Occupational Safety

Arc Blast Hazards

The limitations of metal-clad enclosures to protect workers

By John J. Kolak

A COMMON MISCONCEPTION among electrical workers and electrical engineers is that flame-resistant (FR) clothing is not necessary when working on equipment that is enclosed inside a metal cabinet (metal-clad). The "tabular approach" for selecting FR clothing in NFPA 70E-2004 exacerbates this problem by classifying most equipment as "hazard class 0" (lowest hazard) when the equipment is contained inside a locked metal enclosure. Hazard class 0 equipment does not require FR clothing. This has contributed to the belief that metal-clad enclosures can always be trusted to protect workers from electrical arc blasts.

This is actually not the case. Scientific studies have demonstrated that metal enclosures can only contain electrical arc blasts of limited intensity and duration (Gammon & Matthews, 2003). Several common work practices and equipment failures can precipitate arc blasts that can exceed the structural limits of metal-clad enclosures and still cause injury to nearby workers.

Additional hazards are present any time the metal-clad enclosures have any intentionally installed openings, such as cooling vents. Research has revealed that no regulatory or manufacturing requirements mandate that the doors of metal-clad enclosures be of equal strength to the sides of the cabinets (Gammon & Matthews, 2003). This means that relying on closed and latched doors on enclosures to protect workers from arc blast hazards is sometimes inadequate and that wearing FR clothing even when working on locked enclosures is often a reasonable work practice.

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The Dynamics of Electrical Arcs

An electrical arc is actually electrical current (measured in amperes) flowing through the air via a conductive path comprised of conductive gases or vapors. The conductive gases are ionized gases and plasma mostly comprised of ozone (O_3) and molten metal which are created by the initial fault that precipitated the arc. The oxygen (O_2) component of the air is actually a very good insulator with respect to conducting electrical current. The insulating property of oxygen is what allows energized electrical terminals to be located within only a few inches of each other in electrical equipment without flashing-over to each other (Ferraz Shawmut, 2005).

However, when an arc occurs near electrical conductors, the energy of the arc converts the oxygen to ozone, which creates a very conductive atmosphere within the electrical equipment. This reaction has the same effect as if a person were to deliberately short-out (touch two electrically energized conductors, or one energized and one neutral or grounded conductor together) electrical components (an electrical fault) by bridging them with a metal conductor. The electrical system supplying the panel will then supply every available ampere to the fault, which precipitates the arc blast that is often depicted in safety videos about FR clothing.

Studies conducted by Lee (1982) and others reveal that the heat released in an electrical arc can rise to values of more than 35,000 ºF. This is approximately four times hotter than the surface of the sun. The metal in electrical panels will melt when heated to approximately 2,500 ºF (1,984 ºF for copper) (Kross, 2007). This means that electrical panels can withstand electrical arcs for only a few seconds before panel components begin to disintegrate; the enclosure (usually made of sheet steel) will then melt open (i.e., breach the panel), and the arc heat and the blast will be released into the surrounding area, endangering anyone nearby. Additionally, the emission of superheated plasma causes combustible materials in close proximity to ignite, thus expanding the arcing fault or arc blast into a facility fire.

It is noteworthy to explain that the concept of time must be redefined when considering electrical faults. A fault lasting a "long" time in electrical terms might burn for only a half second. The difference in magnitude of an arc lasting one-third second versus one lasting a half second can be dramatic. Therefore, one must understand that even the slightest delay in extinguishing electrical arcs could result in catastrophic equipment damage and severe burns or death to those exposed to the arcing events.

The Electrical Arc Blast

While this discussion has thus far focused only on the arcing component of an electrical fault, another equally important hazard must be considered, the electrical arc blast. The air we breathe has the chemical property that it can expand several thousand times its normal volume when heated to high temperatures. When the air within an electrical equipment room is superheated to more than 10,000 ºF in less than 1 second, the air rapidly expands, generating a pressure wave that pushes outward from the arc source. This pressure wave is experienced as an explosion and is recognized in electrical vernacular as an arc blast.

The arc blast presents three principle dangers to humans:

1) The concussive force of the blast can directly cause physical trauma similar to that caused by any type of explosion. Studies have shown that pressure can build to more than 15,000 times atmospheric pressure within the first 5 ms of arc initiation (Wactor, Miller, Bowen, et al., 2000). Pressure of this magnitude can easily exceed the structural strength limits of metal enclosures and cause injury to anyone in the vicinity of the arc blast.

