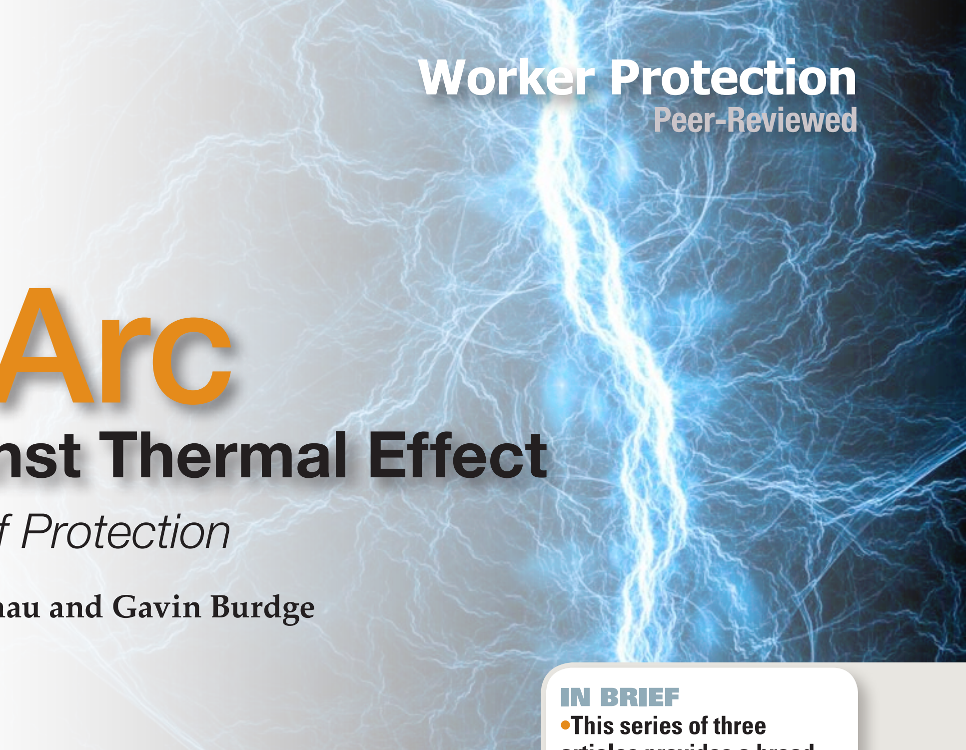


Electric Arc
Protecting Against Thermal Effect
Part 2: Fundamentals of Protection

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 2 identifies thermal and other hazards of an electric arc, and provides an overview of protection fundamentals of electric-arc-rated PPE.**
- **It also offers an analysis of previously published electric arc incidents from the perspective of electric arc type.**

Part 1 of this series of articles identifies electric arc classification, properties, behavior and methods of thermal energy dissipation among the different types of arcs, and factors for the future progress in electric-arc-rated (AR) PPE quality and reliability. Understanding the properties and behaviors of the different possible types of electric arcs is key to assessing AR PPE.

New knowledge of electric arc classification is helpful not only in current arc incident investigation but also in better understanding past arc incidents. Analysis of specific electric arc incidents is complemented with extensive research on electrical trauma trends based on government data. Part 2 of this series addresses arc hazards, protection fundamentals, and data on electrical fatalities and arc burn trauma.

Fundamentals of Electric Arc Protection
Electric Arc Hazards

Electric arc hazards are not limited to the thermal effect. Large amounts of thermal energy released in the electric arc event is also accompanied by extremely bright light flash, momentary and residual flames, heavy smoke and poisonous fumes, loud sound and molten metal droplets. Pressure waves and flying projectiles are also likely as a result of air pressure build-up with cabinet rupture due to the extreme pressure from arcing inside the enclosed cabinet.

