COMPARATIVE STUDY OF ARC MODELING AND ARC FLASH INCIDENT ENERGY EXPOSURES

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Abstract – Despite the growing awareness and increased understanding of the hazards associated with arcing faults, incidents of this type continue to occur and individuals exposed to the hazards may be severely injured or killed as a result. Accurately estimating the available thermal energy is a critical aspect of assessing the severity of the arc flash. Over the past few years, a number of researchers have worked to quantify the thermal energy present during an arc flash exposure. This paper will address the three categories of incident energy models that have been developed: *theory based*, *statistically developed,* and *semi-empirically derived*. Because of the limitations and discrepancies observed using the different techniques, no standard approach has been agreed upon by the engineering community. This work includes an analysis of published arc energy and incident energy data from the past to the present and serves as a critique of available incident energy equations. The insight gained from this evaluation may shape the direction of future arc testing and model development. The authors hope that this paper will help to close the gap between the experimental results, scientific based theory and industrial applications.

Index Terms — Arc flash hazard assessment, Arc modeling, Incident energy calculations, Semi-empirical models, Statistically-based models, Theory-based models, and Comparative study.

I. INTRODUCTION

Although there are many types of electrical injuries, "A ten-year study involving over 120,000 employees performed by Electricite de France found that electrical arc injuries accounted for 77% of all recorded electrical injuries" [1]. This alarming statistic has helped drive the relatively recent emphasis on arc flash hazard research. The arcing phenomenon constitutes a unique hazard, because, unlike electric shock, serious injury and death can occur at some distance from the actual current path. The most frequently identified consequences of arc flash incidents are:

1) *Thermal burn injury*
2) *Blast pressure wave injury*
3) *Hearing loss injury*
4) *Harmful electromagnetic emissions*
5) *Release of highly toxic gases*
6) *Shrapnel injury*

Thermal burn injuries are caused by direct heat exposure and the ignition of clothing. Strong pressure waves from an arc blast can throw workers across the room or knock them off a ladder or scaffolding. The sound blast emanating from an arcing fault can cause hearing loss. Intense light generated by an arc can impair vision and cause blindness. The temperatures generated by electrical arcs vaporize all known materials, producing some highly toxic byproducts as a result. The plasma cloud may contain molten electrode material and the byproducts of burned insulation. Copper oxides, particularly deadly compounds, are formed when cooling copper vapor combines with oxygen. The toxins may cause damage to the lungs, skin, and eyes. Rapidly expanding gases cause shrapnel to be propelled from an arc blast resulting in wounds similar to those caused by weapons designed for warfare.

The potentially detrimental effects of an arc flash incident all depend on the energy conversion that takes place during an arcing fault. As described in the IEEE Buff Book [2], "The arcing fault causes a large amount of energy to be released in the arcing area." While substantial work has been done to assess equipment damage [3], [4], this paper focuses on the hazard that electrical arcs pose to humans. Quantifying incident energy is essential to assessing the potential burn hazard. NFPA 70E defines incident energy as "The amount of energy impressed on a surface, a certain distance from the source, generated during an electrical arc event" [5].

This paper is a continuation of work detailing the evolution of the arc flash standards in the United States. As discussed extensively in reference [6], some members of the engineering community were skeptical of the approach taken to develop IEEE 1584-2002: *IEEE Guide for Performing Arc-Flash Hazard Calculations* [7], [8]. Some critics contended that a wealth of information on the topic of electric arcs was overlooked in the development of the standards. This companion paper specifically addresses some of the other relevant research on electrical arcs.

Many researchers have contributed to the body of knowledge, striving to quantify the possible damage associated with arcing faults. This paper provides a thorough review of the literature pertaining to arc incident energy calculations. Because of the extensive amount of literature published on this topic, the study provided herein does not represent an exhaustive review of all the material available, but rather strives to focus on key incident energy equations. A number of theories have been published and have led to the development of a variety of calculation methods. An on-going debate continues about the proper application and accuracy of the published techniques. The methods are partially successful, but no standard approach has been agreed upon by the engineering and scientific community. Arc energy calculations currently fall into three general categories: 1) theoretical models developed from arc physics, 2) statistical models developed from statistical analysis, and 3) semi-empirical models developed from known observations and numerical analysis. This article provides an overview of the techniques and a comparative study of methods used to estimate the incident energy associated with an arc flash hazard. The discussion begins with a brief summary of the electrical properties of an arc.

II. ELECTRICAL PROPERTIES OF AN ARC

A. Classification of Electrical Arcs and Typical Electrode Configurations

Arcs may be established in three ways: 1) transition from a low current stable discharge such as a glow, 2) transient non-steady spark discharge, and 3) physical initiation. The subject of this paper is arcing faults, in other words, unwanted arcs occurring in power systems. Arc flash incidents occur in the workplace when people drop tools, make wiring errors, or make a physical connection between two energized conductors. Arcs may also be initiated without human intervention by mechanisms such as insulation breakdown and the buildup of conductive dusts.

Sweeting and Stokes observed that “The vast majority of the literature deals with arcs that have been constrained or stabilised” [9]. Furthermore, they noted that “The bulk of the arc literature is based on single-phase opposing electrodes, where the current comes from one side and flows across to the other side” [9]. Single-phase series electrodes have historically received so much attention because this is the configuration utilized to design power system protective devices like circuit breakers and fuses. In this context, arcs are often divided into two main categories: axisymmetric and non-axisymmetric. An *axisymmetric arc* burns uniformly while *non-axisymmetric arcs* are either in a “state of dynamic equilibrium or continuous motion” [10]. Fig. 1 illustrates some of the commonly used arc classifications.

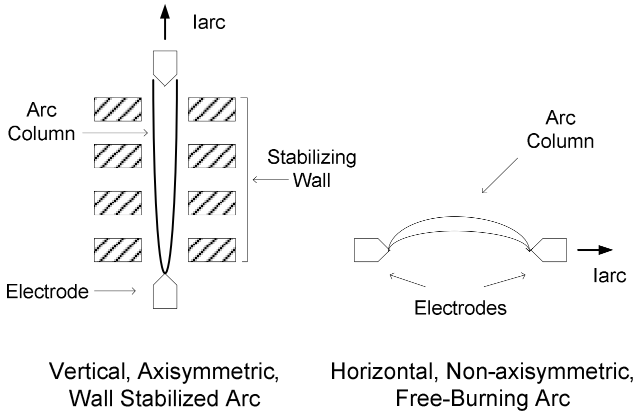

Fig. 1 Series Electrode (Single-Phase) Arc Classification

Hazardous arcing faults occurring in electrical equipment are categorized as free-burning arcs. In industrial applications, arcing faults occur almost exclusively on parallel electrodes and are extremely chaotic in nature. As is well documented in recent arc tests, the orientation of the electrodes plays a major role in the manner of energy transfer to the surroundings [11], [12]. Fig. 2 shows the three-phase parallel electrode configurations typically encountered in industrial applications.

