Electric Arc Hazard

Understanding assessment and mitigation

By H. Landis Floyd II and Daniel R. Doan

HISTORICALLY, ELECTRICAL HAZARDS were viewed primarily as electric shock or electrocution hazards. Electric shock entails passage of electric current through the body. A shock victim generally makes contact with an energized conductor or otherwise becomes part of the electrical circuit. While addressing the electric shock hazard is important—it is the cause of most fatal injuries from electrical energy (Cawley & Homce, 2003, 2006)—it has masked another electrical hazard associated with the intense radiant and convective energy released during an electric arc flash event. A person need not make physical contact with an energized conductor or be part of the electrical circuit to be injured by arc flash. The victim may be several feet away from energized conductors or equipment and be severely injured by the intense thermal energy transfer produced by an electric arc.

Arc hazards are not new. They have been present in industrial and commercial facilities since the beginning of electrification in the late 19th century. What is relatively new is the evolution in the science and technology necessary to understand and manage the hazards. Much has been learned over the last 2 decades.

Arc flash events are usually short occurrences that typically last less than 0.5 seconds. Many different events can initiate an arc flash, such as a tool falling onto an energized conductor, a worker touching an energized conductor thought to be de-energized, voltage testing with inappropriate instruments or operation of a switch that is internally damaged. Most of these events occur faster than the unaided human eye can perceive. High-speed photography of laboratory simulations of arcing faults has provided images of how these events can engulf workers in a ball of fire.

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Electric arcs are extremely hot—second only to the laser as the most intense heat source on earth. Temperatures in the arc can reach 35000 ºF (Baliga & Pfender, 1975; Brown & Cadick, 1980). People within several feet of an arc can be severely burned. Electric arcs can be caused by human, environmental and equipment-related factors. The events are actually multiple energy events, with intense blast, mechanical and acoustic energy accompanying the intense thermal energy.

In 1980, Brown and Cadick described safe electrical work practices that included the use of personal protective clothing to protect against arc flash hazards. In 1982, Lee published a theoretical model for estimating the risk of injury to personnel who may be exposed to an electric arc. This work led to the introduction of arc flash hazard discussions in technical forums, regulations, codes and standards.

By the early 1990s, the extreme thermal and blast hazards of arcing faults in electrical systems were recognized as uniquely different from the hazard of electric shock. Doughty, Floyd & Neal (2000) conducted laboratory testing of high-energy electric arcs, which led to refinements in arc hazard analysis and risk assessment, and in methods to assess protective clothing performance in arc flash exposures. Jones, Liggett, Capelli-Schellpfeffer, et al. (2000) designed and conducted tests involving equipment and work scenarios commonly found in industrial environments. Thermal energy impinging on a surface, or incident energy, was commonly measured in units of calories per square centimeter (cal/cm^2).

As the body of knowledge and understanding of arc flash grew, efforts emerged to change federal regulations and building codes, modify electrical equipment design, apply circuit protection, develop safe work practices, train personnel in the utility, industrial and commercial work environments, and develop and apply PPE. Technologies to further mitigate arc flash hazards were brought to market, including current limitation, metal cladding, venting to redirect arc blast forces and arc-resistant designs.

The work to expand understanding of these hazards continues. Neal and Parry (2005) are among those advancing research in other components of the energy transfer in arc flash events. In 2004, National Fire Protection Association (NFPA) and the Institute of Electrical and Electronics Engineers (IEEE) established a multimillion dollar collaborative research project to further study the phenomena of electric arcs. This collaboration is expected to advance protection against arc flash hazards related to heat, pressure, sound, toxicity and other medical effects.

The SH&E Professional's Role

According to Floyd, Andrews, Capelli-Schellpfeffer, et al. (2001):

> The safety professional's role is critical to improve the safe use of electricity. Electrical incidents do not have to result in injury or death. Every health effect, including death, amputation, burn, crush, blast, blindness, hearing loss, brain injury, is unnecessary. Engineering, scientific and recordkeeping experience over the last 10 years has shown that electrical incidents are not random or rare. Occupational safety professionals are uniquely positioned to respond to every unintentional workplace exposure to electrical energy as a potentially fatal or environmentally threatening scenario.

