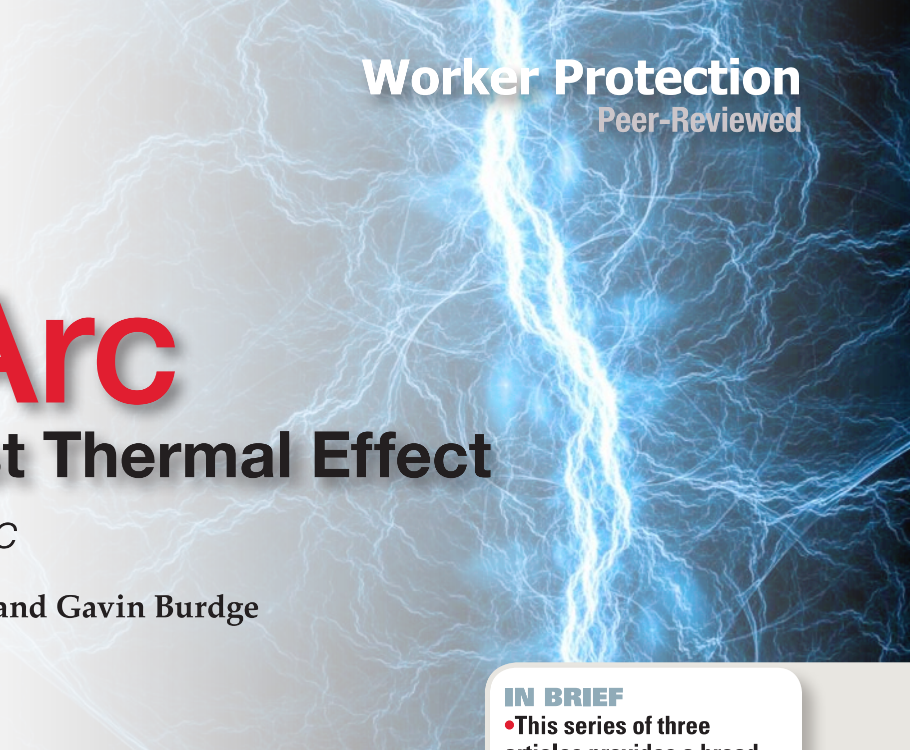


Electric Arc
Protecting Against Thermal Effect
Part 1: Types of Electric Arc

By Mikhail Golovkov, Holger Schau and Gavin Burdge

IN BRIEF
- **This series of three articles provides a broad overview of today's state of the art for protecting electrical workers against electric arc thermal hazard.**
- **Part 1 addresses key factors for further electric arc PPE advancement.**
- **It also discusses the different types of electric arc and why this knowledge is important for safety professionals who perform arc risk assessments.**

The entire industry of PPE against the thermal hazard of an electric arc has existed for 20 years. However, gaps still exist in electric arc knowledge and standardization. This three-article series provides a broad overview of today's state of the art for electrical workers' protection against electric arc thermal hazard.

Part 1 of the series identifies key factors for future progress, and discusses electric arc classification, properties, behavior and methods of thermal energy dissipation.

Statistical trends in general electric and electric-arc-related fatalities and trauma are essential for future improvements. However, information on electric arc incidents is hard to find in government statistical reviews. Part 2 of the series is dedicated to reviewing statistical data and identifying gaps in reporting electric-arc-related incidents and corresponding skin burn trauma. The authors also review previously published electric arc incidents.

Part 3 of the series discusses multiple elements for reliable protection against electric arc. These include arc hazard assessment, standardization for PPE test method requirements, results of the latest research, challenges and suggestions.

Factors for PPE Progress
Fire Retardant Materials

During the past 15 years, revolutionary changes occurred in the availability of different fabrics and materials for PPE used by electrical workers to protect against the thermal effect of an electric arc during live electrical work. Removing flammable and melting materials and fabrics from the face, body and hands was a major factor in reducing burn incidents. These ignitable

Mikhail Golovkov is an independent consultant DBA ArcFlash-CRT specializing in electric arc testing, performing commercial and research arc testing. Prior to this, he was a test contractor and manager for ArcWear.com, and senior test engineer with KEMA-Powertest, which extended his expertise into high-current testing. Golovkov was a high-voltage test equipment designer and test engineer for the Moscow utility Mosenergo. He organized and performed high-voltage diagnostic testing on Russian nuclear power plants and North American utilities. Golovkov holds four Russian patents on high-voltage test equipment and test methods. He holds an M.S. in Electrical Engineering from Moscow Power Engineering Institute, Moscow, Russia, and is a senior IEEE member and a member of ASTM F18, which develops standards related to arc-flash test methods.