All kinds of AR PPE are first and foremost designed and tested to protect the body, hands, face and head from thermal effects. AR PPE may provide supplementary protection

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

Summary of Observations

Protection type	**AR face shield**			**AR clothing**				**AR hand protection**		
	Not used	***Used***	***Used > 40 cal***	***Not used***		***Used***	***Used > 40 cal***	***Not used***	***Used***	***Used > 40 cal***
Arc-rated PPE				***No ignition***	***Ignition***					
Number of cases (54)	42	4	8	11	6	29	8	28	18	8
Number of cases with burn trauma	9	0	0	0	6	9	0	12	4	0
Percent of cases with burn trauma	21%	0%	0%	0%	100%	31%	0%	43%	22%	0%

Type of arc (based on operating voltage and equipment type)

Assumed arc type	***Arc-in-a-box***	***Ejected arc***	***Open air arc***	***Tracking arc***	***Moving arc***
Number of cases	37	11	5	1	0

Note. *Data from "Update of Field Analysis of Arc Flash Incidents, PPE Protective Performance and Related Worker Injuries," by D.R. Doan, E. Hoagland and T. Neal, 2010,* 2010 IEEE IAS Electrical Safety Workshop, Memphis, TN, *pp. 80-87.*

against light flash, molten metal and projectiles, but it provides limited protection against smoke, sound and chronic effects from stress caused by the arc event.

Skin Burn

Skin burn is the most common adverse outcome of an electric arc event. While these injuries can be fatal, they more commonly result in disability when skin is not covered by AR PPE or when non-AR clothing ignites. In both cases, arc exposure may cause burns to large areas of skin. Covering the entire body with AR garments, gloves and face PPE protects against skin burn. The goal is attenuating heat to a level below second-degree skin burn.

The criteria used to evaluate PPE for second-degree skin burn protection was developed by Alice Stoll in the late 1960s as part of her research on thermal protection systems for the U.S. Navy (Stoll & Chianta, 1969). Injurious levels of skin burns correspond to skin temperature elevation above 44 ºC with nearly instantaneous, complete skin destruction above 72 ºC. This groundbreaking research showed that heat flux as low as 1.2 cal/cm^2/s is enough to cause second-degree burns of unprotected skin with only 1 second of exposure. For comparison, 50 cal/cm^2/s heat flux is generated by open air electric arc with the fault current of 8,000 A at the 12-in. distance from an arc. In 1 second of exposure, the temperature on the surface of unprotected skin can reach up to 500 ºC for such arc exposure.

Arc Rating Process Fundamentals

AR PPE are rated based on open arc testing with a standard set of test parameters: 8,000-A current, 12-in. arc gap and test specimen placed at a 12-in. distance from arcing electrodes. An arc rating arc thermal performance value (ATPV) or breakopen threshold energy (EBT) is determined directly as a result of multiple exposure testing for face and hand protection. A minimum of 20 test specimens of face or hand protective PPE are required for different levels of incident energy exposure and determination of arc rating.

Arc-rated fabrics are the raw materials used to construct AR garments. These fabrics are typically sewn to make pants, shirts, jackets, underclothing and coveralls. Once a textile fabric or a multilayer fabric system is arc rated, the arc rating is assigned to the assembled garment made from the fabric or fabric system. ASTM standards do not require garments to undergo direct test exposure, and IEC standards generally only require one garment to undergo exposure. Arc rating is expressed in calories per square centimeter (cal/cm^2). The numerical value is an indicator of the protective level for PPE in only an open arc. Arc rating is higher for multilayer systems and increases with a number of system layers.

Arc Thermal Hazard Assessment & PPE Selection

Arc hazard assessment is an essential part and the first step in creating safe conditions for energized work. The purpose is to estimate possible arc exposure parameters to select proper PPE protection level.

A few different methods exist for assessing hazards and selecting corresponding PPE:

•Identify job task and directly link the task to required PPE arc rating as outlined in tables in NFPA 70E.

•Identify electric arc parameters and link these parameters to required PPE arc rating as outlined in tables of IEEE National Electrical Safety Code.

•Use empirical equations of IEEE 1584 developed for arc-in-a-box or other equations to determine incident energy of exposure and link required PPE arc rating to the calculated value.

No existing arc hazard assessment standards consider type of arc as a starting point. Part 3 of this article series will provide more discussion on arc hazard assessment.

Additional Analysis of Published Electric Arc Burn Injuries

Data for the Analysis

The limited availability of information on electric arc burn trauma incidents, fatal and nonfatal arc incident data, and type of arc involved is somewhat offset by electrical engineering publications, electrical safety conference records, magazines and reports.

