

ARC SURVEYS AS A MEANS TO DETERMINE FIRE ORIGIN IN RESIDENTIAL STRUCTURES

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Abstract: Literature searches failed to locate any published research on the validity of arc surveys in the determination of fire origin. This paper will present a statement of the problem, a discussion on the definition of an arc survey, how to properly perform an arc survey, discussion on the best means for documentation of an arc survey, and issues related to evidence gathering of an arc survey. Furthermore, this paper presents the results of two successful experiments to validate arc surveys as a means to determine the origin of a fire.

Key words: area of origin determination, arc surveys, arc mapping, arcing through char.

INTRODUCTION:

The investigation of fires is principally done to accurately determine the cause for fires and, thereby, prevent such causes from happening again. Cause determination investigations begin, generally, once the point or area of fire origin is identified. Without an accurate determination of the area of fire origin, the cause determination investigation generally becomes nearly impossible.

The principal means for determining the origin of a fire is by the analysis of fire patterns on surviving structural and component surfaces.¹ The difficulty in this technique lies with those fires that have progressed beyond flashover.² Under such conditions, the extent of destruction, the variability of materials' response to attack by fire, suppression activities and a host of other circumstances can make the determination of origin by fire pattern analysis unverifiable. Further confounding the problem is the lack of scientific verification that specific fire patterns can be created exclusively by specific fire effects.

A large majority of residential structures in the United States contain 120-volt, copper electrical conductors, in the form of NM branch circuits, power cords and extension cords, sheathed in a plastic insulation such as poly-vinyl-chloride (PVC). All of these insulation materials have relatively low resistance to thermal deterioration, which results in their maximum operating temperatures being limited.³ These electrical circuits are routinely energized at all times, at least up to their respective switches. These circuits are subject to attack by fire in the structure both within the living spaces and the interstitial spaces. The effects of fire upon electrical distribution systems within residential structures are well known and can range from thermally stressing the insulating medium to melting the conductors. In many residential fires, the extent of destruction involves the charring of the insulation medium, and subsequent arcing through char between energized phase conductors and the neutral or ground or both.⁴

At the onset of a fire inside a residential structure, much of the electrical system remains energized unless the fire origin involves the immediate vicinity of the service entrance equipment. Eventually, the fire will cause the electrical system to de-energize or the fire department will shut off the electrical supply to the structure. In either event, any damage that occurs to the electrical conductors from electrical faulting will have occurred in the earlier stages of the fire.⁵ This relationship between the onset of the fire and when fire-induced arcing occurs permits the investigator to differentiate between those energized circuits that were attacked by fire, from those circuits that were de-energized when fire attacked them. It stands to reason that if a fire investigator can identify the location where fire attacked electrical circuits before they

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were de-energized, and compare the arcing-through-char locations for spatial commonality in the structure, then the circumstantial evidence can argue that the fire originated within the vicinity of the locations where the arcing occurred.

STATEMENT OF PROBLEM:

The argument “it stands to reason” carries little scientific weight given that incorrect application of logic can produce incorrect beliefs. There is anecdotal evidence that arcing has occurred about the area of fire origin. However, relying solely on observations made at a fire scene can produce mistakes as well. The need exists to conduct experiments to validate a hypothesis that locating common arcing sites will assist in identifying the area of fire origin in a residential structure fire.

There is considerable research that 120-volt conductors will arc through charred insulation.^{6,7} There is research that establishes that heat flux as low as 8.5 kW/m² will produce arcing in NM copper conductors.⁸ Although not a stated purpose of the paper, Ferrino’s research developed several issues related to fire-induced arcing in residential wiring.

There is a lack of valid scientific research to establish that the arcing sites will pattern themselves about the area of origin. Conducting an arc survey does not appear to be routinely done at fire scenes, possibly because there has not been a definitive discussion on how to conduct such a survey. If arc surveys are being performed routinely at fire scenes, then the subsequent documentation is not reflected in reviews of the files.⁹ Other issues that enter the discussion include the magnitude of the arc may have been so small that it did not leave evidence readily detectable by touch or sight, the arcing evidence may be perceived to be fire melting, and some residential electrical conductors are made of aluminum which will have widespread melting in most post-flashover fire scenes that would camouflage any evidence of arcing having occurred. For purposes of this paper, all future references to conductors will be referring to copper conductors. Furthermore, the term “bead” will be defined as copper geometry created by arcing, that can take on an appearance of a ball, localized notch, eruption or protrusion or some other anomaly on the surface of the conductor.