Holger Schau, Dr.-Ing. habil., Ph.D., is professor and head of the Department of Electrical Power Supply Systems at Ilmenau Technical University. Prior to this, he was a lecturer at the German Leipzig University of Technology, and special project manager for electrical medium and high plants for Starkstrom-Anlagenbau Leipzig-Halle Co. He holds a Dr.-Ing. habil. (Ph.D. in Engineering) from Germany's Ilmenau Technical University. He serves on several electrical safety standard-setting organizations. He is project team leader for IEC 61482-1-2, Technical Committee (TC) 78 (arc box test method), the European equivalent to ASTM F1506 for testing protective clothing of electrical workers from arc thermal hazards. He is member of the European Committee for Electrotechnical Standardization (CENELEC) for live work protective clothing. Schau also works on several technical committees for Verband der Elektrotechnik, Elektronik und Informationstechnik (VDE), the European Association for Electrical, Electronic and Information Technologies, including the German Electrotechnical Committee Standard DKE UK 214.3 (requirements for live electrical work).

Gavin Burdge, CSP, CIH, is a safety and industrial hygiene freelance writer with a broad industrial hygiene and workplace safety background. He worked as an electrical safety specialist under contract with the U.S. Department of Defense Electrical Safety Working Group. Prior to that he was a senior occupational safety and health analyst with the Naval Safety Center as a consultant to the U.S. Navy Pentagon Safety Liaison Office. He worked in Georgetown University Safety Office and later as a corporate industrial hygienist for a large hazardous waste management firm. Burdge holds an M.S. in Environmental and Occupational Health from West Virginia University. He is a professional member of ASSE's Central Pennsylvania Chapter and is a member of the Society's Industrial Hygiene Practice Specialty.

CAPPAN/ISTOCK/GETTY IMAGES PLUS

TABLE 1
Electric Arc Type Classification

	Open air arc	Arc in a box	Moving arc	Ejected arc	Tracking arc
Electrode geometry and arc gap length	in-line > 6 in.	in-line or parallel < 1.25 in.	long parallel electrodes > 6 in.	long parallel electrodes > 6 in.	any electrode configuration > 6 in.
Nominal voltage	medium and high voltage	low voltage	medium and high voltage	medium and high voltage	medium and high voltage
Shape of arc plasma channel	cylindrical column	cylindrical column	cylindrical column	circular	dependent on circumstances
Enclosure	no enclosure	arc in enclosure	no enclosure	no enclosure	no enclosure
Radiant or convective heat dissipation	predominantly radiant	more convective than radiant	predominantly radiant	more radiant than convective	heart from flowing current
Stationary or moving	stationary	stationary	moving	stationary	stationary
Contact with energized parts	no contact	no contact	no contact	no contact	contact or flashover

and melting materials were substituted by flame-resistant (FR) and electric-arc-rated (AR) materials eliminating ignition of clothing and other PPE.

Electric Arc Incident Analysis

The essential part of any progress is studying and analyzing past experience. Understanding comprehensive electric arc incident data is often a missing link between standardization, laboratory research and development (R&D) testing, and real-life situations. And, most importantly from a PPE perspective, data are valuable for understanding what is working and what is not.

R&D Consideration of Electric Arc Behavior & Energy Dissipation

Because of the extremely wide range of heat generated by electric arcs, the use of FR and AR PPE alone does not guarantee absolute protection from skin burns. Many factors can affect the amount of dissipated thermal energy:

- type of arc, including variables that affect electric arc such as:
  - equipment design (confined compartment or open air);
  - geometrical electrode configuration;
  - operating voltage;
  - distance between arcing conductors (arc gap);
  - contact with energized conductor;
- fault current;
- arc duration;
- distance from an arc.

R&D electric arc testing has enabled better understanding of electric arc behavior. However, research projects are still scattered and not synchronized. Today's electric arc classification distinguishes five types: open arc, arc in a box, moving arc, ejected arc and tracking arc. Thermal hazard assessment, PPE selection and other mitigating means are generally arc type dependent. Differences in arc behavior are not adequately reflected and addressed in electrical safety standards, causing misunderstandings and myths.

