ARC FLASH HAZARD INCIDENT ENERGY CALCULATIONS A HISTORICAL PERSPECTIVE AND COMPARATIVE STUDY OF THE STANDARDS: IEEE 1584 AND NFPA 70E

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Abstract – The exposure to hazards associated with electrical arcing phenomena, while working on energized equipment is a topic of significant interest to industrial plant personnel. This paper provides an overview of the current arc flash standards, focusing on the methods used to calculate incident energy levels in a system. A thorough sensitivity analysis of the arc flash hazard incident energy calculations currently adopted by the IEEE 1584 standard leads to some possible conservative simplification of the equations. These simple equations could be used for a quick “first-cut” assessment of the incident energy levels present in a system. A case study, using data from a typical petrochemical application, provides a comparison of the NFPA 70E and IEEE 1584 arc flash incident energy equations and the results obtained using the proposed simplified calculations.

Index Terms — NFPA 70E, IEEE 1584, Arc flash hazard assessment, Incident energy calculations, Sensitivity analysis, Comparative study.

I. INTRODUCTION

Awareness of the various hazards caused by an arc flash has increased significantly over the past two decades. The regulations, standards, research and application guidelines focus on reducing the exposure of personnel to burn injuries associated with arc flash events in low and medium voltage applications. Currently, the NFPA 70E – *Standard for Electrical Safety in the Workplace* [1] and the IEEE 1584 – *Guide for Performing Arc Flash Hazard Calculations* [2] [3] have the same goal; protecting individuals who must work on or near energized electrical equipment. However, the philosophical approaches used by these two groups to estimate the arc flash hazards are different. For many who are required to apply and follow the standards, the arc hazard calculations and the interpretations, at times, can be confusing, particularly when there are discrepancies among the methods being used. It has been widely accepted in the power industry that there is a need to perform additional research and refine the arc flash calculation methods to more effectively manage the hazard.

This paper focuses primarily on the arc flash incident energy calculations currently being used. Following a summary of the history of arc flash hazard research and a brief review of the calculations, a sensitivity analysis is performed which leads to a potential simplification of the incident energy calculations presented in the standards. It should be emphasized that the sensitivity analysis and the recommendations suggested in this paper are based exclusively on existing test data collected and made available in IEEE 1584 and the equations presented as a part of the NFPA 70E-2004 and IEEE 1584-2002 standards. Finally, calculations are provided to compare the incident energy equations and to validate the proposed simplified approach for estimating energy levels. A number of graphs and charts are added to enhance the understanding and possibly simplify the future application guidelines.

II. EVOLUTION OF ARC FLASH STANDARDS

A. Historical Perspective of the Development of Arc Flash Regulations and Standards

On December 29, 1970 the Occupational Safety and Health Act was signed into law. The general duty clause mandates that each employer “*shall* furnish to each of his employees employment and a place of employment which are free from recognized hazards that are causing or are likely to cause death or serious physical harm to his employees;” [4] The Occupational Safety and Health Administration (OSHA), given the responsibility of providing for worker safety, initiated the development of Federal regulations, including those that targeted identifying the electrical hazards and implementing safe work practices.

OSHA initially used the National Electrical Code (NEC) as a basis for electrical regulations. Because the NEC largely does not address employee safety, it became apparent that a new standard was needed. As a result, on January 7, 1976, a new NFPA electrical standards development committee was formed. This group was given the task of assisting OSHA in preparing standards specifically addressing electrical safety. The Committee on Electrical Safety Requirements for Employee Workplaces published the first edition of NFPA 70E in 1979. The initial edition covered installation safety requirements. Three subsequent editions over the next decade added sections on safety-related work practices, and safety-related maintenance requirements. OSHA used this work to create many of its regulations applying to electrical safety.

Title 29 of the Code of Federal Regulations (CFR), Subpart S, “addresses electrical safety requirements that are necessary for the practical safeguarding of employees in their workplaces. [4]" It was not until 1991 that OSHA added words acknowledging arc flash as an electrical hazard. The fifth edition of the NFPA 70E, published in 1995, became the first standard specifically addressing the arc flash hazard. This printing included requirements for protective clothing and defined a flash-protection boundary. The next two revisions focused on detailed arc flash hazard analysis; providing more specifications regarding the arc flash protection boundaries and incident energy calculations. NFPA 70E-2004, the most recent edition, includes sample calculations of flash protection boundaries in Annex D. It is important to note, as quoted on page 70E-98 of the standard: "This annex is not a part of the requirements of this NFPA document but is included for informational purposes only." [1]

In addition to the NFPA 70E standard and the OSHA Title 29 (CFR), in 2002 the NEC started requiring the use of labels warning workers about potential arc flash hazards. This same year an IEEE working group completed the publication of the standard IEEE 1584-2002: "Guide for Performing Arc-Flash Hazard Calculations". The new standard presented models for estimating incident energy levels based on a large amount of test data. As seen from this brief summary, until recently, the arc flash hazard has not been widely acknowledged. Extensive research and testing performed of late has led to a better understanding of the arc flash hazard. The next section highlights, chronologically, some of the most significant contributions to the body of knowledge pertaining to arcing phenomena and the associated hazards.

B. Significant Milestones in Arc Flash Research

1) *Ralph Lee*: In 1982, "The Other Electrical Hazard: Electrical Arc Blast Burns" [5] was published by Mr. Lee. This paper is considered, by many, to be one of the most important research contributions on arcing phenomena in open-air. This paper was significant in that it quantified the potential burn hazards and educated personnel about the safety implications. Lee established the curable burn threshold for the human body as 1.2 cal/cm^2. Ralph Lee also published a second very relevant paper in 1987 entitled, "Pressures Developed from Arcs." [6] The pressure effects of an arc incident are quantified in this publication.

2) *Doughty, Neal, Dear, and Bingham*: "Testing Update on Protective Clothing and Equipment for Electric Arc Exposure" [7], published in 1997, details the incident energy levels associated with low voltage arc flash events and was the first to describe how an event is intensified when the arc initiates within electrical equipment enclosures.

3) *Doughty, Floyd, and Neal*: "Predicting Incident Energy to Better Manage the Electric Arc Hazard on 600 V Power Distribution Systems" [8] was published in 2000. This paper semi-empirically quantified the incident energy calculations for low voltage systems and is the source of the incident energy calculations used in the NFPA 70E standard.