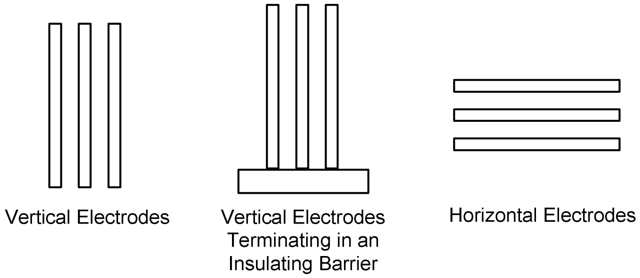

Fig. 2 Parallel Electrode (Three-Phase) Configurations

B. Regions of an Arc

As depicted in Fig. 3, an arc consists of three regions, the anode region, the arc column, and the cathode region. The anode and cathode regions form the transition regions between the gaseous plasma (positive column) and the solid conductors (electrodes). The cathode region is an area of positive ion space charge on the order of a micrometer [9]. The thickness of the anode region is also very small. Electric arc physics is well documented in a book written by Somerville [13].

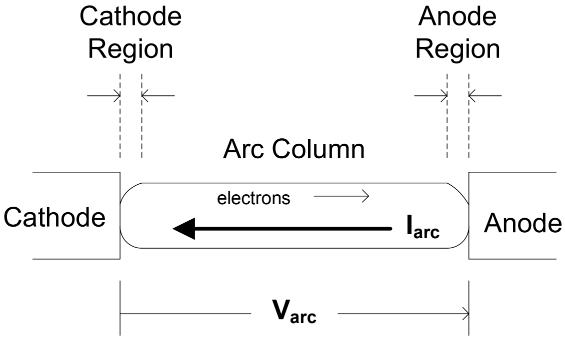

Fig. 3 Electric Arc Characterization

C. Arc Energy

Electric arcs are frequently described in terms of current and voltage characteristics. As shown in Fig. 3 above, the RMS arc voltage, V_{arc}, is the potential difference measured between the electrodes and the RMS arc current, I_{arc}, is the current flowing through the arc column. Typical arc current and voltage waveforms recorded during a 480-V, three-phase arc test are shown in Fig. 4.

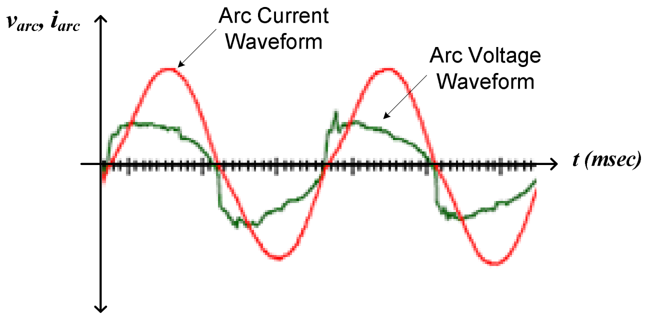

Fig. 4 AC Arc Voltage and Arc Current Waveforms

For general time-varying waveforms, time-average power is determined as follows:

$$P_{ave} = \frac{1}{T}\int_0^T v(t)\, i(t)\, dt \tag{1}$$

With sinusoidal waveforms and a unity power factor, the power may be computed as follows:

$$P_{ave} = VI \tag{2}$$

Because arcing is a non-linear process and the arcing voltage and current contain harmonics (evident in Fig. 4), the time-average power and energy associated with an arc, are approximated as:

$$P_{arc} \approx V_{arc} I_{arc}$$

$$E_{arc} \approx P_{arc}\, t \tag{3}$$

III. DEMYSTIFYING INCIDENT ENERGY

One of the essential elements of an arc flash hazard analysis is the estimation of the incident energy. These calculations help predict the amount of energy available during an arc flash event. Incident energy is typically expressed in (Joules) J/cm^2 or (calories) cal/cm^2. Incident energy calculations are used to establish the flash protection boundary, i.e., the distance from an arc source that would cause the onset of a second degree burn. The energy required to produce a curable, second degree burn on unprotected skin has been established as 5.0 J/cm^2 (or 1.2 cal/cm^2).

Incident energy is the heat transferred to the unfortunate individual(s) and everything else in the vicinity of the arc. Arcing faults cause tragic burn injuries through several modes of heat transfer. Heat can be transferred by conduction, convection, and radiation [14], [15], [16]. Heat conduction occurs between two bodies which are in direct contact. The heat conducted to the anode and cathode where the arc current exits and enters is responsible for the vaporization and melting of the electrodes. Heat conduction causes burn injuries when people are sprayed with molten material during an arc blast or burned from the ignition of clothing. However, heat conduction is not the means of heat transfer used to assess the thermal burn hazard of a potential arcing fault.

The “heat danger” of an arcing fault is determined by the temperature rise in a copper calorimeter(s) at a given distance from an experimental arc test. The energy absorbed by the calorimeter is the heat transferred from the arc by radiation and convection. Each degree rise in calorimeter temperature (Celsius) is converted to incident energy (cal/cm^2) by a multiplier equal to 0.135 cal/cm^2-C. Since copper calorimeters absorb at least 90% of the incident energy, the absorbed energy is assumed to equal the incident energy [17]. An incident energy level of 1.2 cal/cm^2 (5.0 J/cm^2) has been established as the level capable of causing a second degree burn in human tissue. To adequately protect a worker from thermal injury during an arcing fault, the ATPV (Arc Thermal Performance Value) of flame resistant clothing must exceed the potential incident energy to which a worker might be exposed. Incident energy calculations are also used to determine the flash protection boundary distance where the available incident energy is 1.2 cal/cm^2; outside this boundary, PPE is not required.

Arcing faults have been modeled as blackbody radiators [18], [19]. An ideal blackbody at thermal equilibrium is characterized by a distribution of wavelengths, determined by its temperature. Thermal radiation is the emission of electromagnetic waves ranging from 100 nm to 100 μm, which extends from part of the ultraviolet spectrum to part of the infrared spectrum and includes visible light. The radiant energy transmitted to the receiving body is a function of the source temperature to the fourth power and the absorption coefficient of the material. With radiative heat transfer, heat can be transmitted from the source to the receiver through a vacuum or air at a temperature lower than either the source or the receiver. The energy radiated by a body is usually considered a surface phenomenon, since the radiation emitted inside a body is usually absorbed within the body. Similarly, the radiation transmitted to or incident on the receiving body is usually absorbed close to the surface. Infrared heaters operate on this principle.