Doan, Hoagland and Neal (2010) conducted a comprehensive analysis of electric arc incidents. They describe and analyze 40 electric arc incidents involving 54 workers between 1999 and 2008. An additional analysis was performed for each type of arc-rated PPE: face protection, clothing and hand protection. The analysis also reviewed whether sufficient statistical data exists to support perception of safe work conditions when calculated energy of exposure is matched by PPE arc rating. Cases included skin burns from various causes: unprotected skin, ignited non-FR clothing, failed AR PPE overwhelmed by heavy exposure and inadequate protection for the type of arc. Table 1 summarizes the observations.

Important New Observations From the Data

Table 1 observations are grouped to follow the PPE designation.

Face Protection

The 78% (42 of 54) majority of workers were not wearing AR face protection during an incident. Nevertheless, as much as 79% (33 of 42) of workers unprotected against electric arc did not sustain second-degree or more severe face skin burns. Only 21% (9 of 42) of unprotected workers had face burns.

An estimated heat exposure range for the 33 cases of no protection/no burn was:

•as low as 1 cal/cm^2 for several cases without burns even on unprotected skin;

•as high as 50, 60 and even up to 80 cal/cm^2 for several other cases but no skin burns were reported.

The remaining 22% (12 of 54) of workers were wearing AR face protection (AR face shield or AR hood). None sustained face burns.

Clothing

Workers not wearing AR clothing during an arc incident totaled 31% (17 of 54); 65% (11 of 17) of these unprotected workers had no clothing ignition. Where the clothing did not ignite, workers did not sustain second or more severe skin burns. Six of the 17 unprotected workers experienced clothing ignition with burn trauma.

An estimated heat exposure range for the 11 cases of no AR protection/no burn was:

•low for several cases excluding clothing ignition and skin burn;

•as high as 36, 40 and even up to 50 cal/cm^2 for several other cases but no clothing ignition or skin burns were reported.

Workers wearing AR clothing with an arc rating below 40 cal/cm^2 totaled 56% (29 of 54). Nevertheless, 31% (9 of 29) of these workers sustained second-degree skin burns. Some burns were caused by non-AR under-layer ignition or melting.

An estimated heat exposure range for the 9 cases of protection/burn was:

•at least 2.5-times higher than the arc rating of the clothing for seven cases and cannot be included in the statistical data sample for cases with arc rating matched to calculations;

•slightly higher or equal to the arc rating of the clothing for two cases.

The remaining 69% (20 of 29) of workers wearing AR clothing with arc rating below 40 cal/cm^2 did not experience electric arc skin burns.

An estimated heat exposure range for the 20 cases of protection/no burn was:

•insignificant, less than 1.3 cal/cm^2 for eight cases and cannot be included in the statistical data sample for cases with arc rating matched to calculations;

•slightly higher or equal to arc rating of the clothing for five cases;

•at least 1.5 times and up to six times higher than arc rating of the clothing for seven cases and cannot be included in the statistical data sample for cases with arc rating matched to calculations.

Hand Protection

No standard test method for AR gloves existed until 2013. Technically, gloves could not have been rated earlier because the cases under consideration are related to earlier years. Today, OSHA recognizes insulated rubber gloves with leather protectors as AR PPE, although rubber gloves are excluded from the scope of ASTM (2013) F2675, Standard Test Method for Determining Arc Ratings of Hand Protective Products Developed and Used for Electrical Arc Flash Protection.

Workers not wearing rubber gloves with leather protectors or any other gloves totaled 52% (28 of 54). Nevertheless, 57% (16 of 28) of these unprotected workers did not sustain second-degree or more severe skin burns to the hands. The other 12 of 28 workers not wearing gloves sustained hand burns.

An estimated heat exposure range for the 16 cases of no protection/no burn was:

•insignificant, less than 2 cal/cm^2 for six cases and without burn even on unprotected skin;

•between 6 and 80 cal/cm^2 for 10 cases but no skin burns were reported.

An estimated heat exposure range for the 12 cases of no protection/burn was:

•between 6 and 80 cal/cm^2.

Only 33% (18 of 54) of the workers were wearing gloves. Nevertheless, 22% (4 of 18) of these workers suffered second-degree skin burns. The other 14 of 18 workers wearing gloves did not sustain skin burns to the hand.

An estimated heat exposure range for the four cases of protection/burn was:

•between 15 and 70 cal/cm^2;

An estimated heat exposure range for the 14 cases of protection/no burn was:

•insignificant, less than 2 cal/cm^2 for six cases without burn even on unprotected skin;

•between 5 and 30 cal/cm^2 for eight cases.