4) *Jones, Liggett, Capelli-Schellpfeffer, Macalady, Saunders, Downey, McClung, Smith, Jamil, and Saporita*: In 2000, "Staged Tests to Increase Awareness of Arc-Flash Hazards in Electrical Equipment" [9] was also published. Experimental investigations, using mannequins, were conducted to improve the understanding how humans can be adversely affected by arc flash incidents.

5) *IEEE Standard 1584*: The first edition of "IEEE Guide for Performing Arc-Flash Hazard Calculations" [2] was issued in 2002. This standard used extensive test data to develop empirical equations derived from statistical analysis. Tests data were made available from various sources and are included as an Appendix to the standard. A paper written by Gammon and Matthews entitled "IEEE 1584-2002, Incident Energy Factors and Simple 480-V Incident Energy Equations" [10] includes a thorough statistical analysis and summary of the IEEE 1584 test data.

6) *Stokes and Sweeting*: "Electric Arcing Burn Hazards" [11] published in 2006 provides a critical evaluation of the testing methodology, in particular the electrode orientation, used to assess the arc flash hazard for the IEEE 1584 standard development. In addition, this paper included an extensive list of literature on electric arcs. The authors suggest that this body of knowledge has largely been overlooked in the development of the current IEEE 1584 standard. Several discussion articles were published which provided additional analysis of the issues being debated. "Closure to Discussions of "Electric Arcing Burn Hazards" "[12] published by Stokes and Sweeting further documented their concerns.

7) *Wilkins, Lang, and Allison*: "Effect of Insulating Barriers in Arc Flash Testing" [13] was also published in 2006. The authors of this paper used vertical conductors terminated in insulating barriers for their testing methodology. The nature of the arc is very similar to what is observed when the electrodes are oriented horizontally, thus reinforcing the work of Stokes and Sweeting. Lang presented additional information regarding the evaluation of alternate test configurations in February 2007 at the 14th Annual IEEE IAS Electrical Safety Workshop held in Calgary, Alberta, Canada [14].

C. Future Development of Arc Flash Standards

In 2006, the IEEE and NFPA agreed to collaborate on a joint research initiative to increase the understanding of arc flash phenomena. This effort also plans to include working with the international community for global adoption of such a standard. It is the hope that the partnership between these two organizations will lead to a definitive industry standard regarding arc hazard analysis and mitigation. Figure A-1, in the Appendix, summarizing some of the more significant events in the development of arc flash hazard standards and regulations, is provided for future reference only.

III. ARC FLASH INCIDENT ENERGY CALCULATIONS

One of the most important and 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. The calculations detailed by NFPA 70E-2004 and IEEE 1584-2002 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).

A. Factors Influencing Incident Energy Levels

To help the reader fully comprehend the complexity of these types of calculations, a comprehensive (but not necessarily exhaustive) list of the factors influencing the incident energy is provided below. This has been known and well-recognized by researchers over the years.

- System Conditions:
  - Available short circuit current
  - X/R ratio
  - Pre-fault voltages and
  - Loading
- Protective Devices (Time-Current Characteristic of):
  - The first upstream device and
  - The second upstream device
- System Grounding
- Electrical Electrodes and Potential Arc Lengths:
  - Spacing between phases
  - Spacing between phases and ground
  - Orientation and
  - Insulated versus non-insulated
- Size and Shape of Enclosures
- Atmospheric Conditions:
  - Ambient temperature
  - Barometric pressure and
  - Humidity
- Arc Conditions:
  - Randomness of the arc
  - Interruption of the arc
  - Arc plasma characteristics and
  - Other unidentified factors
- Dissipation of Energy:
  - Heat
  - Latent heat of vaporization
  - Light
  - Sound and
  - Pressure wave
- Other Miscellaneous Factors

Reviewing this long list of variables, it is obvious that determining the precise arc flash incident energy to which a worker may be exposed is extremely difficult, if not impossible. Only an estimate of a worker's potential incident energy exposure can be established. Consequently, it is wise to have the calculations be on the conservative or safer side when protecting personnel.

B. NFPA 70E

The sixth edition of NFPA 70E, entitled *Standard for Electrical Safety Requirements for Employee Workplaces* [15], includes a set of equations used to calculate the available incident energy for low voltage systems (600 volts and below). The seventh edition, NFPA 70E-2004, *Standard for Electrical Safety in the Workplace*, moved the incident energy calculations to Annex D. The IEEE 1584-2002 methods for computing incident energy are also included in the annex. The calculations are used to establish the personal protective equipment (PPE) required for a worker. The incident energy calculations, based on fault current, working distance, and protective equipment clearing times are shown below:

$$E_{MA} = 5271\, D_A^{-1.9593}\, t_A\, [0.0016\, F^2 - 0.0076\, F + 0.8938] \quad (1)$$

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

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 from arc electrodes, in. (for distances 18 in. and greater)
t_A, t_B	arc duration, sec.
F	short-circuit current kA (for the range of 16 kA to 50 kA)

C. IEEE 1584

The IEEE 1584-2002 standard was developed using test data compiled from several laboratories. The calculations, which were derived empirically, are used to predict the incident energy an employee could experience while working on energized equipment. These equations also help establish the boundary distances for workers not wearing the proper PPE. This paper does not address the charts and simplified equations that were developed for Class L and RK1 Low Voltage (LV) fuses, or for the materials presented that deal with certain types of LV circuit breakers. A review and assessment of the curves and equations developed to predict the incident energy levels for LV current limiting fuses and circuit breakers is a topic planned for a future paper.

This paper focuses specifically on the incident energy equations that are described below. Compared to the NFPA 70E calculations, the IEEE 1584 equations are more complicated, involving an increased number of variables. It is also apparent that the IEEE 1584 calculations accommodate a wider range of voltage and bolted fault current levels. The equations for the incident energy calculations are summarized below for ready reference:

<u>Arcing Current Calculations</u>

- ***System voltage under 1000V:***

$$\lg(I_a) = K + 0.662 \lg(I_{bf}) + 0.0996\, V + 0.000526\, G + 0.5588\, V \lg(I_{bf}) - 0.00304\, G \lg(I_{bf}) \quad (3)$$

- ***System voltage over 1000 V:***

$$\lg(I_a) = 0.00402 + 0.983 \lg(I_{bf}) \quad (4)$$

$$I_a = 10^{\lg(I_a)} \quad (5)$$

Where,

I_a	arcing current (kA)
K	$-$ 0.153 for open configurations and $-$ 0.097 for box configurations
I_{bf}	bolted 3ϕ fault current (symmetrical rms (kA))
V	system voltage (kV)
G	gap between conductors (mm) (Table I)
lg	log with a base 10

