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The Limitations of Metal-Clad Enclosures to Protect Workers from Electrical Arc-Blast Hazards:

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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 the NFPA 70E-2004 exacerbates this problem by classifying most equipment as "Hazard Class Zero" (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 when this is actually not the case.

Scientific studies have demonstrated that metal enclosures can only contain electrical arc-blasts of limited intensity and duration. There are a number of common work practices and equipment failures that can precipitate arc-blasts that can exceed the structural limits of metal-clad enclosures and still cause injury to nearby workers.

Further, additional hazards are present anytime the metal-clad enclosures have any intentionally installed openings in them, such as cooling vents. Our research has revealed that there are no regulatory or manufacturing requirements mandating that the doors of metal-clad enclosures be of equal strength to the sides of the cabinets(1). This means that relying on closed and latched doors on enclosures to protect workers from arc-blast hazards is sometimes inadequate and wearing FR clothing even when working on locked enclosures is often a reasonable work practice.

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) which is created by the initial fault that precipitated the arc. The Oxygen (O_2) component of the air we breathe 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. However, when even a small 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 purposely "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 H.R. Lee and others reveal that the heat released in an electrical arc can rise to values of >35,000°F (2). This is approximately 4 TIMES hotter than the surface of the Sun. The metal in electrical panels will melt when heated to approximately 2,500°F (3). (1,984°F for Copper) This means that electrical panels can withstand electrical arcs for only a few seconds and then the panel components will begin to disintegrate and the enclosure (usually made of sheet steel) will melt-open (a.k.a. "breaching" the panel) and the arc heat and the blast will be released into the surrounding area endangering anyone nearby. Additionally, the emission of super-heated 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 ½ second. The difference in magnitude of an arc lasting 1/3 second versus one lasting ½ second can be dramatic. Therefore, the reader must understand that even the slightest delay in extinguishing electrical arcs could result in catastrophic equipment damage and severe burns or death to humans exposed to those arcing events.

While this discussion has thus far focused only on the "arcing" component of an Electrical Fault there is another equally important hazard to consider, 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 >10,000°F in less than one 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 pressures can build to over 15,000 TIMES atmospheric pressure within the first 5 milliseconds of arc initiation (4). Pressures 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 (such as partially-melted metal parts, broken insulators, etc.) 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 humans in the vicinity. It is noteworthy that the IEEE 1584 methodology for calculating Incident Energy (IE) levels does NOT take the molten plasma or the pressure-waves into account in the calculated IE values. (5)

Table 130(C) (11) in the NFPA 70E-2004 lists Incident Energy in both calories/cm2 and joules/cm2. Incident Energy relates to the heat (calories) or force (Joules) 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 calories of heat per square centimeter of 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/cm2 can cause "third-degree" or "incurable" burns (6) 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 workers 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 (CB) in the circuit must operate and de-energize the circuit before heat and pressure values build excessively. But there are several situations commonly found in industrial settings that can cause excessively long-lasting arc-blasts. These causes include:

1. ***Poor Maintenance of Electrical Equipment:*** Many organizations do not properly maintain their OCPD. Many NEVER conduct any subsequent 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 merely open the breaker and close it again after first shutting-down large loads connected to the circuit breaker. The contacts in a circuit breaker can become corroded or even "seize" when not operated over a period of years. Should that CB be called upon to trip-open during an Electrical Fault after many years of inactivity, it is possible and very likely that the circuit breaker will not operate precisely as the manufacturer of the breaker predicted it would operate 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 IE values will be understated. This means that workers selecting FR clothing based upon the Arc Flash labels affixed to equipment would not be protected because actual IE values will exceed the calculated values that appear on the labels.

