

1584™

IEEE Guide for Performing Arc-Flash Hazard Calculations

IEEE Industry Applications Society

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Petroleum and Chemical Industry Committee



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Abstract: This guide provides techniques for designers and facility operators to apply in determining the arc-flash hazard distance and the incident energy to which employees could be exposed during their work on or near electrical equipment.

Keywords: arc fault currents, arc-flash hazard, arc-flash hazard analysis, arc-flash hazard marking, arc in enclosures, arc in open air, bolted fault currents, electrical hazard, flash protection boundary, incident energy, personal protective equipment, protective device coordination study, short-circuit study, working distances

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Introduction

(This introduction is not part of IEEE Std 1584-2002, IEEE Guide for Performing Arc-Flash Hazard Calculations.)

A technical paper by Lee, “The other electrical hazard: electric arc blast burns” [B19] provided insight that electrical arc burns make up a substantial portion of the injuries from electrical malfunctions.^a He identified that electrical arcing is the term applied to current passing through vapor of the arc terminal conductive metal or carbon material. The extremely high temperatures of these arcs can cause fatal burns at up to about 5 ft and major burns at up to about 10 ft distance from the arc. Additionally, electrical arcs expel droplets of molten terminal material that shower the immediate vicinity, similar to, but more extensive than that from electrical arc welding. These findings started to fill a void created by early works that identified electrical shock as the major electrical hazard. Mr. Lee’s work also helped establish a relationship between time to human tissue cell death and temperature, as well as a curable skin burn time-temperature relationship.

Once forensic analysis of electrical incidents focused on the arc-flash hazard, experience over a period of time indicated that Ralph Lee’s formulas for calculating the distance-energy relationship from source of arc did not serve to reconcile the greater thermal effect on persons positioned in front of opened doors or removed covers, from arcs inside electrical equipment enclosures.

A technical paper by Doughty, Neal, and Floyd, “Predicting incident energy to better manage the electric arc hazard on 600 v power distribution systems” [B4] presented the findings from many structured tests using both “arcs in open air” and “arcs in a cubic box.” These three phase tests were performed at the 600 V rating and are applicable for the range of 16 000 to 50 000 A short-circuit fault current. It was established that the contribution of heat reflected from surfaces near the arc intensifies the heat directed toward the opening of the enclosure.

The focus of industry on electrical safety and recognition of arc-flash burns as having great significance highlighted the need for protecting employees from all arc-flash hazards. The limitations on applying the known “best available” formulas for calculating the “curable” and “incurable” burn injuries have been overcome. This guide does that with new, empirically derived models based on statistical analysis and curve fitting of the overall test data available.

Conducting an arc-flash hazard analysis has been difficult. Not enough arc-flash incident energy testing had been done from which to develop models that accurately represent all the real applications. The available algorithms are difficult for engineers in offices to solve and near impossible for people in the field to apply. This working group has overseen a significant amount of testing and has developed new models of incident energy. The arc-flash hazard calculations included in this guide will enable quick and comprehensive solutions for arcs in single- or three- phase electrical systems either of which may be in open air or in a box, regardless of the low or medium voltage available.

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^aThe numbers in brackets correspond to those of the bibliography in Annex F.

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Sophisticated statistical analysis was required to develop the empirically derived model which is presented in this guide. The IEEE Std 1584-2002 working group recognizes and thanks Dr. David Berengut for his work on this analysis.

The “Bolted Fault Calculator” worksheet in the “IEEE_1584_Bolted_Fault_Cal.xls” was contributed by Paul and Dick Porcaro. The IEEE Std 1584-2002 working group recognizes and thanks them for this contribution.

The calculators can be accessed via the auxiliary files, “IEEE_1584_Bolted_Fault_Cal.xls” and “IEEE_1584_Arc_Flash_Hazard.xls”, and test data can be accessed via the auxiliary files, “Data_set.xls”, “Test_results_database.xls”, and “CL_Fuse_test_data.xls” provided with this standard (CD ROM for print versions and spreadsheet files for the PDF version).

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IEEE Guide for Performing Arc-Flash Hazard Calculations

1. Overview

1.1 Scope

This guide provides techniques for designers and facility operators to apply in determining the arc-flash hazard distance and the incident energy to which employees could be exposed during their work on or near electrical equipment.

1.2 Purpose

This guide presents methods for the calculation of arc-flash incident energy and arc-flash boundaries in three-phase ac systems to which workers may be exposed. It covers the analysis process from field data collection to final results, presents the equations needed to find incident energy and the flash-protection boundary, and discusses software solution alternatives. Applications cover an empirically derived model including enclosed equipment and open lines for voltages from 208 V to 15 kV, and a theoretically derived model applicable for any voltage. Included with the standard are programs with embedded equations, which may be used to determine incident energy and the arc-flash-protection boundary.¹

Single-phase ac systems and dc systems are not included in this guide.

