APPLICABILITY AND LIMITATIONS OF ARC MAPPING IN VEHICLE AND EQUIPMENT FIRE INVESTIGATION

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ABSTRACT

"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 … based on the predictable behavior of energized electrical circuits exposed to a spreading fire" 2011 NFPA 921-17.4.5. Arc Mapping (or arc surveys) is a commonly accepted method that has been researched and documented to assist in the determination of the area of origin, especially in post-flashover structural fires, with properly fused, alternating current (AC) electrical circuits. Some limitations and cautions in the use of the technique are also discussed in NFPA 921 and elsewhere, but nearly always in the context of a fire in a typical structure.

The authors' experience has found fire investigators and engineers currently commonly using Arc Mapping as a fire origin investigation technique for non-structural fire investigations involving vehicles and commercial equipment. Extending the application of a technique to conditions different from which it was originally developed and typically used requires a consideration of the fundamentals of the bases for the technique and determination of the applicability and potential limitations under those different conditions. There are a number of important features that differentiate the typical structure's configuration from that of typical vehicles and commercial equipment relative to the fire behavior of their electrical circuits. These differences in the fire behaviors between structures and vehicles/equipment then directly relates to the applicability and limitations of Arc Mapping.

The differences of vehicles and equipment from structures includes a group of characteristics that are typical of, and mostly similar in, most vehicles and equipment - direct current of 12 or 24 volts with a shared negative common ground with much of the product electrically connected and conductive, grouped wires bundled into harnesses, and a high current, unprotected battery cable length. There is another group of differences from structures that show the wide variety and non-standardization of the electrical systems in and across vehicles and equipment - different from, and in contrast to, the high degree of similarity and standardization of the electrical systems in structures. These characteristics include numbers of high current batteries, with different lengths and numbers of battery cables without circuit protection, with any number of harnesses containing any number of wires, of any range of current capabilities, protected by any number of different levels of fuses, circuit breakers, or fusible links, that may or may not be energized at the time of the fire, running from any number and location(s) of distribution/protection points.

This analysis explores some of these differences in typical configurations and discuss the effect of these differences to the fire behavior of the product and electrical system fire behavior and thus to the applicability and limitations of Arc Mapping in the fire investigation of typical vehicles and commercial equipment. Two major results come out of this analysis. First is that the differences between the structures and vehicles/equipment and their typical electrical systems produce different fire behaviors and thus different electrical system fire evidence, including arc marks. The second major result of this analysis is the loss of the degree of predictability of the fire behavior of the electrical systems in vehicles and equipment, relative to structures. This lack of predictability directly relates to the ability to

and the likelihood of direct current (DC) circuits redirecting electrical current to unplanned paths of other circuits or through nonelectrical, yet conductive, components such as brackets, reinforced hoses, mechanical cables, etc.

This loss of predictability of vehicles and equipment electrical systems fire behavior directly leads to a lack of reliability of the Arc Mapping technique to assist in fire origin determination in vehicles and equipment. Electrical system fire evidence in vehicles and equipment can be extremely important in a fire investigation to determine potential fire causes and test fire origin and cause hypotheses – it just does not provide sufficiently predictable, reliable information to use in assisting the fire origin determination through a standard Arc Mapping technique as it may, under certain conditions, in structures. Since the term "Arc Mapping" has gained common usage as a fire investigation technique to assist in the determination of the fire origin (in structures), it is proposed that the useful and necessary process of locating, documenting, and analyzing evidence of electrical activity (especially in vehicles and equipment), be referred to as Electrical Activity Survey (EAS) for distinction and clarification.

INTRODUCTION - PERSPECTIVE

Vehicle fires were outnumbered by structure fires in the USA in 2011 by an estimated 219,000 to 484,500, though with the number of deaths and injuries greater in structure fires by approximately 12:1 and property loss greater in structure fires by 7:1.[1] Structure fires, historically, have much greater risk of substantial property loss and loss of life than fires originating in vehicles or equipment. Correspondingly, (and expectedly), the general fire investigation literature, techniques, processes, and experience are focused more toward structure fire investigation. Investigators (such as the authors) that routinely investigate vehicles and equipment fires (or other specialized types of fires) commonly need to analyze the general fire investigation literature, techniques, processes, rules of thumb (often developed around structure fires) for the specific applicability, usefulness, and limitations to vehicle and equipment fires (or the other specialized types of fires). While many investigators usually investigate structure fires and may occasionally be involved with a specialized type of fire, the authors routinely investigate vehicle and equipment fires but rarely investigate structure fires. This background and our engineering training and experience in vehicle design, manufacturing, use, maintenance, and failure analysis provides us a unique set of skills and experience but also a unique perspective to fire investigation. It is this perspective that brought us to directly question and analyze the applicability and limitations of Arc Mapping in vehicle and equipment fire investigation.

