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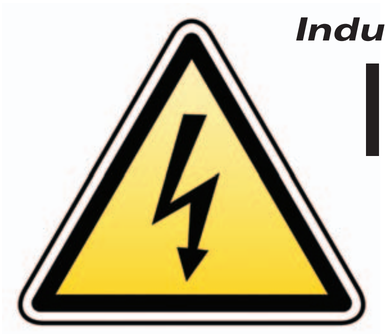

Industry's burning question…

Is Your Electrical PPE Adequate?

Despite the great strides that have been made over the years to get workers into safer clothing, researchers still want to know what level of thermal protection is safe enough.

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The last 15 years have seen tremendous progress in protecting workers against the heat energy associated with arc flash. One major area of improvement has been the steps taken to get workers into safer clothing. The arc rating system developed by ASTM and the development of the predictive equations identified in NFPA70E and IEEE1584 have been instrumental in this effort.

Arc flash testing has been at the center of these developments. The arc thermal performance value (ATPV) of electrical personal protective equipment (PPE) relies on arc flash tests performed in a high power test lab. The IEEE 1584 equations were developed empirically from arc flash tests performed in North American test labs from the late 1990s through 2002.

Recent research into arc flash phenomena, however, indicates that workers could be under-protected against the heat generated during an arc flash event. Test results presented at IEEE conferences [Ref. 1, 2, 3] and at the 2007 IEEE Electrical Safety Workshop show that different configurations of electrodes (conductors) yielded heat energy higher than current predictions due to the directional nature of the arc development. Additionally, initial tests of PPE, when placed within this directional plasma flow, did not provide the level of thermal protection predicted by its APTV.

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Directional nature of arc development

Unrestricted high-current arcs move according to magnetic forces to increase the area of the current loop. Currents flowing in the opposite direction in parallel conductors give rise to forces that drive the arc away from the source to the end of the conductors where they typically burn off the tips of electrodes (busbars).

The behavior of a 3-phase arcing fault in equipment is very chaotic, involving rapid and irregular changes in arc geometry due to convection, plasma jets and electromagnetic forces. Arc extinction and re-ignition, changes in arc paths due to restriking and reconnection across electrodes and plasma parts and many other effects add to this chaotic nature and make it difficult to create equations for accurate predictions of its properties

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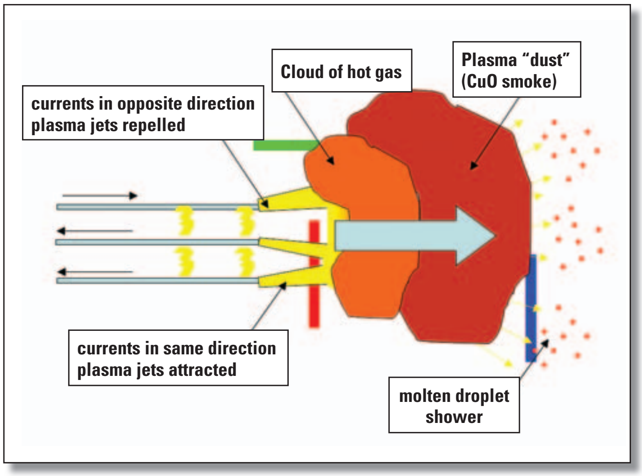

Fig. 1. The general directional nature of an arc; this depiction does not reflect chaotic behavior.

(e.g. impedance). Although it does not capture this chaotic behavior, Fig. 1 demonstrates an arc's general directional nature. The alternating 3-phase current creates successive attractive and repulsive magnetic forces, dramatically moving the plasma jets which feed an expanding plasma cloud. The cloud is driven outward, away from the tips, creating "plasma dust" as the highly energized molecules in the plasma cool, then recombine into various materials. The molten electrode material ejected off the tips also is in this flow.

Arc flash hazards

When the arc is being established, current begins passing through ionized air, generating massive quantities of heat. Large volumes of ionized gases, along with metal from the vaporized conductors, are explosively expelled. As the arc runs its course, electrical energy continues to be converted into extremely hazardous energy forms. Hazards include the immense heat of the plasma, radiated heat, large volumes of toxic smoke, molten droplets of conductor material, shrapnel, extremely intense light and a pressure wave from the rapidly expanding gases.