¹The calculators can be accessed via the auxiliary files, “IEEE_1584_Arc_Flash_Hazard.xls” and “IEEE_1584_Bolted_Fault_Cal.xls”, and test data can be accessed via the auxiliary files, “Data_set.xls”, “Test_results_database.xls”, and “CL_Fuse_test_data.xls”, provided with this standard (CD ROM for print versions and spreadsheet files for the PDF version).

2. References

This guide shall be used in conjunction with the following standards. When the following standards are superseded by an approved revision, the revision shall apply.

ASTM F-1506-01, Standard for Performance Specification for Flame Resistant Textile Materials for Wearing Apparel for Use by Electrical Workers Exposed to Momentary Electric Arc and Related Thermal Hazards.²

ASTM F-1959/F-1959M-99, Standard Test Method for Determining the Arc Thermal Performance Value of Materials for Clothing.

CFR 29, Subpart R, Part 1910.269, Occupational Safety and Health Standards—Electric Power Generation, Transmission, and Distribution.³

CFR 29, Subpart S, Part 1910.301 through 1910.399, Occupational Safety and Health Standards—Electrical.

IEEE Std 141TM-1993, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (*IEEE Red BookTM*).^{4, 5}

IEEE Std 142TM-1991, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (*IEEE Green BookTM*).

IEEE Std 242TM-2001, IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (*IEEE Buff BookTM*).

IEEE Std C37.010TM-1999, IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

IEEE Std C37.20.7TM-2001, IEEE Guide for Testing Medium-Voltage Metal-Enclosed Switchgear for Internal Arcing Faults.

NFPA 70-2002, National Electrical Code[®] (NEC[®]).⁶

NFPA 70E-2000, Electrical Safety Requirements for Employee Workplaces.

3. Definitions

The following definitions apply to this standard. Additional definitions can be found in *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition [B13].⁷

3.1 arc-flash hazard: A dangerous condition associated with the release of energy caused by an electric arc.

²ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA (<http://www.astm.org/>).

³U.S. Regulatory Guides are available from the Superintendent of Documents, U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20013-7082, USA (<http://www.access.gpo.gov/>).

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⁶NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA.

⁷The numbers in brackets correspond to those of the bibliography in Annex F.

3.2 arcing fault current: A fault current flowing through an electrical arc plasma, also called arc fault current and arc current.

3.3 available fault current: The electrical current that can be provided by the serving utility and facility-owned electrical generating devices and large electric motors, considering the amount of impedance in the current path.

3.4 bolted fault current: A short circuit or electrical contact between two conductors at different potentials in which the impedance or resistance between the conductors is essentially zero.

3.5 circuit: A conductor or system of conductors through which an electric current is intended to flow.

3.6 electrical hazard: A dangerous condition in which inadvertent or unintentional contact or equipment failure can result in shock, arc-flash burn, thermal burn, or blast.

3.7 electrical shock: Physical stimulation that occurs when electrical current passes through the body.

3.8 electrical utilization equipment: Equipment that utilizes electric energy for electronic, electromechanical, chemical, heating, lighting, or similar purposes.

3.9 energized: Electrically connected to or having a source of voltage.

3.10 exposed (live parts): Capable of being inadvertently touched or approached nearer than a safe distance by a person. It is applied to parts that are not suitably guarded, isolated, or insulated.

3.11 fault current: A current that flows from one conductor to ground or to another conductor due to an abnormal connection (including an arc) between the two.

3.12 flash hazard analysis: A method to determine the risk of personal injury as a result of exposure to incident energy from an electrical arc flash.

3.13 flash-protection boundary: An approach limit at a distance from live parts that are uninsulated or exposed within which a person could receive a second degree burn. (*Syn:* **arc-flash protection boundary**).

NOTE—In addition to “flash-protection boundary,” see NFPA 70E-2000 for definitions of “limited approach boundary,” “prohibited approach boundary,” and “restricted approach boundary.”⁸

3.14 incident energy: The amount of energy impressed on a surface, a certain distance from the source, generated during an electrical arc event. Incident energy is measured in joules per centimeter squared (J/cm^2).⁹

3.15 shock hazard: A dangerous condition associated with the possible release of energy caused by contact or approach to live parts.

3.16 voltage (nominal): A nominal value assigned to a circuit or system for the purpose of conveniently designating its voltage class (as 120/240 V, 480Y/277 V, 600 V). The actual voltage at which a circuit operates can vary from the nominal within a range that permits satisfactory operation of equipment.

3.17 working distance: The dimension between the possible arc point and the head and body of the worker positioned in place to perform the assigned task.

⁸Information on references can be found in Clause 2.

⁹To convert from cal/cm^2 to J/cm^2 , multiply cal/cm^2 by 4.184. (See Annex E, Units of measure, for further information.)

4. Analysis process

An arc-flash hazard analysis should be performed in association with or as a continuation of the short-circuit study and protective-device coordination study. The process and methodology of calculating short-circuit currents and performing protective-device coordination is covered in IEEE Std 141-1993 (*IEEE Red Book™*) and IEEE Std 242-2001 (*IEEE Buff Book™*), respectively. Results of the short-circuit study are used to determine the fault current momentary duty, interrupting rating, and short-circuit (withstand) rating of electrical equipment. Results of the protective-device coordination study are used to determine the time required for electrical circuit protective devices to isolate overload or short-circuit conditions. Results of both short-circuit and protective-device coordination studies provide information needed to perform an arc-flash hazard analysis. Results of the arc-flash hazard analysis are used to identify the flash-protection boundary and the incident energy at assigned working distances throughout any position or level in the overall electrical generation, transmission, distribution, or utilization system.