   This discussion should NOT be construed to suggest that we recommend that OCPD be subjected to fault-duty on a regular basis! The recommendation is merely to move the internal mechanisms of CB's to ensure they will operate properly. It is also critically important to know that Molded Case Circuit Breakers (MCCB) and Insulated Case Circuit Breakers (ICCB) are rated for as few as 3 operations under Short-Circuit duty (7). CB's are tested at 6 times their rated current for overloads but CB's can easily be subjected to Short-Circuit Current (SCC) values much greater than this level when electrical "faults" occur on high-capacity systems. This is of particular concern for organizations who routinely reset CB 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 requirements, it should not be tripping-out due to overloads or faults. Therefore, the wise Troubleshooter will endeavor to determine WHY the OCPD operated rather than merely attempting to reset the CB 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 at the first indication will often prevent catastrophic damage or injury at a later date.

2. ***Workers Changing Protective Device Setting***s: One of the most common missteps taken by Electrical Workers is 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 incredibly 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 and this amplifies the danger to the workers.

3. Improper Replacement of Protective Devices: Should an OCPD fail for any reason, it is important for workers to replace the device with PRECISELY the same make and model device. Each protective device manufacturer has many different models of CB or fuses, each with a specific application. It is possible, for example, to replace an 80 Ampere fuse with another 80 Ampere fuse from a different manufacturer and *significantly increase the IE levels* in so doing. In addition, fuses should not be "mixed and matched" in that fuses made by different manufacturers are inserted in multiple-phase equipment. Figure 1 below depicts an actual situation discovered during an Arc Flash Hazard Analysis study:

Figure 1: Two 80Amp BUSS Fusetron fuses were installed with an 80A Federal Pacific fuse

Electrical Arcs and Electrical Blasts are often grouped together because every arcing event does precipitate 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 where there is very limited space for the gases to expand, that same blast event could result in severe injury or even fatalities. Some arcing events are also limited in their intensity and the concomitant blast is also very 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. For the purposes of this paper we will refer to electrical arcs and electrical blasts with the term “arc-blast.”

Causes of Arc-Blasts

There are a variety of events that can precipitate an arc-blast. The most common causes are depicted in the Figure 2 below (8):

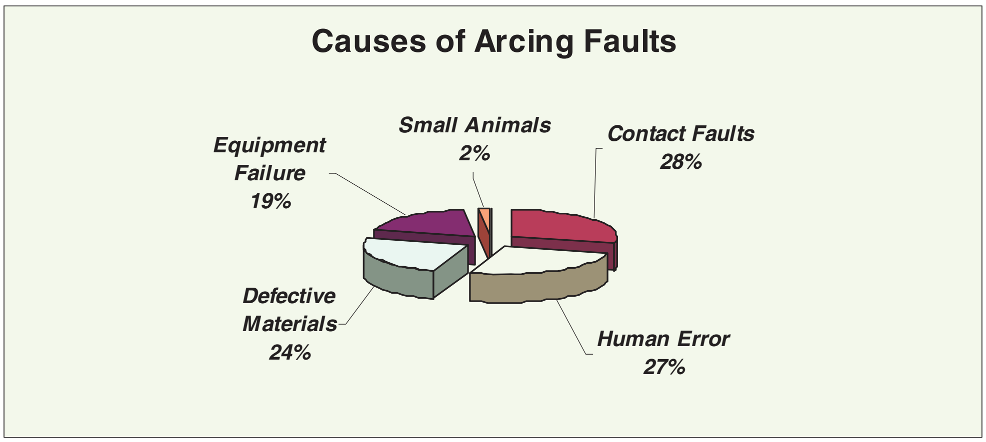

Figure 2: Graphical depiction of Arc-Flash causation

It is important to note that 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 humans continually resetting CB’s without first testing the circuits to determine the reason for the fault. Many organizations have a “one trial close” rule that means that anytime a circuit breaker “trips” or fuse “blows” the worker is to attempt to reenergize the circuit one-time to see if the protective device “holds” (doesn’t trip again). Unfortunately, the majority of the time 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 very 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 point in the future. While it may be tempting to think that “equipment failure” just “happens” as a result of aging equipment, it is nearly certain that a number 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-Circuit Current to which a device is subjected to the SCC Interrupting rating of the device itself. As the name suggests, the SC Interrupting Rating refers to the capability of the protective device to interrupt SCC and still be used again afterwards.

