



PROFESSIONAL POWER SYSTEMS, PLLC

Consulting Engineering



# UNDERSTANDING ARC FLASH REQUIREMENTS



**REVISION 3**

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## 1.0 Background

Arc flash is the ball of fire that explodes from an electrical short circuit. The unfortunate aspect of arc flash is that many times, there is a person standing in its path. This explosion includes a ball of fire and molten metal as well as a pressure force or blast. This overview discusses the ball of fire only. Although the pressure blast can be enormous, enough to knock a person across the room, it is another topic and is not discussed here. Arc flash temperatures can easily reach 14,000 to 16,000 degrees F. These temperatures can be reached by a fault in several seconds if not several cycles. The heat generated by the high current flow may melt or vaporize the material and create an arc. This arc-flash creates a brilliant flash, intense heat, and a fast moving pressure wave that propels the arcing products.

Some of the effects of an arcing fault include:

- Extreme Heat, Pressure Waves, and Sound Waves
- Molten Metal, Shrapnel and Vapor
- Intense Light

Arc flash is related to the available fault current and total clearing time of the overcurrent protective device during a fault. It is not necessarily linear, as lower fault currents can sometimes result in a breaker or fuse taking longer to clear, thus extending the arc duration and thereby raising the arc flash energy. To perform an accurate arc-flash hazard analysis a realistic value for the three-phase bolted fault and the total clearing time for the affected overcurrent protective device must be known.

Arc flash is measured in thermal energy units of calories per centimeter squared ( $\text{cal}/\text{cm}^2$ ) and for arc flash analysis is referred to as the *INCIDENT ENERGY* of the circuit.  $1.2 \text{ cal}/\text{cm}^2$  of thermal energy on a person's skin for a short period of time generally produces a second degree burn. A second degree burn, although painful, is considered curable. This amount of energy can be compared to holding your hand several inches above a disposable lighter. The intent of an arc flash hazard analysis is first to determine the amount of personal protective equipment (PPE) required by the worker to limit any burn to a second degree burn and second, to determine the safe distance away from energized equipment for unprotected persons.

Second degree burns occur if the temperature of human skin is raised to 175 degrees F for 0.1 seconds. Even if the fault is cleared in a shorter period of time, if a workers clothing catches fire or melts to his skin, the time limit of the exposure could be several minutes if not longer. Depending on the material, clothing may ignite when temperatures reach between 700 and 1400 degrees F. If clothing and equipment are worn to limit the exposure of the worker to limits below those identified above, the worker should walk away from an accident, with minimal injury.

## 2.0 Types of Faults

In order to understand the hazards associated with an arc flash incident, it's important to understand the difference between an "arcing" short circuit and a "bolted" short circuit.

A bolted short circuit occurs when the normal circuit current by-passes the load through a very low impedance path resulting in current flow that can be hundreds or thousands of times the normal load current. In this case, assuming all equipment remains intact, the fault energy is contained within the conductors and equipment and the power of the fault is dissipated throughout the circuit from the source to the short. All equipment needs to have adequate interrupting ratings to safely contain and clear the high fault currents associated with bolted faults.

In contrast, an arcing fault is the flow of current through a higher impedance medium, typically the air, between phase conductors or between phase conductors and neutral or ground. Arcing fault currents can be extremely high in current magnitude approaching the bolted short-circuit current but are typically between 38% and 89% of the bolted fault. The inverse characteristics of typical overcurrent protective devices generally results in substantially longer clearing times for an arcing fault due to the lower fault values.

The amount of energy released during an arcing fault depends upon the voltage, the current, and the duration of the arc. The arc duration is dependent on the arcing fault current magnitude and the protective device settings. Due to its nature, the magnitude of an arcing fault is subject to many variables and therefore is difficult to perfectly predict. Using sound judgments and assumptions, it is reasonable to think of the arcing fault as a range of possible currents that result in a minimum and maximum arcing fault current.