Recent tests have shown that an object in the expanding plasma cloud (refer to the red object in Fig. 1) is directly exposed to the highest heat of the event. Temperatures greater than 15,000 C have been cited for this area. In addition to the convective heat transfer from the plasma, this object is directly exposed to the molten metal ejected from the electrode tips and radiated heat from surrounding plasma.

Objects close to the arc but outside of the plasma jets (refer to the green object in Fig. 1) are not likely subjected to as high a quantity of heat. Exposure is predominately radiant heat, but includes convective flow from the thermal expansion of the gases. Objects in line with the electrodes but distant from the plasma jets (refer to the blue object in Fig. 1) receive lower convective heating and less radiant heat and molten metal spray.

The amount of heat absorbed varies with the method of heat transfer and receiving surface properties. For example, the amount of heat transferred from a mass of molten copper to a surface area would be greater if it adhered to the object instead of contacting it for a brief time.

Test setups currently used for standards

Although the overriding principle of electrical safety is to de-energize equipment and place it into an electrically safe condition prior to work, there are numerous cases where companies put workers in PPE to perform tasks on energized equipment. The standards typically utilized to predict the magnitude of heat exposure and the protective ability of flame resistant (FR) fabric worn by exposed workers are based upon two unique electrode configurations in their test procedures. Heat transferred during tests with these orientations is most likely dominated by radiant heat.

Effects on heat measurements with alternate test configurations

Research performed at Ferraz Shawmut's High Power Test Laboratory has uncovered electrode configurations that project significantly more heat energy out of enclosures toward worker locations than currently predicted by the standards. To simulate components found in low-voltage electrical equipment, various setups were created for controlled testing. Heat was measured and compared with results obtained with the standard configuration shown in the Sidebar figure on page 36. Results of these comparisons were published in two recent IEEE papers. [Ref. 2, 3] Configurations that forced the arc's plasma jets outward toward the worker produced heat measurements nearly twice those predicted by current IEEE 1584 equations when studied at typical working distances of 18 inches.

In the barrier configuration setup, the electrodes are "terminated" into a block of insulating material (barrier) as shown on the left in Fig. 2. This setup represents conductors connected to equipment from the top, such as the component shown on right in Fig. 2.

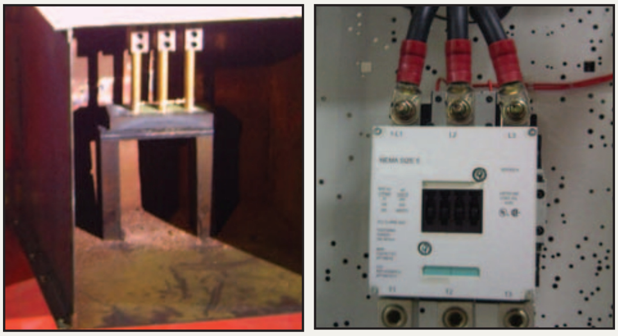

Fig. 2. Barrier test configuration (Left) simulating the line side connections of the starter (Right)

Equations for Prediction of Arc Flash Heat Energy Density for Low-Voltage Applications

- NFPA 70E. First issued in 1979, NFPA 70E, Standard for Electrical Safety in the Workplace, is considered the foremost national consensus standard for electrical safety in public and private places. It covers the full range of electrical safety issues, from work practices to maintenance, special equipment requirements and installation. The 1995 edition first addressed arc flash hazards with the addition of "arc flash hazard boundaries," with the equations based on arcs in open air. "Arc-in-a-box" equations were added to the 2000 edition as options to calculate a worker's potential heat energy density exposure. These equations came from results of arc flash tests with a steel box and vertical electrodes with open tips [Ref. 7, 8] as shown in the photo in this Sidebar. The 2004 edition added the IEEE 1584 equations below.

- IEEE 1584. Issued in 2002, IEEE 1584-2002, Guide for Arc Flash Hazard Calculations, provides guidelines for an analysis to "identify the flash-protection boundary and the incident energy at assigned working distances throughout any position or level in the overall electrical system." The results from over 300 arc flash tests were incorporated into the low-voltage predictive equations for enclosed equipment contained within IEEE 1584. Three enclosure sizes were used in these tests, but all tests also used vertical electrodes with open tips.

