HOT TOPIC

ARC MAPPING

AN EXPLANATION AND EXAMPLE

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This article is intended to be an introduction to arc mapping of the fire scene for the origin and cause investigator by describing and summarizing this process, and utilizing a test burn to illustrate its successful use. Due to space limitations, no diagram has been included in this article.

[NFPA 921, Section 17.1.2 – 2008 Edition]

"Determination of the origin of the fire involves the coordination of information derived from one or more of the following:

(1) Witness information. The analysis of observations reported by person who witnessed the fire or were aware of conditions present at the time of the fire

(2) Fire Patterns. The analysis of effects and patterns left by the fire (See Chapter 6.)

(3) Arc Mapping. The analysis of the locations where electrical arcing has caused damage and the documentation of the involved electrical circuits (See Section 8.10.)

(4) Fire Dynamics. The analysis of the fire dynamics, that is, the physics and chemistry of fire ignition and growth (see Chapter 5), and the interaction between the fire and the building's systems (See Chapter 7.)"

During the course of a fire scene investigation, investigators can utilize several tools, such as Arc Mapping, to successfully determine the origin and cause of the fire. Arc mapping is a valuable tool used by fire investigators to assist in more accurately identifying a quadrant of fire origin within a room(s). By identifying arc locations on energized electrical circuits, investigators may be able to develop a pattern whose analysis will allow for narrowing of focus for an area of origin, and additionally serve as corroboration of fire progression hypotheses (as dictated by the scientific method) .

Arc Mapping Purpose

- Determine locations where fire impinged on circuits while still energized.

- Determine the locations where fire impinged on circuits while de-energized by earlier fire impingement.

- Compare these arch locations with the spatial layout of the circuits as they relate to the power supply system and fire dynamics

- Determine the area of earliest fire progression.

[NFPA 921,Section 17.4.5 – 2008 Edition]

"Arc Surveys or Arc Mapping. Arc surveys (also known as arc mapping) is a technique in which the investigator uses the identification of arc locations or "sites" to aid in determining the area of fire origin. This technique is based on the predictable behavior of energized electrical circuits exposed to a spreading fire. The spatial relationship of the arc sites to the structure and to each other can be a pattern, which can be used in an analysis of the sequence in which the affected parts of the electrical system were compromised. This sequential data can be used in combination with other data to more clearly define the area of origin."

Arc Mapping Theory

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) and/ or severing conductors.

Later stages of Fire Progression

- As you move away from the area of fire origin, towards the power supply, you should have fewer circuits energized and thereby less arcing.

- Multiple locations of arc activity can occur on the same circuit.

What is an Arc?

An arc in air is a luminous discharge between two energized conductors, in which temperatures can be in the range of thousands of degrees Fahrenheit. For the purposes of this article the electrical arcing discussed is not being investigated as a potential source of ignition, rather it is being utilized as a tool for fire investigation. Additionally, for the purposes of this article, we will be assuming that the branch conductors are copper.

Arcing can occur when the insulation surrounding a wire, usually comprised of organic ingredients (e.g. polyvinyl chloride, PVC), is degraded by the fire to form a carbon char. This char is a semi-conductor that allows for electrical current to pass between the two metal conductors and/or metal objects (i.e. copper or steel piping or metal heat ducts) of different electrical potential. The resulting arc exceeds the melting temperature of the conductor (typically copper*) and leaves a permanent disfigurement on it.

In the experience of the authors, in most residential fire scenes, conductors suffer no melting as the temperature needed to melt the copper is not reached (the melting point of pure copper is approximately 1981 Fahrenheit). Therefore, in scenes such as these, arcing evidence survives relatively intact. In larger or longer fire events (i.e. "black hole fire scenes"), the temperature may have reached well beyond 1981 Fahrenheit, lengthening the arc mapping process but not making it necessarily more complicated. Arcs, however, have a much higher temperature and will, in general, cause tell-tale and permanent damage on the copper wire. It should be noted that our test burn described in this article did not reach flashover or temperatures hot enough to melt the copper conductors in the room, enabling the authors to conduct arc mapping.

It should be noted that although electrical arcing in most scenarios does not make a competent ignition source. Arcs in a gaseous or flammable vapor scenario do make a competent ignition source.