### **3.0 Benefits of Performing an Arc-Flash Hazard Analysis**

In addition to reducing or preventing injury to workers, the additional benefits associated with performing an arc flash hazard analysis can include most of the following:

- Provides workers with the best possible PPE.
- Insurance premiums can be reduced.
- Brings electrical system documentation up to date by providing current and accurate one-line diagrams.
- System reliability can be enhanced with a proper protective device coordination study to insure device closest to the fault opens in the least amount of time.
- Overduty equipment can be identified from an accurate system wide short circuit analysis.
- Since the system is typically modeled on software, it will be easy to make future changes or upgrades with minimal expense or effort.
- Most importantly, there will be fewer injured worker when an analysis is performed and recommended procedures are followed.

### **4.0 Costs of Not Performing an Arc-Flash Hazard Analysis**

Costs due to not performing an arc flash hazard analysis can range from minor costs associated with fines, to millions of dollars for lifelong medical cost and can include any of the following:

- Cost of non-compliance fines
- Cost associated with lost productivity
- Increased equipment repair costs
- Medical expenses for injured workers

- Legal costs
- Most importantly, loss of life, there is no price for this.

## **5.0 Prior To Beginning an Arc-Flash Hazard Analysis**

Prior to beginning an arc flash hazard analysis, the following questions should be answered to help in the assessment:

- Are the overcurrent protective devices set to trip in the fastest possible time?
- Is the facility having unexplained outages?
- Has the facility been expanded and/or added new electrical equipment?
- Is the equipment rated to safely clear available fault current?
- What can be done to mitigate excessively high fault currents or long tripping times?
- Has equipment been properly tested and maintained to insure proper operation?

### **NOTE:**

Proper maintenance and coordination of protective devices is vital when doing an arc-flash hazard analysis. All the studies in the world are useless if the equipment does not function as expected or designed.

## **6.0 Steps Required To Accurately Calculate Incident Energy**

The general procedure required to perform an arc flash evaluation include:

- 1) Determine the system modes of operation and confidence tolerance of system model.
- 2) Calculate a minimum and maximum bolted fault current at each equipment bus. The bolted fault current should be as accurate as possible. While assuming an infinite source is conservative for sizing equipment, it is generally not conservative for arc flash calculations. When accurate data is not available, it is prudent to apply a minimum and maximum tolerance for the utility contribution, and component impedance values when calculating the bolted fault current.
- 3) Estimate the minimum and maximum arcing fault current at each equipment bus.
- 4) Determine the arcing fault current seen by each protective device.
- 5) Determine the trip time of each protective device based on the minimum and maximum arcing fault current it sees.
- 6) Calculate the largest incident energy at the specified working distance, including appropriate arcing fault tolerance.
- 7) Calculate the Arc Flash Boundary
- 8) Determine the required PPE level
- 9) Document the results and generate labels to be placed on the equipment.

After an arc-flash hazard analysis has been completed, additional engineering may be required to lower high levels of incident energy to manageable levels. Only a complete electrical system analysis can identify the level of personal protective equipment required at each location in the system.

## **7.0 Industry Requirements**

It is important to cover some important regulations in OSHA and requirements in NFPA 70E related to working on “live” equipment.

OSHA regulations state in 1910.333 (a) that workers should not work on live equipment (greater than 50 volts) except for one of two reasons:

**1. De-energizing introduces additional or increased hazards (such as cutting ventilation to a hazardous location)**

OR

**2. Infeasible due to equipment design or operational limitations (such as when voltage testing is required for diagnostics).**

**Note:** NFPA 70E Standard for Electrical Safety in the Workplace – 2004 in Article 130 states essentially the same requirement.

