Flame-Resistant Clothing

Its role in protecting electric line workers from arc flash burns

By Kirk Wulf

THERE ARE NEARLY 60,000 electric line workers building and maintaining the transmission and distribution lines across the U.S. (U.S. Department of Energy, 2006). The work is hazardous, physical in nature and may be performed in less-than-ideal environmental conditions. Line workers perform much of their work in an energized state due to reliance on electricity. The dangers of contact with electricity are well established and significant resources go into preventing electric contact injuries.

In the 1980s, arc flash hazards gained prominence and protection against these hazards continues to improve. In the 1990s, utilities began to use flame-resistant (FR) clothing as a means of protecting workers from arc flash injuries (Linton, 2002). FR clothing continues to advance from these early fabrics as well. As with other PPE, it is important to understand arc flash hazards and the protection provided by FR clothing—including its limitations. FR clothing is just one aspect of a comprehensive safety program where arc flash hazards are present—an important one due to the unpredictable nature of arc flashes.

This article reviews the research on hazards associated with an arc flash, discusses the effects of burn injuries on the human body, describes the hazards of conventional clothing and shares the benefits of FR clothing in preventing arc flash injuries, as well as the standards and regulations pertaining to FR clothing relating to electric utility workers.

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Arc Flash Hazards

Electric arc hazards have been present since the beginning of electrification in the late 19th century. The technology to better understand and manage these hazards is relatively new—with much of it learned since the 1980s (Floyd & Doan, 2007). An electric arc or an arcing fault is a flashover of electric current through air from one exposed energized conductor to another or to ground. In other words, it is a short circuit through the air.

Electric arcs reach temperatures up to 35,000 ºF, some of the highest temperatures known to occur on earth (Jamil, Jones & McClung, 1997). The thermal hazard is the most significant hazard from arc flash. A worker can be several feet away from a circuit or electrical equipment and still be severely injured by an arc flash (Floyd & Doan, 2007). Stokes and Sweeting (2006) state that both radiant and convective heat energy are present in an arc flash. Additional hazards include an arc blast pressure wave, which can result in ear injuries, and injuries from flying shrapnel. Arc blasts of high energy exposures more than 40 cal/cm^2 are generally required for arc blast pressure waves (Floyd, Doan, Wu, et al., 2005).

Thermal hazard is the focus of this article. ASTM F 1959/F 1959M-36 (2007) defines thermal hazard as the heat energy sufficient to cause burn injury to human tissue subjected to a momentary electric arc. The amount of energy released in an electric arc is dependent on the fault current, duration of the arc, length of the arc, distance from the arc and the source voltage (Makinen & Mustonen, 2002). Available fault current, time or duration of the arc, and length of the arc are primary factors in determining its energy.

The source voltage impacts the magnitude of the arc flash. Higher voltages tend to expand the heat of the flash. The amount of energy released at the arc is referred to as incident energy, which is represented in calories/cm^2. The incident energy or the amount of heat on a certain area is the critical factor in assessing arc flash hazards and determining the level of protection required to protect against burns.

Moritz and Henriques (1947) report that burn injury in human tissue is a function of elevated tissue temperature and the time period for tissue temperature remains elevated. At 44 ºC (111 ºF), burn injury to tissue is at a slow rate (hours). The rate of injury to tissue increases rapidly when temperatures

Abstract: *Electric line workers face many hazards—including exposure to arc flash. This article reviews the research on these hazards, discusses the effects of burn injuries on humans, describes the hazards of conventional clothing and describes the benefits of flame-resistant (FR) clothing in preventing arc flash injuries. It also reviews the standards and regulations pertaining to FR clothing relating to electric utility workers.*

exceed 60 °C (140 °F), where burns occur in seconds. It is commonly accepted that 1.2 cal/cm^2 for a 1-second exposure time can result in second-degree burn on exposed skin (Neal, Bingham & Doughty, 1997).