An SH&E professional without a strong background in electrical technology may feel intimidated by electrical technology and electrical technologists. As a result, electrical safety may be delegated to the electrical experts. However, although electricians, technicians and electrical engineers may be expert in electrical technology and work practices, they may not be expert in regulatory compliance issues, risk assessment and safety management.

> Further progress is not possible without the strategic involvement of safety professionals. The safety professional is best positioned in the general techniques of hazard analysis and risk assessment to significantly impact and accelerate changes for improving electrical safety, serving as the "electrical safety conscience" to owners, managers, electrical experts and the workers most at risk to electrical injuries. "Are we aware of current standards—and what are they?" "Are we using available technology—how do you know?" "How are we staying current in developments impacting electrical safety—are we sure?" "Considering serious electrical accidents are relatively rare, how do we measure the quality of our electrical safety program?" are just a few examples of how to exercise that conscience (Floyd et al. 2001).

Abstract: *Over the past 15 years, the evolution in regulations, codes and standards, as well as the basic understanding of arc hazards, have elevated the importance and priority of managing and mitigating these hazards in the workplace. This article discusses arc flash hazard mitigation and explains the need for SH&E professionals to understand and apply appropriate regulations and standards, implement hazard assessments, evaluate mitigation options, and design and implement controls to reduce/eliminate risks.*

Relevant Regulations, Codes & Standards

Regulations

- OSHA General Duty Clause
- OSHA 1910.132, Personal Protective Equipment for General Industry
- OSHA 1910.269, Electric Power Generation, Transmission and Distribution
- OSHA 1910.335, Safeguards for Personnel Protection

Consensus Standards

- NFPA 70E, Standard for Electrical Safety in the Workplace
- IEEE/ANSI C2, National Electrical Safety Code
- IEEE 1584, Guide for Performing Arc-Flash Hazard Calculations
- ASTM F-1506, Standard Performance Specification for Flame-Resistant Textile
- ASTM F-1891, Standard Specification for Arc and Flame-Resistant Rainwear
- ASTM F-1958, Standard Test Method for Determining the Ignitability of Non-Flame-Resistance Materials for Clothing by Electric Arc Exposure Method Using Mannequins
- ASTM F-1959, Standard Test Method for Determining the Arc Thermal Performance Value of Materials for Clothing
- ASTM F-2178, Determining the Arc Rating of Face Protective Products

Regulatory Requirements & Relevant Codes & Standards

Several U.S. regulations, codes and standards are relevant in implementing an arc flash hazard mitigation program (see sidebar at left). With respect to arc flash hazards, current language in OSHA regulations is not descriptive about arc hazard assessment and mitigation/control. The requirements are clear that employers must assess the workplace for hazards and enable employees to recognize and avoid such hazards, and must implement mitigation and control measures to protect employees from these hazards.

Currently, NFPA 70E-2004, Standard for Electrical Safety in the Workplace, provides the most comprehensive guidance for general industry to accomplish OSHA objectives relative to electrical hazards (NFPA, 2004). For electric utility workers, the applicable standard is ANSI/IEEE C2, National Electrical Safety Code (ANSI/IEEE, 2007). The 2007 version of this standard was expanded to require assessment and implementation of a protective clothing system.

IEEE Standard 1584, Guide for Performing Arc Flash Hazard Calculations, provides the technical basis for several commercial arc hazard analysis software programs available today (IEEE, 2002). To support the technology evolution in personal protective clothing and equipment, American Society for Testing and Materials (ASTM) has published test standards to quantify how well clothing materials perform when exposed to arc flash and flame. These standards have enabled manufacturers of flame-resistant clothing to rate their products for arc flash applications.

Arc Hazard Terms

Arc blast: force of plasma and fire from an electric arc.

Arc flash hazard: danger associated with the arc flash (e.g., the possibility of radiation burns, inhalation of vapors, temporary blindness, hearing damage, lung damage, barotrauma and injury from projectiles).

Arcing fault current: current that flows during a short circuit in which an arc is present. The impedance of the arc reduces the fault current to a level below the bolted fault current.

Barotrauma: injury from pressure caused by acoustic or vibratory forces during an arc blast.

Bolted fault current: current that flows during a short circuit in which the phases are directly connected with no appreciable impedance. During a bolted fault, no arc is present.

Burn, first-degree: burn involving only the outer layer of skin. The skin is usually red, and some swelling and pain may occur.