Thermal radiation is a significant component of the measured incident energy (at some distance from the arc) when the American Society for Testing and Materials (ASTM) test setup with vertical, series electrodes is used (ASTM Standard F1939). However, the arc moves randomly away from the electrode axis, and the heat energy is not transmitted uniformly to calorimeters placed at a given distance from the electrodes; calorimeters placed at uniform distances around the test setup experience different levels of heat [17]. When an arc is initiated in an open-front test enclosure, some radiant energy hitting the sides and the back of the enclosure is reflected and transmitted out the front. The incident energy measured in front of a test enclosure with parallel electrodes entering from the top of the enclosure is higher than for a similar arc initiated in open air [20].

Convection is the transfer of heat between a solid surface and an adjacent fluid in motion. Like heat transfer by radiation, convection depends on the surface area through which the heat transfer takes place; it also depends on temperature, but it is a linear relationship. Convection results from the combined effect of conduction and fluid motion. In still air, some heat would be exchanged by conduction between a solid surface (such as a person) and nearby gas molecules through random motion. The bulk motion of the air removes the airborne molecules near the surface and brings new molecules which exchange heat with the surface. The faster the motion of fluid (such as in an arc blast), the greater the convective heat transfer. An example of convective heat is a forced-air heating system.

In some types of arc testing, convective heating is a significant component of the incident energy measured by the calorimeters. A good example is an arc test setup with horizontal, parallel electrodes pointing directly towards the calorimeters. At the instant of arc initiation, the heat at the calorimeters is thermal radiation; but, after a few milliseconds, the magnetic force associated with the plasma jets drive the plasma cloud with its flow of convective heat toward the calorimeters. Recent testing found that protective clothing fabrics performed at only 50% of their arc ratings when exposed to the large convective heating component of arcs initiated from horizontal or barrier tests. Conversely, face shields surpassed their arc ratings during horizontal or barrier arc testing [12].

IV. CATEGORIES OF INCIDENT ENERGY CALCULATIONS

A. Theory Based Models:

1) Kinectrics' ARCPRO: Kinectrics (located in Toronto, Ontario, Canada) developed a physics-based software package, ARCPRO [21], to calculate the heat flux associated with an arcing fault. The thermal parameters associated with a single-phase, free burning vertical arc are calculated to provide an assessment of the heat exposure on a surface some distance away. The ARCPRO software was designed to help users select adequate protective clothing and to identify the thermal dangers as a function of arc distance. The model has been verified for the following parameter ranges: arc currents from 3.5 to 21.5 kA, gap widths from 1 to 12 inches (2.54 to 30.48 cm), arc durations from 4 to 30 cycles, and arc distances from 8 to 42 inches (20.32 to 60.96 cm). By employing correction factors, the program is often extended to model a single-phase arc-in-a-box and three-phase arcing faults. For a single-phase arc-in-a-box, an appendix of the ARCPRO User's Guide suggests using a multiplication factor of 1.5 with the incident energy calculated for a single-phase arc in air. However, caution is advised: "This factor should be considered as an extremely preliminary approximation based on severely limited data and is to be employed at the user's discretion" [21]. Furthermore, the ARCPRO Help Guide suggests applying adjustment factors of 1.2 to 2.2 for a three-phase arc in open air and 3.7 to 6.5 for a three-phase arc-in-a-box. In addition, correction factors for the three-phase cases are sometimes determined by citing reference [22], the source of the incident energy formulas which appear in the NFPA 70E. "Three-phase test values of maximum incident energy for the open arcs were from 2.5 to 3 times the values predicted by the single-phase models. Three-phase test values of maximum incident energy for arcs in the cubic box were 5.2 to 12.2 times the values predicted by the single-phase models" [22]. Because suggested correction factors vary widely, it is very difficult to select a correction factor with confidence. The ARCPRO model is summarized briefly.

The theoretical model features a one-dimensional, free-burning, axisymmetric arc. Fig. 5 is a representation of the system where r represents the radial component.

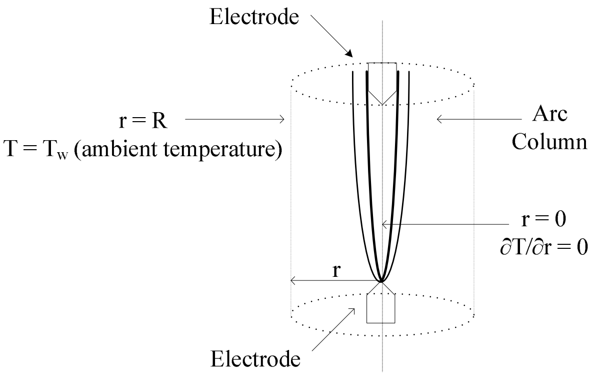

Fig. 5 Vertical, Axisymmetric, Free-Burning Arc

Assuming local thermodynamic equilibrium, the temperature and electric field are determined by using the energy balance equations:

$$\frac{\Delta T}{\Delta t} \approx \frac{\sigma E^2}{\rho C_p} - \frac{U}{\rho C_p} + \frac{1}{\rho C_p}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\eta\frac{\partial T}{\partial r}\right)\right] \tag{4}$$

$$I_{arc} = E\int_0^R \sigma 2\pi\, r\, dr \tag{5}$$

$$V_{arc} = E(L) + V_{electrode} \tag{6}$$

where

E	Electric field in the arc column (V/m)
L	Arc length (m)
V_{arc}	Arc voltage (V)
$V_{electrode}$	Electrode drop (V) (sum of cathode drop plus anode drop)
r	Radial distance from the arc (m)
σ	Electrical conductivity of the gas (S/m)
I_{arc}	Arc current (A)
t	Time (s)
T	Temperature (K)
ρ	Gas density (kg/m^3)
C_p	Gas specific heat at constant pressure (J/(K-kg))
U	Net radiation heat transfer from electrical arc to surroundings (W/m^3)
η	Gas thermal conductivity (W/(m·K))

At atmospheric pressure, the gas properties are considered as temperature dependent only.

ARCPRO assumes that the ohmic heating in the positive column generated by the flow of arc current is balanced by energy leaving the positive column due to convection and radiation. The arc voltage depends primarily on the gap between the electrodes and the arcing current. Assuming the arcing quantities are sinusoidal and that the arc impedance is purely resistive, the total arc power is approximated as described in equation (2). The total heat dissipated by the arc is then given by:

$$H_T = \int P_{arc}\, dt \tag{7}$$

The total heat dissipated by the arc is taken as the sum of the radiated heat (H_R) and the convected heat (H_C).

$$H_T = H_R + H_C \tag{8}$$

$$H_R = \int P_R\, dt \tag{9}$$

$$P_R = \int U\, d\tau \tag{10}$$

In (10), describing the arc power associated with the radiated heat, $d\tau$ is a volume element and the volume integral is over the entire arc; U represents the net radiation heat transfer from the electrical arc to the surroundings (W/m^3).