Incident energy of an actual arc flash is difficult to determine due especially to variables such as the length of the arc, distance between the worker and the arc, and clearing times. Laboratory studies show a 600-V system could produce incident energy of approximately 2 cal/cm^2 at 2 ft from the arc, with the energy increasing to about 11 cal/cm^2 at the point of the flash (Neal, et al., 1997). Incident energy can exceed the 40 cal/cm^2 level that generally results in the arc blast in an electric distribution or transmission system.

Utility workers' exposure to arc flash varies dramatically depending on the job. Exposure may include high current switching where potential incident energy is high while other tasks involve less exposure (Doughty, Laverty, Neal, et al., 2000). The exposure exists in both overhead line work and in underground installations such as padmount transformers and switch cabinets. An arc flash during overhead line work allows the heat energy to dissipate in 360° from the worker. An arc flash in an underground installation presents the danger of a directional blast, known as "arc in a box" that directs thermal hazard at the worker. Electric arcs can occur due to human error, such as accidentally contacting a tool or other piece of conductive material to an energized conductor or equipment. Arcs can also result from equipment malfunctions, poor electrical contact or failure of insulation (Jamil, et al., 1997).

Understanding the Nature of Burn Injuries

The heat associated with the arc flash can be fatal. Often, however, there will be some distance between the arc source and the worker. This is likely reflected in a 20-year study of electrical injuries that compared four categories of electrical injuries: high voltage, low voltage, lightning strikes and arc flash injuries. Arc flash injuries comprised the largest of the four categories at 40% but the lowest mortality rate at only about 1% (Arnoldo, Purdue, Kowalske, et al., 2004).

A significant risk for death or serious injury occurs when the arc ignites the worker's clothing. The most serious of the burn injuries involve the ignition of the victim's clothing (Doughty, Laverty, Neal, et al., 2000). A critical factor in surviving a burn injury is the total body surface area (TBSA); burned and burning clothing quickly increase the TBSA affected.

American Burn Association (2006) provides general statistics on burn injuries. In a 10-year study (1995 to 2005) of acute burn admissions, the group reported the following:

- Work-related injuries comprised 17% of all cases. A total of 187,000 cases were reviewed so 17% translates to more than 31,000 work-related burn cases.
- Of all burn cases, 94.4% survived hospitalization, while 5.6% of all burn cases resulted in fatalities.
- Ignition of highly flammable material with ignition of clothing had the second-highest number of incidents at 10,753, which equals 8.5% of all incidents.

Death from a burn injury is significantly impacted by the victim's age and burn size. Length of hospitalization increases with increased burn size. Table 1 shows the data from the American Burn Association studies. These statistics reveal the significance of the hazards associated with arc flash burns, where 50% TBSA is reaching a 37% mortality rate and an average of 26 days of hospitalization. Burn injuries are costly as well. According to the American Burn Association (2006) report, the average cost of hospitalization for a burn injury is approximately $60,500. However, a burn of 50% TBSA averages almost $300,000. In the 20-year study of electrical injuries, the average burn size was 14.4% TBSA and the average length of hospital stay was 11 days (Arnoldo, et al., 2004).

Finding occupational injury data is more difficult but OSHA's proposed rule changes for electric generation, transmission and distribution offer some indication that the outcome of arc flash burns are significantly worse. Between 1990 and 1998, OSHA investigated 63 burn accidents that resulted in 97 injuries. These only represent the incidents reported by employers. Eighty-four percent of the burn injuries were fatalities or required hospitalization, and 87% of the accidents involved third-degree burns (OSHA, 2005). Clearly, arc flash burns are catastrophic injuries involving weeks of hospitalization and years of recovery. Preventing such burns has become an important part of the comprehensive safety efforts of electric utilities across the U.S.

Table 1

ABA Burn Injury Statistics

Burn size (%TBSA)	% Fatal	Mean hospital stay
0.1 to 9.9 %	0.8%	5.77 days
10 to 19.9%	3.0%	11.78 days
20 to 29.9 %	8.7%	21.15 days
30 to 39.9%	16.7%	29.01 days
40 to 49.9%	26.4%	34.92 days
50 to 59.9%	37.0%	36.83 days
60 to 69.9%	45.6%	37.86 days
70 to 79.9%	58.0%	35.49 days
80 to 89.9%	67.7%	38.43 days
≥ 90%	78.4%	18.39 days

A significant risk for death or serious injury occurs when the electrical arc ignites the worker's clothing. The most serious of the burn injuries involve the ignition of the victim's clothing.