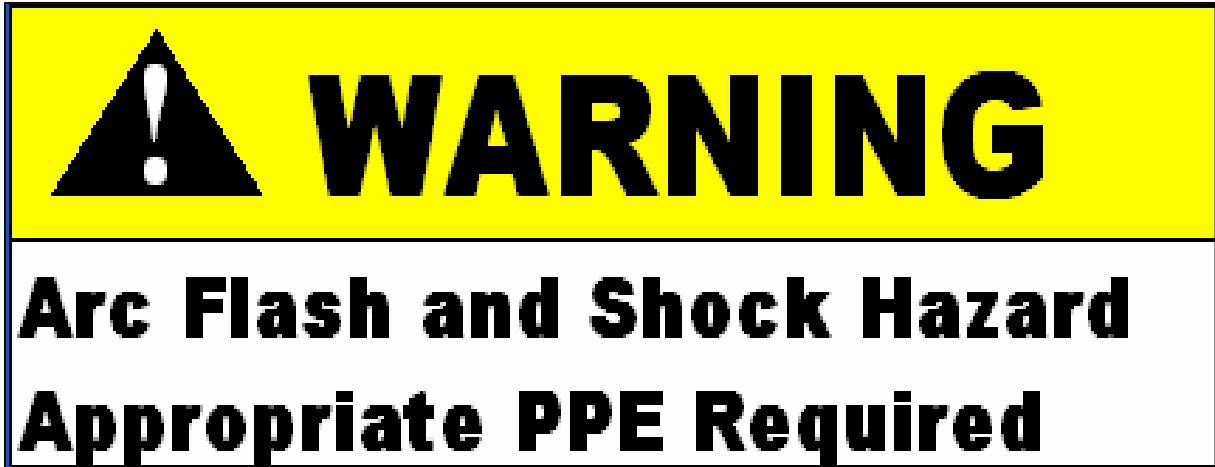
However, when it is necessary to work on equipment “live”, it is necessary to follow safe work practices, which include assessing the risks, wearing adequate personal protection equipment and using the proper tools. The warning label of NEC 110.16 (see below) helps facilitate this practice. It must also be noted that even when de-energizing the system, performing a voltage test requires proper PPE.

It must be understood that financial considerations are not an adequate reason to work on or near energized circuits. Management indicating that it is cheaper to work it hot is not acceptable.

## **8.0 Labeling Requirements**

The only labeling specifically required is identified in NFPA70. NEC-2005 Article 110.16 identifies the minimum arc flash warning label requirements that must be field installed at time of installation. The article states:

**110.16 Flash Protection.** *Switchboards, panelboards, industrial control panels, meter socket enclosures, and motor control centers in other than dwelling occupancies, which are likely to require examination, adjustment, servicing, or maintenance while energized, shall be field marked to warn qualified persons of potential electric arc flash hazards. The marking shall be located so as to be clearly visible to qualified persons before examination, adjustment, servicing, or maintenance of the equipment.*



**Figure 1: Label with Minimum Requirements (NFPA 70)**

To improve safety and worker compliance, additional information can be included on the label including the flash hazard boundary, working distance and required PPE. When additional labeling is included, it must be assured that the information is understood by everyone required to work on the equipment. Too much information that is unclear to the workers will be ignored and can be as bad, if not worse, than no information at all. It is extremely important the labeling is as clear and accurate as possible. While it is obvious that insufficient PPE is dangerous, over-clothing workers can also increase the risk of an arcing fault due to limited mobility and visibility.

Large equipment such as switchgear can often have different levels of incident energy due to feeder and protective device configuration. Multiple labels can also be placed on a single piece of equipment depending on the access point and proximity to the arc source for a given activity. However, it is good practice to provide a single label for the largest incident energy available.

Workers should not enter the flash protection boundary to work on live parts unless they are wearing the proper PPE for the level of hazard that could occur. The specific flash-protection boundary, working distance, and incident energy values should be readily accessible to all workers, either identified by an equipment mounted label, or otherwise documented and available for reference or review.

## **9.0 NFPA 70E**

NFPA 70E is the standard for electrical safety requirements for employee workplaces. Originally requested by OSHA, the National Fire Protection Association developed 70E as a standard for electrical safety. Whereas NFPA 70 (NEC) covers the installation of electrical equipment that is assumed de-energized, 70E was developed to cover the maintenance of the equipment where it has traditionally been energized.