* Melting temperature of copper is 1981 F

Distinct round beads and pits (notches), varying in size and irregularities are some of the more common indicators of electrical activity (arcing). This damage is caused as electrons are moving from the negative conductor to the positive conductor in a gaseous state. These arcs can occur when heat and fire impinge on energized electrical circuits. The heat of fire causes degradation of the wire insulation and the formation of carbon char. This char is an electrical semi-conductor, and will allow an arc to occur through the char. This is referred to as Arcing Through Char (ATC) as referenced in NFPA 921.

[NFPA 921,Section 8.10.3 – 2008 Edition]

"Arcing Through a Carbonized Path Due to Thermal Means (Arcing Through Char). Insulation on conductors, when exposed to direct flame or radiant heat, may be charred before being melted. That char is conductive enough to allow sporadic arcing through the char. That arcing can leave surface melting at spots or can melt through the conductor, depending on the duration and repetition of the arcing. There often will be multiple points of arcing. Several inches of conductor can be destroyed, either by melting or severing of several small segments."

Arc Mapping

As defined in NFPA 921 17.4.5 – 2008 Edition, Arc Mapping is a scene investigation technique whereby investigators identify sites of arcs to aid in the determination of the area of origin. The pattern formed by these identified arcs can be analyzed to see in what sequence these arcs may have occurred. Arcing sites will most likely cause an activation of the circuit's over current protection device and/or sever the conductors, thereby

cutting power to the conductor downstream from the arc. Thus, the arc located furthest downstream on the circuit is, in most instances, the point at which the fire first impinged upon the circuit. Using logic, investigators can deduce that the area of origin, if not adjacent to the arc, is in the vicinity of the arc furthest downstream.

The technique can be of limited value, at times, when the conductors have been completely melted or destroyed by the fire and the investigator has an inability to recognize distinct arcing evidence.

Some circuits that are known to be energized at the time of the fire may not show any evidence of electrical activity in the area of origin. These circuits may be supplied power by a GFCI breaker or outlet, by an AFCI breaker, the circuit could be low voltage (i.e. door bell or alarm) and/or appliance cords with an over current protection device incorporated in the power cord.

To properly utilize arc mapping, investigators must be able to identify tell-tale indicators of arcing and differentiate them from damage caused by melting, alloying and/or mechanical damage.

Arcing of Conductors

- Beads
- Pits/Notches
- Pairs of conductors of different electrical potentials
- Splatter
- Localized / Sharp Edges – Distinct line of demarcation between melted & unmelted surfaces

Melting of Conductors

[**NFPA** 921,**8.10.6.2**– 2008 Edition]

"**Melting by Fire**. When exposed to fire or glowing embers, copper conductors may melt. At first, there is blistering and distortion of the surface, as shown in Figure 8.10.6.2(a). The striations created on the surface of the conductor during manufacture become obliterated. The next stage is some flow of copper on the surface with some hanging drops forming. Further melting may allow flow with thin areas (i.e., necking and drops), as shown in Figure 8.10.6.2(b). In that circumstance, the surface of the conductor tends to become smooth. The resolidified copper forms globules. Globules caused by exposure to fire are irregular in shape and size. They are often tapered and may be pointed. There is no distinct line of demarcation between melted and unmelted surfaces."

Alloying of Conductors

[NFPA 921,8.10.6.3 – 2008 Edition]

"Alloying. Metals such as aluminum and zinc can form alloys when melted in the presence of other metals. If aluminum drips onto a bare copper conductor during a fire and cools, the aluminum will be just lightly stuck to the copper. If that spot is further heated by fire, the aluminum can penetrate the oxide interface and form an alloy with the copper that melts at a lower temperature than does either pure metal. After the fire, an aluminum alloy spot may appear as a rough gray area on the surface, or it may be a shiny silvery area. The copper-aluminum alloy is brittle, and the conductor may readily break if it is bent at the spot of alloying. If the melted alloy drips off the conductor during the fire, there will be a pit that is lined with alloy. The presence of alloys can be confirmed by chemical analysis."

Alloy Characteristics

- A homogeneous mixture or solid solution of two or more metals, the atoms of one replacing or occupying interstitial positions between the atoms of the other
- Different color than original conductor
- Gradual transitions from melted to non-melted metal
- Erosion of original material
- Subtle Changes

Damage due to melting or alloying such as icicle-like melting and non-distinct globules constitute melting and do not indicate an arc. One convenient rule of thumb regarding beads/pits is if the edges are sharp, distinct and non-uniform to the conductor, then it represents an arc. Additionally, remember that there are at least two conductors and/or one conductor and

a metal objects of a different electrical potential are required if the damage is due to an electric arc, many times consisting of a bead/pit pair.