PURPOSE OF PAPER:

This paper will attempt to define an arc survey, offer a practical technique to conduct an arc survey, recommend techniques on how to document such surveys and discuss evidentiary collection methods.

One such research project was performed specifically to test the hypothesis that electrical conductors will arc in the immediate vicinity of the fire origin. A fire was started in three duplicate hotel rooms in which a grid of energized electric wires was placed across the ceiling. At the conclusion of each test burn, the grid was searched for evidence of electrical arcing and the locations pinpointed in relationship to the area of origin of the fire. This paper will introduce this research and its findings.

Lastly, this paper will discuss the potential for error that can occur by the practical use of arc surveys.

DISCUSSION:

An arc survey (also referred to as “arc mapping”)¹⁰ is the identification of all locations on the electrical distribution system where an arc has occurred and the pinpointing, as precisely as possible, of the location of each arc site on a diagram of the structure. The means to identify the locations where an arc occurred is by locating each bead found on the conductors.^{11,12}

Pinpointing the location of beads on a site plan and elevation drawings includes several steps. First is the actual process where the beads are identified on the electrical circuits. This process can be both time

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consuming and difficult. The size of each bead can vary from the obvious indicator where the conductor is severed to the infinitesimal indicator that can only be seen under magnification. The detail in examining each circuit becomes one measure of the validity of the survey. To insure that the search is thorough, one should implement a methodology that allows for a systematic, step-by-step examination of all circuits. One such process is as follows:

1. Identify the area that will be searched;
2. Sketch and diagram the area as completely and accurately as possible;
3. Identify zones within the search area, such as ceiling, floor, north wall, south wall, etc.;
4. Arbitrarily identify all conductors passing through the zone, noting when possible: loads on each circuit, direction of power flow, locations of junction boxes, outlets, switches (or any such control), size of each conductor, and the over-current protection;
5. Search conductors in each zone completely before moving on to the next zone;
6. Determine if the melted copper occurred from arcing or environmental heat;
7. Locate the bead on the sketch and make notes as to its physical characteristics, such as faulted to another conductor in same cable, faulted to conductor from another cable, completely severed conductor, partially severed conductor, etc.;
8. Flag bead location if survey results are to be photographed or videotaped.

Typically, searching each conductor can be done by passing the conductor through one's fingertips, feeling the surface for imperfections, either convex or concave. Once the imperfection is detected, the location is examined visually to assess if the imperfection is the result of metal loss or deposit (a possible arc site), or from some other reason, such as dirt accumulation and charred insulation scale. Search the entire length of the damaged conductor in case there are multiple sites where arcing occurred on the same conductor.¹³ Locate each arc site on the plan and elevation drawings as precisely as possible to assist in reducing the volume of the area within which the arcing occurred.

Fire melting of conductors can be difficult to distinguish from melting caused by arcing through char. The primary distinction between the two is the relative area where the melting is found. Arcing creates quite localized damage where the temperatures will exceed the melting temperatures of copper. Melting from environmental heating will be relatively widespread and may involve numerous conductors in an area. NFPA 921 provides several photographic examples of the two types of damage patterns. Some locations of melting on the conductors may not be quantifiable as to what caused the melting. Such locations can be noted on the documentation as possibilities or as unknowns. Metallurgical analysis may be employed to assist in differentiating environmental heat damage from arcing.

Site sketches and drawings should be of sufficient detail and scale that the distribution system can be accurately depicted. The individual circuits should be described in sufficient detail to indicate their size, overcurrent protection, electric load served and whether they were located in the living spaces or within the interstitial spaces. If some circuits share a common interstitial space, make note of that as well. The data from these sketches can be transferred to scaled two- or three-dimensional drawings which will aid others in interpretation of the data.

Identification of the materials the cables are mounted to and the means used to attach the cables to the substrates should be noted.^{14,15} As destruction levels in the structure increase, the details on each circuit may become more difficult to determine, if not impossible. However, if environmental heating did not cause the individual conductors to melt or fall to ruin, the relative locations of the beads remains significant.

Identification of the overcurrent protection on each branch circuit should be noted if possible. The presence of ground-fault-circuit interrupters (GFCI) and arc-fault-circuit interrupters (AFCI) can add

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considerable detail to the analysis since both of these devices can trigger the de-activation of a circuit or branch quicker than relying on the magnitude of currents from arcing though char.