Summary of Observational Data

Most (37) of the arc incidents illustrated in Table 1 are projected as arc-in-a-box type. One incident involves a possible tracking arc, 11 cases are assumed to be an ejected arc and five cases are an open-air arc. No damage occurred to some unprotected body parts, even with high estimated thermal hazard, which could be explained by the worker's positioning away from thermal energy exhaust direction. However, such worker positions are difficult to determine accurately because operational circumstances of the arc incidents are not reported for many of them. The analysis has returned a complicated landscape of outcomes for the electric arc incidents:

1) There are 87 combined cases of not wearing face, body or hand protection. In 60 of these incidents, no burn injuries occurred to unprotected areas, while exposure range was between 6 and 80 cal/cm^2.

2) Seemingly impossible facts of no electric arc burns on unprotected face and hands with estimated heat hazard up to 100 cal/cm^2 or facts of no skin burns in cases when estimated incident energy overwhelmingly exceeded arc rating of PPE cannot be understood nor explained without the knowledge of arc type and the position of the worker relative to the arc and equipment.

3) On one hand, not wearing AR clothing, face or hand PPE does not necessarily result in ignition or second-degree or more severe skin burns, even if estimated heat exposure levels are very high. Lack of electrical data and incident situational data details (e.g., fault current, arc duration, position of worker relative to equipment) in reporting contribute to uncertainties in investigation.

4) Very high probability for severe skin burns follows the ignition of non-AR clothing.

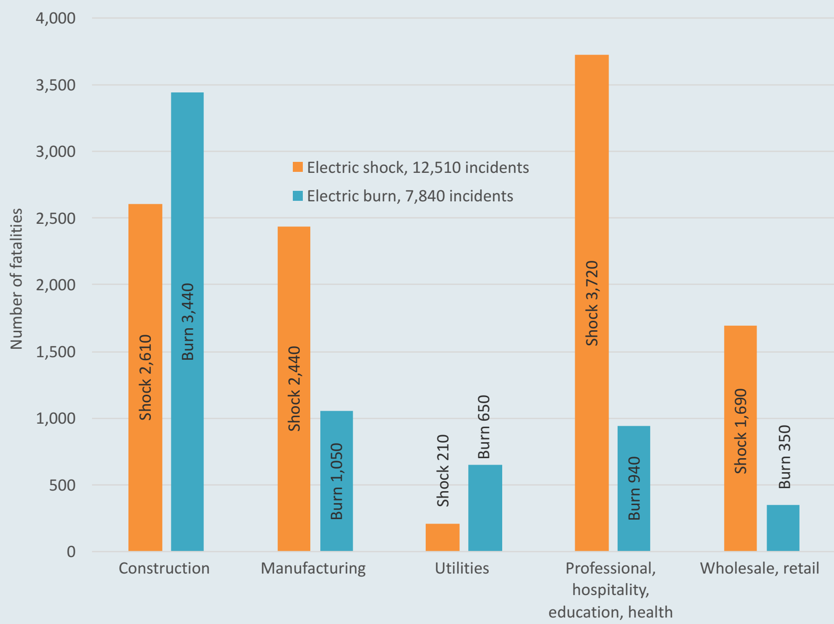
5) On the other hand, wearing AR PPE does not always protect against skin burns in an electric arc event.

6) Workers in eight cases were wearing PPE with arc ratings between 40 and 100 cal/cm^2. Such PPE included heavy multilayer AR suits and hoods. Rubber gloves with leather protectors are also part of this protective ensemble. None of the workers sustained electric arc skin burns. Heavy multilayer protection protected against high heat energy levels in 100% of cases (based on this limited statistical sample size) with energy levels up to 80 cal/cm^2.