Much more elaborate two-dimensional arc models, which incorporate axial and radial plasma temperatures, velocities and pressures have been developed but are beyond the scope of this paper. H. Schau and D. Stade [23], citing a study conducted on closed switchboards, reported that the available energy in an arcing fault is distributed as follows: 40% to 60% of the energy is converted to the pressure rise, 30% to 40% is converted to heat, and the remaining 10% to 20% of the energy is converted to vaporizing the conductor material. Clearly if the energy balance is to receive closer scrutiny, more sophisticated models need to be developed. The ARCPRO model does not consider the heat conducted into the electrodes, the vaporization of materials, and the formation of the pressure wave. Readers interested in a more rigorous treatment of the subject are encouraged to consult a number of references authored by J. J. Lowke, et al. [24], [25], [26], particularly the article entitled “Simple Theory of Free-Burning Arcs” [26].

2) Heat Flux Calculator: Privette developed another approach to quantify the burn hazard associated with an arcing fault. The Duke Power Heat Flux Calculator is available on the Internet as free shareware. The Heat Flux Calculator can be downloaded from a number of sites; a pdf file to explain the theoretical basis for the program is also available [19]. The Heat Flux Calculator is based on the theory of radiation heat transfer. Literature describing the theoretical foundation of the program states that: “Convection accounts for very little energy transfer since the flashover is extinguished before the heated air can become a factor” [19]. This statement might indicate that the software was likely developed for short-lived flashover arcing. The Duke Heat Flux Calculator was developed for single-phase open air configurations. If the program is to be applied to other system types, correction factors must be utilized. One source has suggested that the software can be applied to three-phase arcing faults in open air by multiplying the predicted incident energy by 2.8 [27], while another reference suggests using a factor of 1.7 [28]. As with ARCPRO, it is very difficult to establish the true accuracy of adapting the Duke Heat Flux Calculator to other types of arcing scenarios, because multiple correction factors are cited in the literature.

3) Lee Model: In 1982, Lee published “The Other Electrical Hazard: Electrical Arc Blast Burns” [18]. This article is considered by many to be one of the most important research contributions to open-air arcing faults in industrial power systems. This paper quantified the potential burn hazard associated with an arc flash incident and educated engineers about the potential deadliness of an arcing fault. Lee’s work is incorporated into NFPA 70E-2004 and IEEE 1584-2002. Lee utilized the maximum power transfer theorem and claimed that heat radiation is the main hazard associated with an arcing fault. Both of these statements have been the subject of intense debate within the engineering and scientific community. One critical citation states: “However, we are now of the view that IEEE 1584 should refer explicitly to Lee and give a very clear warning that the material contained there has no value whatsoever for arc analysis or prediction and should not be relied upon for any aspect of arc behavior” [29], [30]. Whatever one’s view, it must be remembered that Lee brought awareness about the arc hazard and provided the first equations which quantified the danger to people.

The Lee model is presented below:

$$D_C = \sqrt{2.65 \times MVA_{bf} \times t} \tag{11}$$

$$= \sqrt{53 \times MVA \times t} \tag{12}$$

where

D_C	Distance for a just curable burn (ft)
MVA_{bf}	Bolted fault MVA at point involved
MVA	Transformer rated MVA, 0.75 MVA and over, for smaller ratings, multiply by 1.25
t	Time of exposure (s)

For calculating the incident energy, Lee’s equation may be written as:

$$E = 5.12\times10^5\, V\, I_{bf} (t/D^2) \tag{13}$$

where

E	Incident energy (cal/cm^2)
V	System voltage (kV)
t	Arcing time (s)
I_{bf}	Bolted 3ϕ fault current (kA)
D	Distance from the possible arc point to the person (mm)

B. Statistically Derived Models

In the analysis of arcs, statistically based equations are frequently used. The analysis of the arc behavior using physical models is quite complex; integral calculus and complex numerical methods are required. Analytical tools, which can be used by a wide audience, are needed to assess the arc hazard.

Statistically derived equations are formulated for arc current and incident energy in terms of test design parameters. Care has to be taken if the equations are used for extrapolation outside the test region. In addition, because these formulations are not based on physical models, some anomalies have been observed [20].

The IEEE 1584 and NFPA 70E Standards provide equations based on arc flash testing. The IEEE 1584 equations were developed from a statistical analysis of over 300 data entries, while the formulas presented in NFPA 70E were statistically derived from a more limited data set. The companion paper [6] provides a thorough overview of the development of the incident energy equations showcased in these two standards. This reference includes a side-by-side appraisal of the incident energy calculations, highlights the conditions of applicability, and presents a summary of variables required. Therefore for the purposes of the following comparative study, the incident energy equations are only briefly summarized.

1) NFPA 70E-2004: Standard for Electrical Safety in the Workplace: Laboratory experiments using a 600 V system were conducted to measure the incident energy exposures produced by three-phase arcs with gaps of 1.25 inches between the electrodes. Doughty, Neal, and Floyd used the data to derive a set of low voltage equations in order to calculate incident energy for arcs in open air and for those initiated within an enclosure [22]. The equations that follow are listed in Annex D of the NFPA 70E-2004 Standard and are considered one of the acceptable approaches for conducting an arc flash hazard analysis. The calculations are used to establish the personal protective equipment (PPE) required for a worker.

$$E_{MA} = 5271\, D_A^{-1.9593}\, t_A [0.0016\, F^2 - 0.0076\, F + 0.8938] \tag{14}$$

$$E_{MB} = 1038.7\, D_B^{-1.4738}\, t_B [0.0093\, F^2 - 0.3453\, F + 5.9675] \tag{15}$$

where

E_{MA}	Maximum open air incident energy (cal/cm^2)
E_{MB}	Maximum 20 in. cubic box incident energy (cal/cm^2)
D_A, D_B	Distance (in.) from arc electrodes, (for distances 18 in. and greater)
t_A, t_B	Arc duration (s)
F	Three-phase short-circuit current (kA) (for the range of 16 kA to 50 kA)

2) IEEE 1584-2002: IEEE Guide for Performing Arc-Flash Hazard Calculations: The IEEE 1584-2002 standard was developed using test data compiled from several laboratories. The equations that follow are used to predict the potential incident energy an employee might experience while working on energized equipment, so that the appropriate PPE can be selected. These equations can also be used to establish the flash boundary distance for workers not wearing the proper PPE.

