lancaster, T., and Meadors, A., Preliminary Analysis of Energized and Non-energized Multi-Stranded Copper Wire within Three Full Scale Compartment Fires, pp. 383-393 in *ISFI 2012—Proc. 5th Intl. Symp. on Fire Investigation Science & Technology*, NAFI, Sarasota FL (2012).
18. Sanderson, J. L., and Dwyer, N. P., Arc Mapping Basics: Inspect, Document and Understand the Pitfalls, *Fire Findings* **13**:2, 9-11 (Spring 2005).
19. Fogle, J. L., In a Fire Scene, What Does a Tripped Circuit Breaker Indicate? *Fire & Arson Investigator* **35**:4, 9-10 (June 1985).
20. Churchward, D. L., Cox, R. M., and Reiter, D., Means to Determine Fire Origin in Residential Structures, *ISFI—Proc. Intl. Symp. on Fire Investigation Science & Technology*, Fire Service College, Moreton-in-Marsh, United Kingdom (2004).
21. Johnson, W., and Rich, L. V., Arc Fault Analysis: Post Flashover Studies of the Power Cord, *2007 Fire and Material Conf.,* Interscience Communications Ltd, London (2007).
22. Karasinski, J., Robin, D., DeMatthies, H., and Hauf, G., Arc Mapping. An Explanation and Example, *Fire Scene* (Newsletter, New York State Chapter of IAAI) (Spring 2009).
23. Babrauskas, V., Short-Circuit Arc Marks, to be published (2017).
24. Carey, N. J., Comparison of Behaviour during Fire: U.K. & U.S. Electrical Wiring Systems, London Fire Brigade (1999).
25. Carey, N. J., Svare, M. J., and Daeid, N. N., Arc Fault Mapping—A Technique to Assist in Identifying a Fire's Area of Origin, presented at The Forensic Science Society, Leicester, England (2003); also *IAAI Annual General Meeting* (2006).
26. West, L., and Reiter, D. A., Full-Scale Arc Mapping Tests, pp. 325-339 in *Fire & Materials 2005*, Interscience Communications Ltd., London (2005).
27. Wood, C. B., and Kimball, A., A Preliminary Report of Full-Scale Arc Mapping Test Results, pp. 615-627 602 in *ISFI 2010 – Intl. Symp. on Fire Investigation Science & Technology*, Natl. Assn. of Fire Investigators, Sarasota FL (2010).
28. Wheeler, D. M., Arc Mapping: Things to Consider, *Fire & Arson Investigator* **66**:1, 18-24 (July 2015).
29. National Electrical Code (NFPA 70), National Fire Protection Assn., Quincy MA (2014); Sec. 300.4.
30. Bernstein, T., Electrical Fires: Causes, Prevention, and Investigation, pp. 116-134 in E. K. Greenwald, ed., **Electrical Hazards and Accidents: Their Cause and Prevention,** Van Nostrand Reinhold, New York (1991).
31. Hoffmann, J. M., Hoffmann, D. J., Kroll, E. C., Wallace, J. W., and Kroll, M. J., Electrical Power Cord Damage from Radiant Heat and Fire Exposure, *Fire Technology* **37**, 129-141 (2001).
32. Johnson, W., and Rich, L. V., Arc Fault Analysis: Post Flashover Studies of the Power Cord, *2007 Fire and Material Conf.,* Interscience Communications Ltd, London (2007).
33. Johnson, W. B., and Rich, L. V., Arc Mapping Follow Up, *Fire Findings* **15**:3, 7-11 (Summer 2007).
34. Hoffmann, J. M., Hoffmann, D. J., Kroll, E. C., and Kroll, M. J., Full Scale Burn Tests of Television Sets and Electronic Appliances, *Fire Technology* **39**, 207-224 (2003).
35. Hazelwood, T. A., The Effectiveness of Arc Mapping to Determine Fire Origin Area, *Claims Magazine* (July 2012).
36. Stahl, D. R., and Parrott, K. D., Applicability and Limitations of Arc Mapping in Vehicle and Equipment Fire Investigation, pp. 617-623 in *ISFI 2012—Proc. 5th Intl. Symp. on Fire Investigation Science & Technology*, NAFI, Sarasota FL (2012).
37. Shanley, J. H., Intra-Appliance (Electric Clothes Dryer) Arc Mapping to Assist Fire Origin and Cause Determinations, pp. 83-89 in *ISFI 2008—Proc. 3rd Intl. Symp. on Fire Investigation Science & Technology*, NAFI, Sarasota FL (2008).
38. Kovarsky, R., Arc Mapping and Appliance Investigations, pp. 293-302 in *Proc. Intl. Symp. on Fire Investigation Science & Technology – ISFI 2016*, Natl. Assn. of Fire Investigators, Sarasota FL (2016).
39. Hoffmann, D. J., Swonder, E. M., and Burr, M. T., Arc Faulting in Household Appliances Subjected to a Fire Test, *Fire Technology* (2016).
40. Hoffmann, D. J., Beyond Tea Leaves—Using Arc Mapping to Pinpoint Origin and Cause of a Fire, *Fire Science and Litigation Seminar*, Defense Research Institute (2013).
41. Buc, E. C., Influence of Overcurrent and Heat on Tin Coated Copper Fuse Elements, pp. 311-324 in *Fire & Materials 2005*, Interscience Communications Ltd., London (2005).
42. Twibell, J. D., and Christie, C. C., The Forensic Examination of Fuses, *Science and Justice* **35**, 141-149 (1995).
43. Kovarsky, R. P., The Use and Misuse of Engineers in Fire Investigation, pp. 371-375 in *ISFI 2012—Proc. 5th Intl. Symp. on Fire Investigation Science & Technology*, Natl. Assn. of Fire Investigators, Sarasota FL (2012).
44. Sanderson, J. L., Arc Mapping May Provide Valuable Clues of Fire's Origin, *Fire Findings* **7**:2, 12-13 (Spring 1999).