2) The blast provides the propellant for projectiles (e.g., partially melted metal parts, broken insulators) that present a serious hazard to anyone in the vicinity.

3) The blast can blow the enclosure doors open, releasing hot gases and molten metal into the area near the electrical equipment. These hot gases and molten metal present significant burn hazards to those in the vicinity. It is noteworthy that the IEEE 1584 methodology for calculating incident energy levels does not take the molten plasma or the pressure waves into account in the calculated incident energy values (IEEE, 2002).

Table 130(C) in NFPA 70E-2004 lists incident energy in both calories/cm^2 and joules/cm^2. Incident energy relates to the heat or force per unit area of a person's skin. Section 130.7(C)(5), "Body Protection," explains that if a heat source can impose 1.2 cal/cm^2 on human skin, a second-degree burn will result. A second-degree burn is characterized by blistering of the skin and will normally heal without advanced medical intervention. This is referred to as a *curable* burn because the skin can normally heal itself. Studies have shown that incident energy exposures of as little as 10.7 cal/cm^2 can cause third-degree or *incurable* burns (Jamil, Jones & McClung, 1997) meaning that skin grafting becomes necessary and burn area will never function as it did before the burn.

Aside from the obvious concussive effects of electrical blasts, one of the greatest dangers for workers is when the blast causes mechanical failures of metal-clad enclosures thereby exposing them to both immediate arc flash hazards caused by expanding arcs or recurring arcs as well as the residual heat and concussive forces caused by the initial arc. Normally, the over-current protective devices (OCPD), such as fuses and circuit breakers in the circuit, must operate and deenergize the circuit before heat and pressure values build excessively. However, several situations common in industrial settings can cause excessively long-lasting arc-blasts. These causes include the following:

- **Poor maintenance of electrical equipment.** In the author's experience, many organizations do not properly maintain their OCPD. Many never conduct any testing or maintenance of OCPD following the initial installation.

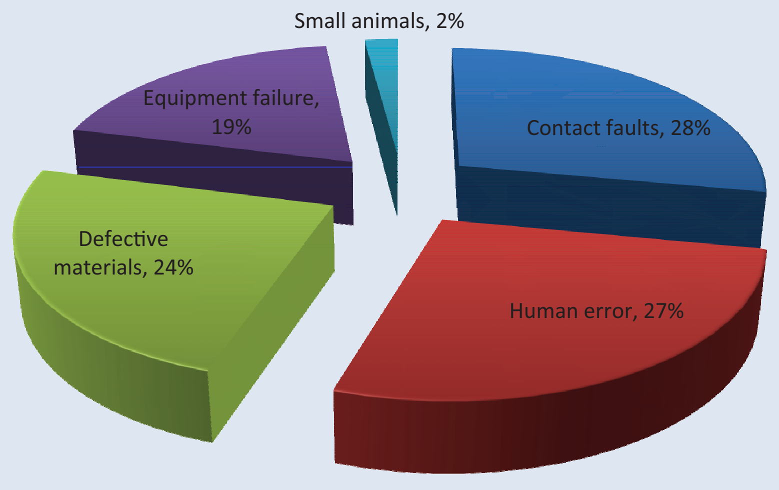
One important maintenance item is to exercise the main circuit breakers in a system at least annually. The term *exercising* means to open the breaker and close it again after first shutting down large loads connected to the circuit breaker. When performing arc flash hazard analysis, the author has found circuit breakers where the contacts are corroded and have seized because they have not been operated over a period of years. Should that breaker be called on to trip-open during an electrical fault, it would obviously not operate as it did when it was new. It is critically important to remember that arc flash hazard analysis calculations use the manufacturer's listed clearing times when calculating incident energy. When OCPD operate more slowly than predicted, the calculated incident energy values will be understated. This means that workers selecting FR clothing based on the arc flash labels affixed to equipment would not be protected because actual incident energy values will exceed the calculated values that appear on the labels.

This discussion is not intended to be taken as a recommendation that OCPD be subjected to fault-duty on a regular basis. The recommendation is merely to move the internal mechanisms of circuit breakers to ensure that they will operate properly. It is also critical to know that molded case circuit breakers and insulated case circuit breakers are rated for as few as three operations under short-circuit duty (Square D Corp., 1999). Circuit breakers are tested at six times their rated current for overloads but they can easily be subjected to short-circuit current (SCC) values much greater than this level when electrical faults occur on high-capacity systems (Square D). This is of particular concern for organizations that routinely reset breakers following faults without first repairing the cause of the fault.