Implementing New Knowledge Into Standardization

Several organizations are involved in standards development and maintenance related to:

- electric arc safety in the workplace;
- requirements for AR PPE;
- electric arc test methods;
- arc hazard assessment.

The broad geography of the standardization landscape ranges from OSHA's government-adopted regulatory standards to consensus international standards of American Society for Testing and Materials International (ASTM), Institute of Electrical and Electronics Engineers (IEEE), International Electrotechnical Commission (IEC), NFPA, and national and regional standards. By accumulating past field experience and electric arc knowledge, standards set rules for how to construct, test, use and maintain AR PPE.

Summary of Factors

To summarize, further reliable protection from electric arc derives from the application and evaluation of many different knowledge areas:

- availability of electric arc incident data for analysis;
- past experience and analysis of real-life incidents with workers exposed to electric arc with sustained damage and area of skin burns with sometimes fatal outcome;
- knowledge of the electric arc behavior based on laboratory research, testing and its correlation with the field incident data analysis.
- standardization on:
  - product requirements for FR and AR PPE;
  - test methods used for evaluating PPE efficacy;
  - heat exposure hazard assessment;
  - workplace electrical safety.

Defining Electric Arc

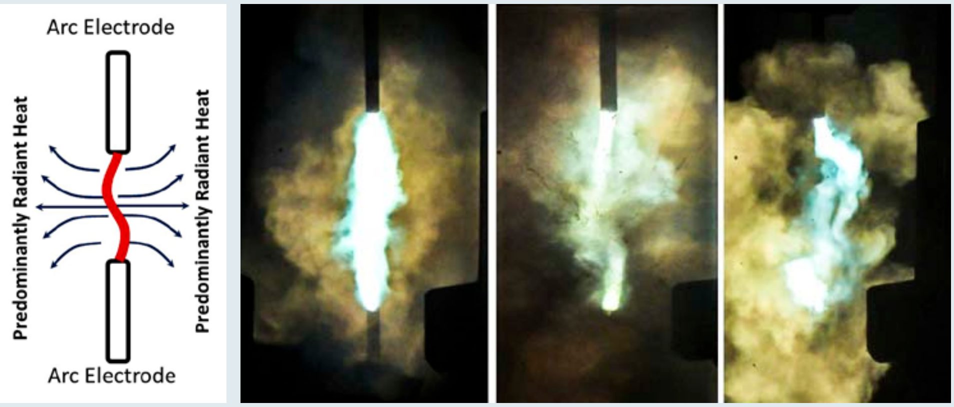
What is electric arc from an electrical safety perspective? Various standards offer several definitions of electric arc.

- ASTM F1506, Standard Performance Specification for Flame Resistant and Arc Rated Textile Materials for Wearing Apparel for Use by Electrical Workers Exposed to Momentary Electric Arc and Related Thermal Hazards, defines electric arc as "a discharge of electricity through gaseous media, normally characterized by a voltage drop in the immediate vicinity of the electrodes, approximately equal to the ionization potential of the gaseous media" (ASTM, 2015).

•IEC 61482-1-1, Live Working—Protective Clothing Against the Thermal Hazards of an Electric Arc—Part 1-1: Test Methods—Method 1: Determination of the Arc Rating (ATPV or EBT50) of Flame Resistant Materials for Clothing, defines electric arc as "self-maintained gas conduction for which most of the charge carriers are electrons supplied by primary-electron emission."

FIGURE 1

Open Arc Electrode Configuration & Examples of Arc Plasma Channel



Note. *Photos from "Effect of Arc Electrode Geometry and Distance on FR Fabric Protection Properties Against Second Degree Skin Burn," (Conference paper ESW2016-15), by M. Golovkov and H. Schau, 2016, IEEE Electrical Safety Workshop, Jacksonville FL. Reprinted with permission.*

•Note to IEC 61582-1-1 arc definition:

> During live working, the electric arc is generated by gas ionization arising from an unintentional electrical conducting connection or breakdown between live parts or a live part of the earth path of an electrical installation or an electrical device. During testing, the electric arc is initiated by the blowing of a fuse wire. (IEC, 2009)

While the definitions contain important characteristics about electric arc, both are excessively scientific, and the note contains the most useful information for a safety professional.