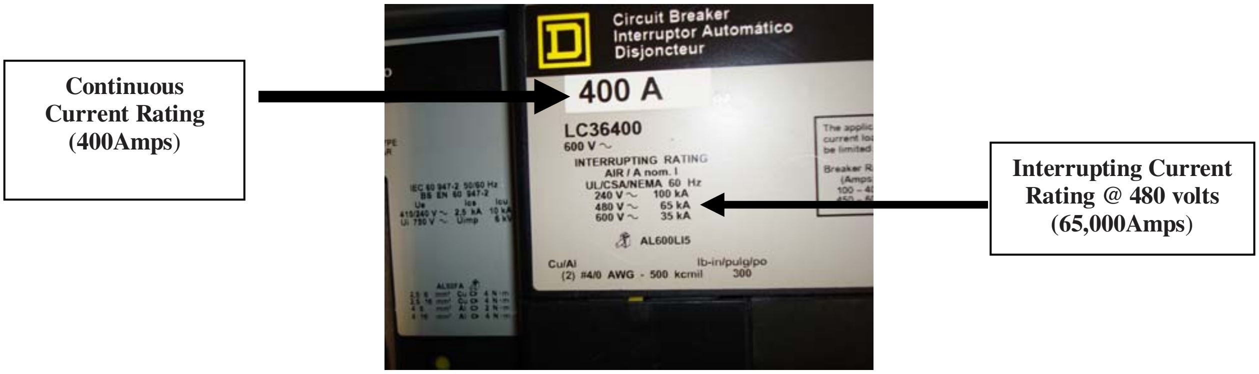

Figure 3: Continuous Current ratings versus Interrupting Duty ratings

Engineering Information on Equipment Enclosures

There is a surprising deficit of available information on the ability of equipment enclosures to withstand electrical arc-blasts. One of the guiding documents is the IEEE std. 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 does have a few noteworthy limitations within the context of this discussion. This standard:

- Does not require that over-current tests be conducted to determine the Fault Current and arc-duration that will breach metal-clad equipment.
- Does not stipulate that the doors of the enclosure must be able to withstand the same arc energies and blast potential as the walls of the enclosure.
- Limits arc duration to 2 seconds or less. Normally, this is very reasonable, as arcing faults lasting 2 seconds are quite rare in normal circumstances. However, any of the issues discussed in the “Dynamics of Arc-Blasts” section of the report could precipitate arcing faults lasting much longer than 2 seconds.

Other scientific studies have attempted to identify Energy levels that will damage electrical equipment but have achieved general acceptance within the engineering community. One study that does contain useful information, conducted by H.I. Stanback (9) is able to predict the amount of metal burned-away by various combinations of arcing faults. Although Stanback’s models included only single-phase, 277 volt arcs, (single phase to ground or neutral of a 480 volt WYE connected electrical system) it does provide at least a general idea of the capability of electrical arcs to damage electrical equipment. An example calculation using Stanback’s models will help illustrate the point:

> A single-phase (277 volt) fault occurs on a 1000 KVA transformer rated at 277/480 volts @ 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 (10). 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.)

Short-Circuit Current (in Amperes)	*Arc Duration (in seconds)*	*Steel (in^3)*	*Copper (in^3)*	*Aluminum (in^3)*
11,480	0.1	0.8	0.9	1.4
11,480	0.5	4.0	4.5	9.0
11,480	2.0	16.2	17.8	37.4

While this table does not precisely predict whether arcs of this magnitude would breach electrical panels it does clearly indicate the capacity of electrical arcs to burn-away metal. At a minimum, these arcs would damage equipment necessitating repair or replacement. It is also quite possible that arcs of this magnitude could breach panel enclosures and still injure personnel in the vicinity of the fault.

NFPA 70E-2004 Requirements

The 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 page 34 references a variable E_{BT} which stands for "Break-Through Energy." This relates the Force of the arc-blast that would "blow-open" ("break-through") clothing thereby exposing bare skin underneath the clothing to Incident Energy and injury from the blast components.