- ASTM 1959. The current edition of ASTM F1959, Standard Test Method for Determining the Arc Rating of Materials for Clothing, uses a single phase opposing electrode orientation. This standard determines the ATPV rating of material used in arc rated PPE. The test procedure places materials in locations surrounding the area where the arc would occur. The majority of the heat transferred to the material is likely radiated from the arc. This open air arrangement from the 1980s would simulate flashovers on overhead power systems.

References:

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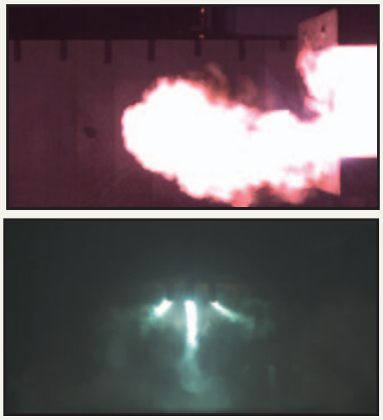

Fig. 3. (Top) Arc development from barrier test 4ms into event, compared to that from the vertical test 3ms into event (Bottom)

With the barrier in place, the arc's downward motion is halted and plasma jets are formed along the plane of the barrier top surface (i.e. perpendicular to the plane of the electrode). This significant finding is demonstrated in Fig. 3. The photo on the top shows a side view of arc development along the plane of the barrier in a setup without side panels. This test shows the possibility of higher convective heat transfer toward workers than the open vertical setup, shown from the front, on the bottom in Fig. 3. The barrier configuration also ejected significantly more molten electrode material. [Ref. 3]

Chart 1 compares heat measurements (made with copper calorimeters) with the barrier setup to standard predictions. The black line represents predictions of IEEE 1584 equations for switchgear (20" cubic box) for the available fault currents with a fixed 6-cycle clearing time. Alarmingly, the barrier test results almost always rose above the line—*sometimes more than twice the prediction. All tests with the vertical configuration at this voltage were at or below the prediction.*

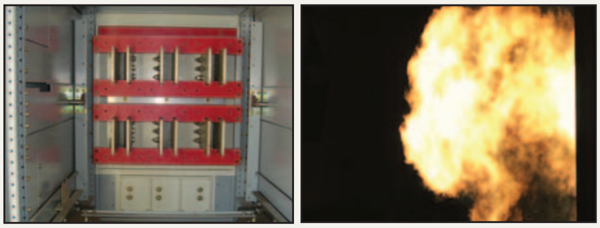

Fig. 4. The horizontal test setup was designed to simulate back-fed equipment like this unit (Left); side view of plasma flow at 8 milliseconds into a 44kA 600V arcing event for electrodes recessed in the horizontal setup test box (Right)

Another configuration that deserves serious consideration is the "horizontal electrode configuration." This setup simulates equipment where bussing is open-ended, but pointing toward the front of the enclosure, like that in the equipment shown on the left in Fig. 4. The arc development, very similar to that described for Fig. 1, is shown on the right in Fig. 4. Like the barrier configuration, all tests resulted in heat measurements significantly above the predicted levels.

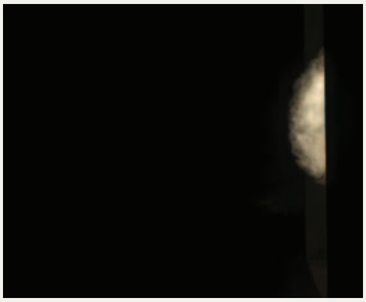

Fig. 5. Photo of maximum reach of plasma with current-limiting effect of 600A UL Class RK1 fuses. Test conditions are the same as those described in Fig. 4.

Of equal concern is the fact that arcing currents were below predicted levels for this configuration (see Chart II). In some applications, clearing times will be significantly longer than expected if the arcing current is too low to operate the short circuit element of the upstream overcurrent protective device (OCPD). In these applications, the increase in arc flash heat energies will be far greater than the differences obtained in tests with a fixed clearing time of six cycles.

A number of tests with current-limiting fuses showed, with proper fuse selection, that workers will be exposed to far less heat energy even when standing in locations subject to the plasma flow (Fig. 5). The results were very close to those predicted by current equations. Plants currently employing this conservative method of protection will still need to recalculate arc fault currents and determine if fuses will be operating in their current-limiting modes for arc faults on equipment with horizontal electrodes.