Utility safety programs are likely to include a simpler and better identifying hazard definition: Electric discharge in a gaseous media consisting of a plasma channel between electrodes of different polarity. Arc is the electrical discharge; at least two electrodes are needed for an arc to exist. A discharge channel between electrodes is filled with plasma that is a conductive media consisting of ionized gas and electrons. The plasma temperature is a minimum of 5,000 °C. In so-called arc jets, temperature is much higher in the arc electrode area.

Electromagnetic forces occur between currents in electrical conductors. Significant electromagnetic forces occur during an arc event, and an arc plasma channel, which is not part of the ASTM or IEC definition, greatly affects arc behavior. In normal operation, when load currents are in the range of hundreds of amperes and probability for an arc flash event is low, electromagnetic forces are insignificant in magnitude. However, during a fault, an electric arc event can occur where the fault current increases into the kilo-amperes range. Electromagnetic forces not only become highly destructive for equipment but also interact with the plasma channel to move or change its shape and length.

Five Types of Arc

Not all electric arcs in electrical equipment in industrial and utility transmission and distribution networks are the same. Differences in arc configuration and behavior determine the way in which thermal energy is distributed, which in turn affects PPE protection properties.

There are five types of electric arc. The arc type classification is based on several differentiating factors: arc electrode geometrical configuration; nominal voltage of electrical installation; shape of arc; arc inside enclosure or in the open air, and predominant radiant or convective heat dissipation; stationary or moving arc; and contact with energized parts or voltage flashover. Table 1 summarizes electric arc attributes.

Open Air Arc

Open air electric arc is a medium- or high-voltage arc burning in open air with no enclosure around the arc (Figure 1). The in-line electrode geometry of the open air arc does not generate electromagnetic interaction between current flowing in electrodes and current in the electric arc plasma channel, which would force the plasma channel out of and away from the arc gap. Electromagnetic forces only cause spinning of arc jets in the electrode area as shown in Figure 1.

An open air arc is stable and will last until a protective device clears the fault. The shape of the plasma channel can be described as a cylinder. The heat energy is dissipated equally in all directions predominantly through radiated light.

An open air arc can start as a result of:

•bushing flashover at high and medium voltage transformer (power and instrument) or breaker;

•flashover of a support and suspend insulators of power lines;

•flashover at substation buswork.

FIGURE 2

Arc in a Box Electrode & Enclosure Configuration & Example of Discharge

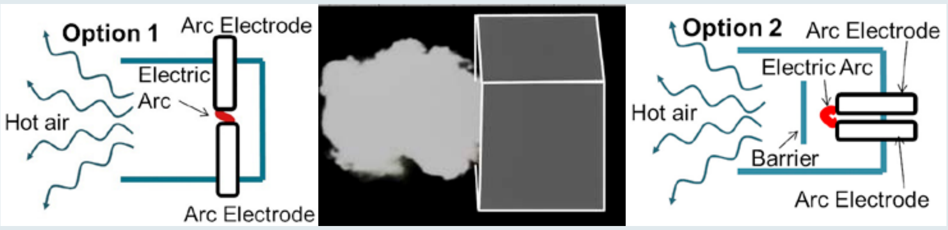


FIGURE 3

Moving Arc Electrode Configuration & Arc Movement

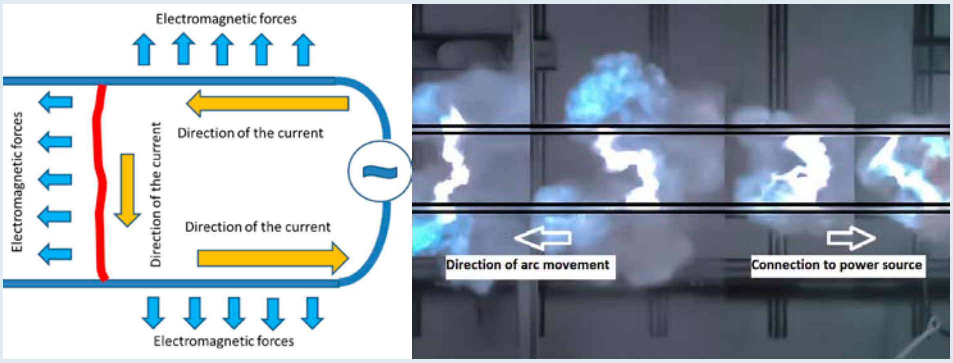
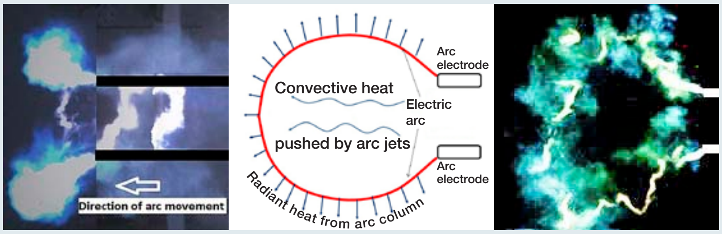