Evolution of Clothing Standards in the Utility Industry

Exploring the evolution of standards covering utility line workers and FR clothing provides insight to the recognition of FR clothing as a means of preventing burns in arc flash incidents. It was not until 1995 that 29 CFR 1910.269, OSHA's standard for electric generation, transmission and distribution became effective. The original proposal had been issued in January 1989, and the final rule was issued in January 1994. At the time, much of the concern came from fabrics that would ignite and melt when exposed to an arc flash. Natural materials, such as cotton, wool or silk, would not melt and were considered safer. American Society for Testing and Materials (ASTM) Committee F-18 was exploring possible standards on the application of clothing, but at the time no standard existed (OSHA, 2005).

The current language dealing with protecting line workers from arc flash burns is found in 1910.269 subpart L. The language is prohibitive in nature, saying only that the employer shall ensure that an employee who is exposed to flames or electric arcs does not wear clothing that when exposed to flames or electric arc could increase the extent of the injury. OSHA identifies the prohibited clothing fabric either alone or in blends as acetate, nylon, polyester and rayon unless the employer can demonstrate the fabric has been treated to withstand the conditions that may be encountered (OSHA, 1995).

OSHA also referenced ASTM Committee F-18. In 1997, a subcommittee developed two tests for FR clothing. The first test method determined the ignitability of non-FR materials for clothing; it became ASTM F1958 standard used today. The second was the standard test method for determining the arc rating of FR clothing; it is the current ASTM F1959 standard (Doughty, Neal, Dear, et al., 1999).

Numerous ASTM standards relate to either assessing the burn hazard associated with clothing, protecting workers against arc flash burns or measuring the protection against burns of FR clothing. These include:

- ASTM F1506-02a: Standard Performance Specification for Flame-Resistant Textile Materials for Wearing Apparel for Use by Electrical Workers Exposed to Momentary Electric Arc and Related Thermal Hazards.
- ASTM F1958-99: Standard Test Method for Determining the Ignitability of Non-Flame-Resistant Materials for Clothing by Electric Arc Exposure Method Using Mannequins.
- ASTM F1959: Standard Test Method for Determining the Arc Rating of Materials for Clothing.
- ASTM F 1891: Standard Specification for Arc and Flame Resistant Rainwear.
- ASTM D6413: Standard Test Method Flame Resistance of Textiles (Vertical Flame Test).

The growing body of knowledge these test methods provide has helped improve the understanding of what occurs when conventional clothes are exposed to the incident energy of an arc flash and have shown the ability of FR clothing to prevent burns in these situations. As a result, industry standards such as NFPA 70E and the National Electrical Safety Code (NESC) C2-2007, which is the guiding standard for electrical line work, provide language that arc flash hazards shall be determined and adequately rated FR clothing shall be worn to protect against the anticipated incident energy. OSHA has proposed revisions to its electric power generation, transmission and distribution standards. Among them is a proposal to replace the prohibitive language noted earlier with language that is more consistent with NESC C2-2007 in that where there is arc flash exposure, arc protective clothing shall be worn.

Conventional Clothing

Cotton clothing was commonly used by utility workers because it is comfortable and did not melt when exposed to the heat of an arc flash. However, cotton can ignite, resulting in serious burns. The ASTM F18.65 Subcommittee developed test method ASTM F1958 to determine ignitability of a textile material in single layer or multiple layers.

The results showed variability in ignition of cotton due to the incident energy of an arc due to fabric weight, moisture and fabric color. Cotton fabrics of heavier weight, high moisture content and lighter color required greater incident energy for ignition. Lighter weight cotton fabric and darker colored fabric required less incident energy for ignition (Doughty, et al., 2000).