A related issue of note is to remember that OCPD are indicators as well as protective devices. If an electrical system is properly designed and installed per the National Electrical Code (NEC) requirements, it should not be tripping out due to overloads or faults. Therefore, the troubleshooter should endeavor to determine why the OCPD operated rather than merely attempting to reset the breaker or replace the fuse. In many cases, the electrical system will provide forewarning of catastrophic system failure as components begin to fail, precipitating operation of OCPD. Correcting the root cause of these operations

Abstract: *Many electrical workers and electrical engineers wrongly believe that metal-clad enclosures can always be trusted to protect workers from electrical arc blasts. This article explains the limitations of metal-clad enclosures and offers suggestions for ensuring worker safety—starting with proper equipment design and installation.*

Figure 1
Causes of Arcing Faults



at the first indication will often prevent catastrophic damage or injury at a later date.

• **Workers changing protective device settings.** One common misstep taken by electrical workers occurs when they dial up (increase ampere settings or fuse sizes) OCPD to the maximum current settings to ensure that circuits stay online rather than tripping out after overloads. This unsafe work practice can often result in catastrophic faults should the equipment that is fed from these OCPD fail. Additionally, the incident energy most often is increased at these settings, which amplifies the danger to workers.

• **Improper replacement of protective devices.** Should an OCPD fail for any reason, workers must replace the device with the exact same make and model device. Each protective device manufacturer has many different models of circuit breakers or fuses, each with a specific application. It is possible, for example, to replace an 80 A fuse with another 80 A fuse of a different style and significantly increase the incident energy levels in so doing.

A case study illustrates this point. A maintenance technician was called to change a 600 A Ferraz Shawmut A4BQ-style fuse that protected a large power panel in an industrial facility. The A4BQ fuse is a Class L fuse intended for use on main disconnects for power panels, which is what the technician was working on in this case. Incident energy calculations on this circuit had previously indicated that the bus protected by this fuse would present 0.8 cal/cm^2.

Unfortunately, the technician had no more A4BQ fuses on hand so he used a 600 A Ferrazz Shawmut A6D fuse. He believed it would work given that it was the same size fuse made by the same manufacturer. However, the A6D fuse is a Class RK-1 fuse intended to be used on motor circuits and it includes a time-delay that the A4BQ fuse does not. Incident energy calculations using the A6D fuse indicate that workers would now be exposed to 2,832 cal/cm^2 on the same bus.

Electrical arcs and electrical blasts are often grouped together because every arcing event precipitates a blast event as well. However, some arcing events occur in open areas where the expanding gases are free to expand infinitely in any direction and the blast is not readily noticed as having occurred. Should that same blast occur in a manhole or vault that has limited space for the gases to expand, the same blast event could result in severe injuries or even fatalities.

Some arcing events are also limited in their intensity and the concomitant blast is also minor in intensity and may go virtually unnoticed. The best approach is to anticipate that any electrical arc could precipitate an arc blast as well and design protective systems to guard against both hazards. In this context, electrical arcs and electrical blasts are referred to with the term *arc blast*.