FIGURE 4

Ejected Arc Electrode Configuration & Examples of Moving Arc Converting Into Ejected Arc & Arc Plasma Channel Shape



Open air type of arc is used in most electric arc test methods such as:

•ASTM F1959, Standard Test Method for Determining the Arc Rating of Materials for Clothing;

•IEC 61482-1-1, Live Working—Protective Clothing Against the Thermal Hazards of an Electric Arc—Part 1-1: Test Methods—Method 1: Determination of the Arc Rating (ATPV or EBT50) of Flame Resistant Materials for Clothing;

•ASTM F2621, Standard Practice for Determining Response Characteristics and Design Integrity of Arc Rated Finished Products in an Electric Arc Exposure;

•ASTM F2675, Standard Test Method for Determining Arc Ratings of Hand Protective Products Developed and Used for Electrical Arc Flash Protection;

•ASTM F2178, Standard Test Method for Determining the Arc Rating and Standard Specification for Eye or Face Protective Products.

Some of these test methods are referenced in product specification standards ASTM F887, Standard Specifications for Personal Climbing Equipment, and ASTM F1891, Standard Specification for Arc and Flame Resistant Rainwear.

Arc In a Box

Arc in a box is a low-voltage electric arc in an enclosure. Thermal energy is dissipated although only one side is open for the performed task, or because of lock or hinge failure. Arc electrodes could be in-line or parallel with a short gap (Figure 2). An arc plasma channel is not visible in Figure 2 as the arc plasma is completely inside the enclosure and only the exhaust of extremely hot air through one open side can be seen. Arc-in-a-box type arc is used in the arc test method in IEC 61482-1-2, Live Working—Protective Clothing Against the Thermal Hazards of an Electric Arc—Part 1-2: Test Methods—Method 2: Determination of Arc Protection Class of Material and Clothing by Using a Constrained and Directed Arc (Box Test).

The nominal voltage of industrial electrical installations is typically between 400 and 1,000 V. The low-voltage arc can exist only in short gaps of 2 in. or less. Sustainable electric arc in 120-V equipment is unlikely, and in 240-V equipment the low-voltage arc can or cannot be sustained, depending on design. Generally, the design spacing (arc gap in a potential electric arc event) between phases is too large for the voltage of 120 or 240 V to support a stable and lasting arc.

Arc in a box is a stable arc. The heat energy is dissipated through radiated light and mostly as convective heat of very hot air. Hot air emitted from the box is concentrated in one direction through the open or broken door.

Arc in a box can start as a result of equipment breakage or malfunction during closing/opening operations or human unintentional actions such as tool drops in enclosures. Arc in a box can occur in the following types of electrical equipment:

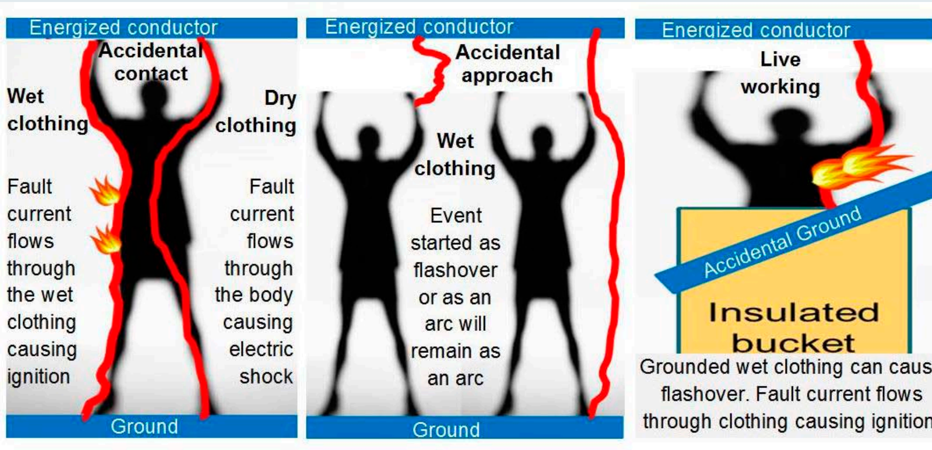
•panels;