SCOPE

The scope of this paper is the analysis and review of the applicability and limitations of electrical Arc Mapping, as a fire investigation technique, *to determine an area of origin* in vehicles and equipment. Arc Mapping as a technique in structural fire investigation is typically stated (or implied) to be used in the determination of an area of origin as its main purpose in structural fires, usually after the fire progressed past flashover and obscured local fire patterns in the area of origin. Witness information, fire patterns, Arc Mapping, and fire dynamics are noted as information sources to be used in fire origin determination.[2] The use of the term "Arc Mapping" throughout this paper refers specifically to arc surveys or arc mapping (locating, verifying, recording, and analyzing) to assist in the determination of the area of fire origin as described in NFPA 921- rather than just a general evidentiary survey for electrical fire evidence (that includes potential arc marks) to provide information for cause determination, hypothesis testing, or other analyses.

This analysis does not negate (but rather emphasizes) the potential importance of locating, mapping, examining and analyzing evidence of arcs and other types of electrical faults in determining the potential cause of fires and for testing hypotheses of both fire origin and cause in vehicles and equipment. Electrical abnormalities (including arc marks) should be considered along with all other evidence present after a fire.

The development of this analysis was initially focused on commercial vehicles such as trucks, tractor-trailers, buses, step vans, etc. and commercial equipment such as agricultural tractors and combines, construction bulldozers and cranes, logging equipment, mining trucks and shovels, industrial chippers and forklifts, truck mounted drillers, sweepers, and the wide variety of other similar commercial equipment. This analysis and conclusions though also hold, in general, for cars, light trucks, recreational vehicles (RVs), and other products that share the noted product characteristics and resulting fire behaviors. This analysis is also presented for simplicity relevant to the characteristics of structures and vehicles and equipment typically found in the USA and North America but again holds in general for other parts of the world.

BACKGROUND OF ARC MAPPING

Arc Mapping as a source of information in origin determination first appeared in NFPA 921 in the 2001 edition although only described as "Noting the location where electrical arcing has caused damage and the electrical circuit involved"[3] without use of the Arc Mapping terminology. The Arc Mapping technique has been named and further expanded and discussed in subsequent editions. Nearly all references to Arc Mapping refer, either explicitly or implicitly, to use in structural fire investigations. All studies of the reliability of Arc Mapping in fire investigation origin determination reviewed[4-6] have been done with structures and no known studies regarding Arc Mapping in vehicles or equipment.

The general basis for Arc Mapping as a technique to determine the area of fire origin is based on the idea that as a fire progresses (especially past flashover) and expands at and from the area of origin, the insulation of wires on energized circuit(s) in the area of fire origin will be thermally degraded to the point where arcing (through air, char, or other means) occurs. Then through analysis of the arc location(s) and potential sequence of the arc(s) development, this information can assist in the determination of the area of origin.[7]

Use of the Arc Mapping analysis technique thus requires that the fire behavior of the electrical circuits show predictable, substantially similar, repeatable fire behavior for the technique to be reliable with a scientific basis – with the ability for the fire investigator to routinely determine when other than predictable fire behavior has occurred.

Continuing debate, discussion, and research about the reliability and limitations of Arc Mapping in structures is ongoing as demonstrated by the request for further study by the NFPA 921 technical committee.[8]

ARC MAPPING IN STRUCTURES - RELEVANT CHARACTERISTICS OF STRUCTURES

Structures are known to generally share a group of common properties that are expected to be important to the expected behavior of their electrical systems during fires. This fire behavior produces certain electrical system fire evidence that is expected to be sufficiently common and repeatable to enable Arc Mapping - if certain abnormal fire behaviors are determined to not have occurred.[9] These common properties characteristic of typical structures are:

1. 60 hertz Alternating Current (AC) electrical systems,
2. with 120/240 voltage levels,
3. with a separate (neutral) wire providing the reference voltage for each electrical circuit,
4. with high electrical insulation and separation across and throughout the structure (outside of the electrical system), (i.e. the structure is not mostly electrically conductive),

5. with common, standardized circuit protection on all electrical circuits,
6. with limited total current available, protected just past the point of a standardized entry,
7. with individual electrical circuits run separately (or in limited similar groupings),
8. with all circuits normally energized,
9. with spatially distributed circuit layout distribution throughout the structure,
10. with standardized electrical circuit design and layout characteristics.