4.1 Cautions and disclaimers

As an IEEE guide, this document suggests approaches for conducting an arc-flash hazard analysis but does not have mandatory requirements. Following the suggestions in this guide does not guarantee safety, and users should take all reasonable, independent steps necessary to minimize risks from arc flashes.

Users should be aware that the models in this guide are based upon measured arc current incident energy under a specific set of test conditions and on theoretical work. 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.

This document is intended to provide guidance for the calculation of incident energy and arc-flash protection boundaries. Once calculated, this information can 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 deenergized, applying arc-resistant switchgear, and following other engineering techniques and work practices.

This guide is based upon testing and analysis of the hazard presented by incident energy. The 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.

Available bolted fault currents should be determined at the point of each potential fault. Do not use overly conservative bolted fault current values. 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.

Where used, PPE for the arc-flash hazard is the last line of defense. The protection is not intended to prevent all injuries but to mitigate the impact of an arc flash upon the individual, should one occur. In many cases, the use of PPE has saved lives or prevented injury. The calculations in this guide will lead to selection of a level of PPE that is a balance between the calculated estimated incident energy exposure and the work activity being performed while meeting the following concerns:

- a) The desire to provide enough protection to prevent a second degree burn in all cases.
- b) The desire to avoid providing more protection than is needed. Hazards may be introduced by the garments such as heat stress, poor visibility, and limited body movement.

Professional judgement must be used in the selection of adequate PPE.

While it is outside the scope of this document to mandate PPE, 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 required during the tests to verify the absence of voltage after the circuits are deenergized and properly locked out/tagged out.

This information is based on technical data believed by the IEEE Std 1584-2002 working group to be reliable. It is offered as a tool for conducting an arc-flash hazard analysis. 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. IEEE, those companies that contributed test data, and those people who worked on development of this standard make no guarantee of results and assume no obligation or liability whatsoever in connection with this information.

This guide 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 deenergized and in an electrically safe work condition. But even this act, creating an electrically safe work condition, subjects the worker to potential hazards, which if they occur, require PPE for protection against arc-flash burns.

Work intentionally performed on or near energized equipment or circuits is limited by standards and regulations, such as those issued by OSHA. OSHA 29 CFR Subpart S.1910.333 severely limits the situations in which work is performed near or on equipment or circuits that are or may be energized.

“Live parts to which an employee may be exposed shall be deenergized before the employee works on or near them, unless the employer can demonstrate that deenergizing introduces additional or increased hazards or is infeasible due to equipment design or operational limitations.”

Financial considerations are not an adequate reason to work on or near energized circuits.

For ready access to the specific needed flash-protection boundary, working distance, and incident energy, such calculated values should be prominently displayed on every piece of electrical equipment where an arc-flash hazard exists in a workplace or otherwise be made available to workers.

Safety by design measures should be actively considered during the design of electrical installation to improve personnel safety. For example, properly tested and installed arc resistant switchgear (see IEEE C37.20.7-2001) can provide safety for operating personnel, while the doors are secured. Remote control and remote racking are also examples of methods to improve safety by design. Similarly, providing suitable and readily accessible disconnecting means separate from equipment to be worked upon will enable isolation and deenergization. Engineering designs can also specify the appropriate system design, equipment, protection, etc., to minimize fault current magnitude and duration. Changing protection settings can reduce the fault current. It is also possible to consider alternate work practices that provide increased work distances.

4.2 Step 1: Collect the system and installation data

The largest effort in an arc-flash hazard study is collecting the field data. Even for a plant with nominally up-to-date single-line diagrams, time-current curves, and short-circuit study on a computer, the field part of the study will take about half of the effort. Regular site employees who are familiar with the site and its safety practices may be able to do this part of the job best.

While the data required for this study is similar to data collected for typical short-circuit and protective-device coordination studies, it goes further in that all low-voltage distribution and control equipment plus its

feeders and large branch circuits must be included. Annex A contains a sample form for most of the equipment and system data needed to perform the electrical system studies. Similar forms may be prepared in advance for all electrical equipment.

Begin by reviewing the single-line diagrams and electrical equipment site and layout arrangement with people who are familiar with the site. The diagrams may have to be updated to show the current system configuration and orientation before the arc-flash study can begin. The single-line diagrams must include all alternate feeds. If single-line diagrams are not available, create them.

It is very important for electrical safety to have up-to-date single-line diagrams available. Refer to IEEE Std 315-1975 and IEEE Std 315A-1986 plus IEEE Std C37.2-1996 for examples.