Arcing Current Calculations

System voltage under 1000 V:

$$\begin{aligned} \lg(I_a) = {} & K + 0.662\lg(I_{bf}) + 0.0966V + 0.000526G \\ & + 0.5588V \lg(I_{bf}) - 0.00304G \lg(I_{bf}) \end{aligned} \tag{16}$$

1000 V < System voltage < 15,000 V:

$$\lg(I_a) = 0.00402 + 0.983\lg(I_{bf}) \tag{17}$$

$$I_a = 10^{\lg(I_a)} \tag{18}$$

where

I_a	Arcing current (kA)
K	-0.153 for open configurations and -0.097 for box configurations
I_{bf}	Bolted 3-phase fault current (kA)
V	System voltage (V)
G	Gap between conductors (mm) (Table I)
lg	Log with a base 10

Incident Energy Calculations

$$\lg(E_n) = K_1 + K_2 + 1.081 \lg(I_a) + 0.0011\, G \tag{19}$$

$$E_n = 10^{\lg(E_n)} \tag{20}$$

where

E_n	normalized incident energy (J/cm^2)
K_1	-0.792 for open configurations and -0.555 for box configurations
K_2	0 for ungrounded & high-resistance grounded systems -0.113 for grounded systems
I_a	arcing current (kA)
G	gap between conductors (mm) (Table I)
lg	log with a base 10

$$E = C_f\, E_n\, (t/0.2)\, (610^x/D^x) \tag{21}$$

where

E	Incident energy (cal/cm^2)
C_f	Calculation factor 1.0 for voltages above 1 kV 1.5 for voltages below 1 kV
E_n	Normalized incident energy (J/cm^2)
t	Arcing time (s)
D	Distance from the possible arc point to the person (mm)
x	Distance exponent (Table I)

TABLE I
FACTORS FOR EQUIPMENT AND VOLTAGE CLASSES

System Voltage (kV)	Equipment Type	Typical gap between conductors (mm)	Distance Exponent (x)
0.208 - 1	Open Air	10 - 40	2.000
	Switchgear	32	1.473
	MCC and panels	25	1.641
	Cable	13	2.000
> 1 - 5	Open Air	102	2.000
	Switchgear	13 - 102	0.973
	Cable	13	2.000
> 5 - 15	Open Air	13 - 153	2.000
	Switchgear	153	0.973
	Cable	13	2.000

3) Simplified IEEE 1584 Equations: A quick “first-cut” approach for estimating the incident energy levels was developed in the companion paper [6]. The severity of the arcing fault is largely determined by the available fault current

and the clearing times of the protective devices as is evident in these equations. The simplified versions of the IEEE 1584 incident energy equations are provided.

For system voltages 480 V and below:

$$E = 1.5\ (0.258\ I_{bf})\ (t/0.2)\ (610/D)^{X} \qquad (22)$$

For system voltages 600 V and below:

$$E = 1.5\ (0.344\ I_{bf})\ (t/0.2)\ (610/D)^{X} \qquad (23)$$

For system voltages over 1000 V:

$$E = (0.57\ I_{bf})\ (t/0.2)\ (610/D)^{X} \qquad (24)$$

where

E	Incident energy (cal/cm^2)
I_{bf}	Bolted 3-phase fault current (kA)
t	Arcing time (s)
D	Distance from the possible arc point to the person (mm)
x	Distance exponent (Table I)

C. Semi-Empirically Derived Electrical Heat Based Model

Because of the complexity of the physical processes occurring within an arc, it is commonly believed that theoretical models would produce more accurate results. The truth is that arcing faults are extremely chaotic processes and are difficult to accurately model using theoretical physics. Consequently, semi-empirical electrical heat based models have been developed. Knowledge of arc physics is used to develop the test program and to identify the main parameters affecting arc current, arc energy, and incident energy. The arcing phenomena is observed during the tests, model parameters are selected, and equations are formulated which conform to the present knowledge and observation of arcing faults.

Wilkins' Simple Improved Method: This incident energy model [31] is a simplified version of an approach Wilkins, Allison, and Lang developed [20]. Both methods correct the anomalies observed in the IEEE 1584 arcing current and incident energy equations. The simplified approach does not use a complex time-domain model; as a result, it is suitable to more general applications. Fig. 6 shows the equivalent circuit used to model a three-phase arcing fault.

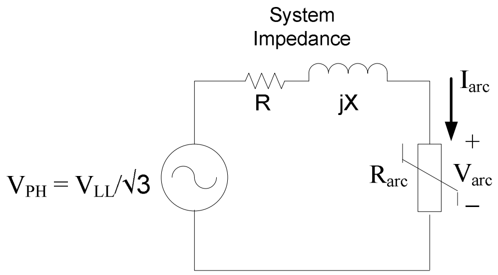

Fig. 6 Per-Phase Equivalent Circuit Model

The arc voltage is determined using the equation below.

$$V_{arc} = 1.757 I_{arc}^{\ 0.1457} g^{0.2476} V_{LL}^{\ 0.4166} \qquad (25)$$

where

V_{arc}	RMS arc voltage (V)
I_{arc}	RMS arc current (A)
g	Electrode gap (mm)
V_{LL}	Line-to-line voltage (V)

Dividing equation (25) by the arc current gives an expression for the arc resistance.

$$R_{arc} = 1.757 I_{arc}^{\ -0.8543} g^{0.2476} V_{LL}^{\ 0.4166} \qquad (26)$$

Equations (25) and (26) are applicable for arcs in open air. For arcs initiated within a box, the formulas must be multiplied by 0.821. Based on the per-phase circuit model, the magnitude of the arcing current is given by:

$$I_{arc} = \frac{V_{PH}}{\sqrt{(R_{arc}+R)^2 + X^2}} \qquad (27)$$

Because the arc resistance is a function of the arc current, equations (23) and (24) must be solved iteratively. At this point the total arc energy for the three-phase system is calculated from the following equation.

$$E_{arc} \approx 3 P_{arc}\, t \approx 3 V_{arc} I_{arc}\, t \qquad (28)$$

Formulas are provided for both arcing in open air and in a box configuration.