Most modern structures in the USA share these properties in a large part due to their general commonality of construction methods and materials and adoption and use of the National Electrical Code[10] defining the electrical systems in structures. This commonality of these properties of the structure, and its electrical system, prior to a fire produces a reliably similar fire behavior and reliably similar electrical system fire evidence after the fire, allowing the reliable use of Arc Mapping - except potentially when there is deviation from this commonality or abnormal fire behavior due to other circumstances.

CORRESPONDING, RELEVANT CHARACTERISTICS OF VEHICLES AND EQUIPMENT

Vehicles and equipment are also known to generally share a group of common properties which are directly relevant to the fire behavior of the product, effects of fire on the product's electrical system, electrical faults and evidence, and thus the potential applicability of Arc Mapping, but are *not* characteristic of typical structures. These properties are:

1. Direct Current (DC) electrical systems,
2. with significantly lower electrical 12(/24) voltage level(s),
3. with a shared negative common electrical reference voltage (ground),
4. with high electrical conductivity and connection of much, if not most, of the product structure and mass,
5. with varied circuit protection of different response characteristics on most electrical circuits,
6. with multiple current sources of higher current capability usually unprotected for some length,
7. with independent, various sized, electrical circuits bundled together in harnesses,
8. with some circuits potentially not energized depending on the state of operation,
9. with very localized, non-distributed circuit layout distribution,
10. lacking standardized electrical circuit design and layout characteristics.

There are two separate, notable features of these common properties of vehicles and equipment. First is the similarity across vehicles and equipment of some of these common properties including that they have 12 or 24 volt, DC electrical systems, with a shared negative electrical common "ground" of much of the product's mass and surfaces, with an unprotected length of battery cable, and bundled wires in harnesses. These are common properties of vehicles and equipment with similarity in and across the various types of vehicles and equipment and *different from structures*.

The other feature of a number of some of these properties is their general commonality across vehicles and equipment as different from structures - but noting the tremendous variability of these properties across vehicles and especially across and within equipment. Unlike the electrical system standardization present from structure to structure, each vehicle or piece of equipment may have different numbers of batteries, with different lengths and numbers of battery cables without circuit protection, with any number of harnesses containing any number of wires, of any range of current capabilities, protected by any number of different levels of fuses, circuit breakers, or fusible links, that may or may not be energized at the time of the fire, running from any number and location(s) of distribution/protection points.

There are exceptions to the commonality of the noted properties in vehicles and equipment such as:

- dual AC and DC circuits in motor homes and other RVs,
- significantly higher voltage levels in electric and electric-hybrid vehicles,
- products with substantially less conductive sections or bodies such as a fiberglass car body or composite bodied step vans,
- sleeper truck-tractors using electric inverters and AC shore power, etc.

The notable feature of all these exceptions is while they are examples of deviations from the noted common properties of vehicles and equipment, even more importantly; they all are deviations from the common properties of structures that were listed earlier. Any deviation from the listed common properties of structures would be expected to increase the likelihood of fire behaviors different than that found in structures and thus Arc Mapping would be expected to be a much less reliable, or unreliable, technique under those conditions.

FIRE BEHAVIOR OF ELECTRICAL CIRCUITS IN VEHICLES AND EQUIPMENT

Direct Current circuits especially at lower voltages are known to behave differently in terms of their electrical activity behavior as the wire insulation degrades during a fire with less probability of arcing.[11]

It is also known that DC circuits with a shared common ground are capable of electrically completing a circuit through other, potentially multiple, ground paths when the insulation thermally (or mechanically) degrades. These other ground paths are often not obvious and potentially very remote to the initiating electrical activity. The authors have seen other electrical circuits, mechanical shifter cables, the wire mesh layer of pressure hoses, brackets, leaf springs, steering gears, frame rails, etc. become alternative electrical paths. Such components of lower conductivity can then experience resistance heating and initiate or spread fires in adjacent flammable materials.

Battery cables are typically unprotected for some length in vehicles and may allow large amounts of current through other energized or un-energized circuits or other conductive components regardless of whether the short circuit is a cause or an effect of a spreading fire. Commercial diesel trucks can often have four batteries with over three thousand total amperes power capacity available. Other circuits have various types of circuit protection that may or may not de-energize a circuit depending on the current flow through the short circuit and the protection device's response characteristics.