7) Wearing AR clothing with a rating lower than 40 cal/cm^2 and with a rating slightly higher or equal to estimated exposure resulted in mixed outcomes in electric arc incidents. Seven such incidents were reported after exclusion of incidents with insignificant estimated heat exposures or overwhelmingly high estimated exposures. This statistical data sample is insufficient in size to support the notion of a safe work condition when

FIGURE 1

Nonfatal Electric Shock & Electric Burn Injuries by Industry Sector, 2003-2010



Note. *Data from "Workplace Electrical Injury and Fatality Statistics, 2003-2010," by Electrical Safety Foundation International, 2010; and "Fatal Occupational Injuries in 2014, Chart Package," by Bureau of Labor Statistics, 2016.*

FIGURE 2

Occupations With High Fatal Work Injury Rates, 2014

Note. *Fatal work injuries per 100,000 workers. Data from "Workplace Electrical Injury and Fatality Statistics, 2003-2010," by Electrical Safety Foundation International, 2010; and "Fatal Occupational Injuries in 2014, Chart Package," by Bureau of Labor Statistics, 2016.*

arc rating based on open arc testing is matched to IEEE 1584 calculations with empirical equations based on arc-in-a-box.

Three key factors can explain the complicated and seemingly counterintuitive outcomes of the electric arc incidents. One factor is the necessary knowledge of the arc type and position of the worker relative to the arc and equipment involved in the incident. Different types of arc have different ways of heat dissipation from an arc channel, namely the difference in a ratio between radiant and convective components in heat flux and the difference in directionality of heat flux among different types of arc. The second factor is the arc rating variability. The most significant variables affecting arc rating are available fault current and worker distance from the arc event. The third factor is the position of the worker's body relative to arcing electrodes.

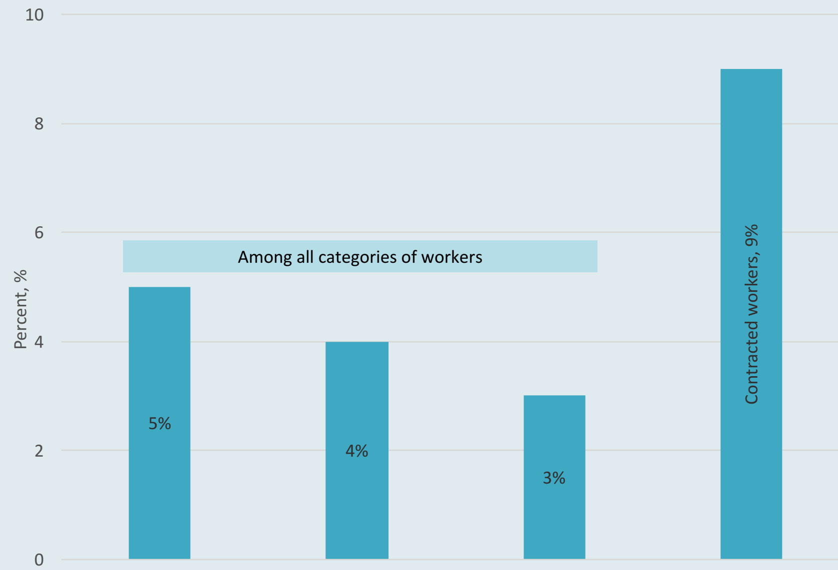
Electrical Arc Burn Injuries

Burns from arcs can occur to the face, body (including torso and legs) and hands. Burns to the body from electrical arcs occur primarily from clothing ignition that continues to burn and/or melt to the skin after the initial flash occurs. For example, in 29 arc-flash incidents when ignitable or non-AR clothing was worn, nine cases (31%) involved burn trauma, second-degree burns over part of the body or worse. When AR clothing was not worn in six incidents of ignited clothing, burn trauma occurred for each case (100%). When AR clothing was not worn and no ignition of the clothing occurred, no cases of burn trauma occurred.

These observations indicate that AR clothing, which is flame resistant, prevents burn trauma by preventing clothing ignition. For the face and hands, significant reduction of burn risks can occur by wearing AR face shields for face protection and gloves for hand protection (Doan, Hoagland & Neal, 2010).