The Institute of Electrical and Electronics Engineers (IEEE) published a document from the ESMOL subcommittee (2001) regarding estimating the ignition hazard of 100% cotton clothing worn by transmission and distribution line workers. A general finding of clothing tests indicates cotton fabric has a 50% probability of ignition in the range of 0.8 to 1.2 cal/cm^2.

As indicated, fabric weight and color play a significant role in whether cotton will ignite. A 5.2 oz blue cotton twill shirt had a 50% probability of ignition when exposed to 4.6 cal/cm^2 whereas 12.8 oz denim blue jeans could withstand 15.5 cal/cm^2 of incident energy before reaching a 50% probability of ignition.

A study comparing burning behavior of polyester-cotton blends and pure cotton textiles produced interesting results (Umbach, 1981). In some cases, 100% cotton fabrics transmitted more thermal energy to an underlying area than polyester-cotton blend fabrics. Flames spread more rapidly in 100% cotton garments as well. Therefore, Umbach concluded that burns resulting from ignition of 100% cotton clothing produce deeper, more severe burns than those resulting from polyester-cotton blends.

A study by Rossi, Bruggmann and Stampfli (2005) produced similar findings. A mannequin with sensors was used to examine flame spread—or flame propagation rate—of different textiles and to predict the extent of burn injuries. Natural fibers (such as cotton, silk and wool), synthetic fibers (such as polyester, polyamide and acrylic) and blended fabrics were tested. For this study, European standards were used and a flame propagation rate exceeding 90 mm/s was considered excessive.

The flame propagation rate of cotton was found to increase with decreasing weight. This trend was found to be exponential in cotton garments less than 120 g/m^2 (approximately 4 oz). Cotton garments with a weight less than 70 g/m^2 (2.5 oz) would exceed the flame propagation rate of 90 mm/s. Silk and wool were found to have low propagation rates as did the heavier weight cotton fabrics. Many of the synthetic fibers were found to have a flame propagation rate that was lower than lightweight cotton garments.

The fire behavior of blended fabrics depended on the percentage of cotton, where garments with greater than 50% cotton tended to exhibit the same characteristics of 100% cotton garments. Although some synthetic garments had a low flame propagation rate, the heat transfer rate was high due to the melting of fibers. It is the melting of the synthetic fabrics that presents the increased risk to the worker. The most significant finding is that every contact with skin with an open flame will lead to burns.

These studies present interesting findings compared to the current OSHA standard for electric line workers. The standard provides that clothing which may increase the extent of the injury cannot be worn. However, these studies conclude that in certain cases 100% cotton garments, when ignited, can significantly increase the extent of the injury. In some cases, 100% cotton garments can experience a relatively quick flame spread rate and high transfer of heat energy compared to the prohibited fabrics identified in the 1910.269 standard. While the melting of synthetic fibers will significantly increase the extent of a burn to a worker, it should not be construed that 100% cotton is providing protection against an arc flash. If anything, these studies illustrate that OSHA regulations are minimum standards which must be exceeded to truly protect workers.

Flame-Resistant Clothing

The use of FR clothing began in the 1960s in the molten metal industry—typically consisting of a heavy work coat. Oil refiners began to use FR clothing in the 1970s, and petrochemical and electrical utilities began to use it in the 1990s (Linton, 2002).

Protective Clothing for Line Workers

The protective clothing cited would need to have an arc thermal performance value sufficient to protect against the incident energy. The incident energy would be determined by each utility for its system.

- FR long-sleeve shirt
- FR pants
- Hardhat with face shield
- Safety glasses
- Insulated rubber gloves
- Insulated rubber sleeves
- Insulated rubber cover-up

In addition, FR coats, bibs and other outerwear are available for use in cold weather climates, as are stocking caps and face masks.

Prohibited Fabrics for Electric Line Workers

- Acetate
- Nylon
- Polyester
- Rayon

FR clothing will not support combustion after the heat source is removed. On exposure to a flame, FR fabric hardens, starts to melt, discolors and chars, thereby forming a protective coating. The char formation is beneficial because first, it inhibits the release of flammable gases and second, it forms an insulating barrier against thermal energy (Norman & Street, 1985).