When the basic electrical system scheme is complete on the diagrams, add the data needed for the short-circuit study. The study must take into account all sources, including utilities, standby and power generators, and large motors—those 37 kW and larger that contribute energy to short circuits.¹⁰ The diagrams must show all transformers, transmission lines, distribution circuits, electrical system grounding, current limiting reactors and other current limiting devices, voltage correction or stabilization capacitors, disconnect switches, switchgear, motor control centers (MCCs), panelboards/switchboards including protective devices, fused load interrupter switches including fuse types and sizes, feeders and branch circuits, as well as motors down to the 600 V or 400 V level, and transformers supplying instrument power and protective devices. Equipment below 240 V need not be considered unless it involves at least one 125 kVA or larger low-impedance transformer in its immediate power supply.

Get the available fault MVA and power angle or X/R ratio from the utility. Most utilities will readily supply information on the available fault level and X/R ratio at point of service. When information is not provided, public utility commissions can be requested to require utilities to furnish this information. Available fault data must be realistic; not conservatively high.

For transformers, generators, large motors, and switchgear, note all the nameplate data. Typically this would include voltage/voltage ranges or tap settings, ampacity, kilowatt or kilovolt amperes, momentary or interrupting current rating, impedance or transient/subtransient reactance data, etc.

Next note conductor and cable data along with its installation (routing and support method) for all electrical circuits between the utility and the distribution and control equipment. Typical data might be: 300 m of 3 single conductor 500 kcmil copper in overhead magnetic duct; 500 m of 6 single conductor 4/0 AWG copper in underground nonmagnetic duct; 100 m of 3/C 250 kcmil aluminum in overhead cable tray; or 1000 m pole line with 3 single conductor 4 AWG hard drawn copper conductors in a delta configuration with 500 mm spacing. This information is needed for calculation of impedances. Typical sources of cable/conductor impedance data are available in software package libraries, and tables located in IEEE Std 141-1993. See Annex A for a sample data collection form for cables.

Finally, transformers supplying instrument power (current transformer, voltage transformer, or control power transformer) and protective-device data must be collected. It should be available on nameplate or time-current curves. If not, it may be available in specifications or in recent maintenance test reports. In any case, the user should verify old data is still up-to-date by checking with the owner's representative and, if necessary, by checking in the field. In some cases a field inspection is required to determine the types and ratings of fuses actually installed, as well as the settings of circuit breaker trips and/or the settings of protective relays.

¹⁰37 kW = 50 HP

4.3 Step 2: Determine the system modes of operation

In a site with a simple radial distribution system there is only one mode of operation—normal—but a more complex system can have many modes. Examples of modes include:

- One or more utility feeders in service.
- Utility interface substation secondary bus tie breaker open or closed.
- Unit substation with one or two primary feeders.
- Unit substation with two transformers with secondary tie opened or closed.
- MCC with one or two feeders, one or both energized.
- Generators running in parallel with the utility supply or in standby.

It is important to determine the available short-circuit current for modes of operation that provide both the maximum and the minimum available short-circuit currents.

4.4 Step 3: Determine the bolted fault currents

Input all data from the single-line diagrams and the data collection effort into a short-circuit program. Commercially available programs can run thousands of buses and allow easy switching between modes. The simplified calculator included with this standard can determine bolted fault currents for radial systems for up to 600 V (see Figure B.1). Find the symmetrical root-mean-square (RMS) bolted fault current and X/R ratio at each point of concern—all locations where people could be working—by making each of these points a bus. Not every bus needs to be run for every mode because some modes will not significantly impact bolted fault current at some buses. For example, connecting transformer secondaries together may not increase fault energy on the primary side.

It is important to include all cables because to err on the high side does not necessarily increase safety: it may reduce it. Lower fault currents often persist longer than higher currents as shown on protective-device time-current curves.

4.5 Step 4: Determine the arc fault currents

The arc fault current at the point of concern and the portion of that current passing through the first upstream protective device must be found.

The arc fault current depends primarily on the bolted fault current. The bolted fault current in the protective device can be found from the short-circuit study by looking at a one-bus-away run. This will separate fault contributions from normal feeder, alternate feeder, and downstream motors.

The arc fault currents can then be calculated. The calculated arc fault current will be lower than the bolted fault current due to arc impedance, especially for applications under 1000 V. For medium voltage applications the arc current is still a bit lower than the bolted fault current, and it must be calculated. The equations shown in 5.2 are incorporated in the programs offered with this standard.

4.6 Step 5: Find the protective device characteristics and the duration of the arcs

In the field survey up-to-date system time-current curves may have been found. If not, it is best to create them—commercially available software makes this task easy. Alternatively, for a very simple study, it is possible to use protective device characteristics, which can be found in manufacturer's data.

For fuses, the manufacturer's time-current curves may include both melting and clearing time. If so, use the clearing time. If they show only the average melt time, add to that time 15%, up to 0.03 seconds, and 10%

above 0.03 seconds to determine total clearing time. If the arcing fault current is above the total clearing time at the bottom of the curve (0.01 seconds), use 0.01 seconds for the time.

For circuit breakers with integral trip units, the manufacturer's time-current curves include both tripping time and clearing time.