This document provides procedures and requirements for:

- Electrical safe work practices
- Electrical shock and arc flash boundaries
- Proper personal protective equipment

NFPA 70E stipulates three shock boundaries and a flash protection boundary that must be known and observed. The shock boundaries are dependent on the system voltage and can be found in Table 130.2(C). The standard provides the formulas for this critical information as well as other important information on safe work practices, personal protection equipment and tools to use.

The NFPA 70E – 2004 revision includes several new requirements related to arc flash and energized work.

- Appropriate safety-related work practices shall be determined before any person approaches exposed live parts within the Limited Approach Boundary by using both shock hazard analysis and flash hazard analysis.
- A flash hazard analysis shall be done in order to protect personnel from the possibility of being injured by an arc flash. The analysis shall determine the Flash Protection Boundary and the personal protective equipment that people within the Flash Protection Boundary shall use.
- If live parts are not placed in an electrically safe work conditions (i.e., for the reasons of increased or additional hazards or infeasibility per 130.1) work to be performed shall be considered energized electrical work and shall be performed by written permit only.
- The incident energy exposure level shall be based on the working distance of the employee's face and chest areas from a prospective arc source for the specific task to be performed.

While the body of the NFPA 70E standard does not include arcing fault, incident energy and flash boundary equations, Annex D outlines two calculation methods. One method follows equations originally published in the NFPA 70E and calculates values using 100% of the bolted fault current and 38% of the bolted fault current. The other method uses the IEEE 1584 empirical equations. It must be understood that this Annex is not part of the standard and is included as reference only.

NFPA 70E also provides an optional table method to determine PPE when specific data and information is not available. The table method assumes several criteria and specifies PPE based on the task involved. Limits and assumptions are identified throughout the tables. Due to assumptions and limitations, the table method may produce conservative results. When actual circuit conditions do not fall within the prescribed boundaries, a full computational analysis is required.

Note:

The NFPA issued a Technical Interim Amendment (TIA) effective May 5, 2004 that changed and modified many of the values used in the tables.

## 10.0 IEEE 1584

IEEE Standard 1584 is a standard released in 2002 and revised in 2004. It provides empirical equations to estimate arcing fault current, incident energy and flash boundary distances for work on electrical systems rated from 208 Volt to 15 kV 3-phase. The standard uses a theoretical equation published by Ralph Lee for application voltage or currents outside of the test range.

Many engineers follow the IEEE 1584 method because the empirical equations provide a more accurate estimate of the arcing fault current, more test data and variables were used to develop the IEEE 1584 incident energy equations, and the IEEE 1584 equations are valid over a wider range of voltages and fault currents. The calculated arcing fault current varies with voltage, bolted fault current, gap between the conductors and whether the arc occurs in open air or in a box.

The trip time is determined based on the arcing fault current that flows through the protective device when the arcing fault occurs. Note that due to parallel contributions and voltage transformations, the fault current through the protective device may not equal the total arcing fault current at the equipment bus. When tolerances are used, the trip time must be determined for the minimum arcing fault and the maximum arcing fault.

Additional environmental variables are needed to calculate the incident energy, including working distance, whether the equipment is grounded or ungrounded, and the equipment type with related bus gap.

**Note:**

**The equations below are included as a reference only. Please refer to the actual documents when performing any arc flash study.**

The incident energy is calculated in two steps, including a calculation normalized to a 0.2 second arc at a working distance of 610mm followed by an adjustment to the actual trip time and working distance.

$$\log (En) = K1 + K2 + 1.081 \log (Ia) + 0.0011 G$$

En Incident energy (J/cm<sup>2</sup>) normalized for 0.2s arcing duration and 610mm working distance

- K1 -0.792 for open configuration  
-0.555 for box configuration (switchgear, panel)
- K2 0 for ungrounded and high resistance grounded systems  
-0.113 for grounded systems
- Ia Arcing fault current
- G gap between bus bar conductors in mm

solve  $En = 10 \log(En)$

The first calculation includes variables for open air versus in a box, grounded versus ungrounded equipment, the arcing fault current, and the gap between the bus bar conductors.