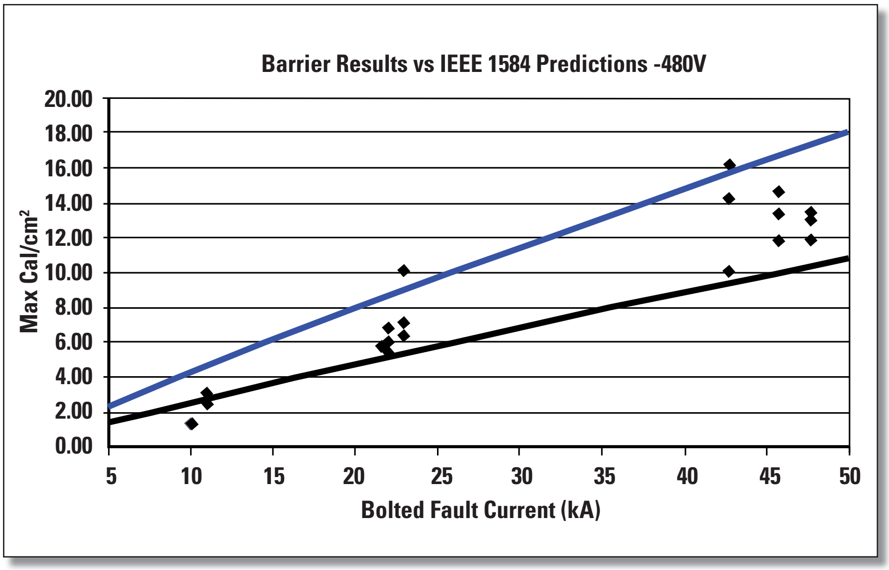

Chart I. Comparison of barrier results to predictions of IEEE 1584 equations for switchgear. The black line represents prediction; the blue line is 167% of the prediction.

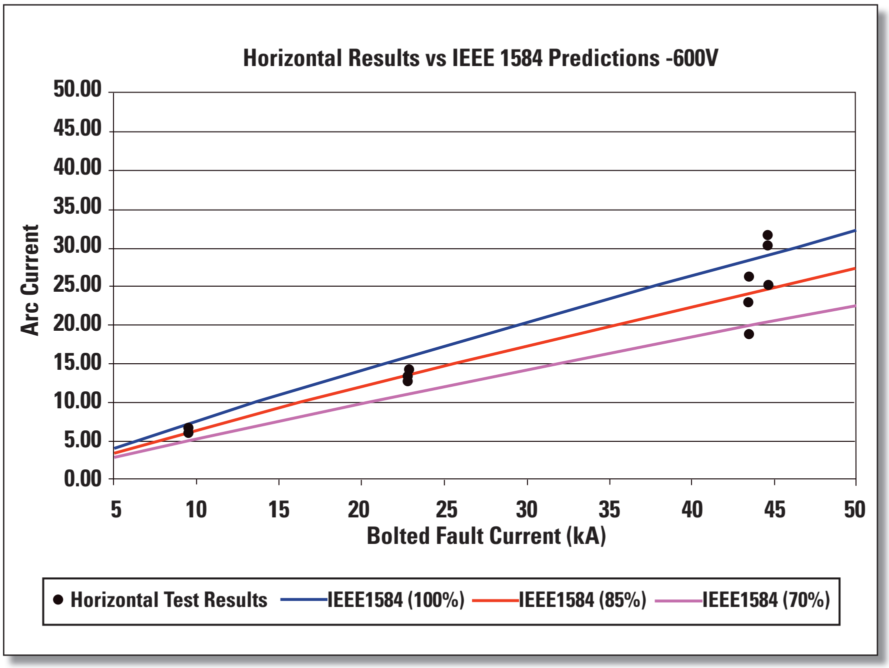

Chart II. Comparison of arc currents from horizontal tests to predictions of IEEE 1584 equations for switchgear. Note that some of the test results were below even the 85% value recommended by the standard.

The IEEE/NFPA Arc Flash Collaborative Research Project

The IEEE and NFPA are asking for support to help fund needed arc flash research.