For relay operated circuit breakers, the relay curves show only the relay operating time in the time-delay region. For relays operating in their instantaneous region, allow 16 milliseconds on 60 Hz systems for operation. The circuit breaker opening time must be added. Table 1 shows recommended circuit breaker operating times. Opening times for particular circuit breakers can be verified by consulting the manufacturer's literature.

Table 1—Power circuit breaker operating times^a

Circuit breaker rating and type	Opening time at 60 Hz (cycles)	Opening time (seconds)
Low voltage (molded case) (< 1000 V) (integral trip)	1.5	0.025
Low voltage (insulated case) (< 1000 V) power circuit breaker (integral trip or relay operated)	3.0	0.050
Medium voltage (1–35 kV)	5.0	0.080
Some high voltage (> 35 kV)	8.0	0.130

^aThis table does not include the external relay trip times.

For a limited set of cases this information is incorporated into the model and time-current curves are not required. Some classes of current limiting fuses were tested to determine the effect of current limiting action on incident energy and results have been included in the model. See 5.6 for a list of the fuse classes and ratings tested. A generalized solution has been developed for some circuit breakers with integral trip units, and it is part of the model. It is implemented only if the arc current is in the instantaneous or highest level trip range for the circuit breaker. See 5.7 for the types of circuit breakers included in the model.

4.7 Step 6: Document the system voltages and classes of equipment

For each bus, document the system voltage and the class of equipment as shown in Table 2. This will allow application of equations based on standard classes of equipment and bus-to-bus gaps as shown in Table 2.

4.8 Step 7: Select the working distances

Arc-flash protection is always based on the incident energy level on the person's face and body at the working distance, not the incident energy on the hands or arms. The degree of injury in a burn depends on the percentage of a person's skin that is burned. The head and body are a large percentage of total skin surface area and injury to these areas is much more life threatening than burns on the extremities. Typical working distances are shown in Table 3.

Table 2—Classes of equipment and typical bus gaps

Classes of equipment	Typical bus gaps (mm)
15 kV switchgear	152
5 kV switchgear	104
Low-voltage switchgear	32
Low-voltage MCCs and panelboards	25
Cable	13
Other	Not required

Table 3—Classes of equipment and typical working distances

Classes of equipment	Typical working distance ^a (mm)
15 kV switchgear	910
5 kV switchgear	910
Low-voltage switchgear	610
Low-voltage MCCs and panelboards	455
Cable	455
Other	To be determined in field

^aTypical working distance is the sum of the distance between the worker standing in front of the equipment, and from the front of the equipment to the potential arc source inside the equipment.

4.9 Step 8: Determine the incident energy for all equipment

A software program for calculating incident energy must be selected. Clause 6 identifies and discusses the two calculators included with this guide and possible future commercial products. In each case the equations in the models, which appear in Clause 5, are embedded in the program or worksheet. In some programs the problem is solved one bus at a time; with others, hundreds or thousands of buses can be solved simultaneously.

4.10 Step 9: Determine the flash-protection boundary for all equipment

To find the flash-protection boundary, the equations for finding incident energy can be solved for the distance from the arc source at which the onset of a second degree burn could occur. The incident energy must be set at the minimum energy beyond which a second degree burn could occur. The programs include the flash-protection boundary based on an incident energy of 5.0 J/cm^2 .¹¹

¹¹ $5.0 \text{ J/cm}^2 = 1.2 \text{ cal/cm}^2$

5. Model for incident energy calculations

An empirically derived model is provided to enable calculations. Development of this model is discussed in Clause 9. Software programs for applying the model are discussed in Clause 6 and Annex B, and also presented in the auxiliary files.¹² The equations in the model are embedded in the spreadsheet, because it is impractical to solve them by hand.

5.1 Ranges of models

The empirically derived model (see 7.5 and Clause 9), based upon statistical analysis and curve fitting programs, is applicable for systems with

- Voltages in the range of 208 V–15 000 V, three-phase.
- Frequencies of 50 Hz or 60 Hz.
- Bolted fault current in the range of 700 A–106 000 A.
- Grounding of all types and ungrounded.
- Equipment enclosures of commonly available sizes.
- Gaps between conductors of 13 mm–152 mm.
- Faults involving three phases.

A theoretically derived model, based upon Lee's paper [B19], is applicable for three-phase systems in open air substations, and open air transmission and distribution systems. This model is intended for applications where faults will escalate to three-phase faults. Where this is not possible or likely, this model will give a conservative result. Where single-phase systems are encountered, this model will provide conservative results.

5.2 Arcing current

The predicted three-phase arcing current must be found so the operating time for protective devices can be determined.