Incident Energy Calculations

$$\lg(E_n) = K_1 + K_2 + 1.081 \lg(I_a) + 0.0011\, G \quad (6)$$

$$E_n = 10^{\lg(E_n)} \quad (7)$$

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
G	gap between conductors (mm) (Table I)

$$E = C_f\, E_n\, (t/0.2)\, (610^x/D^x) \quad (8)$$

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 (sec)
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

D. Lee Method

For cases outside the ranges established for use in both the NFPA 70E and IEEE 1584 standards, the Lee method is to be used. The Lee model is presented below:

$$E = 5.12\times10^5\, V\, I_{bf}\,(t/D^2) \quad (9)$$

Where,

E	incident energy (cal/cm^2)
V	system voltage (kV)
t	arcing time (sec)
I_{bf}	bolted 3ϕ fault current (kA)
D	distance from the possible arc point to the person (mm)

Figure B-1, in the appendix, provides a comparison between the NFPA 70E and IEEE 1584 standards. This side-by-side appraisal of the standards includes a summary of variables needed to calculate the incident energy and the conditions for which the calculations are applicable. This provides a snapshot for any future reference.

IV. SENSITIVITY ANALYSIS OF IEEE 1584 INCIDENT ENERGY CALCULATIONS

Many companies follow the IEEE 1584 methodology when calculating incident energy levels because it was developed using a large number of test data and encompasses a wider range of voltage and current. This method is believed, by many, to provide more accurate results. On the other hand, the increased complexity of the required calculations suggests that a computer program should be used to manage the equations effectively. The IEEE 1584-2002 standard comes equipped with a set of spreadsheet calculators to assist with an arc flash study. These calculators are not always easy to follow and at times can be confusing. Some companies rely heavily on commercial software packages to help estimate incident energy levels within their facility.

In an effort to provide a clearer understanding of the IEEE 1584 incident energy calculations, the sensitivity of the equations to the assorted variables was investigated. This is to be emphasized, that no effort has been made in this paper to validate the equations presented in the IEEE Std. 1584. The approach is demonstrated on the equations derived for low voltage and medium voltage systems. A discussion of three cases follows: A.) system voltages 480 V and below, B.) system voltages below 600 V, and C.) system voltages over 1000 V. These voltage values are selected so that some comparison could be made with the experimental results provided in the IEEE standard 1584.

A. System Voltages 480 V and Below

Equations (3) and (5) were evaluated for different conductor gap distances on a 480 V system with a box configuration as shown in Figure 1.

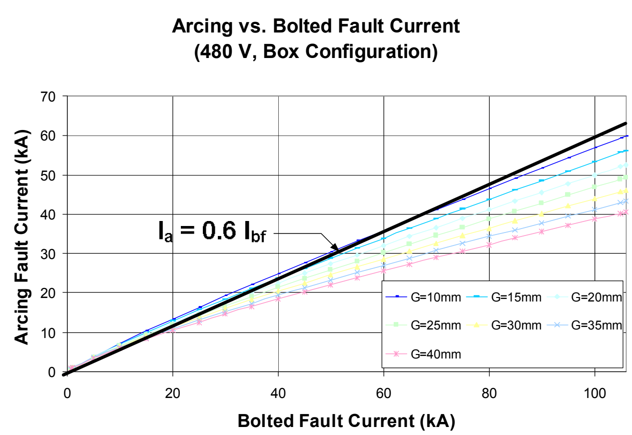


Fig. 1 Sensitivity to Gap between Conductors: 480V and Below

Figure 1 reveals that a worst case relationship between the arcing current and the bolted fault current, for voltages less than 480 V, in closed configurations, could be approximated by the simplified equation of a straight line given by (also shown in Figure 1):

$$I_a = 0.6\ I_{bf} \qquad (10)$$

Utilizing information extracted from the IEEE 1584 test results database, arcing current and three-phase bolted fault current data corresponding to voltages less than 480 V is plotted (scatter-plot) in Figure 2.

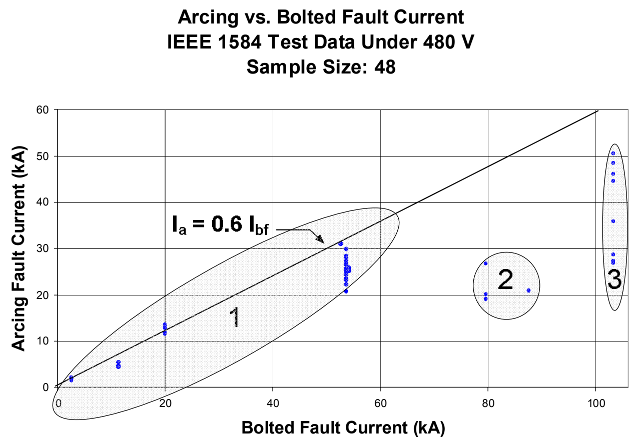


Fig. 2 Scatter-Plot of IEEE 1584 Low Voltage Test Data: 480V and Below

A line representing equation (10) is superimposed over the IEEE 1584 test data. Test points on the scatter-plot are grouped into three shaded areas as identified. Group 3 is of particular interest because of the wide variation in arcing current levels observed for fault currents over 100 kA. This is attributed to the test procedure, which investigated a broad range of conductor gap distances varying from 7 – 32 mm. Figure 1 reveals that the incident energy equation models the increasing influence of conductor gap distance at higher fault current levels. The simplified approach does not account for this because only the worst case was considered, i.e. a conductor gap of 10 mm. Nevertheless, all of the data points fall beneath this line, confirming that this simple linear equation could be used as a worst case approximation of the relationship between the arcing current and bolted fault current, for voltages less than 480 V, in closed configurations. It will be interesting to see whether this simplification could be proven by additional testing.