Burn, second-degree: burn involving both the first and second layers of skin. In these burns, the skin reddens intensely and blisters develop. Severe pain and swelling occur, and the chance for infection is present.

Burn, third-degree: burn involving all the layers of skin. This is the most serious type of burn. Fat, nerves, muscles and even bones may be affected. Areas may be charred black or be dry and white in appearance, and infection may occur. If nerve damage is substantial, there may be no pain at all.

Electric arc: flow of current between two electrodes through ionized gases and vapors. It is started by flashover or the introduction of some conducting material between energized parts.

Electrically safe work condition: state in which the conductor or circuit part to be worked on or near has been disconnected from energized parts, locked/tagged in accordance with established standards, tested to ensure the absence of voltage and grounded if determined necessary.

Flash hazard analysis: study investigating a worker's potential exposure to arc flash energy, conducted for the purpose of injury prevention and the determination of safe work practices and the appropriate levels of PPE.

Flash hazard boundary: boundary within which arc flash PPE is required.

Incident energy: total arc energy, both radiant and convective, that is actually received per unit area, in calories per square centimeter.

Plasma: a collection of charged particles that exhibits some properties of a gas but differs from a gas in being a good conductor of electricity and in being affected by a magnetic field.

PPE: clothing and equipment designed to mitigate the effects of hazards to which workers might be exposed.

Qualified person: individual who has skills and knowledge related to the construction and operation of the electrical equipment and installations and has received safety training on the hazards involved.

Working near: any activity inside the limited approach boundary of exposed, energized electrical conductors or circuit parts that are not put into an electrically safe working condition.

Working on: coming in contact with exposed, energized electrical conductors or circuit parts with the hands, feet or other body parts, or with tools, probes or test equipment, regardless of the PPE an individual is wearing.

Estimating Frequency of Arc Flash Incidents & Cost of Program Implementation

Cawley and Homce (2006) provide the most comprehensive analysis of occupational electrical injuries. Their research revealed that from 1992 to 2002, 29,046 nonfatal occupational electrical injuries occurred from electric shock, and 18,360 from electrical burns. Doan, Floyd and Neal (2004) evaluated the lost workday frequency for one global science and technology company and determined that the number of arc flash events with the potential for serious injury was equivalent to 3% of all lost workday injuries.

While serious electrical injuries are relatively infrequent compared to other causes of occupational injury, the cost of evaluation, treatment and rehabilitation is significantly higher than average. Wyzga and Lindroos (1999) report that a study of injury costs in one large utility found that electrical injuries accounted for less than 2% of all injuries in the company, yet accounted for 28% to 52% of total injury costs. Their study reported that the lifetime medical costs for a person seriously injured by electrical energy was $12.8 million (in 1991 dollars).

Doan, et al. (2004) estimate the total cost of implementing an arc flash protective clothing by considering three options: 1) do nothing, 2) achieve minimum compliance and 3) apply protective measures based on state-of-the-art hazard analysis methods. This comparison is summarized in Table 1.

This is an ideal comparison based on the assumption that all recommendations are followed. In practice, human error and other factors can increase injury frequency and overall costs with either method. The cost comparison is based on a workforce with responsibility for approximately 10,000 pieces of electrical equipment, and nearly 1 million electrical switching or troubleshooting tasks each year. PPE costs are calculated based on workers' exposures and typical PPE costs for different protection levels. Analysis costs are estimated at $200 per piece of equipment for detailed analysis. Finally, injury costs are based on average medical costs for actual burn injuries, with the highest average of $400,000 for cases where clothing could be ignited and the worker burned over a large portion of the body.

Implementation Choices

As noted, an employer's choices range from doing nothing to achieving minimum compliance to implementing a state-of-the-art program with arc hazard analysis as the basis for a full range of controls. The do-nothing approach is out of step with current regulatory requirements and electrical safety knowledge. It is also likely the most costly choice in the long term.

A common question about developing an arc flash hazard protection program is, "Can you provide a simple chart to show what PPE to wear in various work tasks?" While an approach that is based primarily on providing PPE provides an improved measure of safety, it does not provide opportunities to identify, reduce and possibly eliminate hazard exposure and risk.