However, if the damage does not have distinct edges, appears to be sagging or thinning, is not localized and is discolored, then it is the result of melting or alloying. In addition, investigators should be cautioned about mechanical damage suffered by conductors. This damage will be readily apparent as fracture lines, cuts or breaks which can be viewed under magnification.

Arc Mapping and Documentation

Arc Mapping Procedure

L. I. M. P. D.

Locate conductor damage
Identify Type of Damage
Differentiate damage due to Arcing
- Electrical Arcing –
- Alloying/Melting
Mark Conductor Damage due to Arcing
Photograph
Diagram Circuit specifics

Power Supply and other devices

Arc mapping can be a simple process. It should be noted that Arc mapping is also an example of the use of the "Scientific Method" as applied to Origin Determination. First, investigators identify an area of a fire scene (usually a room or area of a room) where they are going to conduct the examination. A sketch is utilized to document the room dimensions and the circuits throughout. All conductors, switches, receptacles, appliances, and fixtures should be documented on this sketch, including the breakers/fuses that supply power to the circuits. Record the position of the breakers (On/Off/Tripped). If simple enough, this information can be placed on the sketch investigators would normally complete for their scene examination.

Investigators then systematically examine all of the conductors in the room, through visual and hand-held examination, searching for evidence of arcing. Investigators should gently run their fingertips over each conductor while visually examining them. This may include the use of a magnifying glass (in the past, the authors were able to find useful magnifying glasses at Big Lots for less than $2) Investigators should be as non-destructive as possible, leaving intact conductors in place, preventing unnecessary damage.

When an investigator finds damage to the conductor, the investigators must use his/her training and skills to differentiate between evidence of arcing and damage due to melting alloying and/or mechanical damage. In some cases Electrical Engineers are called upon to differentiate the difference through significant magnifying of the suspected arc area

During the examination of the wiring, investigators should use colored tape or some other method to identify and mark arc evidence. After being marked, the arc evidence should be documented in both photographs and/or on their sketch. Investigators should preserve the arc evidence when warranted. This may be a difficult undertaking as conductors can be fragile. It is important to note that if the conductors are taken as evidence, they are properly tagged and documented as to their origin, in accordance with ASTM Standard E 1188-05 and NFPA 921. Also, the value of the arc evidence is maintained only when lengths of wiring are retained as evidence. Normally the length of wire from where the wire enters the area or room of origin to where the wire exits the area or room of origin is retained when possible. If possible cut the wire where the wire insulation is still intact.

Fire investigators are aware of how important documenting the fire scene can be. Arc mapping should be documented with the same meticulous level as the rest of the scene examination. This documentation should include:

a. Overall Photographs
b. Mid-range photographs
c. Close-up photographs
d. Diagram and/or sketch

Investigators should not assume that arc mapping is only useful in smaller fire scenes or just residential structure fires. The authors have individually inves-

tigated large loss and industrial fire scenes in which they have successfully used arc mapping. Following the same principals described above, the authors have utilized arc mapping in these large, devastating scenes to corroborate or identify areas of origin

Example of Arc Mapping inside industrial fire scene

Arc Mapping

Location of electrical arcs **A T C**
(**A**rcing **T**hrough **C**har)
- Location on conductor
- Location within cable (Hot to Neutral, Hot to Ground)

Power Supply
- Circuit Breaker Panel
- Breaker (Size, On/Off/Tripped)

Circuit
- Devices (JBs, Outlets, Switches)
- Load (Space Heater, Toaster Oven)

Spatial Relationship
- Within Room
  Level – Floor, Mid, Ceiling
- In ceiling, wall or under floor

There are also things that an investigator(s) can do that become detrimental to your investigation. Whenever possible avoid these actions as they will hamper your investigation.