Next the sensitivity of the normalized incident energy to the conductor gap distance was evaluated using equations (6) and (7). Results for ungrounded or high-resistance grounded systems are shown in Figure 3. Ungrounded systems are featured in this study because our investigation confirmed other literature which states that "typically an ungrounded system results in the incident energy level that's about 30% greater than that of a solidly grounded system." [16] Taking the worst case, as depicted on the graph below, in a similar approach as before, a simplified equation for the incident energy is derived as follows:

$$E_n = 0.43\ I_a \qquad (11)$$

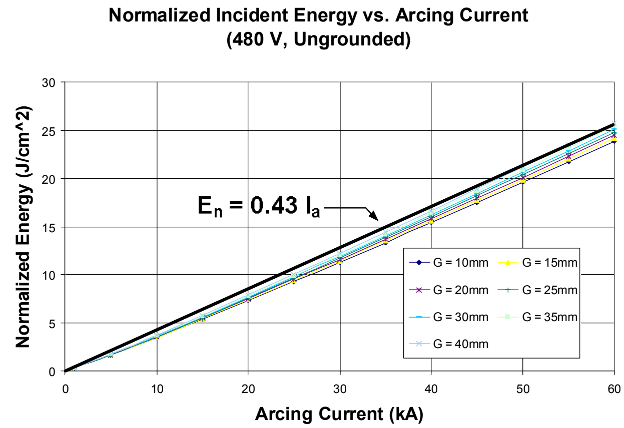


Fig. 3 Sensitivity to Gap between Conductors: 480V and Below

Lastly, the incident energy is calculated using equation (8). Continuing to simplify the equations using the worst case approach, the working distance (D) is set to 457 mm (18 in.), and the value of 1.641 is selected for the distance exponent (x) for G = 25 mm. It should be noted that selecting the worst case condition for the distance exponent could be problematic. It has been shown that the procedure adopted to calculate the incident energy using a distance exponent can give anomalous results [17] and it should be further investigated. Because this is a low voltage system being evaluated, 1.5 is used for the calculation factor (C_f). The incident energy calculation shown with the values selected for the variables follows:

$$E = 1.5\ E_n\ (t/0.2)\ (610/457)^{1.641} \qquad (12)$$

Combining equations (10) through (12) results in a simplified form of the incident energy equation:

$$E = 3.11\ (I_{bf})\ (t) \qquad (13)$$

Where,

E	incident energy (cal/cm^2)
I_{bf}	bolted 3ϕ fault current (kA)
t	arcing time (sec)

B. System Voltages 600 V and Below

A similar procedure was applied for different conductor gap distances on a 600 V system with a box configuration. Figures 4 – 6 summarize the information. As before, the data is grouped into three distinct regions. A scatter-plot of the data confirms that as a worst case the relationship between the arcing current and bolted fault current, for voltages less than 1000 V in a closed configurations, could be approximated by the simplified equation:

$$I_a = 0.8\ I_{bf} \qquad (14)$$

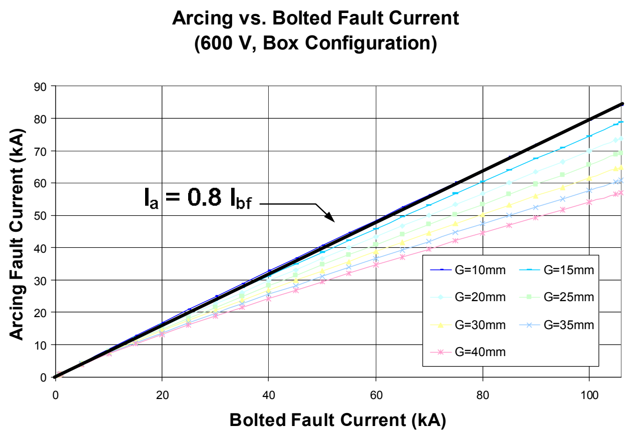


Fig. 4 Sensitivity to Gap between Conductors: 600V and Below

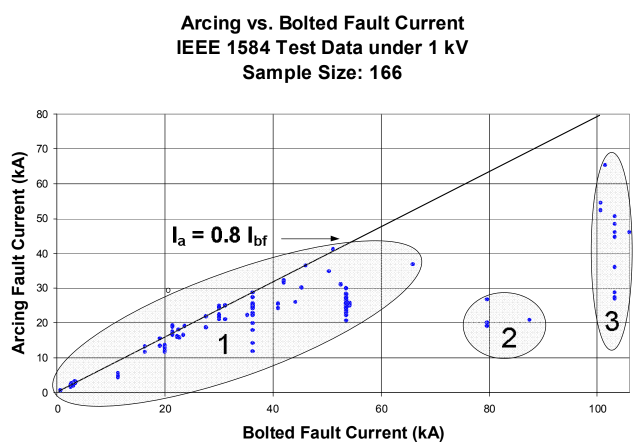


Fig. 5 Scatter-Plot of IEEE 1584 Low Voltage Test Data: 600V and Below

Taking the worst case shown on the graph, as before, a simplified expression for the incident energy is derived:

$$E_n = 0.43\ I_a \tag{15}$$

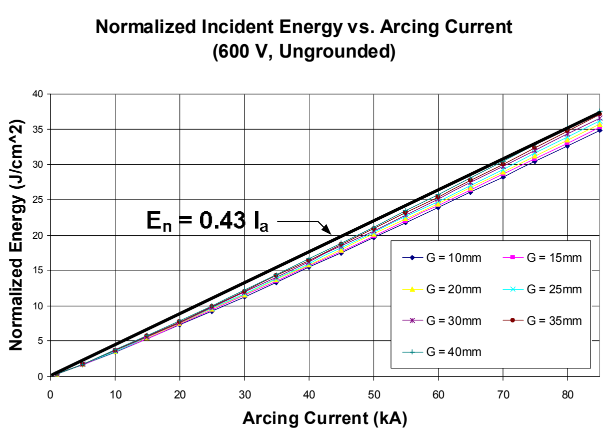


Fig. 6 Sensitivity to Gap between Conductors: 600V and Below

Finally, using the procedure previously described, the incident energy calculation derived for this case is summarized below:

$$E = 4.14\ (I_{bf})\ (t) \tag{16}$$

C. System Voltage Over 1000 V

A similar approach was used to evaluate the incident energy calculations for voltages over 1000 V using the IEEE 1584 equations listed as (4) and (5). Figures 7 through 9 detail the data used to develop the rather simplified equations. Interpreting the information on the graphs produces the equations that follow:

$$I_a = 0.95\ I_{bf} \tag{17}$$

$$E_n = 0.60\ I_a \tag{18}$$

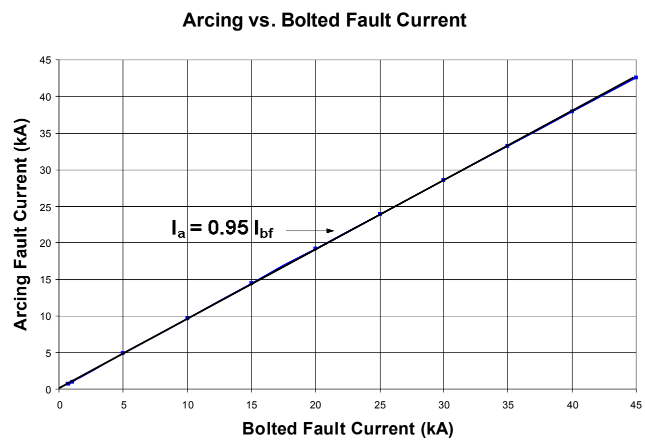


Fig. 7 System Voltage over 1 kV

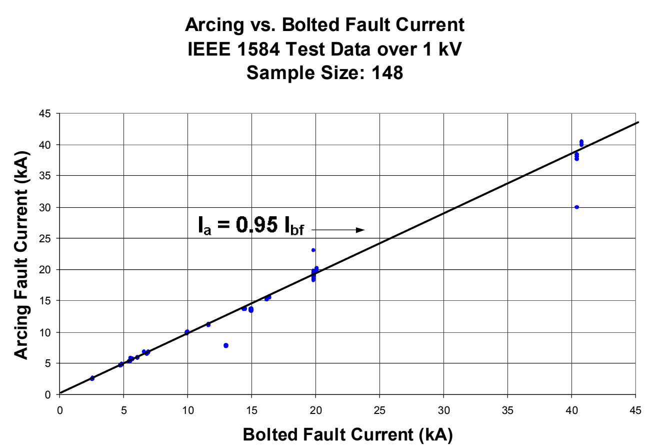


Fig. 8 Scatter-Plot of IEEE 1584 Medium Voltage Test Data: Over 1kV

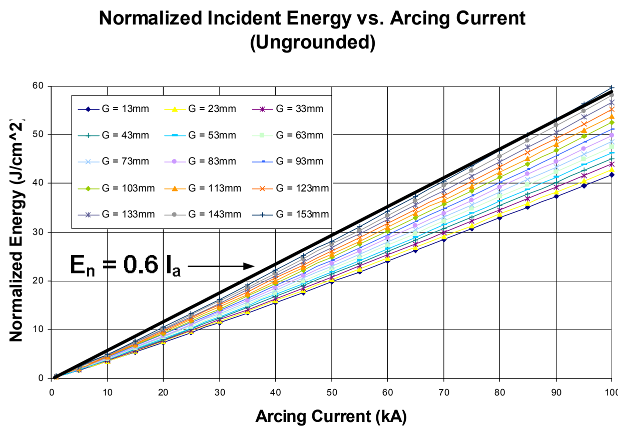


Fig. 9 Sensitivity to Gap between Conductors: Over 1kV

To conclude this process, the incident energy for an ungrounded system and a box configuration is calculated using equation (8). The working distance (D) is set to 457 mm (18 in.), and the value of 2.000 is selected for the distance exponent (x). Because the voltage of the system being evaluated is greater than 1 kV, 1.0 is used for the calculation factor (C_f). Equation (19) summarizes this approach:

$$E = 1.0\ E_n\ (t/0.2)\ (610/457)^{2.000} \qquad (19)$$

Combining equations (17) through (19) results in a simplified form of the incident energy equation:

$$E = 5.1\ (I_{bf})\ (t) \qquad (20)$$

D. Verification of Results Derived for the Low Voltage Case

To check the validity of the simplified approach presented in this paper, average incident energies and bolted fault currents data from the IEEE 1584 test database are plotted for voltages under 1000 V. The values selected correspond to arc durations of approximately 6 cycles (100 msec). If the time in equations (13) and (16) is set equal to 100 msec (0.1s), then the expressions become:

$$E = 0.31\ (I_{bf}) \qquad (21)$$

$$E = 0.41\ (I_{bf}) \qquad (22)$$

Figure 10 shows that all the available data points fall below the lines representing the equations derived for the 480 V and 600 V cases, indicating that the simplified approach results in conservative estimates for the incident energy levels in a low voltage system when compared to the available test data.

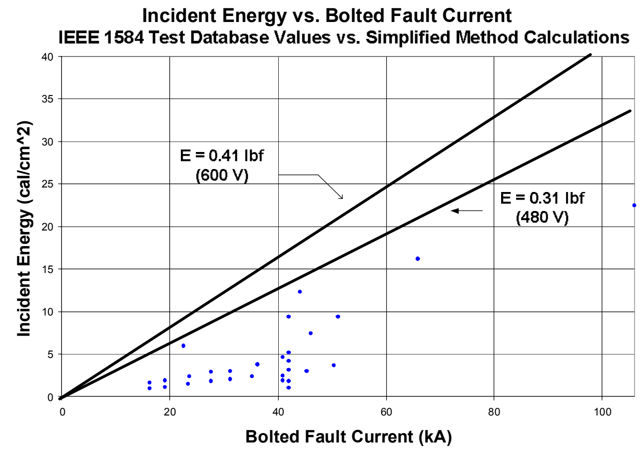


Fig. 10 Validation of Simplified Approach

As an additional means of verification, the simplified version of the equations presented in this paper are compared to the results derived from the NFPA 70E and IEEE 1584 incident energy equations. NFPA 70E incident energy levels were derived using equation (2) and IEEE 1584 equations (3) and (5) – (8) were used to calculate the incident energy levels. Figure 11 provides a summary of the calculations in a graphical form, confirming that the simplified approach gives conservative values in most cases. The NFPA Hazard/Risk Categories are also shown on the figure for reference.

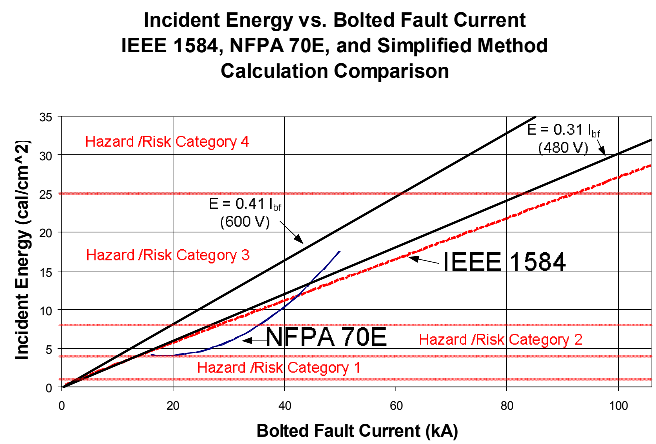


Fig. 11 Comparison of Various Results

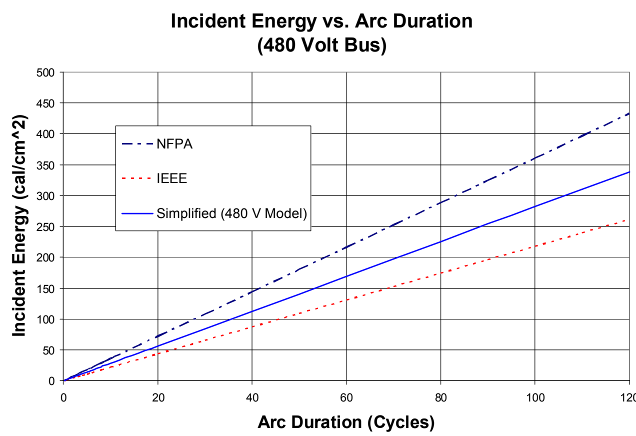
E. Discussion of Results for the Low Voltage Case