•motor control centers (MCC);

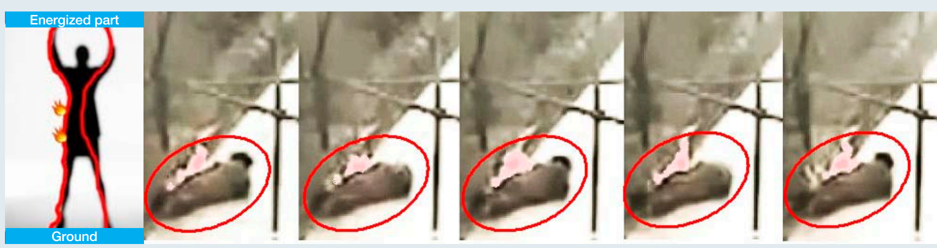
- control gear;
- fused disconnect;
- switchgear;
- electrical meters.

The arc-in-a-box configuration is the most common type of arc in industrial and utility environments. Most low-voltage electrical equipment is enclosed within cabinets, panels or other kinds of electrical boxes.

FIGURE 5
Tracking Arc



Variations of Tracking Arc



Accidental Indirect Contact to Energized Conductor Through Moving Scaffolding
Event has started as electric shock and worker was unable to evacuate from the contact. Clothing ignition followed due to the fault current flowing through wet clothing. Screen shots from video. Worker is conscious and moving his head.

Accidental Approach to Energized Conductor, Flashover & Electric Arc
Man on the roof of the train.

Moving Arc

Moving arc is a medium- or high-voltage arc in open air propagating between two long parallel conductors. Arc current flowing through the ionized plasma channel interacts electromagnetically with fault currents flowing in conductors. As a result, the plasma channel is forced to move along the conductors in the direction away from the power source such as generation station or feeding substation (Figure 3).

Moving electric arcs can be initiated as a flashover or insulation breakdown on medium- and high-voltage overhead lines and/or substation buswork. Moving arc plasma channel is generally contained within the arc gap between parallel conductors but the arc plasma is not stationary. Heat energy dissipation is equal in all directions and radiated light is similar to the open air arc except that the source of radiated light is moving.

Velocity of the moving arc is dependent on fault current magnitude and can exceed 100 mph. This high velocity reduces the time of potential arc exposure when a worker is on the side of the line. At a distance of 12 in., side-of-the-line position of the worker can significantly reduce potential arc exposures. For example, experimentally measured incident energy on the side of the line was below 2 cal/cm^2. However, the outcome of arc exposures will be very different if workers are positioned between electrodes or between phases of an overhead line. This type of exposure is much more dangerous because of the direct contact with a plasma channel that has a temperature of 5,000 °C or more.

Ejected Arc

Ejected arc is a medium- or high-voltage arc formed at the tips of parallel conductors or electrodes. One example of an ejected arc forming is when the moving arc reaches the end of long parallel conductors. As with a moving arc, ejected arc current flows through the ionized plasma channel and interacts electromagnetically with fault currents flowing in conductors. As a result, the arc plasma channel is forced out of the gap between conductors; the channel is elongated and changes its shape from a column to nearly a circle (Figure 4).

Most importantly, the ejected arc elongation and corresponding heat energy dissipation are generally directional. Ejected arc is elongated in the direction of an imaginary continuation of parallel arc electrodes. The ejected type of arc is used in ASTM F2676, Standard Test Method for Determining the

Protective Performance of an Arc Protective Blanket for Electric Arc Hazards, test method for arc protective blankets.

Both the radiant energy component from the plasma channel and the convective heat component strengthened by the arc jets from the electrode tips are strong. The heat conductive component will likely become considerable because the arc channel elongation delivers extreme temperatures of 5,000 °C into close proximity or in direct contact with a worker's clothing and other PPE. Known field cases and lab tests resulted in ignition of non-AR clothing as far as 7 ft (2.1 m) from arcing electrodes or equipment.

Although ejected arc is not the most common configuration, it is the most dangerous type of arc because a large human body area is subjected to extremely high temperatures.

There is currently no test method for clothing, face or hand PPE associated with an ejected arc. An ASTM task force is considering and evaluating the necessity for an ejected arc test method.