Detrimental Actions

Here's what **NOT** to do

- **Don't** flip all of the circuit breakers to the "OFF" position
- **Don't** cut all the wires near the panel
- **Don't** remove wires prior to marking, noting their location and breaker or fuse that supplied circuit power
- **Don't** assume that it is an electrical fire because you found electrical arcing
- **Don't** disassemble evidence at the fire scene to look for internal arcing (other than removing and replacing a cover)

Live Burn Testing

In October 2008, the authors, with the valuable assistance of Rochester Fire Department FIU Lieutenant Allyn Borrino, Webster Fire Department Chief Steve Andrews and the Wallington Engine Co., conducted two live burns in Webster, NY. The test burns were attended by numerous fire investigators from the Rochester area. The purpose of the burns was to test several different fire investigation issues and techniques, including arc mapping, fingerprinting, fire debris analysis, thermocouple measurements, video photography, still photography, and 3D diagramming computer programs. This article will be limited to describing the live burn tests and arc mapping, and for the sake of being concise, will only describe one specific room test.

Investigators used a single room within a vacant house as the test facility for this fire. The second-story room, was accessed by a single door on the east wall. Two single pane, wooden framed windows were situated on the west wall and the south walls. A closet (accessed by a wooden door) was located on the north wall. The walls and ceiling consisted of lathe and plaster mounted to 2" x 4" studs and 2" x 6" joists, respectively. The investigators furnished the room as if it were a living room, placing several fuel packages and furniture normally found in such a room. This included a foam cushioned loveseat along the west wall, a foam cushioned chair along the south wall, a particle

board cabinet adjacent to the couch, and several other items throughout. Notably, in the southwest corner of the room, an infant car seat and radio were placed on the floor, while an iron was placed on the south wall window sill. The iron was plugged into an extension cord, but not in the "On" position, while the radio was plugged into an extension cord and in the "On" position and energized. In addition, a contractor light was plugged in and situated along the west wall.

The house, which had no electric service to it prior to the test burn, was safely energized by Engineers Hauf and DeMatties. A pre-fire inspection of the existing electrical system was performed. The burn room branch circuits were isolated in the main electrical panel, and then they were supplied power through a circuit breaker in the main panel utilizing generators.

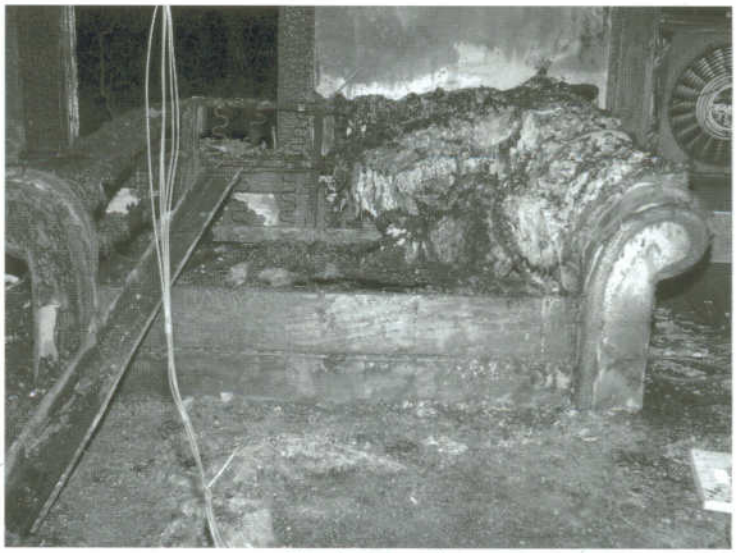
The room contained two receptacles, one each on the east and south walls, and these were both energized. There was an overhead florescent light fixture that was energized via a wall switch on the north wall. An 8', 2C16AWG zip cord was run from the receptacle on the south wall, under the couch along the base of the south wall to the lamp and radio in the southwest corner of the room. A contractor light situated along the west wall was attached to the receptacle on the east wall, and was also energized.

Investigators utilized a series of Type K thermocouples affixed in the center of the room to record temperatures throughout the fire event. The thermocouples were vertically spaced off the floor at floor level, 3', 4', 5', 6', 7' and ceiling level. It should be noted that the thermocouple located at 5' off the floor was not operational and did not provide any data during the event. The thermocouples were attached to a Fluke Data Acquisition "book" (Model 2680A) that allowed for real time monitoring and recording of temperatures during the fire event and suppression efforts.

In addition, investigators utilized a video monitoring system to record the event. The camera was covered with protective HVAC heat resistant, reflective tape to ensure its survivability and maximum video life; and then was mounted to the floor to provide as much of an overall room view as possible.