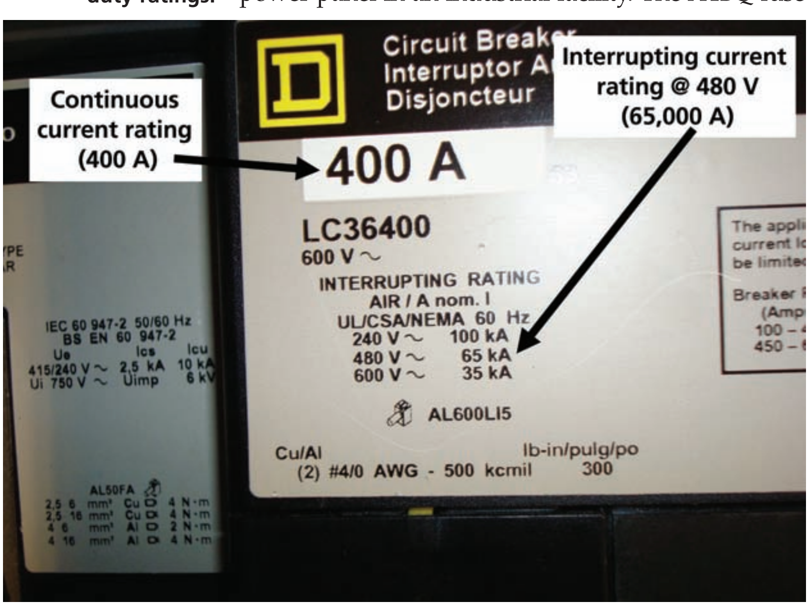
Causes of Arc Blasts

Various events can precipitate an arc blast (Figure 1). Many of the causal factors for arc blasts relate to human error and unsafe work practices. For example, many equipment failures are actually caused by workers continually resetting circuit breakers without first testing the circuits to determine the reason for the fault. The author has worked with many organizations that have a one trial close rule. Essentially, this means that anytime a circuit breaker trips or fuse blows, the worker is to attempt to reenergize the circuit one time to see whether the protective device *holds* (does not trip again). Often, the circuit is still faulted and the circuit breaker or fuse operates again.

The problem with this practice is that resetting circuit breakers on faulted circuits creates significant magnetic and heat stresses on all the devices included in the circuit that supplies current to the fault. These stresses weaken circuit components, often resulting in equipment failure at some future time. While it may be tempting to think that equipment failure just happens as a result of aging equipment, it is nearly certain that some of these events are the result of unsafe work practices such as the one trial close rule.

Another important concept to understand is that of equipment duty ratings of electrical equipment. The term *equipment duty* refers to the ratio of short-

Photo 1: Continuous current ratings versus interrupting duty ratings.



Example Calculation Using Stanback's Models

A single-phase (277 V) fault occurs on a 1,000 KVA transformer rated at 277/480 V at 5% impedance. This transformer is a commonly sized unit for many industrial plants. The arcing fault current on this transformer is approximately 11,480 Amperes per phase (NFPA, 2004). Table 1 indicates the amount (in cubic inches) of steel, copper and aluminum that would be burned away for arcs lasting the listed duration (in seconds).

Arcing Fault Current (I_{arc})

$$\text{Log } I_{arc} = K + 0.662\text{Log } I_{bf} + 0.966\ V + 0.000526G + 0.5588\ V(\text{Log } I_{bf}) - 0.00304\ G(\text{Log } I_{bf})$$

Where:

Log is the Log10
I_{arc} is the arcing current in kA
K is -0.153 for open configurations and -0.097 for closed configurations
I_{bf} is bolted fault current
V is system voltage in KV
G is the gap between conductors in (mm)

Full load current on a 1,000 KVA transformer = KVA x 1,000/(voltage x 1.732)
= 1,000 x 1,000/(480 x 1.732)
= 1,202 Amperes
I_{bf} = 1,202/Z= 1,202/0.05
= 24,040 Amperes (24.04 kA) = I_{bf}

Log I_{arc}
= -0.153 + 0.662(Log 24.04) + 0.966(0.48) + 0.000526(32) + 0.5588 V(Log 24.04) - 0.00304 (32)(Log 24.04)
Log I_{arc} = 1.06
I_{arc} = 11.48 kA or 11,480 Amperes

Table 1

Example Calculations of Equipment Damage as a Function of Arcing Time

Short-circuit current	Arc duration	Steel (in^3)	Copper (in^3)	Aluminum (in^3)
11,480 A	0.1 s	0.8	0.9	1.4
11,480 A	0.5 s	4.0	4.5	9.0
11,480 A	2.0 s	16.2	17.8	37.4

circuit current to which a device is subjected to the short-circuit interrupting rating of the device itself. As the name suggests, this rating indicates the protective device's capability to interrupt short-circuit current and still be used again afterward (Photo 1).

Engineering Information on Equipment Enclosures

There is a surprising deficit of information on the ability of equipment enclosures to withstand electrical arc blasts. One guiding document is IEEE C37.20.2-1999, IEEE Standard for Metal-Clad Switchgear. While this standard provides excellent guidance regarding proper design and installation of metal-clad equipment, it has a few noteworthy limitations within the context of this discussion This standard:

- Assumes fault events will be within the rated interrupting/withstand ratings of the OCPD. Therefore, there is no requirement that the enclosures can contain an arc blast.
- Requires that the walls of enclosures be at least 3 mm (steel) thick while doors may be only 1.9 mm.
- Limits arc duration to 2 seconds or less. Normally, this is reasonable, as arcing faults lasting 2 seconds are quite rare in normal circumstances. However, any of the issues discussed in the "Dynamics of Electrical Arcs" section (p. 46) could precipitate arcing faults lasting much longer than 2 seconds.