The second equation includes variables for voltage, the normalized incident energy, arc duration, working distance, and the type of equipment.

**Incident Energy converted from normalized:**

$$E = 4.184 C_f E_n (t/0.2) (610X / DX)$$

- E incident energy (J/cm<sup>2</sup>)
- C<sub>f</sub> 1.0 for voltage above 1 kV and  
1.5 for voltage at or below 1 kV
- t arcing duration in seconds
- D working distance
- x distance exponent

x	Equipment Type	kV
1.473	Switchgear	<= 1
1.641	Panel	<= 1
0.973	Switchgear	> 1
2	Cable, Open Air	

**Arc flash boundary (mm) at incident energy of 5.0 (J/cm<sup>2</sup>)**

$$DB = [ 4.184 C_f E_n (t/0.2) (610X / EB) ]^{1/X}$$

where

- EB incident energy set 5.0 (J/cm<sup>2</sup>)
- C<sub>f</sub> 1.0 for voltage above 1 kV and  
1.5 for voltage at or below 1 kV
- t arcing duration in seconds
- x distance exponent

x	Equipment Type	kV
1.473	Switchgear	<= 1
1.641	Panel	<= 1
0.973	Switchgear	> 1
2	all others	

The flash boundary is essentially a reverse calculation to determine the distance where the incident energy is equal to 1.2 cal/cm<sup>2</sup>.

Due to the inverse characteristics of typical overcurrent devices, a small reduction in available fault current can sometimes result in a large increase in incident energy due to a longer trip time, therefore the IEEE 1584 standard requires calculation of trip time and incident energy for 85% and 100% of the calculated arcing fault current, to account for variations in test data. The larger of the results should be used.

Traditionally, fault calculations have been performed to provide a basis for conservative equipment ratings and selection. Utility contributions were often represented as an infinite source. For arc flash hazard analysis, it is important to estimate the available fault current as accurately as possible. A conservatively high value may result in lower calculated incident energy than may actually be possible depending on the protective device's time-current response. The lower results would be caused by using a faster time-current response value from the protective device's time-current curve. To account for inaccuracies in the system model, tolerances should be used to estimate both minimum and maximum short circuit currents for use in the arc flash calculations.

## **11.0 Personal Protection Equipment**

Personal protective equipment (PPE) is required to limit workers exposure to incident energy should an incident occur. Incident energy causes burns, which are the major hazard to individuals from an arc flash. As a benchmark,  $1.2 \text{ cal/cm}^2$  is the energy at which a 2nd degree burn will occur. At  $3 \text{ cal/cm}^2$  a light weight cotton shirt may ignite. One layer of flame-retardant material typically provides protection up to  $4 \text{ cal/cm}^2$ . Three layers of flame-retardant material typically provide protection up to  $25 \text{ cal/cm}^2$ . The PPE should be based on the highest expected incident energy from the calculations.

The NFPA 70E 2004 standard provides 5 Arc Rating levels of PPE

- Class 0 for incident energy up to  $1.2 \text{ cal/cm}^2$
- Class 1 for incident energy up to  $4 \text{ cal/cm}^2$
- Class 2 for incident energy up to  $8 \text{ cal/cm}^2$
- Class 3 for incident energy up to  $25 \text{ cal/cm}^2$
- Class 4 for incident energy up to  $40 \text{ cal/cm}^2$

Once the incident energy, flash boundary and required PPE are determined, labels can be generated and displayed on each piece of equipment or results can be documented for reference.

Some examples of where PPE may be required are: during load interruption, during the visual inspection that verifies that all disconnecting devices are open, and during the lockout/tagout. Adequate PPE is also required during the tests to verify the absence of voltage after the circuits are de-energized and properly locked out/tagged out.