45. Carey, N., Powerful Techniques—Arc Fault Mapping, *Fire Engineers J./Fire Prevention* 47-50 (Mar. 2002).
46. Land, H. B. III, The Behavior of Arcing Faults in Low-Voltage Switchboards, *IEEE Trans. on Industry Applications* **44**, 437-444 (2008).
47. Babrauskas, V., **Ignition Handbook**, Fire Science Publishers/Society of Fire Protection Engineers, Issaquah WA (2003).
48. Beavis, E. A., Cable Short Circuit Currents, *Electrical Review* **150**:3874, 385-388 (22 Feb. 1952).
49. Utt, D. P., Bringing Science into the Courtroom, *2009 IEEE Symp. on Product Compliance Engineering*, IEEE (2009).
50. Novak, C. J., An Analysis of Heat Flux-Induced Arc Formation in Residential Electrical Cables (M.S. thesis), Univ. Maryland, College Park (2011).
51. DeHaan, J. D., and Icove, D. J., **Kirk's Fire Investigation**, 7th ed., Brady/Prentice-Hall, Upper Saddle River NJ (2012).
52. Babrauskas, V., Charring Rate of Wood as a Tool for Fire Investigations, *Fire Safety J.* **40**, 528-554 (2005).
53. Goodson, M., Perryman, T., and Colwell, K., Effects of Polyurethane Foam Systems on Wiring Ampacity, *Fire & Arson Investigator* **52**:4, 47-50 (July 2002).

Fire and Materials 2017

15th International Conference

San Francisco, California, USA

6th – 8th February 2017

Published by

interscience communications

London, UK

www.intersciencecomms.co.uk

The organisers wish to thank and acknowledge the companies for their sponsorship

American Chemistry Council | North American Flame Retardant Alliance

FTT Fire Testing Technology

Kingspan

FM Global