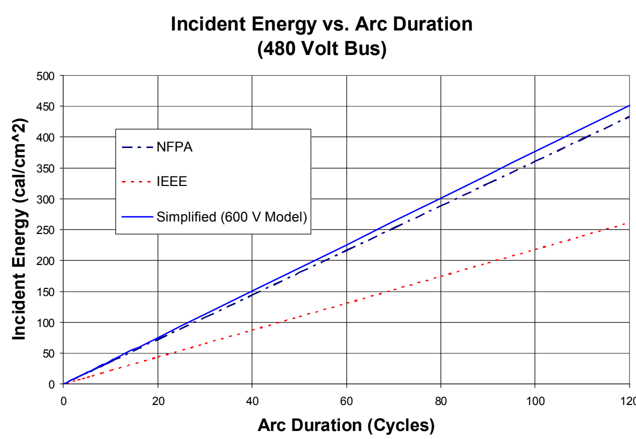
As observed in the preceding analysis, the simplified approach provides conservative estimates of arcing fault current and the incident energy levels. Caution applying this simplified approach is advised at bolted faults below 20 kA, because arc sustainability issues are probable at these current levels.

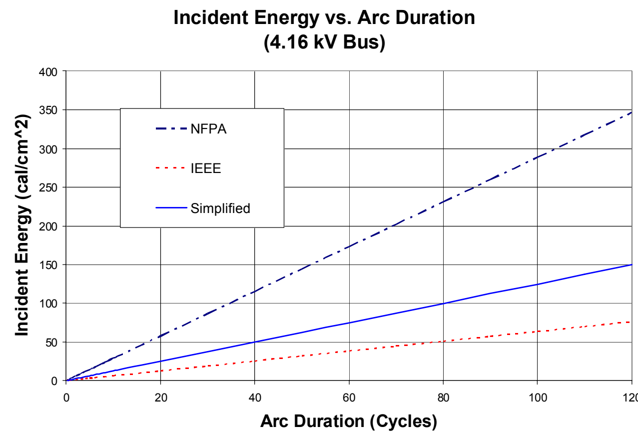
Validation of the simplified approach in this section focused on the relationship observed between incident energy and bolted fault current. It is well documented that the available fault current and time current characteristics of the protective devices have the most significant effect on arc flash hazard incident energy levels. Therefore, the next section which features a case study, provides an analysis of the relationship between the incident energy and the arc duration.

V. PETROCHEMICAL SYSTEM: A CASE STUDY

Data from a typical petrochemical power distribution network was used to perform an arc flash comparative study utilizing one of the commercial software packages available. A one-line diagram of the power system is included as Figure C-1 in an appendix. Nominal voltages of 480 V, 4.16 kV, and 12 kV are present in the system, providing a good opportunity to compare both the low voltage and medium voltage incident energy calculations. Figure 12 shows some of the results of the study. Recall that the NFPA 70E incident energy calculations are valid for voltage levels up to 600 V and for bolted fault currents between 16 – 50 kA. Therefore, the Lee method was used to estimate the energy values for the 4.16 and 12 kV buses. A working distance of 18 inches was used for all the calculations.







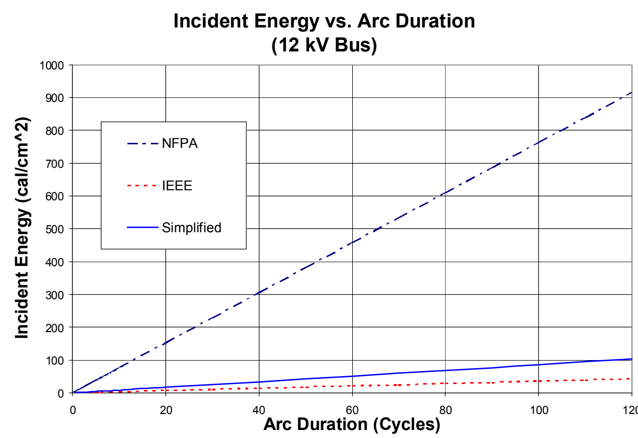


Fig. 12 Comparison of Incident Energy Calculations

There are two graphs showing results for the 480 V bus. The first figure displays the results for the simplified approach derived specifically for voltages 480V and lower. The second graph provides a plot of the more generalized formula representative of system voltages 600V and lower. This second approach is more conservative, as reflected in the results of the comparative study.

Using the calculations described in the arc flash standards, the NFPA 70E approach typically produces more conservative estimates (higher values) for the incident energy in the cases explored for this study. One of the drawbacks of using the NFPA 70E approach is the potential to overprotect the workers. Using a sensitivity analysis, the alternative method proposed in this paper, produces more conservative estimates of the potential incident energy exposure than the IEEE 1584-2002 equations. This is to be expected as the method is based on some simplifications of the IEEE 1584-2002 equations. However, the estimates for incident energy gleaned from the approximations are less conservative than the NFPA 70E calculations.

VI. CONCLUSIONS

This paper has reviewed the incident energy equations used in the NFPA 70E standard as well as the empirically based equations of the IEEE 1584 document. A simplified "quick assessment" approach has been proposed for performing incident energy calculations.

The question is then, "which method should be used?" This issue is complex, because research focused on modeling arc flash events and predicting incident energy levels is still in its infancy. As emphasized in this paper, real arc flash exposures are very difficult to predict because of their random complex nature and the large number of variables involved. Further complicating matters are the varied working conditions and actual equipment configurations encountered.