If one needs photographic documentation of the arc sites, colored ribbon or tape can be attached to the electrical conductors and photographed or videotaped in place. Should the need exist to take as evidence the “proof” of the arc survey, then one can harvest the electrical circuits in the structure. Harvesting each circuit, both those that arced and those that did not, will only be of value to others, however, if the spatial relationship of the circuits is maintained. This spatial relationship means that each harvested circuit must be identified sufficiently that someone can take it to the fire scene and place it back in its original location and pathway. Without this level of detail, any electrical circuit with or without arc sites on it becomes just another length of copper wire. The relationship in space of the arc sites to those cables that did not arc, and the individual arc sites, are the significant evidence; not the roll of fire damaged cable taken out of context.

Care needs to be taken to properly identify, tag and harvest electrical conductors.¹⁶ The conductors are occasionally brittle and can be quite fragile. Rough handling will result in fractures which make labeling and tagging much more tedious. Attachments to the conductors, such as junction box remains, can fracture, become loose and fall away which can potentially prevent any future circuit tracing.

TEST BURNS FOR CONDUCTING ARC SURVEYS:

On January 29, 2001, the initial phase of a testing program was begun to explore the arc mapping theory. Three compartments (test cells) were outfitted with identical electrical conductors in identical configurations. Identical circuit protective devices (circuit breakers) were used for each circuit and each test. Identical furnishings were installed in each compartment and identical ignition sources were utilized. It was theorized that with all the variables being equal for repeated tests, the progression of the fires could be documented by the time and location of the arcs, which occurred in the active electrical circuits as a result of the fires. In essence, the purpose of this undertaking was validation of the arc survey (mapping) technique with respect to fire origin determination.

The structure used for this full-scale burn test was an old 1950’s vintage motel in Marshall Township, Pennsylvania. Electrical power was provided to the structure via an aerial service drop from a pole-mounted transformer. That service fed an old 100-ampere, main disconnect switch. From this point, a 22.8 meter (75 foot) section of #2 AWG (American Wire Gauge) cable provided power to a new, moveable Cutler-Hammer circuit breaker panel. The breaker panel was moved into rooms behind each test cell so that it could be safely videotaped and not affected by the fire.

The ceiling in each cell was outfitted with a .61m by .61m (2 ft. by 2 ft.) grid of #14/2 NM Romex cable. Each horizontal run of Romex was powered from a separate new 15-ampere Cutler-Hammer circuit breaker in the panel. As the panel was moved behind each test cell and reconnected to the new grid, the same circuit breaker was used for the same numbered run of Romex (i.e., breaker #1 fed circuit #1, etc.).

The entire electrical distribution was analyzed for available fault current. It was calculated that the maximum amount of fault current available in each cell was approximately 320 amperes RMS for a line to neutral/ground arc.

Each cell was then burned. Ignition was accomplished using a roll of cotton batting soaked in 113.4 grams (4 oz.) of gasoline. This “igniter” was placed on the right side of each couch toward the back and up against the armrest. The fire in cell #1 began aggressively but soon extinguished due to a lack of ventilation. Only minimal data was collected from that test. Consequently, the last two test burns were considered in formulating these results.

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Cells # 2 and 3 burned as expected after modifications to increase ventilation. Each cell was allowed to burn for 12 minutes; neither one reached flashover. Figure 1 shows one of the cells after the burn. The Romex grid is visible on the ceiling. Patterns on the wall behind the couch and the severe calcinations in the corner of the ceiling might suggest that the fire originated in the middle or toward the left side of the couch.

During each burn test, the sequence of circuit breaker tripping was recorded along with the time. That data was ultimately compiled on spreadsheets. All of the conductors in each cell were then carefully examined for evidence of arcing and shorting. When an arc was found, its location was recorded and it was tagged with yellow ribbon. Figure 2 is a plan view drawing of cell # 3 showing the arc locations. The square box at the end of each wire run signifies the circuit number. The circles show the position of each arc and the number inside defines when in the sequence it occurred. Each conductor was then cut down and subsequently examined in a laboratory environment.