One significant deficit in the 70E relates to the Personal Protective Equipment (PPE) required when working on "exposed" versus "dead-front" equipment. The words "dead-front" refers to equipment with a solid Barrier (usually metal panel covers) such that it has no exposed parts energized to 50 volts or more on the operating side of the enclosure. The circuit breaker panel included in most newer homes is a good example of a dead-front installation. Opening the access door on the circuit breaker panel reveals only dielectric (non-conductive) 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 home owner from direct exposure to the energized elements inside the enclosure. There is considerable evidence in the forensic investigative world of arcing faults that burn through the enclosure cover or sides and causing fires. If a worker or home owner had been adjacent to the panel when the fault occurs, the person could possibly be harmed by residual arc-energy or the arc-blast.

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 pages 29-31 of the 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 >1,000 volts. 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” that are necessary 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. NOTE: it is important NEVER to seal cooling vents in enclosures, as they do 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 Electric Arcs” section of this paper could precipitate arcs of unacceptably-long duration. Videotapes of arcing events have documented that that arcing fault have lasted more than 20 minutes. 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 2 or 3 “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 the casual access to the interior but, often they are not able to contain the possible arc-blast. They are by far the most likely component of the enclosure to fail when subjected to an arc-blast.

The main point of this discussion is that there are many times when a worker would be wise to wear FR clothing even when the 70E Tabular method for selecting FR clothing 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 CB on any fault of unknown origin. Section 130.6(K) of the 70E prohibits resetting devices after a fault-trip unless testing has been performed by a Qualified Person to ascertain the cause of the trip. If, after all such troubleshooting efforts fail to identify the nature of the fault, the CB may be reset but this represents a very hazardous situation warranting additional protective measures.

2. Resetting or Racking a CB 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 of this 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 etc.

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 National Electrical Code (NFPA 70) and the National Electrical Safety Code (ANSI C2). Designs can include venting of arc blast to a safe area and there are some manufacturers that have incorporated this attribute in their designs. Some have made this option available for several years. However, there are many manufacturers who do not offer the option. Many enclosures rated for high available fault currents do not provide enclosures that will withstand the blasts that are possible with an arc-blast under the maximum conditions.

Additional 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 but the actual purpose of AFHA 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. The National Electrical Code 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 as discussed earlier. While the subject of this paper relates to the limitations of dead-front equipment to protect workers from arc-blasts, dead-front equipment remains an important element of protecting workers from arc-blast hazards.

The least effective means of protecting electrical workers would be to provide them with FR clothing and the use of Safe Work Practices (SWP). The reason the use of FR clothing and SWP is not considered equally effective is that 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, is it important for Electrical Workers and Engineers to understand the limitations of such enclosures to protect the workers on the job. There are a number of circumstances that can compromise the integrity of metal-clad enclosures, however, most are predictable and arc-blast hazards can be effectively controlled.

The most effective means to control the hazards posed by arc-blasts is to either eliminate or mitigate Incident Energy levels through engineering interventions such as Arc Flash Hazard Analysis plus proper equipment design, installation and proper periodic preventive maintenance. Personal Protective Equipment 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 at mitigating Incident Energy have been exhausted. National Electrical Safety Code 110.16 requires proper AFHA labeling at each facility. Further, worker must be trained to properly interpret AFHA labels and know appropriate safe work procedures.

There are several instances where effectively protecting workers will necessitate 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 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 are 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.

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Arcing Fault Current (I_{arc})

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

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 1000 KVA transformer = KVA × 1000/(Voltage × 1.732)

= 1000 × 1000 / (480 × 1.732)

= 1202 Amperes

$I_{bf} = 1202/Z = 1202/.05$

=24,040 Amperes (24.04 kA) = $I_{\text{bolted fault}}$

$\text{Log } I_{arc} = -0.153 + 0.662(\text{Log } 24.04) + 0.966(.48) + 0.000526(32) + 0.5588\ V(\text{Log } 24.04) - 0.00304\ (32)(\text{Log } 24.04)$

$\text{Log } I_{arc} = 1.06$

I_{arc} =11.48kA or 11,480 Amperes