Other studies have attempted to identify energy levels that will damage electrical equipment but these have not achieved general acceptance within the engineering community. One study conducted by Stanback provides useful information (Gammon & Matthews, 2003). It predicts the amount of metal burned away by various combinations of short circuit current and time duration of arcing faults. Although Stanback's models included only single-phase 277 V arcs (single phase to ground or neutral of a 480-V WYE connected electrical system), it provides at least a general idea of the ability of electrical arcs to damage electrical equipment.

An example calculation using Stanback's models helps illustrate the point (see sidebar above). While the information in Table 1 does not precisely predict whether arcs of this magnitude would breach electrical panels, it clearly indicates the capacity of elec-

Photo 2: The arc in this case lasted long enough for sufficient heat to develop to melt the steel enclosure.

trical arcs to burn away metal. At a minimum, these arcs would damage equipment to the point that it required repair or replacement. It is also possible that arcs of this magnitude could breach panel enclosures and still injure personnel in the vicinity of the fault.

NFPA 70E-2004 Requirements

NFPA 70E-2004 provides important guidance regarding protection from electrical arcs, but only ancillary guidance from electrical blasts. The footnote to the FR clothing table [Table 130.7(C)(11)] on p. 34 of the standard references a variable EBT, which stands for break-through energy. This relates the force of the arc blast that would blow open (break-through) clothing, thereby exposing the bare skin underneath to incident energy and injury from the blast components.

One potential deficit in NFPA 70E relates to the PPE required when working on exposed equipment compared to dead-front equipment. The term *dead-front* refers to equipment with a solid barrier (usually metal panel covers) such that it has no exposed parts energized to 50 V or more on the operating side of the enclosure.

The circuit breaker panel included in most newer homes is a good example of such an installation. Opening the access door on the circuit breaker panel reveals only dielectric (nonconductive) circuit breakers and a solid metal door that completely covers the circuit breakers and the rest of the panel opening. This dead-front is primarily designed to protect the homeowner from direct exposure to the energized elements inside the enclosure.

Considerable evidence suggests that arcing faults can burn through the enclosure cover or sides and injure workers or cause fires. Photo 2 illustrates this point. In this case, a worker had installed protective grounds on the 480-V conductors inside of a pad-mounted transformer (the grounds were incorrectly applied). Workers then mistakenly energized the circuit and an arc flash developed. As the photo illustrates, the arc lasted long enough for sufficient heat to develop to melt the steel enclosure.

As the name suggests, exposed parts have no such barrier and anyone could touch energized parts without having to remove a barrier to access those parts. A common example of exposed parts would be a solid blade disconnect installed on air conditioning units in many homes. Opening the door of this device reveals bare solid blade disconnect contacts and bare cable terminations.

A review of the FR clothing selection tables on pp. 29-31 of NFPA 70E-2004 reveals that FR clothing is not required for work on dead-front installations (listed as having the doors closed) unless the equipment contains parts energized to more than 1,000 V. The problem with this is three-fold:

1) Electrical arcs will exit the equipment through any opening in the enclosure. Many enclosures contain cooling vents to keep the internal components within temperature limits for normal operation. Anyone standing in front of the equipment when an arc occurs within could be burned by the arc exiting the enclosure through these openings. It is important to never seal cooling vents in enclosures, as they serve an important function in the operability of the equipment. Results of arcing also include the fires that are possible with the incident.

2) Arcs that last longer than a few seconds can easily generate heat levels that will breach the enclosure and still present a hazard to workers in close proximity to the gear. Any of the issues outlined in the "Dynamics of Electrical Arcs" section (p. 46) could precipitate arcs of unacceptably long duration. The arc duration is determined by the length of time it takes for the arc to either operate OCPD or to consume, electrically, the metal in the faulted circuit.

3) The blast generated by the arc can cause the doors of the enclosure to burst open, again exposing anyone standing in front of the equipment to physical trauma. An inspection of typical metal-clad electrical enclosures reveals that the back side of the gear is often secured by 4 to 10 hardened-steel bolts, while the access door is often held in the closed position by only two or three convenience latches where a tongue-like metal latch merely slides underneath the lip of the door frame to secure the door. These latches are good when a lock is inserted to prevent casual access to the interior but often they are not able to contain the possible arc blast. By far, they are the most likely component of the enclosure to fail when subjected to an arc blast.