The laboratory documentation consisted of cleaning each site, recording observations and macro-photography. Of particular interest was the varying amount of conductor damage observed even though the circuits were protected by identical breakers and the available fault current remained constant. Figure 3 shows a substantial amount of damage in that the conductors are severed and there is some copper material missing. Figure 4, on the other hand, shows arc damage of an almost imperceptible nature. It was also noted that some of the arcs occurred between a “hot” conductor and a “ground” conductor while others took place between the “hot” and “neutral.” Some arcs involved all three conductors in the Romex bundle.

ANALYSIS:

Although one of the three cells self-extinguished, a substantial amount of useful data was developed from the other two. Thirteen arcs were documented in each cell. The location of each arc and its respective time of occurrence bore witness to the fire’s development. The first arcs took place almost directly above the fire’s origin. Subsequent arcs were observed to then occur in a radial dispersion outward from the original fire plume. The sequence of events dramatically characterized a typical fire growth scenario whereby the initial fire plume impacts a localized spot on the ceiling. Then, as the fire grows, a hot gas layer is created that progressed radially outward from the initial impact site on the ceiling. Theories contemplated before the test predicted this same type of arc pattern. Hence, the testing conducted on these two successful fires validated those theories. Additional, more-sophisticated testing should serve to reinforce this “arc survey” concept of fire origin determination.

ERROR DISCUSSION:

Conducting two successful experimental fires does not offer an overwhelming argument for arc surveys as a tool to successful fire origin determinations. A sample number larger than two would provide additional data for evaluation. However, all data points in these experiments were consistent with the hypothesis that such arc data is indicative of the area where the electrical circuits were first impacted by the fire.

In Ferrino’s tests, arc sites concentrated about the locations of metal staples used to affix her samples to the chosen substrate. All of the samples had a staple mounted mid span in the length of cable that was subjected to the heat flux. Almost all of the samples arced at one of the staple locations verses in space between the staples. In that testing, the staples used were full metal stirrups encompassing three sides of the cables. The apparent outcome is that full metal staples will promote arcing on fire-damaged cables sooner than in the instance of cables without full metal staples. The relative shifting of any arcing on cables because of the influence of metal staples should not unduly influence the arc survey results. The purpose of the survey is to identify an area of fire origin, not a point of fire origin. Furthermore, the National Electric Code® requires restraints periodically along the length of cables (in modern

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construction). Such a length of unrestrained cable may skew the results of the survey depending upon the relative size of the area of origin determined by the investigation.¹⁷ Noting the type and location of cable restraints will aid in addressing specific error questions in the survey.

Ferrino's work, as well as Hoffmann's, identified that the time for arcing to commence in externally heated cables varied depending on the substrate to which the cable was affixed. The dynamics of heat transfer between the heat source and the cable in air, or mounted on a substrate, caused the cables to fail at differing times. However, the difference in time may be of little importance to the origin determination as compared to when the electric power is OFF. It is the accumulation of multiple points where arcing occurred in one area of the structure that provides the basis of origin development hypotheses, not when each specific arc occurred in relationship to another arc. Again, noting the type of substrate to which the cable is attached, if any, will assist in answering specific error questions in the survey.

CONCLUSIONS:

These experiments support an argument that arc surveys can aid in the determination of fire origin. As observed, the electrical array above the flaming fuel package began to arc upon impact from the rising plume. As the ceiling layer spread radially from the plume, the array began to arc about the centerline of that impact point. The test was terminated prior to flashover. Assuming that flashover did occur and the copper conductors did not melt away, these arc sites would have survived to aid fire investigators.

The aid comes in the form of factual data of where the insulated electrical cables arced as a result of the fire's environment. The spatial relationship of where the arc sites are located in the structure can offer the investigator facts to form an opinion as to where the fire damaged the electrical distribution system before the electricity was shut off. Unless there are extenuating circumstances, such as complete destruction of the electrical distribution system, post-fire re-energizing of the electrical system, or the inability to recognize arc damage on conductors, the reasoning behind the hypothesis should stand an ensuing challenge.