One option provided in NFPA 70E-2004 is based on tables that list common tasks and note appropriate protective equipment for each task. These tables can be useful, but they can also be misapplied. The explanatory footnotes accompanying the tables must be diligently applied. These notes explain that

Table 1

Cost Comparison: Mitigation Strategies

Method	PPE costs	Analysis costs	Injury costs	Total costs
No arc flash PPE	0	0	$20,800	$20,800
Two hazard level PPE	$1,570	$100	$6,150	$7,820
Detailed analysis	$835	$2,000	$150	$2,985

Note. *Comparison is in U.S. $1,000 of average 5-year cost for example company for three mitigation options.*

Table 2

Arc Flash Incident Comparison

	Case 1 (1999)	Case 2 (2003)
Equipment	Drawout power circuit breaker	Drawout power circuit breaker
Voltage	480 V	480 V
No. of people within arc flash boundary	6	1
No. of people necessary within arc flash boundary	1	1
Estimated incident energy	75 cal/cm^2	50 cal/cm^2
PPE rating	25 cal/cm^2	100 cal/cm^2
PPE selection method	Company-developed task table	Hazard assessment using IEEE 1584 methods
Injuries	4 lost workdays	1 first-aid case

the electrical system must have certain specifications for the tables to be applicable. The user must be sure that the electrical system meets these requirements, and an electrical system study may be required to ensure that the requirements in the notes are met.

An approach based on a detailed arc hazard assessment is one that can help identify where exposure potential exists; eliminate the hazards completely through engineering design changes or administrative controls; reduce the frequency of potential arc flash events; reduce the magnitude of energy release; and helps to ensure that PPE is appropriately rated for exposures.

Two Case Histories

The authors were involved in the investigations of two incidents involving actual and potentially severe arc burn injuries. The equipment, work activity and energy release were similar in both cases, but the outcomes were quite different. Aspects of the two incidents are summarized in Table 2. In Case 1, a loose piece of metal contacted an energized bus and created an arc flash that burned four workers. In Case 2, a worker switched on a circuit breaker that was internally damaged and shorted to ground. The resulting arc flash could have burned the worker and a backup worker nearby.

In Case 1, control measures were limited to the use of PPE that had been chosen using a company-developed selection table based on technology known at the time. From information available in standards published after 2000, the protective clothing was not rated for the energy exposure.

The much-less-severe outcome in Case 2 was primarily because of the implementation of a state-of-the-art arc hazard assessment and implementation of a full range of control measures. The electrical safety program in place for Case 2 included an arc flash hazard mitigation program based on a detailed arc hazard assessment. Based on the results of the study, engineering design changes were made to reduce incident energy for many exposures; equipment was labeled with warnings and specific PPE requirements; administrative controls were implemented to restrict the number of people working within arc flash hazard boundaries; and protective clothing was specified to match or exceed predicted energy transfer for specific tasks and equipment. In addition, electricians, operators, supervisors and managers were trained on hazard awareness and the need for these control measures.

Planning & Preparing for an Arc Hazard Assessment

Implementing an effective arc flash mitigation program begins with top management commitment. Electrical engineering design and consulting firms and engineering services from manufacturers of electric power equipment are generally good sources for conducting these assessments. The amount of work and cost associated will depend on the availability and quality of engineering design documentation for the facility's electrical power system.