Arcs in Open Air:

The heat transfer depends on the spherical energy density.

$$E_s = \frac{E_{arc}}{4\pi d^2} \qquad (29)$$

where

d	Distance from arc (mm)

Utilizing the IEEE 1584 test database, and data from 37 additional tests performed at another high power laboratory, Wilkins derived the following best-fit equation.

$$E_{MAX} = 114.9 E_S^{\ 1.0655} g^{0.2562} V_{LL}^{\ -0.5697} \qquad (30)$$

where

E_{max}	Mean maximum energy density at a distance d, (cal/cm^2)
g	Electrode gap (mm)
V_{LL}	Line-to-line voltage (V)

Arcs in a Box with One Side Open:

The same basic approach can be used for arcs initiating within a box where the spherical energy density component is replaced by a value E_1 that accounts for the focusing effect of an enclosure. In other words, the term, E_1, represents the additional energy reflected by the back and sides of the enclosure. Heat transfer textbooks provide a discussion of radiative view factors [32].

$$E_{MAX} = 114.9 E_1^{1.0655} g^{0.2562} V_{LL}^{-0.5697} \quad (31)$$

$$E_1 = k \frac{E_{arc}}{a^2 + d^2} \quad (32)$$

Listed in Table II are Wilkins' optimum values of a and k [31] for the three equipment classes described in the IEEE 1584 guide.

TABLE II
OPTIMUM VALUES OF k AND a

Enclosure	Width (mm)	Height (mm)	Depth (mm)	a (mm)	k
Panelboard	305	356	191	100	0.127
LV Switchgear	508	508	508	400	0.312
MV Switchgear	1143	762	762	950	0.416

V. COMPARATIVE STUDY

A comparative study was performed in order to assess the accuracy of the techniques under a variety of operating conditions.

A. *Incident Energy Calculation Methods Used in the Comparative Study*

For the reader's convenience, the incident energy calculation methods used in this study are briefly summarized below.

Single-Phase Arcs:

- ARCPRO: Proprietary software designed for predicting the behavior of single-phase arcs in open air.
- Duke Heat Flux Calculator: Free shareware designed for modeling single-phase arcs in open air.

Three-Phase Arcs:

- Lee Method: The Lee Method was derived for a three-phase arc occurring in open air. Equation (13)
- NFPA 70E: Used to predict the incident energy exposure for arcs in open air and initiated within enclosures for low-voltage applications. Equations (14) and (15)
- IEEE 1584: Used to predict the incident energy exposure for arcs in open air and initiated within enclosures for low- and medium-voltage applications. Ungrounded systems are featured in this study because an ungrounded system results in the highest incident energy levels. Equations (16) – (21)
- Simplified IEEE 1584: Simple equations used for a quick "first-cut" assessment of the incident energy levels caused by an arc in a box. Equations (22) – (24)
- Wilkins' Simplified Model: Used to predict the incident energy exposure for arcs in open air and initiated within enclosures for low- and medium-voltage applications. Equations (25) – (32)

B. *Case Studies*

Test results from the IEEE 1584 database were used to gauge the accuracy of the methods investigated. As a result, the following test cases were defined based on the available IEEE 1584 test data. The 480-V arc in open air is the exception, because no IEEE 1584 data was available that lay within the applicable bolted-fault current range of the NFPA 70E equation. As previously noted, multiple correction factors for ARCPRO and the Duke Heat Flux Calculator have been proposed in the literature; however, none were included in this comparative study since the adjustment factors vary over a wide range. Four cases were investigated using the incident energy calculation methods described in this paper.

1) Case 1 - Low Voltage (480 V):
    i. Arc in a Box
    ii. Arc in Open Air

2) Case 2 - Low Voltage (600 V):
    i. Arc in a Box
    ii. Arc in Open Air

3) Case 3 - Medium Voltage (2.4 kV):
    i. Arc in a Box
    ii. Arc in Open Air

4) Case 4 - Medium Voltage (13.8 kV):
    i. Arc in Open Air

The results from the comparative study are summarized as Figs. 7 – 14. As a point of reference the NFPA 70E hazard risk categories are summarized in Table III [5].

TABLE III
NFPA 70E HAZARD RISK CATEGORIES

Hazard Risk Category	Incident Energy Level
Category 0	<1.2 cal/cm^2
Category 1	1.2 - 4 cal/cm^2
Category 2	4.1 - 8 cal/ cm^2
Category 3	8.1 - 25 cal/cm^2
Category 4	25.1 - 40 cal/cm^2
Risk Not Acceptable	**>40.0 cal/cm^2**