Knowledge and understanding of electric arc type is generally the major factor of AR PPE progress and the starting point of arc hazard assessment specifically.

Tracking Arc

Tracking arc is significantly different from all other types. A tracking arc can occur on a worker's skin surface under the clothing as a result of a worker having a direct or indirect contact with the energized part, or as a result of a worker approaching the energized part (Figure 5, p. 53). The tracking arc event represents a double hazard of electrocution and non-AR clothing ignition.

Tracking arc cases are also known for igniting a non-AR cotton or synthetic under-layer such as a T-shirt under AR clothing. The AR clothing does not provide protection from arc-generated heat flux in tracking arc but limits the extent of the injury by preventing ignition.

Most commonly, tracking arc can be initiated under the following conditions:

- Accidental direct contact with medium-voltage energized conductor or touching lifting or other construction machinery while the machinery is in contact with a medium-voltage energized conductor, and the worker's non-AR clothing or underlayer is wet from sweat or rain.
- Approaching an energized conductor at a short enough distance to cause flashover. Electric arc flows onto the worker's body where the arc will cause ignition of non-AR clothing.
- Wet clothing becomes accidentally grounded causing flashover and fault current flowing through wet clothing and igniting non-AR clothing.

Conclusion

Knowledge and understanding of electric arc type is generally the major factor of AR PPE progress and the starting point of arc hazard assessment specifically. It helps predict the most probable direction of thermal energy release and is used to prepare safe workplace procedures should the task be completed energized. Moreover, a severity of passible arc exposure and concentration of thermal energy is determined by the arc type.

Since electric arc properties are identified, its hazards and fundamentals of protection will be described in the next articles. Arc type knowledge was used for a retroactive analysis of previously published electric arc incidents with the purpose of better understanding encountered damages. The results will be presented in Part 2 of this article series. Analysis of specific electric arc incidents will be complemented with extensive research of electrical trauma trends based on government statistics. **PS**

References

ASTM International. (2015). Standard performance specification for flame resistant and arc rated textile materials for wearing apparel for use by electrical workers exposed to momentary electric arc and related thermal hazards (ASTM F1506). Retrieved from www.astm.org/Standards/F1506.htm

International Electrotechnical Commission (IEC). (2009). Live working—Protective clothing against the thermal hazards of an electric arc—Part 1-1: Test methods—Method 1: Determination of the arc rating (ATPV or EBT50) of flame resistant materials for clothing (IEC 61482-1-1:2009). Retrieved from https://webstore.iec.ch/publication/5497

Institute of Electrical and Electronics Engineers (IEEE). (2002). IEEE guide for performing arc flash hazard calculations (IEEE 1584-2002). Retrieved from https://standards.ieee.org/findstds/standard/1584-2002.html

IEEE. (2017). National electric safety code (IEEE C2-2017). Retrieved from https://standards.ieee.org/findstds/standard/C2-2017.html

Golovkov, M., Hoagland, E., Schau, H., et al. (2015, Jan./Feb.). Effect of arc electrode geometry and distance on cotton shirt ignition. *IEEE Transactions on Industry Applications*, *51*(1), 36-45.

Golovkov, M. & Schau, H. (2016, March). Effect of arc electrode geometry and distance on FR fabric protection properties against second degree skin burn (Conference paper ESW2016-15). IEEE Electrical Safety Workshop, Jacksonville FL.

Hoagland, E., Golovkov, M., Maurice, C., et al. (2014, July/August). Clothing in arc flash: Four types of arc exposure and the effect of moisture on garment appearance after an arc event. *IEEE Transactions on Industry Applications*, *50*(4), 2370-2374.

Lang, M., Jones, K. & Neal T. (2011, July/Aug.). Impact of arc flash events with outward convective flows on worker protection strategies. *IEEE Transactions on Industry Applications*, *47*(4), 2370-2374.

Neal, T. & Lang, M. (2008, March). The impact of arc flash test conditions on the arc rating of PPE (Conference paper ESW2008-05). IEEE Electrical Safety Workshop, Dallas, TX.

NFPA. (2015). Standard for electrical safety in the workplace (NFPA 70E). Quincy, MA: Author.

Short, T. & Eblen, M. (2012, Jan./Feb.). Medium-voltage arc flash in open air and padmounted equipment. *IEEE Transactions on Industry Applications*, *48*(1), 245-253.