ELECTRICAL ARCS AND SPARKS: A LITERATURE REVIEW OF DEFINITIONS AND THEIR IMPLICATIONS IN THE ANALYSIS OF 12 VOLT DIRECT CURRENT ELECTRICAL SYSTEM FIRES

Kerry D. Parrott, BSME, CFI, CVFI, CFEI
Douglas R. Stahl, PE, CVFI, CFEI
Stahl Engineering & Failure Analysis, LLC

ABSTRACT

It is common for fires in vehicles and equipment to be caused by any one of many forms of electrical failures. For commercial vehicles, the Technology and Maintenance Council (TMC) of the American Trucking Association (ATA) created a task force to collect data regarding electrical fire events in the trucking industry for the purpose of helping to develop corrective maintenance practices. Based on responses to their survey, this task force determined that approximately 17% of all reported fires were caused by electrical failures. If the trucks were parked, either with the engine running or with the engine off, 43% of all fires were caused by electrical failures[1]. When all highway vehicle types are considered, NFPA reports that from 2003 to 2007 there was an average of 267,600 vehicle fires reported per year in the United States of which 23% were caused by some type of electrical failure or malfunction[2].

Many other statistics are available that describe the number of vehicle and equipment fires that have electrical causes. Regardless of the actual percentage, there is no question that electrical failures are the cause of a significant number of vehicle and equipment fires. The majority of the vehicles and equipment in the United Sates are designed and built to operate with a 12 volt direct current electrical system and are powered by a combination of lead acid batteries and an alternator.

There are a significantly larger number of structural fires in this country than vehicle and equipment fires. These structural fire losses also tend to have a larger risk of both property loss and loss of life than vehicle and equipment fires. NFPA reports a yearly average of 498,400 structures burned between 2007 and 2011[3]. NFPA also reports that in 2011, 13% of these fires involved some type of electrical failure or malfunction.[4] The majority of these structures utilize 120/240 volt single phase alternating current electrical systems, with industrial facilities typically operating with 480 volt three phase alternating current electrical systems. Because there is larger number of structural fires than vehicle and equipment fires, and because the risk of loss is greater, it is understandable that the amount of literature, test data, and practical experience from investigators available on 120/240 volt single phase alternating current systems far exceed that of 12 volt direct current systems.

The terms arc, spark, and arc mapping are commonly used in the fire investigation community and are also commonly applied universally to all alternating current (AC) and direct current (DC) electrical systems of various voltage levels, regardless of it being a structural or vehicle and equipment fire. The phenomenon of an arc is also closely related and involved with arcing through char, arc tracking, parting arcs, contact arcs, and arc duration. Sparks can be created electrically or mechanically and need to be well defined in order to understand terms such as contact arcs, contact sparks, and parting arcs, and mechanical sparks. All of these terms will be defined and discussed in this paper.

This paper has three main purposes: (1) to research and aggregate the definitions and descriptions of these terms and phenomena from available published information; (2) to compare these definitions

and descriptions of these phenomena in terms of how they apply and how they vary in alternating current and direct current electrical systems of different voltage levels and, (3) to discuss how these definitions and descriptions can be more appropriately used and applied to fire origin and cause determinations in the 12 volt direct current electrical systems typically found in most vehicles and vehicle related equipment.

The goal of all fire cause and origin investigations is to arrive at a correct causal determination. A full and accurate understanding of the electrical terms and associated electrical phenomena listed above will help fire investigators apply the terms as accurately and correctly as can be supported within the scope of available and appropriate scientific documentation.

ARCS

NFPA®921 2014 edition defines an (electric) arc as "A high temperature luminous electric discharge across a gap or through a medium such as charred insulation."[5] The text further explains that "temperatures within the arc are in the range of several thousand degrees, depending on circumstances, including current, voltage drop, and metal involved. For an arc to jump even the smallest gap in air spontaneously there must be a voltage difference of at least 350 volts."[6] The Ignition Handbook further defines it as a "continuous" [7] discharge between two electrodes. The word continuous is important in this definition and will be discussed later in terms of differentiating between arc and a spark. This minimum required voltage for an arc to form through air is known as Paschen's Law.