The key point is that there are many times when a worker would be wise to wear FR clothing even when the 70E tabular method for selecting this gear indicates that no such clothing is required. Examples of situations where wearing FR clothing as a precautionary measure are warranted, even when working with dead-front equipment, include the following:

1) Resetting circuit breaker on any fault of unknown origin. Section 130.6(K) of NFPA 70E prohibits resetting devices after a fault trip unless testing has been performed by a qualified person to determine the cause of the trip. If troubleshooting efforts fail to identify the nature of the fault, the breaker may be reset but this represents an hazardous situation warranting additional protective measures.

2) Resetting or racking a circuit breaker when the

enclosure has cooling vents or other openings in the door or walls.

3) Operating any device when there is evidence that the device has been subjected to water, heat or mechanical stress. Examples would be carbon on any part of the enclosure, flashover of insulators, hairline cracks on insulators or melting of conductor insulation, or excessive condensation, leaking or rising water.

4) Installing personal protective grounds on a circuit of any voltage.

Protection From Arc Blasts

Protecting workers from the effects of arc blasts begins with proper equipment design and installation to prevent arc blasts from occurring in the first place. This includes following the design and installation practices outlined in the NEC (NFPA 70) and National Electrical Safety Code (IEEE, 2007). Designs can include venting of arc blast to a safe area and some manufacturers have incorporated this attribute in their designs and made this option available for several years. However, many manufacturers do not offer the option. Thus, many enclosures rated for high available fault currents do not provide enclosures that will withstand the blasts which are possible with an arc blast under the maximum conditions.

Other design improvements include locating operational handles several feet away from the devices they actuate. Incident energy decreases significantly with distance from the arcing terminals so remotely locating switches is often easily accomplished and yields significant improvements in worker safety.

Another effective method for protecting workers would be to limit the energy released in arc blasts through the use of electrical engineering such as arc flash hazard analysis (AFHA). Many people believe that the purpose of AFHA is to accurately predict what type of FR clothing is appropriate for various work practices. However, its actual purpose is to reduce incident energy levels thereby mitigating the hazards to people. AFHA also generates the labels that warn qualified workers of arc flash hazards. NEC 110.16 requires that equipment presenting an arc flash hazard be labeled to warn workers of these hazards.

The next best method to protect workers would be to design electrical enclosures to contain electrical arc blasts. This includes the use of dead-front electrical equipment. While this article examines the limitations of dead-front equipment to protect workers from arc blasts, such equipment remains an important element of protecting workers from arc blast hazards.

The least effective means of protection would be to provide workers with FR clothing and the use of safe work practices. AFHA often reveals that incident energy levels can exceed the insulating capabilities of any FR clothing available. This means that there is no way to insulate workers from the effects of arc blasts of this magnitude. Therefore, the appropriate use of FR clothing should be considered a last resort to manage the residual risk that remains after all reasonable efforts to reduce incident energy levels have been exhausted.

Conclusion

While metal-clad enclosures often provide excellent protection from the devastating potential of electrical arc blasts, electrical workers and engineers need to understand the limitations of such enclosures to protect the workers on the job. Several circumstances can compromise the integrity of metal-clad enclosures, although most are predictable, meaning arc blast hazards can be effectively controlled.

The most effective means to control arc blast hazards is to either eliminate or mitigate incident energy levels through engineering interventions such as AFHA plus proper equipment design, installation and proper periodic preventive maintenance. PPE such as FR clothing should always be viewed as a last resort and used only to control residual hazards that remain after all reasonable efforts to mitigate incident energy have been exhausted. NEC 110.16 requires proper AFHA labeling at each facility. Workers must also be trained to properly interpret AFHA labels and know appropriate safe work procedures.

Several instances occur where effectively protecting workers will require that workers exceed minimum standards as set forth by OSHA and the NFPA 70E. It is critical to understand that safe work practices set minimum standards and that proper training and good judgment are necessary to work safely with electrical energy.

Additional research in equipment enclosure development and methods of reducing incident energy exposures is needed to more effectively protect electrical workers. The integrity of electrical enclosures must be tested with specific emphasis on deriving methods for predicting when arc blast events will exceed the design limitations of electrical enclosures. ■

Protecting workers from the effects of arc blasts begins with proper equipment design and installation to prevent arc blasts from occurring in the first place.

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