For applications with a system voltage under 1000 V solve the equation (1):

$$\lg I_a = K + 0.662 \lg I_{bf} + 0.0966 V + 0.000526 G + 0.5588 V (\lg I_{bf}) - 0.00304 G (\lg I_{bf}) \quad (1)$$

where

- $\lg$ is the $\log_{10}$
- I_a is arcing current (kA)
- K is -0.153 for open configurations and
is -0.097 for box configurations
- I_{bf} is bolted fault current for three-phase faults (symmetrical RMS) (kA)
- V is system voltage (kV)
- G is the gap between conductors, (mm) (see Table 4)

For applications with a system voltage of 1000 V and higher solve the equation (2):

$$\lg I_a = 0.00402 + 0.983 \lg I_{bf} \quad (2)$$

The high-voltage case makes no distinction between open and box configurations.

¹²See Footnote 1

Convert from lg:

$$I_a = 10^{\lg I_a} \quad (3)$$

Calculate a second arc current equal to 85% of I_a , so that a second arc duration can be determined (see 9.10.4).

5.3 Incident energy

First find the $\log_{10}$ of the incident energy normalized. This equation is based on data normalized for an arc time of 0.2 seconds and a distance from the possible arc point to the person of 610 mm.

$$\lg E_n = K_1 + K_2 + 1.081 \lg I_a + 0.0011 G \quad (4)$$

where

- E_n is incident energy (J/cm^2) normalized for time and distance ¹³
- K_1 is -0.792 for open configurations (no enclosure) and
is -0.555 for box configurations (enclosed equipment)
- K_2 is 0 for ungrounded and high-resistance grounded systems and
is -0.113 for grounded systems
- G is the gap between conductors (mm) (see Table 4)

Then:

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

Finally, convert from normalized:¹⁴

$$E = 4.184 C_f E_n \left(\frac{t}{0.2} \right) \left(\frac{610^x}{D^x} \right) \quad (6)$$

where

- E is incident energy (J/cm^2)
- C_f is a calculation factor
1.0 for voltages above 1kV, and
1.5 for voltages at or below 1kV
- E_n is incident energy normalized ¹⁵
- t is arcing time (seconds)
- D is distance from the possible arc point to the person (mm)
- x is the distance exponent from Table 4.

The other cases are handled similarly.

¹³Measurement utilized in test laboratories was cal/cm^2 .

¹⁴See E.3.1 for calculation using cal/cm^2 .

¹⁵See Footnote 1.

Table 4—Factors for equipment and voltage classes^a

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

^aThe distance x factor is used in 5.3 as an exponent.

5.4 Lee method

For cases where voltage is over 15 kV, or gap is outside the range of the model, the theoretically derived Lee method can be applied and it is included in the IEEE Std 1584-2002 Incident Energy Calculators.¹⁶ See 7.2 and 9.11.4.

$$E = 2.142 \times 10^6 V I_{bf} \left(\frac{t}{D^2} \right) \quad (7)$$

where¹⁷

- E is incident energy (J/cm²)
- V is system voltage (kV)
- t is arcing time (seconds)
- D is distance from possible arc point to person (mm)
- I_{bf} is bolted fault current

For voltages over 15 kV, arc fault current is considered to be equal to the bolted fault current.

5.5 Flash-protection boundary

For the IEEE Std 1584-2002 empirically derived model:¹⁸

$$D_B = \left[4.184 C_f E_n \left(\frac{t}{0.2} \right) \left(\frac{610^x}{E_B} \right) \right]^{\frac{1}{x}} \quad (8)$$

For the Lee method:¹⁹

¹⁶See Footnote 1.

¹⁷See Footnote 14.

¹⁸See Footnote 14.

$$D_B = \sqrt{2.142 \times 10^6 V I_{bf} \left(\frac{t}{E_B} \right)} \quad (9)$$

where

- D_B is the distance of the boundary from the arcing point (mm)
- C_f is a calculation factor
 - 1.0 for voltages above 1 kV, and
 - 1.5 for voltages at or below 1 kV,
- E_n is incident energy normalized²⁰
- E_B is incident energy in J/cm² at the boundary distance
- t is time (seconds)
- x is the distance exponent from Table 4.
- I_{bf} is bolted fault current

E_B can be set at 5.0 J/cm² for bare skin (no hood) or at the rating of proposed PPE.²¹

5.6 Current limiting fuses

Formulae for calculating arc-flash energies for use with current-limiting Class L and Class RK1 fuses have been developed. These formulae were developed based upon testing at 600 V and a distance of 455 mm using one manufacturer's fuses. The variables are as follows:

- I_{bf} is bolted fault current for three-phase faults (symmetrical RMS) (kA)
- E is incident energy (J/cm²).

5.6.1 Equations for Class L fuses 1601 A–2000 A

For $I_{bf} < 22.6$ kA, calculate arcing current and use time-current curves to determine energy per 5.2 and 5.3:

For I_{bf} , such that $22.6 \text{ kA} \leq I_{bf} \leq 65.9 \text{ kA}$,

$$E = 4.184 (-0.1284 I_{bf} + 32.262) \quad (10)$$

For I_{bf} , such that $65.9 \text{ kA} < I_{bf} \leq 106 \text{ kA}$,

$$E = 4.184 (-0.5177 I_{bf} + 57.917) \quad (11)$$

For $I_{bf} > 106$ kA, contact manufacturer for information.