Paschen's Law describes the relationship between voltage and the formation of a sustained electric arc provided there is a sufficient current when bringing two electrodes closer together. In non-ionized air and at room temperature, this minimum voltage required for the formation of an arc, also referred to as the breakdown voltage, is calculated to be 340 volts for a gap measuring 0.007mm (0.00027 inches).[8] 340 volts DC is equivalent to 340 peak volts in an AC circuit.[9] In AC circuits, voltages are generally expressed in terms of RMS voltages. RMS stands for "root mean square" and is simply a mathematical way of measuring a quantity that varies, such as an AC or voltage. RMS voltage is 0.707 times peak voltage for a sinusoidal wave.[10] Therefore, a typical 240 volt AC system has a peak of 340 volts.

In describing Paschen's Law above, we have been very careful to define it at room temperature and in non-ionized air. These two variables are important and it is possible to create an arc with 14 volts DC under the right circumstances, but it cannot occur spontaneously across an air gap.[11] Situations where this can happen, such as a parting arc, will be discussed separately. From a practical standpoint, this means that when arc is involved in a 14 volt DC circuit it is most likely an effect of a fire and not the cause. "Although there is no doubt that arcing can start a fire, it is more often the result of the fire than the initiator of the fire."[12]

ARC DURATION

Once an arc is established in a DC circuit, it will remain established as long as the power supply continues or until the gap becomes too large. Note that the arc tends to quickly erode metallic electrodes increasing the size of the gap[13], which will then extinguish the arc. In an "AC circuit an arc will self-extinguish…each time the current goes to zero. But may re-ignite…"[14] In a 120 volt AC system, arcing "will be short-lived, usually between one-half and 4 cycles. Since each cycle is about 16 milliseconds (ms), this means an arcing time of 0.008 to 0.050 seconds"[15] before extinguishing.

CONTACT ARCS

Contact arcs are defined as arcs that occur when electrodes come in contact and occur regularly in electric switches, relays, or solenoids. "They also occur inadvertently when, for example, two bare current-carrying conductors are accidentally shorted."[16] Closing contacts in a switch are also called "make-arc."[17] An arc caused when contacts open and the electrodes pull apart is called a parting arc, break arc, or opening arc.[18] All of these terms are interchangeable, with parting arc being the most common.

NFPA®921 defines a parting arc as "a brief discharge that occurs as an energized electrical path is opened while current is flowing, such as by turning off a switch or pulling a plug. At 120/240 volts AC, a parting arc is not sustained and will quickly be quenched. Ordinary parting arcs in electrical systems are usually so brief and of low enough energy that only combustible gases, vapors, and dusts can be ignited."[19] NFPA®921 further explains that "Another kind of parting arc occurs when there is a direct short circuit or ground fault. The surge of current melts the metals at the point of contact and causes a brief parting arc as a gap develops between the metal pieces."[20] By this definition, NFPA®921 uses the term parting arc to describe contact arcs, parting arcs, and short circuits, and does not differentiate if the arc is caused when the two electrodes come together or when they pull apart. The terms contact arc, break arc, and opening arc are not used in NFPA®921.

The actual physical mechanism that occurs when two energized conductors come together to form a contact arc is as follows: As the conductors get very close to each other, they first touch in a very small area of adjacent high spots. As these high spots make contact, they will draw current through a very small surface area. This small surface area will then heat up, melt, and rupture, ejecting a small amount of conductor.[21] This identical mechanism is described in NFPA®921 as a parting arc; "Another kind of parting arc occurs when there is a direct short circuit or ground fault. The surge of current melts the metals at the point of contact and causes a brief parting arc as a gap develops between the metal pieces. The arc quenches immediately but can throw particles of melted metal (i.e., sparks) around."[22] The mechanism described above is similar when conductors or contacts are pulled apart, except that the small area of conductor carrying all of the current occurs because the contacts are being pulled apart instead of pushed together. This seems like a minor difference, but its importance will become more apparent later in this paper when we discuss fire causation from short circuits. It is also important to note that during a contact arc, if the two conducts are held together at the point where the material is melted, the two surfaces can weld together as the molten material solidifies. This is referred to as electric welding. "Arc welding is one of several fusion processes for joining metals. By applying intense heat, metal at the joint between two parts is melted and caused to intermix ... upon cooling and solidification, a metallurgical bond is created"[23]