Electrical circuits in vehicles and equipment are typically run bundled in groups of various current capabilities harnessed in bundles running next to and crossing other wire bundles and electrically conductive hoses, cables and other components. Failed circuits and overheated wires within those bundles short to unpowered circuits or components resulting in unpredictable behavior and thus unpredictable fire evidence.

It is this wide range of electrical behaviors during a fire that is potentially and often extremely complicated, unpredictable, and outside the scope of most fire investigations to completely reconstruct, even if it were practicably able to be accomplished. It is also this wide range of behaviors that are different than the substantially more predictable electrical behaviors typically occurring in the electrical systems of a structure during a fire. Fire behaviors of electrical circuits in vehicles and equipment different than those seen in structures are the normal expectation in a vehicle or equipment fire.

APPLICABILTY, RELIABILITY, AND LIMITATIONS OF ARC MAPPING

This analysis has explored some of these differences in typical configurations and discussed the effect of these differences to the fire behavior of the product and electrical system fire behavior. These differences in both configuration and fire behavior thus relate to the applicability and limitations of Arc Mapping in the fire investigation of typical vehicles and commercial equipment.

Two major results come out of this analysis. First is that the differences between the structures and vehicles/equipment and their typical electrical systems produce different fire behaviors and thus different electrical system fire evidence, including arc marks. The second major result of this analysis is the loss of the degree of predictability of the fire behavior of the electrical systems in vehicles and equipment, relative to structures. This lack of predictability directly relates to the ability to and the likelihood of direct current (DC) circuits redirecting electrical current to unplanned paths of other circuits or nonelectrical conductive components such as brackets, reinforced hoses, mechanical cables, etc. The other significant factor in the loss of predictability of the fire behavior of vehicles/equipment electrical systems is the lack of similarity and standardization of their electrical system configurations, especially as compared to structures.

This loss of predictability of vehicles and equipment electrical systems fire behavior directly leads to a lack of reliability of the Arc Mapping technique to assist in fire origin determination in vehicles and equipment. Electrical system fire evidence in vehicles and equipment can be extremely important in a fire investigation to determine potential fire causes and test fire origin and cause hypotheses – it just does not provide sufficiently predictable, reliable information to use in assisting the fire origin determination through a standard Arc Mapping technique, as it may under certain conditions, in structures.

While some investigators implicitly, or explicitly, indicate the applicability of Arc Mapping to vehicles and equipment (or any other special type of fire), no analysis, validation, or testing has been found to provide a scientific basis for the reliability and repeatability of Arc Mapping in anything but standard structures. No testing and verification studies have been found for Arc Mapping as applied to vehicles or equipment.

Considering the substantial differences of the electrical systems between structures and vehicles/equipment, and the noted potential differences in fire behaviors attributable to those differences, it should *not* be expected that Arc Mapping would be a reliable fire investigation technique in vehicles and equipment.

SUMMARY AND CONCLUSIONS

1. There are a number of significant differences between vehicles/equipment and structures in the configuration and properties of these products and their electrical systems that lead to significantly different behavior in a fire related to the creation of electrical arc marks and other fault evidence.
2. No testing, analysis, or study verifying the applicability of Arc Mapping as a fire investigation technique utilized to assist in the determination of the fire area of origin was found in the literature.
3. The different fire behaviors between vehicles/equipment and structures prevent the Arc

Mapping technique from being a dependable, robust technique when translated from structures to vehicles and equipment.

4. Arc Mapping, as a fire origin investigation technique, does not have a scientific basis for use in typical vehicles and equipment when utilized to assist in the determination of the fire area of origin as it can for structures. Surveys and analysis of arc marks and other electrical fault evidence may be important the fire cause determination and hypothesis testing.
5. Since the term "Arc Mapping" has gained common usage as a fire investigation technique to assist in the determination of the fire origin (in structures), it is proposed that the useful and necessary process of locating, documenting, and analyzing evidence of electrical activity be referred to as "Electrical Activity Survey" (EAS) for distinction and clarification, especially in vehicles and equipment.
6. Fire investigators need to assure that an investigation technique, method, or process is applicable, reliable, and has a scientific basis when applied outside of the parameters for which it was developed and tested.

ABOUT THE AUTHORS

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ENDNOTES

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