Fire damage to exterior of test structure

Investigators started the fire with an open flame within a normal trash can that contained normal paper combustibles. The area of origin was in the southwest corner of the room, at floor level, adjacent to the couch and the energized extension cord. The fire progressed upward and outward, eventually involving many of the fuel packages throughout the room traveling towards the ventilation window which was partially ajar at the time of ignition.



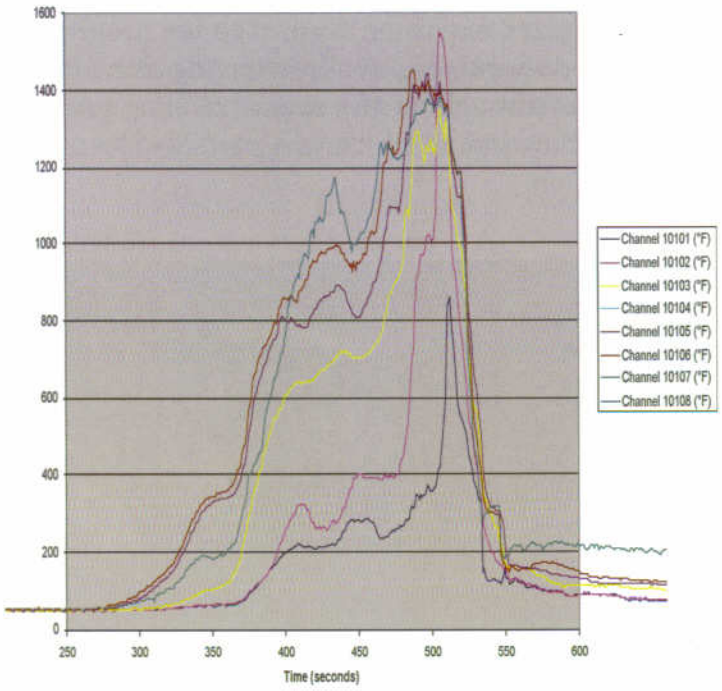
Fire damage to love seat

Fire results

The entire fire event lasted for approximately five minutes and did not result in flash over. Approximately 3 minutes into the fire event, the investigators recorded

the highest temperature readings for the ceiling, approximately 363 Fahrenheit at floor level and 1443 Fahrenheit just below ceiling level. At this juncture, the couch and other fuel packages were involved in fire. During the fire event, the door to the room was manipulated to ensure the fire had enough ventilation to grow.

Shortly thereafter (approximately 15 seconds later), floor temperatures reached a maximum of 861 Fahrenheit, doubling in that short span). At this point the ceiling temperature had started to fall and recorded 1338 Fahrenheit. The video feed, though intact, was not providing much value at this point as the smoke layer in the room had descended to the floor. The floor temperature reading indicates that the fire did not have the capability to cause copper wiring to melt*. Their survivability enhanced the Fire Investigators ability to make the origin determination.



Time versus Temperature graph recording fire event. Note the dark blue line represents floor level, while the green line represents ceiling level.

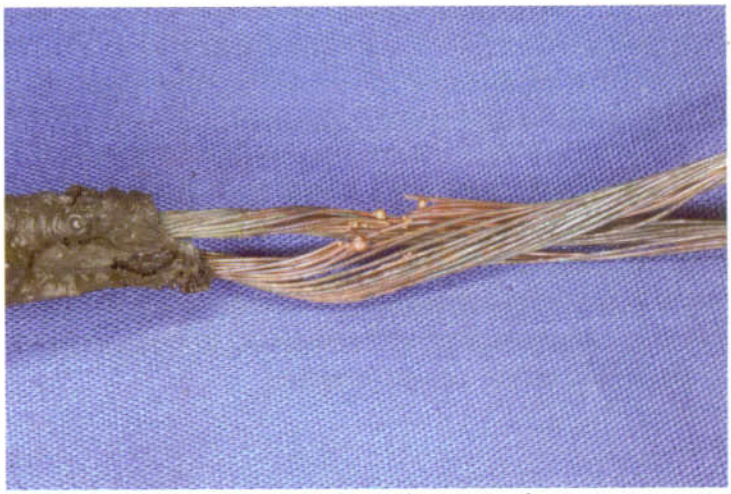
Following the fire, investigators examined the room and conducted arc mapping. Prior to a substantive examination, investigators photographed the room and the fire artifacts. Investigators then accurately identified arcing evidence, and collected it for further inspection at the Forensic & Failure Analysis laboratory located in Syracuse NY.