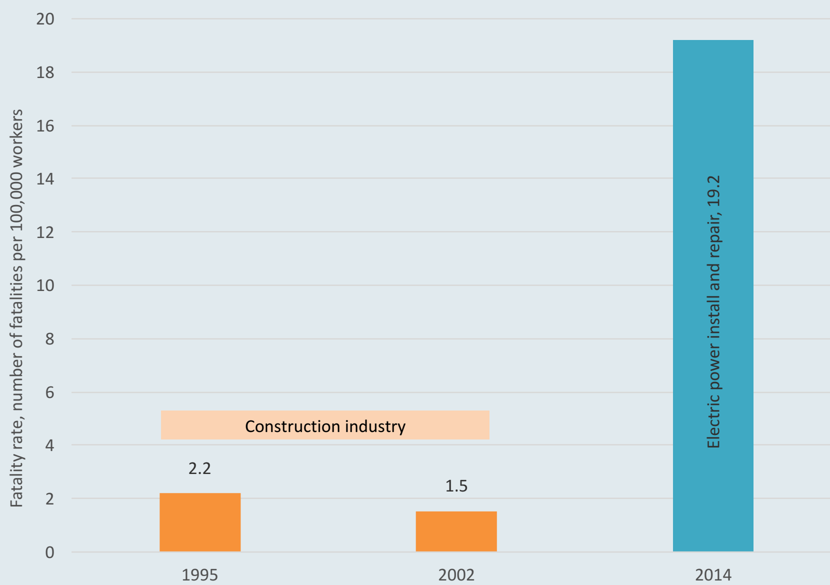
American Burn Association's National Burn Repository report of data from 2004 to 2013 indicates 6,546 electrical burn injury cases, including 591 cases with unknown or missing circumstances of injury. Electrical shocks, electrical contact burns and electrical conduction injuries were all pooled in this analysis of electrical injuries, making broad interpretation of these findings difficult. The percentage of burns caused by arc burns cannot be accurately determined. According to the report, "the low voltage contact burn will obviously behave much different than an electric arc or electrical conduction injury" (American Burn Association, 2014). For place of occurrence, "the majority of these burns occur in industry (39.5%) with the second-most-common place of occurrence being the home (30.2%). Similar

FIGURE 3
Trend for Electrical Fatalities



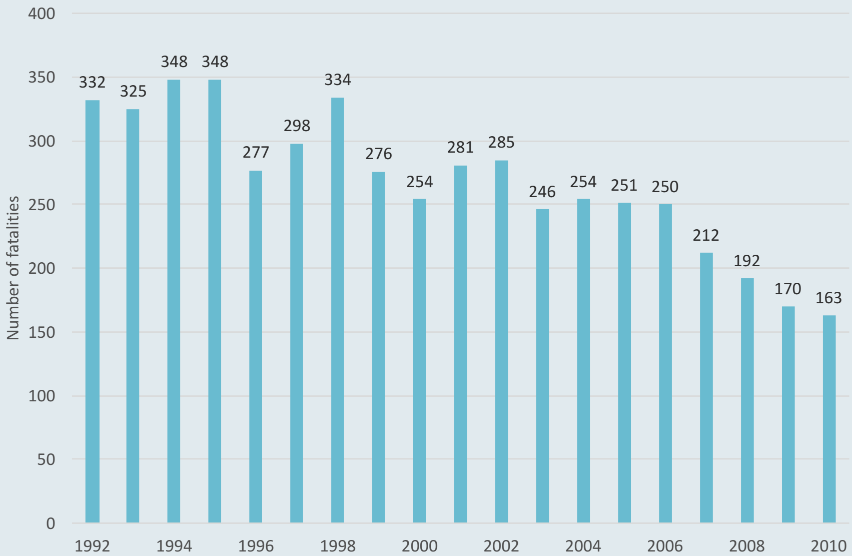
Note. *Share of electrical causes in occupational fatalities. Data from "Workplace Electrical Injury and Fatality Statistics, 2003-2010," by Electrical Safety Foundation International, 2010; and "Fatal Occupational Injuries in 2014, Chart Package," by Bureau of Labor Statistics, 2016.*

FIGURE 4
Rate of Electrical Occupational Fatalities



Note. *Data from "Workplace Electrical Injury and Fatality Statistics, 2003-2010," by Electrical Safety Foundation International, 2010; and "Fatal Occupational Injuries in 2014, Chart Package," by Bureau of Labor Statistics, 2016.*

FIGURE 5
Total Number of Electrical Fatalities per Year



Note. *Data from "Workplace Electrical Injury and Fatality Statistics, 2003-2010," by Electrical Safety Foundation International, 2010; and "Fatal Occupational Injuries in 2014, Chart Package," by Bureau of Labor Statistics, 2016.*

to chemical burns, the majority of these injuries were reported under work-related circumstances (61%), with only 33% of these incidents occurring in a nonwork-related scenario.