When used, PPE represents the last line of defense against injury. The protection is not intended to prevent all injuries but to mitigate the impact of an arc flash upon the individual, should an incident occur. In many cases, the use of PPE has saved lives or prevented injury. The calculations represented herein will provide a level of protection that is balanced between the calculated estimated incident energy exposure and the work activity being performed. It is important to realize that too much PPE can also be a hazard. Workers can be protected for more incident energy that is available but may not be able to perform their intended duties due to heat stress, poor visibility, and limited body movement. At all times, professional judgment must always be used in the selection of adequate PPE.

## **12.0 Current Limiting Devices**

Current limiting protective devices can reduce incident energy by clearing the fault faster and by reducing the current seen at the arc source. These current limiting effects are typically only applicable at high fault currents. It is important to understand that if the available fault is not within the current limiting range of the fuse, the faster clearing time may not be achieved, and a false sense of security may exist. Since the arcing fault current is often substantially less than the bolted fault, the current-limiting effects must be evaluated carefully. It is typical practice to use the faster trip times associated with current-limiting devices without making adjustments for any reduced let through current. Arcing faults that clear in  $\frac{1}{2}$  cycle or less, as required in current-limiting devices, will typically, but not necessarily, result in lower incident energy.

## **13.0 Parallel Sources**

Arcing faults can also be fed from parallel sources as is typical in a Main-Tie-Main configuration or with on site generation capabilities to name a few. It is important to understand that the energy at the fault location will be based on the total fault current from all of the sources, while the time required to clear the fault will be based on the portion of the fault current that flows through each protective device. It is also important to understand that some fault sources, such as utility feeds, are constant, whereas other fault sources, such as induction motors, are transient and only contribute current for a few cycles. The total clearing time of the overcurrent protective device depends on all these variables.

## **14.0 System Reliability**

Traditionally, protective device coordination was used to protect equipment and provide reliable system operation by incorporating time delay trips for upstream breakers. Arc flash protection now adds worker safety into the equation, resulting in the possibility of giving up some coordination for safety by requiring faster trip times, resulting in lower arcing fault currents. Since less energy is released the faster you can clear the arcing fault, alternative protection schemes such as differential, zone-interlocking, and arc-sensing trip units are finding their way into protection schemes. The downside is that faster trip times can cause less power system reliability through reduced selectivity and an increased chance of nuisance tripping. No matter what, life safety concerns shall always take precedence.

## **15.0 Implementation**

Long hand calculations can be performed to calculate incident energy and flash boundary values. But even for small systems, the process is somewhat involved. Spreadsheets can be used to automate the process and complete the arc flash calculations, yet you still need to manually determine a minimum and maximum fault current at the bus, determine the total arcing fault current flow through the primary protective device, determine the trip time from manufacturer's trip curves, and manually document the results in report and label formats. Determining the trip time is probably the most time consuming process. Time current curves are sometimes hard to obtain and is typically prone to error when processed manually. Making changes is also a tedious process by hand.

Off the shelf software products have been developed for this purpose and greatly simplify the process by performing all the calculations and generating labels and work permits. The main advantage of a full software solution is that the calculations are performed for the entire power system model simultaneously and changes to any part of the system(s) are automatically calculated throughout the entire model. The software solution also has the advantage of integrated protective coordination drawings and the capability of analyzing several scenarios at once to easily evaluate alternative designs and configurations.

## **16.0 Summary**

This overview of arc flash requirements suggests several approaches for conducting an arc-flash hazard analysis for typical electrical systems. Following the suggestions contained herein does not guarantee complete safety, and users should take all reasonable, independent steps necessary to minimize risks from arc flashes.

Users should be aware that the models described herein are based upon measured arc current incident energy under a specific set of test conditions and on theoretical work on the subject. Distances, which are the basis for equations, are based on the measured distance of the test instrument from the arc-flash point source. These models will enable users to calculate the estimated maximum incident energy and the estimated arc-flash boundary distance. Real arc exposures may be more or less severe than indicated by these models. The equations included herein are intended for explanation only and any actual work or study should be completed with the actual codes and standards referenced.