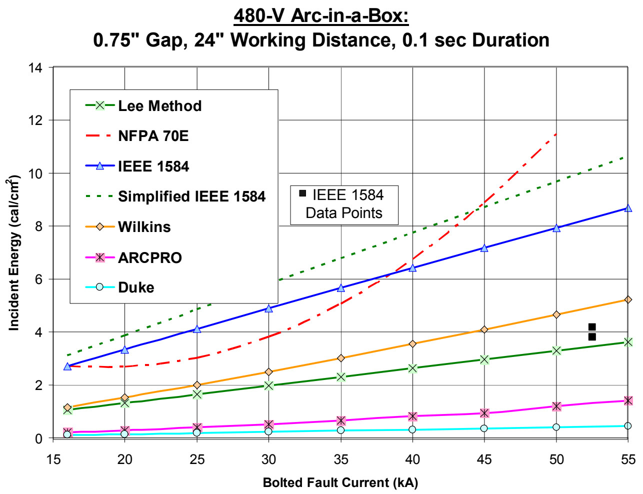

Fig. 7 Incident Energy vs. Bolted-Fault Current
480-V Arc-in-a-Box

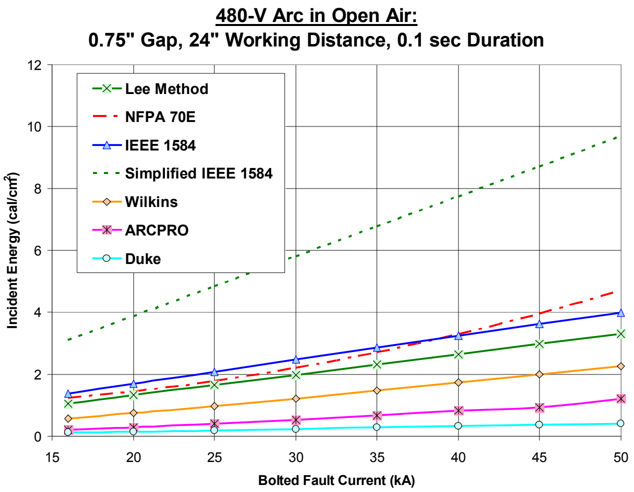

Fig. 8 Incident Energy vs. Bolted-Fault Current
480-V Arc in Open Air

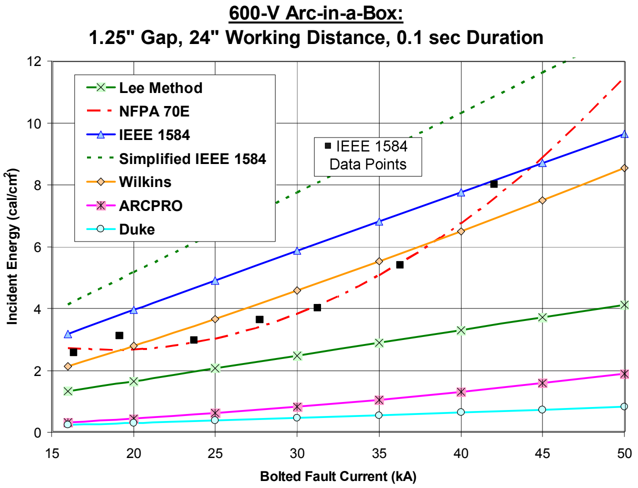

Fig. 9 Incident Energy vs. Bolted-Fault Current
600-V Arc-in-a-Box

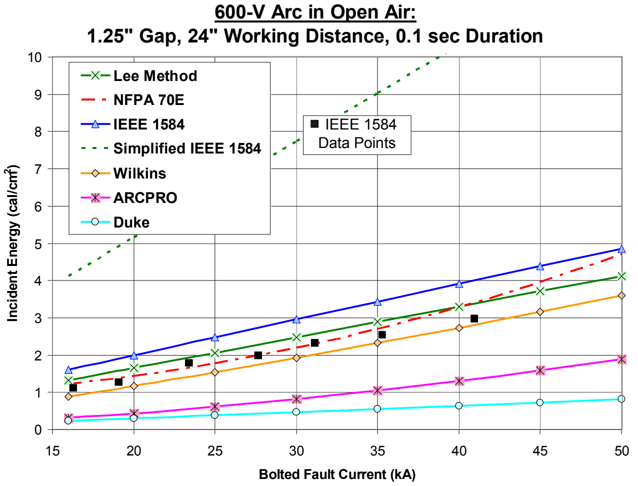

Fig. 10 Incident Energy vs. Bolted-Fault Current
600-V Arc in Open Air

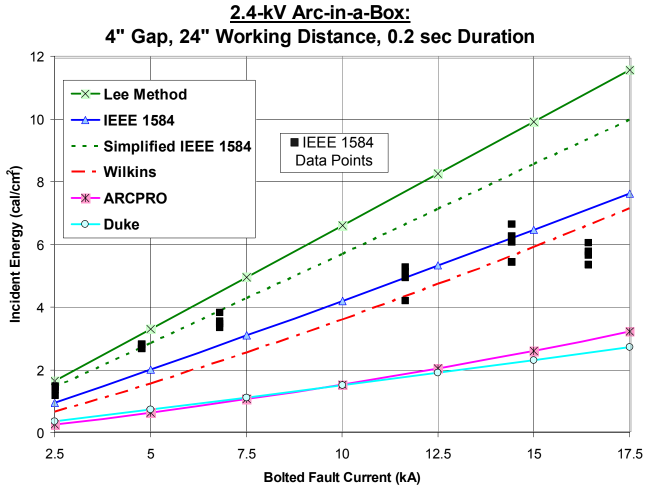

Fig. 11 Incident Energy vs. Bolted-Fault Current
2.4-kV Arc-in-a-Box

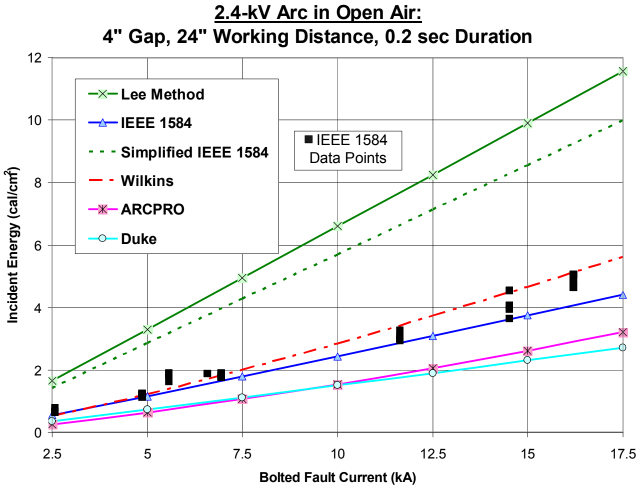

Fig. 12 Incident Energy vs. Bolted-Fault Current
2.4-kV Arc in Open Air

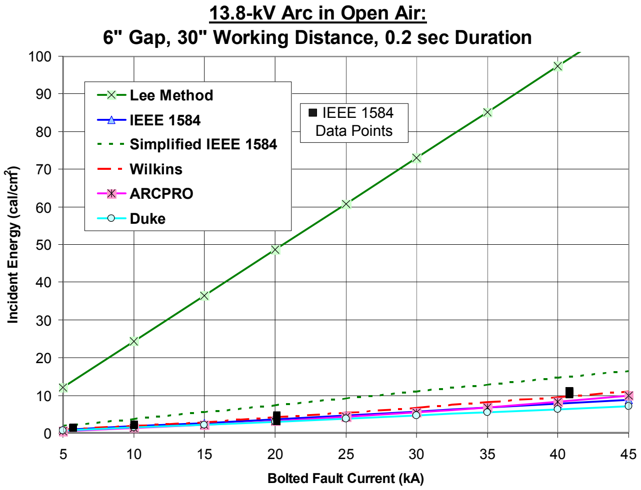

Fig. 13 Incident Energy vs. Bolted-Fault Current 13.8-kV Arc in Open Air (Lee Method Included)

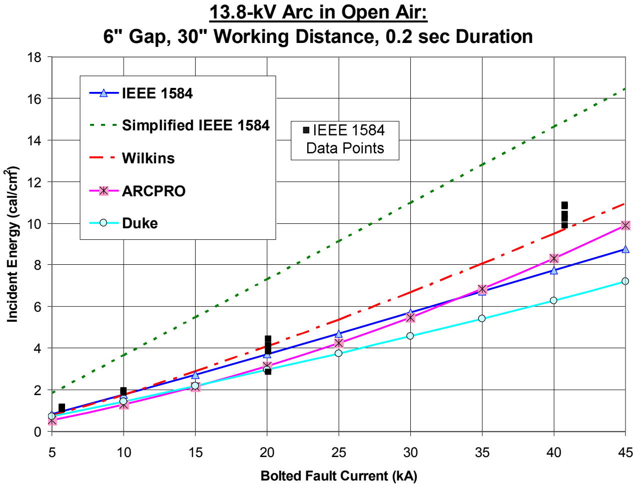

Fig. 14 Incident Energy vs. Bolted-Fault Current 13.8-kV Arc in Open Air (Lee Method Removed)

VI. DISCUSSION OF RESULTS

The figures in Section V show the incident energy for pre-defined arc durations. In reality, the arc duration is determined by the response time of the overcurrent protective device, which is a function of arc current. To accurately predict incident energy exposures in an industrial setting, a technique must recognize the potential variability of the arc current and of the response time of the overcurrent protection device. The IEEE 1584 technique accounts for the possible impact of the protective device's response time on incident energy by requiring a second incident energy computation at 85% of the calculated arc current.