Previous studies outside the U.S. have reported that the possibility of a fatal event caused by an electric burn from electric arc is low. However, extreme costs are associated with the long-term treatment, rehabilitation and disabilities related to burns caused by electric current. A 2015 Fire Protection Research Foundation report summarizes studies of occupational injuries from electric shock and electric arc events in the U.S. and other countries (Campbell & Dini, 2015). Electrical Safety Foundation International (ESFI, 2010) analyzed electric shock and electric burn data from Bureau of Labor Statistics, which is reflected in Figure 1 (p. 42).

Utility personnel have experienced fewer total numbers of both types of injuries, which could be explained by a smaller workforce and better electric safety programs, electric safety training, electric arc awareness and PPE use. Despite progress in electrical safety, nonfatal electric burn and shocks still fill burn trauma centers, emergency rooms and statistical injury charts (Figure 1, p. 42).

Little research is specific to electric arc injury rates. Washington state reports that from September 2000 to December 2005, "350 Washington workers were hospitalized for serious burn injuries occurring at work. Of these, 30 (9%) were due to electric arc. Total workers' compensation costs associated with these 30 claims exceeded $1.3 million" (Washington Department of Labor and Industries, 2006).

Workplace Electrical Fatalities Among Different Industries

In the U.S., the fatal injury rate among electrical power installers and maintainers was in the top 10 for 2014 with a 19.2 workplace fatality rate, nearly six times higher than the rate for all workers (Figure 2, p. 42). This rate is even higher than for construction (Figure 4, p. 43). For comparison, a Japanese study found workplace electrical fatality rates from 2002 to 2011 were less than 0.3 for all industries (Ichikawa, 2016).

Contractor workers who are exposed to electrical hazards experience higher numbers of fatalities. Bureau of Labor Statistics (BLS, 2015) reports that, for fatal occupational injuries for 2014, four types of incidents each constituted a greater share of fatalities among contracted workers than they did for all workers: 1) falls to a lower level (33% of contracted worker deaths); 2) struck by an object or equipment (17%), 3) pedestrian or vehicular incidents (12%); and 4) exposure to electricity (9%).

Workplace Electrical Fatality Summary

According to BLS (2015) data, exposure to electricity resulted in 141 fatalities in 2013 and 156 in 2014 (3% of total). Cawley and Homce (2003) show that from 1992 to 1998, electrical shock caused 99% of fatal and 62% of nonfatal electrical incidents. Their follow-up research examined fatal and nonfatal occupational electrical injuries from 1992 to 2002 (Cawley & Homce, 2008). This study indicates that the construction industry accounted for nearly half (47%) of all electrical fatalities between 1992 and 2002, and "during 1997, nearly 1 in 20 occupational fatalities were from electrical causes" (Cawley & Homce, 2008).

A follow-up study by Cawley (2015) includes results from 1992 to 2002 for trending occupational electrical injuries in the U.S. from 2003 to 2009. The study analyzes fatal and nonfatal electrical injuries based on BLS information. Of the 38,124 workplace deaths from 2003 to 2009 for all causes, 4% (1,573) were caused by contact with electric current (Cawley, 2015). Although the overall trend in electrical fatalities is downward, fatalities were relatively high among contracted workers (Figure 3, p. 43).

The construction industry accounted for nearly half of all electrical fatalities, "but showed overall improvement from 1995 to 2002 by reducing its electrical fatality rate from 2.2 to 1.5 per 100,000 workers" (Cawley & Homce, 2006). Figure 4 shows a comparison of the rate of workplace electrical fatalities between the construction industry and electric power installers and repairers. Differences are explained by the much larger number of all construction workers compared to the number of electric power installation and repair workers.

Although total work-related fatalities have not decreased at a commensurate rate, electrical fatalities are trending downward over the past 2 decades (Figure 5). Collective improvements of electrical safety consensus standards, IEEE electrical safety culture change of the annual Electrical Safety Workshop, and electric shock and arc PPE standardization have all contributed to this trend.

Conclusions

Assumed arc type in the previously published electric arc incidents helped to understand and explain otherwise inconsistent outcomes such as not sustaining burns on unprotected skin and vice versa. Wearing ignitable clothing does not always result in ignition, but all ignition cases resulted in heavy burns. On the other hand, wearing full-body high rated (> 40 cal/cm^2) PPE resulted in no skin burn even in very intense exposures. A statistical pool of 54 incidents is in some correlation with government statistics.