This information included in this report is intended to provide guidance only for the calculation of incident energy and arc-flash protection boundaries. Once calculated, this information needs to be used as a basis to develop strategies that have the goal of minimizing burn injuries. Strategies include specifying the rating of personal protective equipment (PPE), working de-energized, applying arc-resistant switchgear, and following other engineering techniques and work practices. The information included addresses the hazard presented by incident energy only. Other potentially hazardous effects of molten metal splatter, projectiles, pressure impulses, and toxic arc by-products have not been considered in these methods. It is expected that future work will provide guidance for these other electrical hazards.

The information presented is not intended to imply that workers be allowed to perform work on exposed energized equipment or circuit parts. It must be emphasized that the industry-recommended way to minimize electrical injuries and fatalities is to ensure that equipment is de-energized and in an electrically safe work condition. But even the act of creating an electrically safe work condition, subjects the worker to potential hazards, which if they occur, require PPE for protection against arc-flash burns.

Obviously, the best way to prevent an arc-flash hazard is to totally de-energize the equipment. It would be great if we could turn off the country everyday so electrical workers could go to work. However, even if you can totally de-energize the equipment you need to open devices upstream somewhere. It is best if this can be done remotely,

but if it cannot be, workers must be trained and know the proper arc flash protection required for the given task.

## ***Definitions***

- **Limited Approach Boundary** - A shock protection boundary not to be crossed by unqualified persons unless escorted by a qualified person.
- **Restricted Approach Boundary** - A shock protection boundary to be crossed by only qualified persons. When crossed the use of shock protection techniques and equipment is required.
- **Prohibited Approach Boundary** - A shock protection boundary only to be crossed by qualified persons. When crossed the same protection is required as if direct contact is made with the live part.
- **Flash Protection Boundary** - Distance at which the incident energy level equals  $1.2 \text{ cal/cm}^2$  for fault clearing time greater than 0.1 seconds. For voltages greater than 1000V, use  $1.5 \text{ cal/cm}^2$  for clearing times that are 0.1 seconds or faster.

## ***About the Author***

The author of this article is a Licensed Master Electrician in the State of Virginia and a Registered Electrical Engineer in the State of Virginia, Texas, and North Carolina. He is presently the sole owner and manager of Professional Power Systems, PLLC, a consulting engineering firm. Prior to earning a BS in Electrical Engineering from Old Dominion University in 1997, he worked as an electrician from 1975 until returning to school full time in 1992. He has been doing arc flash studies since some time around 2004. He has worked and designed both low voltage and medium voltage industrial and utility systems. He has hands on experience with everything from installing telephone booths to medium voltage power distribution circuits and freely admits to being in extremely hazardous situations more than once back in the days when it was “macho” to work all circuits hot. As a testimony, he worked a storm one day where he was in a bucket truck, in the pouring down rain, literally standing in 3 inches of water, trying to open a 34.5 kV cutout with a hot stick and old, untested rubber gloves because his boss told him to go out and fix some downed wires. Real gung ho, but not real smart at the time. His goal is to prevent the next electrician from being forced into the same or similar circumstances he encountered. The next may not be so lucky. Any feedback is strongly encouraged. You can reach him at:

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## DISCLAIMER

This information presented is based on current and industry accepted technical data and studies believed by Professional Power Systems to be compiled of reliable and sound data. It is offered as an explanation and tool for understanding and conducting an arc-flash hazard analysis only. It is intended for use only by those experienced in power system studies and is not intended to substitute for the users' judgment or review in such studies. It is subject to revision as additional knowledge and experience is gained. PPS makes no guarantee of information included herein or results and assumes no obligation or liability whatsoever in connection with this information.

## **APPENDIX A – BIBLIOGRAPHY**

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