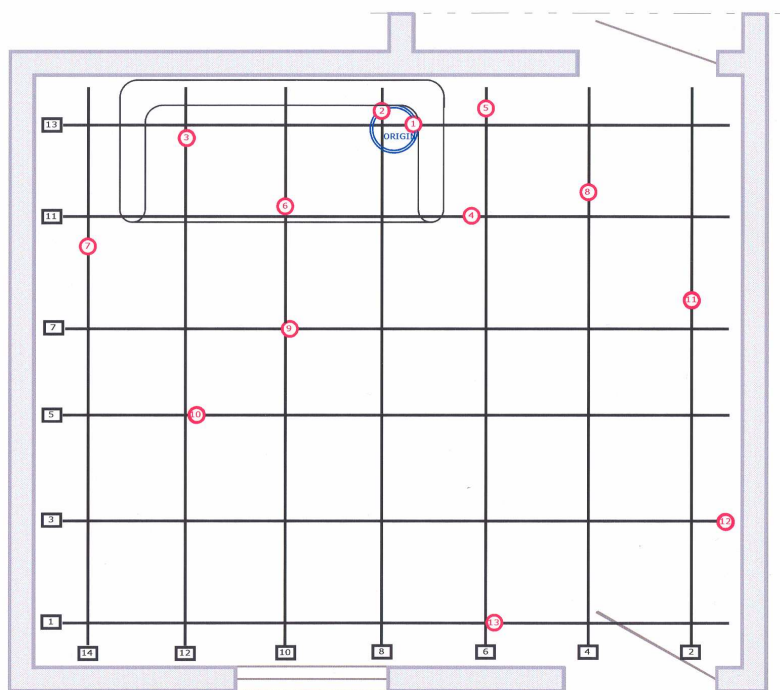
The need exists for additional test fires to confirm or refute these theories. Procedurally, arc surveys are an accepted means to conduct origin determinations.¹⁸ However, without a basis of science behind the practice, the threat exists that results gained by this investigative method may not be allowed in the legal or technical arena. This paper offers such foundation although the authors recognize the need for additional research.

Unfortunately, fire pattern analysis is relatively subjective. It is not uncommon for investigators to disagree as to what information fire patterns are relating to them. Such inconsistency can be the result of different investigators capabilities (i.e. experience levels, training, education and even initiative), unusual fire dynamics and a host of other subtle variables in a fire's progression. Arc evidence on the other hand is tangible. In most cases it cannot be misconstrued or misinterpreted. Its existence verifies that electrical power was still available in a specific area when a hostile fire attacked the conductors. Surveying or mapping arcs on different circuits and evaluating them in a spatial context are an extremely powerful tool to assist in origin determination. The progression of arcs in a structure fire can be likened to "footprints in the snow" that provide an incontrovertible picture of an event under analysis.

Figure 1



Figure 2

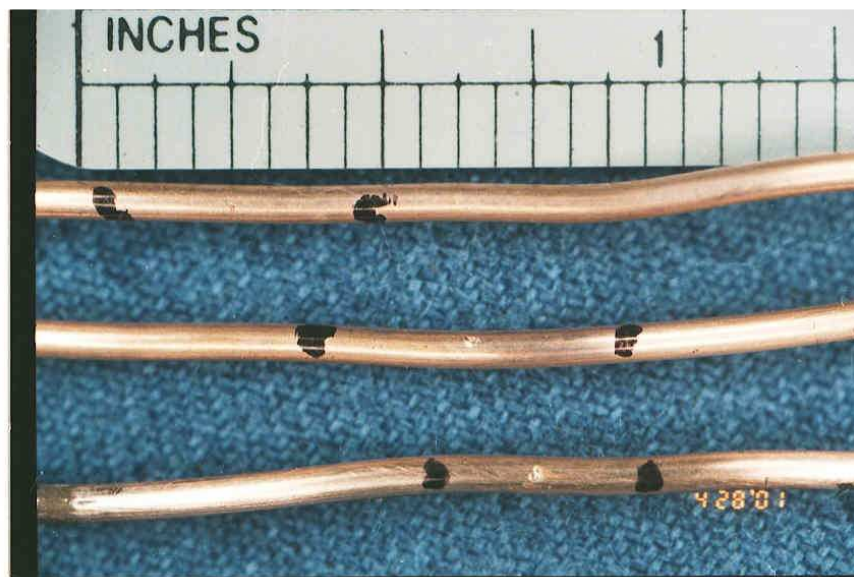


ARC LOCATIONS - CELL # 3

Figure 3



Figure 4



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- ³ National Fire Protection Association, NFPA 70, National Electric Code, rev. ed. (1911; rpt. Quincy, MA: NFPA, 2002) Table 310
- ⁴ NFPA 921, § 8.10.3 Arcing Through Char
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- ¹⁸ NFPA 921 §17 Origin Determination