Contact arcs and parting arcs are both very short duration events. Remember that arcs are also described as "continuous" events, and since conductive material is being ejected, contact and parting arcs may be better described as a contact or parting spark, as will be described later in the "SPARK" section.

ARCING THROUGH CHAR

Arcing through char and arc tracing are two commonly encountered terms that seem to be used sometimes interchangeably and sometimes concurrently. NFPA®921 defines arcing through char as "Arcing associated with a matrix of charred material (e.g. charred conductor insulation) that acts as a semi conductive medium."[24] It further explains that "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."[25] It is also very specific that testing in AC circuits demonstrates that "Arcing through char can occur at voltages as low as 30 volts (RMS). The time to form the conductive path, create the bead, and trip the overcurrent protection within a timeframe of investigative interest (i.e., minutes vs. hours) generally occurred with voltages in excess of 60 volts (RMS).[26]

NFPA®921 then goes on to define arc tracking as "Arcing between two conductors separated by a solid insulator can become possible if the insulator becomes carbonized. The two primary means by which carbonization is created is by flow of electric current or by thermal means not involving electricity. If carbonization is due to flow of electric current, the phenomenon is commonly called arc tracking."[27] It also explains that "Arcs may occur on surfaces of nonconductive materials if they become contaminated with salts, conductive dusts, or liquids. It is thought that small leakage currents created through such contamination cause degradation of the base material leading to the arc discharge, charring or igniting combustible materials around the arc. Arc tracking can be a problem not only at high voltages, but also in 120/ 240 volt AC systems."[28]

Chapter 27 of NFPA®921 defines Arc (Carbon) Tracking as "An electrical potential applied across an insulating material can result in a short circuit by a phenomenon called arc tracking, see 9.9.4.5. The process occurs more quickly if the surface is contaminated with road salt or other conductive materials. The process can occur with 12-volt electrical systems."[29] Using the word "carbon" as part of the term seems inconsistent with salt contamination which contains no carbon.

Babrauskas defines arc tracking as "A phenomenon whereby an arc between two or more wires, on initiation, will sustain itself through a conductive path provided by degradation of the insulation for a measurable length."[30] He goes further to explain that arc tracking is only one of three mechanisms by which arcing across a carbonized path can be accomplished. They are "(1) arc tracking; (2) overheating (by electrical overcurrent, external radiant heating, etc.); (3) impingement of fire upon the insulation."[31]

A study by the Motor Vehicle Fire Research Institute reported that "There is also another phenomenon called 'Carbon Tracking' which can be present at 14 volts, but will be more common at 42 volts. It is caused by an electric field across an 'insulator.' " "Insulators" can conduct small amounts of electricity and gradually convert the hydrocarbons in the plastic to carbon - which is a good conductor. After considerable time (i.e. 10-15 years of a vehicle lifetime), this deposit of carbon can grow until it is capable of conducting a large amount of current. Shortly after the current builds up, the material will effectively short and cause an arc, and the material can ignite."[32] Studies show that "aliphatic polymers (e.g., polyethylene, PTFE) tend not to undergo arc tracing, while aromatic ones…do."[33] A simper way of describing this is that "arc tracking can only happen if a polymer can char."[34] In design, the resistance to arc tracking is controlled by two means; (1) selection of a well-performing insulation material, ad (2) observing adequate *creepage* distances."[35] Creepage distance is the distance an arc would have to travel through a solid insulating material.