5.6.2 Equations for Class L fuses 1201 A–1600 A

For $I_{bf} < 15.7$ kA, calculate arcing current and use time-current curves to determine energy per 5.2 and 5.3:

For I_{bf} , such that $15.7 \text{ kA} \leq I_{bf} \leq 31.8 \text{ kA}$,

$$E = 4.184 (-0.1863 I_{bf} + 27.926) \quad (12)$$

¹⁹See Footnote 14.

²⁰See Footnote 13.

²¹5.0 J/cm² = 1.2 cal/cm²

For I_{bf} , such that $31.8 \text{ kA} < I_{bf} < 44.1 \text{ kA}$,

$$E = 4.184 (-1.5504 I_{bf} + 71.303) \quad (13)$$

For I_{bf} , such that $44.1 \text{ kA} \leq I_{bf} \leq 65.9 \text{ kA}$, E is 12.3 J/cm^2 ²²

For I_{bf} , such that $65.9 \text{ kA} < I_{bf} \leq 106 \text{ kA}$,

$$E = 4.184 (-0.0631 I_{bf} + 7.0878) \quad (14)$$

For $I_{bf} > 106 \text{ kA}$, contact manufacturer for information.

5.6.3 Equations for Class L fuses 801 A–1200 A

For $I_{bf} < 15.7 \text{ kA}$, calculate arcing current and use time-current curves to determine energy per 5.2 and 5.3:

For I_{bf} , such that $15.7 \text{ kA} \leq I_{bf} \leq 22.6 \text{ kA}$,

$$E = 4.184 (-0.1928 I_{bf} + 14.226) \quad (15)$$

For I_{bf} , such that $22.6 \text{ kA} < I_{bf} \leq 44.1 \text{ kA}$,

$$E = 4.184 (0.0143 I_{bf}^2 - 1.3919 I_{bf} + 34.045) \quad (16)$$

For I_{bf} , such that $44.1 \text{ kA} < I_{bf} \leq 106 \text{ kA}$, $E = 1.63$

For $I_{bf} > 106 \text{ kA}$, contact manufacturer for information.

5.6.4 Equations for Class L fuses 601 A–800 A

For $I_{bf} < 15.7 \text{ kA}$, calculate arcing current and use time-current curves to determine energy per 5.2 and 5.3:

For I_{bf} , such that $15.7 \text{ kA} \leq I_{bf} \leq 44.1$,

$$E = 4.184 (-0.0601 I_{bf} + 2.8992) \quad (17)$$

For I_{bf} , such that $44.1 \text{ kA} < I_{bf} \leq 106 \text{ kA}$, $E = 1.046$

For $I_{bf} > 106 \text{ kA}$, contact manufacturer for information.

5.6.5 Equations for Class RK1 fuses 401 A–600 A

For $I_{bf} < 8.5 \text{ kA}$, calculate arcing current and use time-current curves to determine energy per 5.2 and 5.3:

For I_{bf} , such that $8.5 \text{ kA} \leq I_{bf} \leq 14 \text{ kA}$,

$$E = 4.184 (-3.0545 I_{bf} + 43.364) \quad (18)$$

For I_{bf} , such that $14 \text{ kA} < I_{bf} \leq 15.7 \text{ kA}$, $E = 2.510$

For I_{bf} , such that $15.7 \text{ kA} < I_{bf} \leq 22.6 \text{ kA}$,

²² $12.3 \text{ J/cm}^2 = 2.93 \text{ cal/cm}^2$

$$E = 4.184 (-0.0507 I_{bf} + 1.3964) \quad (19)$$

For I_{bf} , such that $22.6 \text{ kA} < I_{bf} \leq 106 \text{ kA}$, $E = 1.046$

For $I_{bf} > 106 \text{ kA}$, contact manufacturer for information.

5.6.6 Equations for Class RK1 fuses 201 A–400 A

For $I_{bf} < 3.16 \text{ kA}$, calculate arcing current and use time-current curves to determine energy per 5.2 and 5.3:

For I_{bf} , such that $3.16 \text{ kA} \leq I_{bf} \leq 5.04 \text{ kA}$,

$$E = 4.184 (-19.053 I_{bf} + 96.808) \quad (20)$$

For I_{bf} , such that $5.04 \text{ kA} < I_{bf} \leq 22.6 \text{ kA}$,

$$E = 4.184 (-0.0302 I_{bf} + 0.9321) \quad (21)$$

For I_{bf} , such that $22.6 \text{ kA} < I_{bf} \leq 106 \text{ kA}$, $E = 1.046$

For $I_{bf} > 106 \text{ kA}$, contact manufacturer for information.

5.6.7 Equations for Class RK1 fuses 101A–200 A

For $I_{bf} < 1.16 \text{ kA}$, calculate arcing current and use time-current curves to determine energy per 5.2 and 5.3:

For I_{bf} , such that $1.16 \text{ kA} \leq I_{bf} \leq 1.6 \text{ kA}$,

$$E = 4.184 (-18.409 I_{bf} + 36.355) \quad (22)$$

For I_{bf} , such that $1.6 \text{ kA} < I_{bf} \leq 3.16 \text{ kA}$,

$$E = 4.184 (-4.2628 I_{bf} + 13.721) \quad (23)$$

For I_{bf} , such that $3.16 \text{ kA} < I_{bf} \leq 106 \text{ kA}$, $E = 1.046$

For $I_{bf} > 106 \text{ kA}$, contact manufacturer for information.