The incident energy information derived from an arc flash study is used to help develop strategies for minimizing burn injuries. Effectively modeling a large scale power system, analyzing and accurately calculating the energy released during an arc fault event is the cornerstone of an arc flash hazard analysis. NFPA 70E incident energy calculations are based on theoretical concepts and from models derived using very limited test data. Similarly, IEEE 1584 includes a theoretically derived model developed for three-phase, open air systems, applicable for any voltage. In other words, both standards use Ralph Lee's paper [5] as the theoretical basis for understanding electrical arcing phenomena. Lee's research includes many simplifying assumptions, most notably that "*the shape of the arc is not important*." [5] Certainly a methodology developed for open-air is not suitable for situations where the arc initiates within an enclosure or in cases where the system buses are tightly spaced. In an attempt to fill in the obvious gaps, the IEEE 1584 standard also featured empirically derived models for incident energy calculations based on a significant amount of test data. Test results obtained for the IEEE 1584 Standard were compiled using a vertical orientation of the three-phase arcing electrodes. The effect of different electrode orientations and the use of insulating barriers have been investigated and the results indicate that a horizontal electrode configuration produces higher incident energy levels [11] - [14]. A number of specific items were presented at the 2007 IEEE IAS Electrical Safety Workshop [14] recommending ways to incorporate this research into subsequent versions of the arc flash hazard standards.

In the meantime, the quick "first-cut" approach developed in this paper represents an effective way to estimate the arc flash hazard incident energy levels based on the current IEEE 1584 standard. Available fault current and the clearing time of the protective devices, as known, have the greatest impact on the potential arc flash hazard. The simplified versions of the IEEE 1584 incident energy equations, proposed in this paper, emphasize these relationships. Furthermore, it has been demonstrated that consistent results are obtained using this method.

VII. ACKNOWLEDGEMENTS

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IX. VITA

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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.

APPENDIX A

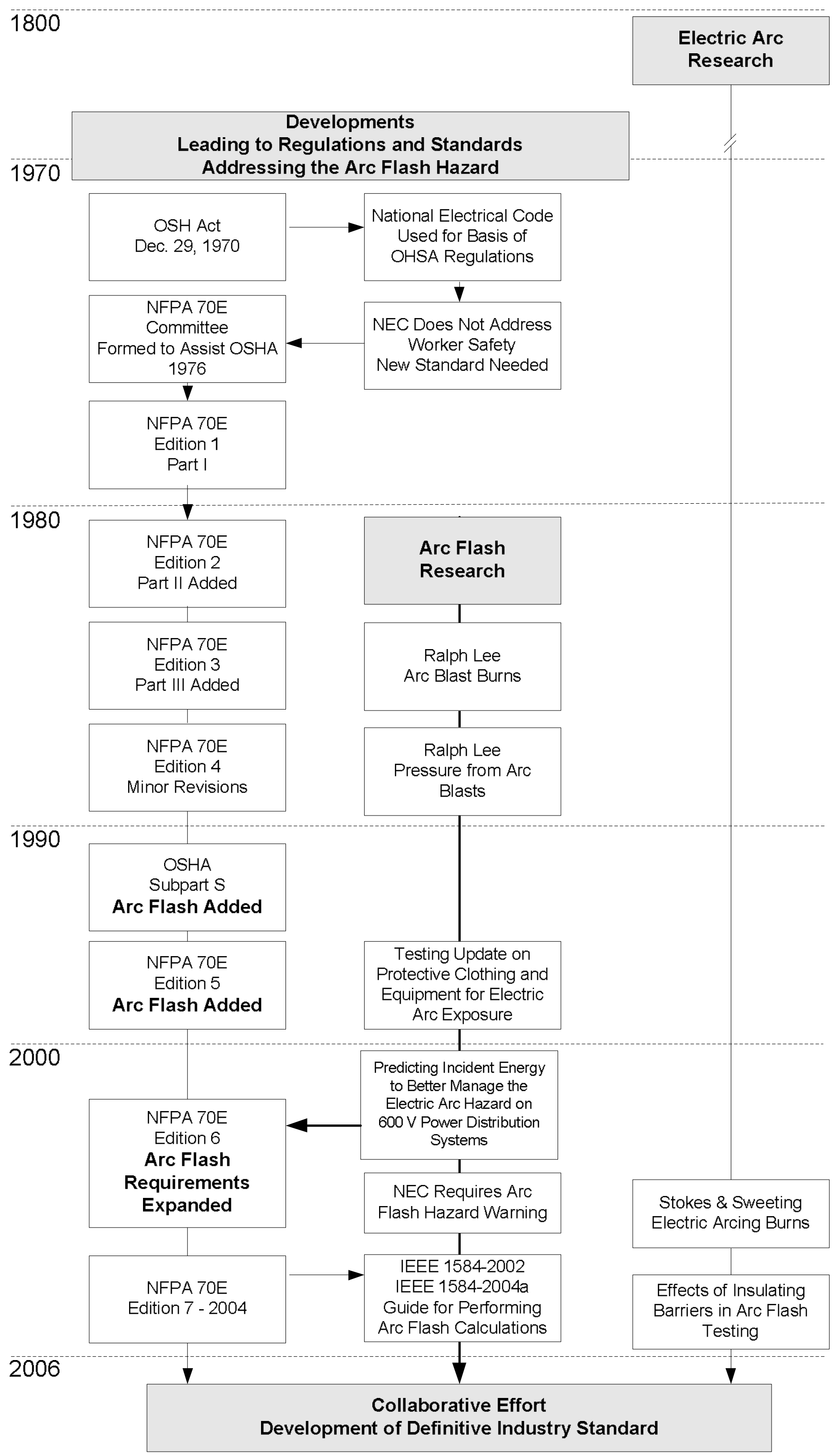

Fig. A-1: HISTORICAL DEVELOPMENT OF ARC FLASH STANDARDS

APPENDIX B

NFPA 70E – 2004 *Standard for Electrical Safety in the Workplace*	IEEE 1584 – 2002 *Guide for Performing Arc Flash Hazard Calculations*

System Application Limits

Parameter	NFPA 70E-2004	IEEE 1584-2002
Working Distance	457 mm (18”) or more	457 mm (18”) or more
Type of Installation	Open Air or Cubic Box	Open Air, Cubic Box & Cable Bus
Voltage Level	208 – 600 V	208 V – 15 kV
Range of Current	16 – 50 kA	0.7 – 106 kA
Time of Arc Exposure	Unlimited	Unlimited

Incident Energy Equations (Incident Energy in cal/cm²)