Another process that can create an arc track in DC systems is known as a "dendrite". Dendrites are current conducting paths formed of metal and metal oxides in the presence of a water film containing ions and salts, and can affect bare electrical conducts that are closely spaced.[36] Current paths on the surface of an insulator, such as dendrites, have a high resistance and therefore generate heat along a small localized area.[37] This heat can then ignite the insulation material, or continue to form char.

It should also be noted that the difference between high voltage and low voltage is simply a matter of definition, with most industries having their own definition. According to the NEC, voltages less than 600 volts are considered low voltage. In the automotive, truck, and equipment world, the definition of high and low voltages is defined by the Society of Automotive Engineers (SAE). According to SAE Standard J1128, low voltage denotes DC voltages of less than 60 volts.

SPARKS

NFPA®921 defines sparks as: "A moving particle of solid material that emits radiant energy due either to its temperature or the process of combustion on its surface."[38] The term is further described as **"**Sparks are luminous particles that can be formed when an arc melts metal and spatters the particles away from the point of arcing... For purposes of electrical fire investigation, the term *spark* is reserved for particles thrown out by arcs, whereas an arc is a luminous electrical discharge across a gap."[39]

According to Babrauskas, the term sparks applies to both electrical sparks and mechanical sparks. By his definitions: an electric [spark] can be thought of as a transfer of electrons across a gap, with the primary difference between a spark and an arc is that a "spark is a transient event; while an electric arc is a sustained event."[40]

Kirk's Fire Investigation defines mechanical sparks being created when "iron, steel, and some other metals will spark when struck by a suitable object, as during grinding operations or when a portion of a vehicle strikes a stone-surfaced roadway"[41] creating a small incandescent particle."[42] This is consistent with Babrauskas' definition of a mechanical spark as "a small incandescent particle."[43] NFPA®921says that mechanical sparks are formed when "metal-to-metal contact (steel, iron, or magnesium) or metal-to-road surface contact can create frictional contact sparks"[44]

ARC MAPPING

NFPA®921 defines arc mapping as "The systematic evaluation of the electrical circuit configuration, special relationships of the circuit components, and identification of electrical arc sites to assist in the identification of the area of origin and analysis of the fire's spread."[45] For the purpose of this paper, it is most important to note that "…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."[46]

CONCLUSIONS and ANALYSIS

It is important to note at this point, all of the definitions and information presented above apply to electrical systems and not to small scale electronics - as it now better understood that small electronic devices that operate with low voltages and currents can be competent ignition sources.[47]

The goal of this paper, as presented in the abstract, is to help fire investigators to arrive at a correct causal determination. For this to happen, fire investigators need to accurately understand the electrical terms discussed here, the electrical phenomena these terms represent, and how these phenomena relate to vehicle and equipment fires.

Arcs, generally speaking, do not occur at voltages below the Paschen's law threshold. This suggests that "arcing" alone cannot be the cause of a typical vehicle or equipment fire. Generally, perhaps the most common electrical failure in vehicles or equipment consists of an energized wire rubbing, chafing and eventually shorting to a ground. In this example, and based on the definitions presented above, the evidence of short circuit left on the wire is the mark caused by a contact spark. We know the voltages involved are too low for an arc to form, and we know that a small amount of material melted and was ejected from the wire at the first point of contact. This mechanism seems to fit the definition of a spark better than the definition of an arc. Circumstances where low voltage arcs can occur include areas of high temperatures within an ionized environment. Since these circumstances are expected to only exist after a fire has initiated, evidence that arcing occurred in a vehicle or equipment (that is not a contact spark) is therefore probably an effect of the fire and not a possible cause of the fire. Arcs that form inside relays and solenoids are also generally not an issue as they are confined within their enclosures. The most common failure mode for a relay or solenoid is for the contacts to weld together causing the entire device to overheat. In this case the closing/parting arc is not the cause of the fire, but rather the overheated components are the cause.

In the example above where wire insulation chafed and created a short to ground; it is arguable that the true root cause is not the contact sparks or the subsequent over-current and heating of the wire, but rather poor routing, clipping, or maintenance of the wire harness. Techniques such as *r*FMEA can be used to help arrive at a correct root cause determination.[48] The duration of an arc is usually not expected to be an issue in vehicles or equipment as arcs are not expected to occur with normal 12 volt DC electrical system operation. All wires in vehicles or equipment are typically insulated, routed together in harnesses, with the entire harness covered with various protective materials as needed.