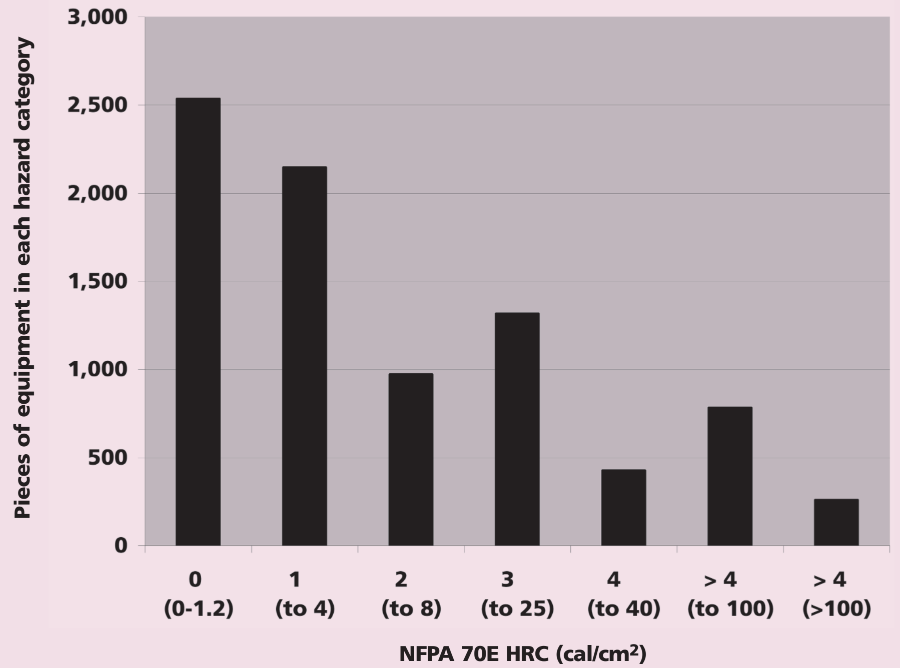
Arc flash assessment studies should be conducted by someone familiar with power system analysis software. Most commercially available programs feature a module that extracts information from the power system design and protection analysis needed to perform the arc hazard assessment. The documents and information needed include:

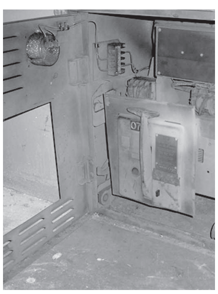
- power system single line drawings;
- power system protection coordination study if available;
- utility short circuit data and protective device information;
- system operating conditions, such as normal operating switch positions, tie conditions if present or possible, parallel feeds from transformers;
- information on transformers including impedance, ratings and grounding method;
- information on cables including type, size and approximate length;
- manufacturer, model, trip unit and settings of circuit breakers;
- manufacturer, type and size of fuses;
- information on motors larger than 100 horsepower;

An approach based on a detailed arc hazard assessment helps to ensure that PPE is appropriately rated for exposures.

Figure 1

Electrical Equipment Sorted by Hazard Categories & Incident Energy





Electric arcs are extremely hot. People within several feet of an arc can be severely burned.

•equipment type (motor control center, panel, or switchgear) for equipment being studied;

•working distance for the task being studied at each piece of equipment.

This information is entered into a modeling software to find the three-phase short circuit current value at each piece of equipment. Then, the arc flash hazard calculations can be performed, using IEEE 1584 equations for the best available estimate of the incident energy for each piece of equipment. Results should be reviewed for data input errors. Very high-energy points—those above 40 cal/cm^2—should be studied carefully. Low-voltage switchgear (transformer secondary equipment) is almost always above 20 cal/cm^2, usually above 40 cal/cm^2 and sometimes above 100 cal/cm^2. Low-voltage switchgear results below 20 cal/cm^2 should be checked for errors.

Doan and Sweigart (2003) summarize arc flash hazard studies at more than 30 industrial facilities. They found that about 10% of equipment will be assessed at more than 40 cal/cm^2 for normal exposure tasks such as switching and maintenance (Figure 1). The hazard levels referred to in the figure are based on the hazard categories determined by NFPA 70E. The hazard/risk category (HRC) numbers 0 through 4 correspond to the arc flash incident energy possible to the worker for different tasks and equipment, up to 40 cal/cm^2. Currently, NFPA 70E does not designate HRC above 4 or energy above 40 cal/cm^2.

The 10% of equipment with high energy (over 40 cal/cm^2) is of particular concern because of the high risk to workers and certain chance of clothing ignition. These high-energy points are often due to conditions in the power system such as:

•Primary fusing on a substation transformer higher than needed. Example: 1,000 kVA transformer at 35 kV primary voltage has full load amps around 16 A; typical primary fusing should be sized at 25 A. If the existing primary fuse is sized at 50 A or 65 A, the incident energy at the secondary will be high.

•Low-voltage power circuit breaker settings are all turned to maximum. The settings of switchgear circuit breakers are critical to reducing or limiting the arc flash energy. The "short time" settings on the breaker trip unit are especially important. If these are set to the maximum, then the incident energy will be high.

•Low-fault current due to long cable lengths. Long cable lengths decrease the fault current that will flow during an arc incident. Protective devices such as fuses and circuit breakers take more time to trip when they sense lower fault current; the longer time means higher incident energy.