Many of the incident energy calculation methods are applicable for a very specific range of values, so care must be exercised when applying these techniques. The results of the comparative study clearly illustrate this point. Several examples are presented below.

- The NFPA 70E equations fit the 600-V test data quite well as depicted in Figs. 9 and 10. This set of equations was based on the statistical analysis of 600-V incident energy test data for the range of bolted-fault current shown on the figures.
- The Simplified IEEE 1584 equations provide consistent results with the IEEE 1584 formulas in the Arc-in-a-Box cases as shown in Figs. 7, 9, and 11. This is as is expected, since the simplified method was developed to provide a quick assessment of the available incident energy. As a result, the simplified method was developed for the worst case arc-in-a-box scenario. In addition, ungrounded or high-resistance grounded systems are featured because these conditions result in the highest calculated incident energy levels. If desired, a similar set of equations could be developed specifically for arcs in open air [33]. The comparative study provides further evidence that the Simplified IEEE 1584 method provides a quick "first-cut" approach for estimating incident energy levels without extensive and potentially confusing calculations.
- ARCPRO and the Duke Heat Flux Calculator were developed for single-phase arcs in open air. As expected the results do not correlate well with the three-phase arc test results. While it is not the intent of this paper, the comparative study results could be used to establish still another set of correction factors.
- Results from the comparative study confirm the criticism voiced by Stokes and Sweeting [29], [30] which state that Lee's method overestimates the hazard for medium-voltage exposures. It is clear from Figs. 12 and 13, that the incident energy levels predicted by the Lee equation are significantly higher than the levels predicted by other methods. In addition, the calculation underestimates the incident energy levels caused by the arc initiating within an enclosure, as observed in Figs. 7 and 9, because the method was derived for an arc occurring in open air.
- The Wilkins method gives the most consistent results when compared to the available test data. Furthermore, the resulting semi-empirically derived equations are relatively easy to use and are more suitable for a wide audience.

The methods compared in this study predict a wide variety of outcomes. Individuals given the daunting task of assessing the risk associated with an arc flash hazard are left to ponder which approach is best. When the hazard is underestimated, workers are not adequately protected and might be seriously injured or killed in an arc flash event. When the hazard is overestimated, workers are overprotected which can interfere with their productivity. For example, incidents might result from the limited mobility associated with bulky PPE, or heat exhaustion might result because the protective equipment can be extremely hot.

VII. CONCLUSIONS

This paper has reviewed the theoretical, statistical, and semi-empirical models used to estimate the incident energy present during an arc flash exposure. A comparative study of the various techniques has highlighted the limitations and discrepancies of the methods. Elaborate theoretical models developed from calculus-based physics often require specialized computer tools; as a result, theoretical models are not practical for use by a wide audience. Furthermore, their accuracy has not been proven superior to other methods. Statistically based methods have been employed because the effect of many parameters can be formulated into fairly simple equations. However, the equations are valid only within the testing range, and even within the testing range, anomalies still occur. Semi-empirical models are often more applicable to wider range of conditions because this approach combines scientific understanding with an extensive analysis of test data. Whatever the approach, recent work has shown that three-phase arcs initiated from horizontal electrodes or vertical electrodes terminating in barriers behave differently than three-phase arcs initiated from vertical electrodes used for much of the testing in the last decade. In the 1990s, it became evident that three-phase arcing initiated from the parallel, vertical electrodes exhibited different characteristics than the single-phase, series electrode configurations used in fabric testing.

It is clear from recent research and this comparative study that electrode configuration and the presence of an enclosure add to the complexity of developing a method for accurately predicting incident energy. The insight gathered from this comparative study may help to shape the direction of future arc testing and model development. The most effective approach might be to use a semi-empirical approach similar to Wilkins' method. On the other hand, it might be more effective to develop a set of simple equations formulated to represent each type of likely exposure, where the effect of electrode configuration, enclosure, electrode gap, and other parameters are already built into the equations.

VIII. NOMENCLATURE

a	Constant
D	Distance to arc (mm)
E_{arc}	Arc energy (J)
g	Gap width (mm)
I	Current (A)
I_{arc}	Arc current (A)
I_{bf}	Bolted fault current (A)
IE	Maximum incident energy (cal/cm^2)
k	Constant
P_{arc}	Arc power (W)
P_{ave}	Average power (W)
P_R	Power from heat radiation (W)
R	System resistance (Ω)
R_{arc}	Arc resistance (Ω)
t	time duration (s)
T	Period (s)
V	Voltage (V)
V_{arc}	Arc voltage (V)
V_{LL}	Line voltage (V)
V_{PH}	Phase voltage (V)

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XI. VITA

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Tammy Gammon (IEEE Sr. Member) is the research manager for the IEEE/NFPA Arc Flash Collaborative Research and Testing Project. Since 2003 Tammy has also been a senior electrical engineer for John Matthews and Associates, Inc. Her expertise lies in modeling arcing faults and in analyzing power systems and electrical components. From 1999 to 2003, Tammy worked for the NC State engineering program at UNC-Asheville. She has taught a wide variety of courses ranging from power systems to microprocessor embedded systems. Tammy Gammon received a B.E.E., M.S.E.E. and Ph.D. from the Georgia Institute of Technology in 1993, 1994, and 1999; she is a registered a professional engineer in the state of North Carolina.

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John P. Nelson (IEEE F’98) received his BSEE from the Univ. of Illinois, Urbana, IL in 1970 and MSEE from the University of Colorado, Boulder, CO in 1975, respectively. Mr. Nelson spent 10 years in the electric utility industry and the last 27 years as an electrical power consultant. Mr. Nelson has been active with IEEE IAS/PCIC for 25 years, and has authored numerous papers (over thirty) involving electric power systems, grounding and protection, and protection of electrical equipment and personnel safety. Many of those papers are also published in the IEEE Transactions on Industry Applications and Industry Applications Magazine. Mr. Nelson is the founder/CEO of NEI Electric Power Engineering, Inc. located in Arvada, CO. He is a registered professional engineer in the state of Colorado and numerous other states. Mr. Nelson has co-taught graduate and undergraduate classes at the University of Colorado at Denver, Colorado School of Mines along with a number of IEEE tutorials and seminars.