FR clothing is made by using inherent FR fibers, by chemically treating fabric or by some combination of both (Horrocks, 1996). Inherent FR clothing means the fibers used to create the garment are flame resistant. Treated garments are manufactured by adding chemicals to naturally flammable fabrics, such as cotton or cotton blends, to make the fabric flame-resistant (DuPont, 2007).

Garments made from inherent FR fibers are often referred to as high-performance fibers. Meta-aramid fibers, referred to as m-aramid, were first developed in 1967 by DuPont under the trademark Nomex. The m-aramid family is primarily used for FR clothing due to its high resistance to heat and flame. M-aramid fiber retains its FR properties at temperatures as high as 370 °C (698 °F) (Bourbigot & Flambard, 2002).

An ammonia cure finishing process is the most common method used to make cotton garments flame resistant. This technology has been around for about 30 years, but it has advanced significantly. Early ammonia-cured garments retained their FR properties for 25 industrial or 50 home launderings. Today, manufacturers are guaranteeing the FR properties of the ammonia-cured cotton garments for the life of the garment (Westex, 2005).

House and Squire (2004) studied the durability of FR cotton clothing. They compared new FR cotton garments and the same type of garments after they had been worn approximately 56 days and laundered 20 times over a 12-week period. The study sup-

Another consideration is protecting the worker's face and hands. Safety glasses and a hardhat with a polycarbonate face shield provide protection, as do insulated rubber gloves and leather protectors.

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ports that worn and laundered garments afford the same protection as the new garments.

Following the manufacturer's recommendation on laundering is important. For example, chlorine bleach should not be used when washing FR fabrics because it significantly reduces the life of a garment and can break down the flame retardants in chemically treated garments, making them ineffective after several washes with bleach (Hoagland, 1996).

Flame-Resistant Clothing as Arc Flash Protection

Chemically treated and inherent FR clothing are viable choices for employers. Level of protection, durability, comfort and cost are factors to consider when selecting FR clothing. This clothing provides two levels of protection to a worker exposed to an arc flash. It will not support combustion and, therefore, protects the worker from burns associated with the ignition of clothing. In addition, FR clothing prevents burns from the heat energy of the arc by providing a thermal barrier (Doughty, et al., 2000).

However, for a worker to be afforded the protection provided by FR clothing, the clothing rating must be appropriate for the potential incident energy available in an arc flash. Therefore, one must understand the terminology in the ASTM standards to ensure that workers are adequately protected. Key definitions are found in ASTM F1959, Standard Test Method for Determining the Arc Rating of Materials for Clothing (ASTM, 2007).

- **Arc rating.** Value attributed to materials that describes their performance to exposure to an electrical arc discharge. The rating is expressed in cal/cm^2.
- **Arc thermal performance value (ATPV).** In arc testing, the incident energy on a material or a multilayer system of materials that results in a 50% probability that sufficient heat transfer through the tested specimen is predicted to cause the onset of a second-degree burn injury.
- **Breakopen.** In electric arc testing, a material response evidenced by the formation of one or more holes in the material which may allow thermal energy to pass through the material. A specimen is considered to experience breakopen when any hole is at least 1.6 cm^2 (0.5 in.^{2}) in area or 2.5 cm (1.0 in.) in any dimension.
- **Breakopen threshold energy (EBT).** The incident energy on a material or material system that results in a 50% probability of breakopen.
- **Incident energy (Ei).** The total heat energy received at the surface of the panel as a direct result of an electric arc.

As these definitions reveal, the use of FR clothing does not preclude the possibility of sustaining a burn injury (Neal, et al., 1997). For example, if a worker is exposed to 5 cal/cm^2 of incident energy and is wearing an FR garment with an ATPV of 5 cal/cm^2, there exists a 50% chance that the worker will sustain second-degree burns. Wearing FR clothing with a rating below the incident energy of an arc flash can result in failure—or breakopen—of the clothing, leaving parts of the body unprotected. ASTM F1506 (2004) requires FR apparel to contain a label indicating that it meets the standard's performance specifications. Apparel must be labeled with care instructions, fiber content and arc rating (APTV) or breakopen threshold.