Once the arc flash hazard assessment is complete, the incident energy values can be used to determine PPE requirements for the tasks. Equipment labeling and training are required so workers know how to apply the information in their daily work. Workers responsible for operating and maintaining the electrical system must be familiar with the effects of their work on the arc flash incident energy. For example, if a process upset occurs, and the worker changes out a fuse to a larger size (because no fuse of the existing size was available quickly), then s/he needs to understand that the equipment's arc flash energy has been changed and may be higher.

Applying Control Measures to Reduce Risk

The arc hazard assessment enables informed and factual decisions on the design and implementation of a full range of controls. ANSI/AIHA Z10-2005, Occupational Health and Safety Management Systems, provides a hierarchy of controls applicable to any hazard in the workplace (ANSI/AIHA, 2005). Table 3 lists recognized control measures and examples of possible applications to arc flash hazards. This is not a complete list of how each control could be actualized, and measures may vary based on industry, facility age and other considerations. The hierarchy provides a way to identify the most effective measures to reduce risks associated with hazards in the workplace.

At the time of this writing, it is the authors' observation that the use of personal protective clothing is too often the only control measure being addressed. SH&E professionals need not be expert in the electrical technology aspects of these control measures. By engaging experts in electrical technology and work practices, SH&E professionals can facilitate discussion about and identification of mitigation solutions aligned with all control measures.

To Learn More

Ten years ago, few articles and resources addressed the topic of arc flash hazards and mitigation. Today, articles on this topic are common in electrical and safe-

Table 3

Manufacturing Technologies/Processes & Mutually Exclusive Alternatives Tested

Control measures (from ANSI/AIHA Z10-2005)	Application examples for arc flash hazards
1) Elimination	•Establish expectation that working on or near energized electrical equipment having potential for arc flash hazard is an exception and not routine (NFPA 70E-2004, article 130.1). •Establish high level of approval for any work on or near energized electrical equipment having potential for arc flash hazard [NFPA 70E-2004, article 130.1(A)].
2) Substitution of less-hazardous system or equipment	•Current-limiting fuses and circuit breakers to limit magnitude of arc flash energy; high resistance grounding to limit frequency of high energy arcs in 480 V power systems; "smart" networked equipment that allows troubleshooting without opening enclosures (Doughty, Neal, Macalady, et al., 2000; Gregory, Lyttle & Wellman, 2003; Blair, Doan, Jensen, et al., 2001).
3) Engineering controls	•IP20-compliant shrouding on terminal blocks and devices to minimize possibility of tool or metallic object initiating an arc flash event.
4) Warnings	•Labels as required by National Electrical Code article 100.116.
5) Administrative controls	•Redesigned switching, troubleshooting and operating procedures that reduce exposure and risk.
6) PPE	•Clothing and equipment rated for arc flash exposures, selected to perform for predicted exposures (NFPA 70E-2004, article 130.7).

ty publications. Manufacturers and suppliers of electric power equipment and PPE frequently host seminars as well. Two credible sources of information are NFPA and IEEE, both of which are standards development organizations with no commercial interests in electrical equipment or personal protective clothing. NFPA conducts seminars to aid implementation of safe work practices described in NFPA 70E-2004 (visit www.nfpa.org for more information). IEEE hosts the Electrical Safety Resource Center at http://standards.ieee.org/esrc/index.html.

Another resource is the IEEE IAS Electrical Safety Workshop, sponsored by the IEEE Industry Applications Society. This annual forum aims to advance the electrical safety culture to enable sustainable improvement in eliminating electrical incidents, injuries and fatalities. It targets two areas: 1) advancing the application of state-of-the-art knowledge and practices; and 2) stimulating innovation in creating the next generation of safe work practices, technology and management systems. Information is available at www.ewh.ieee.org/cmte/ias-esw.

Conclusion

Arc hazards are present in many industrial and commercial workplaces. Left unassessed and uncontrolled, their consequences can be significant. The most effective strategy is to implement a state-of-the-art program with arc hazard analysis as the basis for a full range of controls. Such an approach can help an organization identify where exposure potential exists; eliminate hazards through engineering design or administrative controls; reduce the frequency of potential arc flash events; limit the magnitude of energy release; and better ensure that PPE is appropriately rated for exposures. ■

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