Analysis and Conclusion

Investigators noted heavy and significant fire damage to the room. Though there were no structural component failures, the window panes had partially failed during the fire and the doors in the room suffered heavy damage.

The furniture in the room was also heavily damaged. The loveseat along the west wall, underneath which the extension cord ran, suffered destruction of its cushioning and deep charring on its wooden frame. This damage was greater on the south side of the couch adjacent to the area of origin. The chair suffered fabric destruction on its upper surfaces; the damage lessening the further from the southwest corner where it was located. Other items such as the radio and infant car seat were destroyed by the fire. Plastic containers further away from the west wall exhibited much more survivability. This damage would have allowed most investigators to narrow their focus to the southwest quadrant of the room. In this type of scenario, the arc mapping would serve to further validate an area of origin hypothesis. By validating this area as the possible quadrant of origin, investigators can possibly eliminate numerous other ignition sources located within the fire room.

The electrical evidence removed from the scene, contained the extension cord which was heavily damaged by the fire. Much of the insulation had been destroyed, particularly in the area to the south of the couch where it lay exposed, and it took careful processing to dig out the extension cord from the scene. An examination of the extension cord revealed an arc approximately 58" from the plug head and wall outlet, corroborating the fire area of origin



Arc evidence located on zip cord

It should be noted that because of the relatively light load on the extension cord, the arc damage was relatively small. Though small, this damage was identifiable both at the scene and the laboratory. A recommendation for investigators is to stock your processing kit with a magnifying glass to assist in examining potential arc evidence.

It should also be noted that melted and re-solidified debris, such as metal and aluminum may need to be collected for x-ray analysis at a later date. The x-ray analysis will often reveal any wires or components that are contained in the debris. These components can then be extracted in a laboratory setting at an appropriate time.

Investigators also examined the contractor's light and observed no evidence of arcing; corroborating the area of origin on the opposite side of the room, and substantiated their fire origin hypothesis.

In this basic scenario, investigators corroborated the area of origin through the use of arc mapping. The fire damage to the room was significant and many of the fuel packages were destroyed by the fire. The investigators utilized the arc evidence to corroborate their theory of the area of origin.

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References

Carey, NJ, Svare, MJ, Daeid, N, "Arc Fault Mapping – A Technique to assist in Identifying a Fire's Area of Origin"

Lentini, John, Scientific Protocols for Fire Investigation. Taylor & Francis Group, Boca Raton, FL, 2006.

National Fire Protection Association, NFPA 921 2008 edition, 2008.

DeHaan D. John, Kirk's Fire Investigation, Sixth Edition. Pearson Education, Inc., Upper Saddle River, New Jersey, Copyright 2007.

ARC MAPPING REFERENCE

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* Determine locations where fire impinged on circuits while still energized.

* Determine the locations where fire impinged on circuits while de-energized by earlier fire impingement.

* Compare these arc locations with the spatial layout of the circuits as they relate to the power supply system and fire dynamics.

* Determine the area of earliest fire progression.

Arc Mapping Theory

* 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) and/or severing conductors.

* Later Stages of Fire Progression :
  - As you move away from the area of fire origin, towards the power supply, you should have fewer circuits energized, and thereby less arcing.
  - Multiple locations of arch activity can occur on the same circuit.

Arc Mapping Procedure L I M P D

* ***L***ocate conductor damage.

* ***I***dentify Type of Damage
  - Differentiate damage due to arcing
    - Electrical Arcing
    - Alloying/Melting
* ***M***ark Conductor Damage due to Arcing
* ***P***hotograph
* ***D***iagram Circuit specifics
  -Power Supply and other devices

Arc Mapping

* Location of electrical arcs ***A T C*** (***A***rcing ***T***hrough ***C***har)
  - Location on conductor
  - Location within cable (Hot to Neutral, Hot to Ground)

* Power Supply
  - Circuit Breaker Panel
  - Breaker (Size, On/Off/Tripped)

* Circuit
  - Devices (JBs, Outlets, Switches)
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* Spatial Relationship
  - Within Room
    - Level - Floor, Mid, Ceiling
  - In ceiling, wall or under floor