FR clothing should be worn for arc hazard exposures where incident energy has the potential of exceeding 2 cal/cm^2 (Neal, et al., 1997). Currently, FR apparel have ATPV ratings as high as 100 cal/cm^2; however, these full flash suits would not be practical everyday gear for electrical line workers as they would create other hazards. In addition, most exposures for line work would be well below the 100 cal/cm^2 level, especially when incorporating engineering and work practices to reduce arc exposure.

Layering clothing is an effective means of adding thermal protection. Air gap between layers is a very good thermal insulator. This should be considered in determining the underclothing (Norman & Street 1985). In many cases, a 100% cotton garment under an FR garment is sufficient as much of the incident energy will be dramatically reduced by the FR outer garment and the air gap.

Another consideration is protecting the worker's face and hands. Doughty, et al. (1999) addressed this issue. Safety glasses alone reduce the energy but still allow about 40% of the incident energy to reach the eyes. The rest of the face remains unprotected. Use of safety glasses and a hard hat with a polycarbonate face shield provides more protection, allowing about 25% of the incident energy to reach the eyes and about 48% to reach the mouth.

Heavy-duty leather work gloves were tested and found to provide significant protection to approximately 12 cal/cm^2. When working on live energized systems, line workers often must wear insulating rubber gloves and leather protectors. Salisbury, a rubber glove manufacturer, sent in rubber gloves to be tested in the same manner as FR clothing. Class 2 gloves, common in electrical distribution systems work, did not record burns to the hands until after ignition. A 50% chance of ignition occurred in a range from about 35 cal/cm^2 to about 93 cal/cm^2, depending on the actual thickness of the glove. The lower rating represented a 1.3 mm thick glove and the higher rating represented a 2.05 mm thick glove, although the gloves were of the same classification (Ostrovsky, 2005).

In its proposed rule, OSHA (2005) notes that no burn injuries resulted when the worker was wearing rubber gloves. Where rubber gloving is required, workers hands appear to be well protected. The face remains exposed, however, as many workers wear just hardhats and safety glasses. The use of a polycarbonate face shield would provide additional protection from an arc flash, but wearing this gear could pose visibility problems in some work situations.

Conclusion

FR clothing is an effective means of protecting electrical line workers against arc flash hazards. Many utilities already use FR clothing, although some continue to use 100% cotton clothing. Many utilities may require FR shirts but allow workers to wear denim jeans. More and more of the electric distribution system involves underground construction. Work with underground transformers and switchgear result in arc flash exposure to the torso and legs compared to overhead construction where a worker's legs are protected by the aerial lift bucket. As the literature indicates, 100% cotton garments can ignite and will continue to burn with significant thermal heat transfer to the worker. Ignition of clothing significantly increases the severity of the injury. FR clothing forms a char that prevents the transfer of heat to the employee and does not support combustion. This charring provides the worker protection from the thermal transfer of heat and prevents ongoing burning of the fabric.

The effectiveness of FR clothing for electric line workers is reflected in the progress of NESC and OSHA's proposed rule, which would require that employers assess the incident energy and provide protection to workers adequate for the potential incident energy. Assessing the arc flash hazard is a critical step in ensuring that the clothing delivers adequate protection.

While the knowledge of arc flash hazards continues to develop, it is important to recognize that getting an accurate assessment can be difficult. Much of what is known about arc flash comes from laboratory-controlled conditions. Variables, such as the length of the arc and distance to the worker, would be rough estimates in real-world situations. Matching the clothing's incident energy protection to the potential incident energy exposure is critical to preventing burns.

Finally, it is important to remember that although FR clothing is effective in preventing burns, in the hierarchy of safety it is considered PPE. A comprehensive arc flash hazard program must include the full complement of engineering and work practices in conjunction with appropriately rated FR clothing to help protect workers from arc flash hazards. ■

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