Overall, electrical fatalities have steadily declined over the past 2 decades. AR PPE helps save lives. Industry standard recognition and implementation, replacing ignitable and melting PPE materials with FR and AR materials contribute to reduced fatality rates and help eliminate deaths from non-FR clothing ignition in an electric arc. However, statistical data on nonfatal electrical injuries show that an average of 3.75 electric skin burn incidents occur every work day. This high number can be attributed to several factors: no AR PPE used, insufficient PPE used or PPE that is inadequate for arc type used. Since reporting does not separate contributing factors, it is impossible to reliably estimate the effectiveness of proper AR PPE selection for the task.

Part 3 of this article series will detail fundamentals of protection against electric arc. It will address challenges, uncertainties and gaps in arc thermal hazard assessment, in determination of arc rating, and in standardization for AR PPE specifications and test methods. The article will propose protection improvements based on research of material reaction in different arc types. **PS**

References

American Burn Association. (2014). 2014 National Burn Repository report of data from 2004-2013. Retrieved from www.ameriburn.org/2014NBRAnnualReport.pdf

ASTM International. (2013). Standard test method for determining arc ratings of hand protective products developed and used for electrical arc flash protection (F2675/F2675M-13). Retrieved from www.astm.org/Standards/F2675.htm

Bureau of Labor Statistics (BLS). (2015, Sept. 17). National census of fatal occupational injuries in 2014 (preliminary results). Retrieved from www.bls.gov/news.release/archives/cfoi_09172015.pdf

BLS. (2016). Fatal occupational injuries in 2014, chart package. Retrieved from www.bls.gov/iif/oshwc/cfoi/cfch0013.pdf

Campbell, R.B. & Dini D.A. (2015). Occupational injuries from electrical shock and arc flash. Quincy, MA: Fire Protection Research Foundation.

Cawley J.C. (2015, Feb. 18). Occupational electrical accidents in the U.S., 2003-2009 (White paper). Retrieved from www.esfi.org/resource/esfi-white-paper-occupational-electrical-accidents-in-the-u-s-2003-2009-278

Cawley, J.C. & Homce, G.T. (2003). Occupational electrical injuries in the United States, 1992-1998, and recommendations for safety research. *Journal of Safety Research*, *34*(3), 241-248.

Cawley, J.C. & Homce, G.T. (2006). Trends in electrical injury, 1992-2002. *Record of Conference Papers, IEEE Industrial Applications Society 53rd Annual Petroleum and Chemical Industry Conference*. Retrieved from http://xplorestaging.ieee.org/document/4199082

Cawley, J.C. & Homce, G.T. (2008). Trends in electrical injury in the U.S., 1992-2002. *IEEE Transactions on Industry Applications*, *44*(4), 962-972. Retrieved from www.cdc.gov/niosh/mining/userfiles/works/pdfs/tieii.pdf

Doan, D.R., Hoagland, E. & Neal, T. (2010). Update of field analysis of arc flash incidents, PPE protective performance and related worker injuries. *Proceedings of the 2010 IEEE IAS Electrical Safety Workshop, Memphis, TN, USA*, 80-87. doi:10.1109/ESW.2010.6164450

Electrical Safety Foundation International (ESFI). (2010). Workplace electrical injury and fatality statistics, 2003-2010. Retrieved from http://files.esfi.org/file/Workplace-Electrical-Injury-and-Fatality-Statistics-2003-2010.pdf

Ichikawa, N. (2016). Three hundred forty-nine case studies and their consideration of electrical accidents in Japan (Paper No. ESW2016-36). *Proceedings of the 2016 IEEE IAS Electrical Safety Workshop, Jacksonville, FL, USA*.

Institute of Electronics and Electrical 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

Stoll, A.M. & Chianta, M.A. (1969). Method and rating system for evaluation of thermal protection. *Aerospace Medicine*, *40*(11), 1232-1238.

Washington Department of Labor and Industries. (2006). Burn injury facts: Arc flash/blast (Report No. 86-1-2006). Retrieved from www.lni.wa.gov/safety/research/files/arcflashhazardreport.pdf

PS EXTRA

Part 1 of this three-part article series appeared in the July 2017 issue. Read it at www.asse.org/assets/1/7/F3Gol_0717z.pdf.