Sparks can be created electrically and mechanically. Both of these are of interest in vehicle and equipment fire investigations. Electrical sparks formed when energized wires first touch are competent ignition sources. The overheating of conductors during a short circuit is also a component ignition source. The propensity of DC electrical circuits to weld together during a short circuit also allows for a low resistance path and subsequent overheating of circuits. Mechanical sparks formed during accidents are also documented competent ignition sources.

The definitions of arcing through char and arc tracking suggest that even though these terms are often used interchangeably, they can be thought of as different phenomena. All of these definitions describe phenomena with current flowing through a path that was once nonconductive. The main difference is that arc tracking itself happens when you have a large enough voltage to overcome the resistive property of the insulation, while arcing through char happens only after the insulating materials have degraded and carbonized. The texts also stress the importance of the insulation materials, the age of the insulation materials, and the environment they have been exposed to - all contributing to their propensity for allowing arcing through char to occur. In addition, the arc path can form along the surface of the material when a wet film, salts, and metal particles are present. This conductive path is known as a dendrite. Published literature suggests that these dendrites are high resistance paths, and are therefore more likely to cause resistive heating of components rather than actually allow for the formation of an arc. It is clear that arc tracking is a sufficiently complicated phenomenon to require investigators to have a thorough understanding of the materials involved and of their environments before arc tracking or arcing through char can be determined as a cause.

Arcing, by definition, will thus not typically occur with a 12 volt DC electrical system. With a known lack of predictable behavior of energized electrical circuits exposed to a spreading fire, and without any known testing of arc mapping conducted in vehicles or equipment to validate any scientific basis for reliability and repeatability, arc mapping is not appropriate for use in vehicle and equipment fire investigations.

The fire investigation community needs to review and refine the usage of this terminology and definitions discussed in this paper dealing with the phenomena and ensuing evidence of different types of electrical activity that are a part of fire origination, potential fire causes, and fire investigation. Based on the definitions previously discussed, it is proposed that for vehicle and equipment fire investigations:

- Relays and solenoids are the only components, during normal operation, that are sometimes closed and then open - thus the term arc should only be used in the context of relays and solenoids.
- That the marks typically visible on wires after a short circuit are the result of contact sparks and not of an arc.
- Arc tracking should only be used when the materials involved and the environment that the materials have been exposed to have been properly identified and correlate with the occurrence of this phenomena.
- Arc mapping is not appropriate for use in vehicles and equipment (with 12 volt DC electrical systems) and this activity could more accurately be called an “electrical activity survey”.

ABOUT THE AUTHORS

Kerry Parrott is a senior engineer and fire analyst focused on commercial vehicle and commercial equipment fire investigation failure analysis. His experience includes fire origin and cause and product liability analyses in private practice and for a major truck and bus OEM for over fifteen years. He earned a BS in Mechanical Engineering from the University of Kentucky and holds CFEI/CVFI-NAFI certifications and CFI-IAAI certification. He is a principal member of the NFPA 1192/1194 Technical Committee on Recreational Vehicles and also serves as member of the SAE Motor Vehicle Fire Investigation Task Group.

Doug Stahl is a forensic engineer focused on engineering failure analysis investigations of commercial vehicles and commercial equipment. His experience includes fire origin and cause, product liability, and accident investigations in private practice and for a major truck and bus OEM for over twenty years. He is a Professional Engineer and earned a BS in Materials Science and Metallurgical Engineering from the University of Cincinnati and a MS in Metallurgy with a minor in Mechanical Engineering from Georgia Tech. Doug holds CFEI/CVFI certifications, serves as a member of the SAE Motor Vehicle Fire Investigation Task Group, a member of the NFPA 1192/1194 Technical Committee on Recreational Vehicles, and holds a number of patents.

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