The combined effort to identify, understand and learn how to mitigate or protect employees in the workplace against the potential "electrical arc flash hazards" is estimated to cost $6-$7M (US). For more information on this project, log on to: http://standards.ieee.org/esrc/arcflash/index.html

For more information on ASTM Technical Committee F18 visit: http://www.astm.org/cgi-bin/SoftCart.exe/COMMIT/COMMITTEE/F18.htm?L+mystore+zapd8129

Fig. 6 Fabric test setup with barrier test (Left); Front view of bare and fabric covered calorimeter (Right)

Effects of alternate configuration tests on PPE

Preliminary investigations showed that many protective FR fabrics did not yield the same level of thermal protection when placed within the directional plasma flow for the barrier configuration. Tests were performed with FR fabric placed at 18 inches from the electrodes of the vertical, barrier and horizontal configurations (see Fig. 6 for fabric test setup). A variety of currents and clearing times were used in these 480V tests to generate a range of heat energies for the tests.

There were surprising results with the barrier and horizontal tests, as some fabrics performed at only 50% of their arc ratings. Initial testing of the vertical configuration also indicated that the arc rating of FR fabrics was reduced. It is suspected that greater heat transfer through the material because of the increased convective energy component is responsible for its decreased performance in the plasma-rich region of the arc. Equally surprising results were obtained for arc rated faceshields, which exhibited an increased arc rating. This would be expected since, unlike the permeable FR fabrics, faceshields are impermeable to the increased convective energy component.

Moving forward

There are two major areas of improvement for better protection of workers against the heat of arc flash events. Both areas are related to the possibility that workers could be directly immersed in the developing plasma flow described in the foregoing text.

First, equipment configurations that would direct arc development outward need to be clearly identified and models developed to better predict the levels of heat energy that can be presented to workers from arc flashes in such equipment.

Second, the test method and a modified arc rating system for PPE need to be developed to address the reduced performance of PPE for hazards involving equipment configurations that would direct the plasma flow outward toward the worker.

Industry action

Leading organizations concerned with electrical safety are currently investigating the results of the research outlined in this article. The IEEE 1584 working group has joined with the NFPA 70E committee to form the IEEE/NFPA joint collaborative initiative on arc flash research. The goal of this research is to provide the information and knowledge needed to enhance safety standards that predict the hazards of arc flash events and improve safeguards for workers. The research and test planning committee has already developed a comprehensive test protocol to further quantify these findings and investigate the many other hazards of arcing events (e.g. pressure waves, sound, toxic smoke).

Additionally, the ASTM F18.65 subcommittee on Wearing Apparel has formed a task force to further study the performance of materials in the plasma flow. The task force will identify any needed modification or additions to the test protocols of ASTM F 1959F/F1959M-06a for material performance. ❖

Be Careful Out There!

Until the standards provide better guidance on these configurations, greater vigilance is necessary. Review your electrical safety program and enhance procedures to keep workers out of energized equipment.

If equipment is suspected to be similar to the alternate plasma flow configurations described above, then consider the rating of protective clothing to be half the listed arc rating. When using the NFPA 70E Tables 130.7(C)(9)(A) and 130.7(C)(10) to select protective clothing and PPE, add one Hazard Risk Category number to HRC0, HRC1, HRC2 and HRC3. For HRC4 hazards, avoid using the Tables or select PPE with a rating of at least 80 cal/cm2.

Arc flash hazard analysis studies will be more important than ever. As better models of arc faults become available, users will be able to quickly update and assess situations where greater hazards will be expected.

For those who have already completed studies, it is strongly recommended that you review these studies and implement projects to mitigate the hazards wherever possible. Among other things, actions could be as simple as:

- Switching Class H, K and RK-5 fuses to RK-1s. Lower threshold currents provide the widest range of current-limiting operation and lowest energies. Tests with all configurations yielded results of 0.5 cal/cm2 or less when fuses operated in their current-limiting modes.
- Reducing Circuit Breaker Settings. Where advantageous, lower pick-up settings to ensure that arc fault currents will operate circuit breakers in their instantaneous modes.

For other suggestions visit us.ferrazshawmut.com/arcflashinfo

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5. IEEE Guide for Performing Arc-Flash Hazard Calculations. IEEE Standard 1584, IEEE, September 2002

6. ASTM F1959/F1959M-06a Standard Test Method for Determining the Arc Rating of Materials for Clothing

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