NFPA 70E – 2004

Maximum open air incident energy (cal/cm²)

$E = 5271\ D^{-1.9593}\ t\ [0.0016\ I_{bf}^{2} - 0.0076\ I_{bf} + 0.8938]$

Maximum 20” cubic box incident energy (cal/cm²)

$E = 1038.7\ D^{-1.4738}\ t\ [0.0093\ I_{bf}^{2} - 0.3453\ I_{bf} + 5.9675]$

IEEE 1584 – 2002

System voltage under 1,000V

$\lg I_a = K + 0.662 \lg (I_{bf}) + 0.0996\ V + 0.000526\ G + 0.5588\ V (\lg (I_{bf})) - 0.00304\ G (\lg (I_{bf}))$

1,000V < System voltage < 15 kV

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

$I_a = 10^{\lg(Ia)}$

$\lg (E_n) = K_1 + K_2 + 1.081 \lg (I_a) + 0.0011\ G$

$E_n = 10^{\lg (En)}$ Normalized incident energy (J/cm²)

$E = C_f\ E_n\ (t / 0.2)\ (610^x / D^x)$

Required Variables and Constants

Required Variable	NFPA 70E	IEEE 1584
V: System Voltage (kV)	✓	✓
I_{bf}: Fault Current (kA)	✓	✓
t: Arcing Time (sec)	✓	✓
D: Working Distance (mm)	✓	✓
Open/Enclosed Equipment	✓	✓
G: Conductor Gap (mm)		✓
K: Grounded, Ungrounded, and High-Resistance Grounded Systems		✓
C_f: Calculation Factor		✓
x: Distance Factor		✓

Constants

K: – 0.153 for open configurations
– 0.097 for box configurations

K_1: – 0.792 for open configurations (no enclosure)
– 0.555 for box configurations (enclosed equipment)

K_2: 0 for ungrounded & high-resistance grounded systems
– 0.113 for grounded systems

C_f: calculation factor
1.0 for voltages above 1 kV
1.5 for voltages below 1 kV

Distance Factors and Typical Conductor Gaps

System Voltage (kV)	Equipment Type	Typical Gap between Conductors (mm)	Distance x Factor
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

Lee Method: $E = 5.12\times10^{5}\ V\ I_{bf}\ (t / D^{2})$

Used to predict the open-air incident energy levels in cases where working voltages and/or conductor gaps fall outside of the range of The NFPA 70E and IEEE 1584 Standards

Fig. B-1: SUMMARY OF INCIDENT ENERGY CALCULATIONS

APPENDIX C

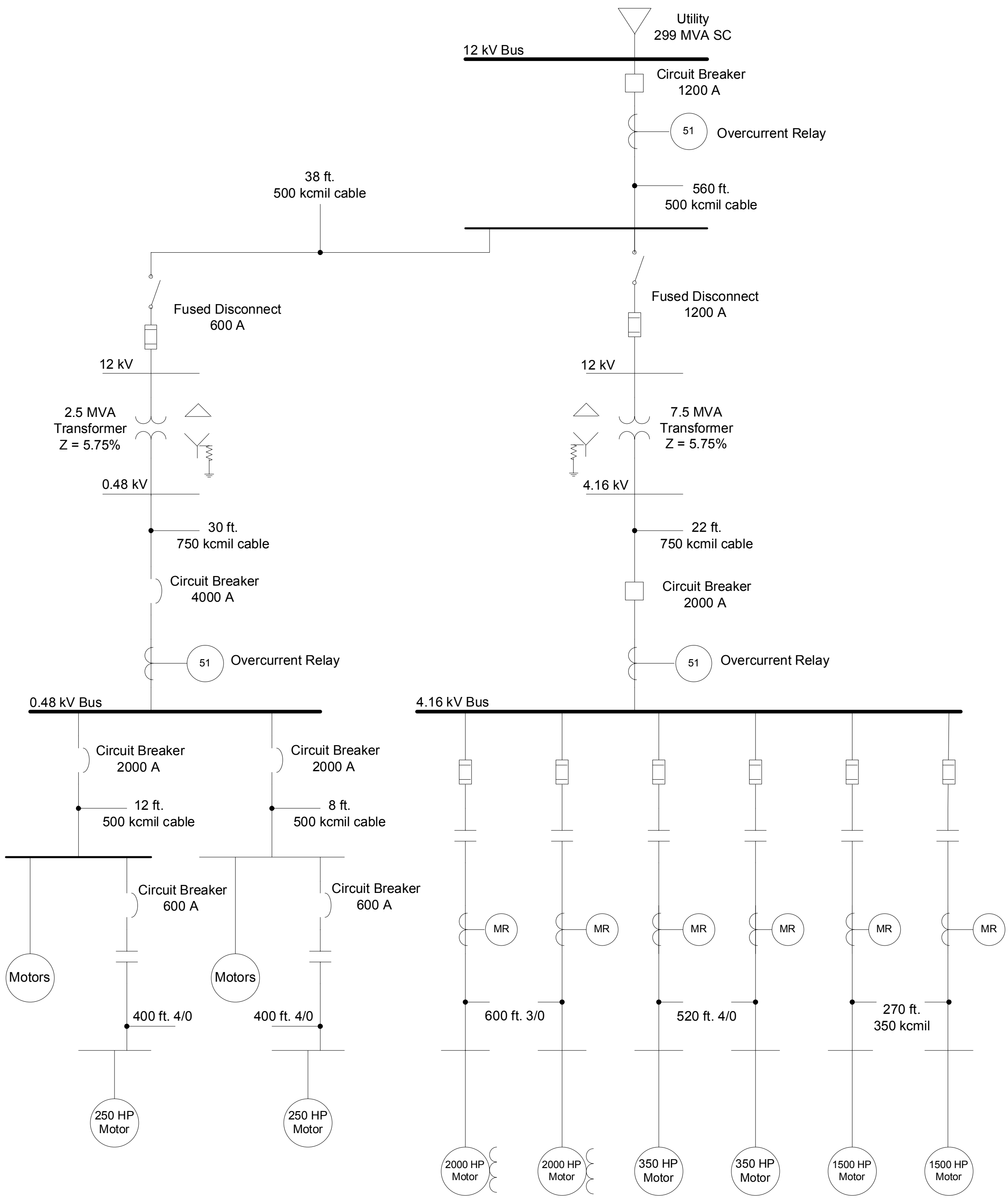

Fig. C-1: PETROCHEMICAL FACILITY SIMPLIFIED ONE- LINE DIAGRAM