5.6.8 Equations for Class RK1 fuses up to 100 A

For $I_{bf} < 0.65 \text{ kA}$, calculate arcing current and use time-current curves to determine energy per 5.2 and 5.3:

For I_{bf} , such that $0.65 \text{ kA} \leq I_{bf} \leq 1.16 \text{ kA}$,

$$E = 4.184 (-11.176 I_{bf} + 13.565) \quad (24)$$

For I_{bf} , such that $1.16 \text{ kA} < I_{bf} \leq 1.4 \text{ kA}$,

$$E = 4.184 (-1.4583 I_{bf} + 2.2917) \quad (25)$$

For I_{bf} , such that $1.4 \text{ kA} < I_{bf} \leq 106 \text{ kA}$, $E = 1.046$

For $I_{bf} > 106 \text{ kA}$, contact manufacturer for information.

5.7 Low-voltage circuit breakers

Equations have been developed for systems using low-voltage circuit breakers that will output values for incident energy and flash-protection boundary when the available bolted fault current is known or can be calculated. These equations do not require availability of the time-current curves for the circuit breaker, but they must be used within the appropriate range indicated below. See 9.14 for details on development of this part of the model. For conditions of bolted fault current below the range indicated for Table 5, the arc current and incident energy equations in 5.2 and 5.3 must be used.

Table 5—Equations for incident energy and flash-protection boundary by circuit breaker type and rating^a

Rating (A)	Breaker type	Trip unit type	480 V and lower		575–690 V	
			Incident energy (J/cm ²) ^b	Flash boundary (mm)	Incident energy (J/cm ²)	Flash boundary (mm)
100–400	MCCB	TM or M	$0.189 I_{bf} + 0.548$	$9.16 I_{bf} + 194$	$0.271 I_{bf} + 0.180$	$11.8 I_{bf} + 196$
600–1200	MCCB	TM or M	$0.223 I_{bf} + 1.590$	$8.45 I_{bf} + 364$	$0.335 I_{bf} + 0.380$	$11.4 I_{bf} + 369$
600–1200	MCCB	E, LI	$0.377 I_{bf} + 1.360$	$12.50 I_{bf} + 428$	$0.468 I_{bf} + 4.600$	$14.3 I_{bf} + 568$
1600–6000	MCCB or ICCB	TM or E, LI	$0.448 I_{bf} + 3.000$	$11.10 I_{bf} + 696$	$0.686 I_{bf} + 0.165$	$16.7 I_{bf} + 606$
800–6300	LVPCB	E, LI	$0.636 I_{bf} + 3.670$	$14.50 I_{bf} + 786$	$0.958 I_{bf} + 0.292$	$19.1 I_{bf} + 864$
800–6300	LVPCB	E, LS ^c	$4.560 I_{bf} + 27.230$	$47.20 I_{bf} + 2660$	$6.860 I_{bf} + 2.170$	$62.4 I_{bf} + 2930$

^aRefer to Annex E for Table 5 (Table E.1) in cal/cm².

^b I_{bf} is in kA, working distance is 460 mm.

^cShort time delay is assumed to be set at maximum.

The types of circuit breakers are as follows:

- MCCB: molded-case circuit breaker
- ICCB: insulated-case circuit breaker
- LVPCB: low-voltage power circuit breakers

The types of trip units are briefly defined as follows:

- TM: Thermal-magnetic trip units.
- M: Magnetic (instantaneous only) trip units.
- E: Electronic trip units have three characteristics that may be used separately or in combination,
 - (L) long-time
 - (S) short-time and
 - (I) instantaneous. A trip unit may be designated LI when it has both long-time and instantaneous features. Other common designations are LS and LSI.

The range of these equations is 700 A–106 000 A for the voltages shown in Table 5. Each equation is applicable for the range $I_1 < I_{bf} < I_2$.

I_2 is the interrupting rating of the CB at the voltage of interest.

I_1 is the minimum bolted fault current at which this method can be applied. I_1 is the lowest bolted fault current level that generates arcing current great enough for instantaneous tripping to occur or for circuit breakers with no instantaneous trip, the lowest current at which short time tripping occurs.

To find I_1 , use the manufacturer's time-current curve, if it is readily available, and take the instantaneous trip value, I_t , from the curve as shown in Figure 1. If the curve is not available, but the instantaneous trip setting is shown on the breaker, use that setting. When the tripping current, I_t , is not known, use a default value of 10 times the continuous current rating of the CB, except for CBs rated 100 A and below, use a default value of $I_t = 1300$ A. Where an LS trip unit is used, I_t is the short-time pick-up current.

The corresponding bolted fault current, I_{bf} , is found by solving the model equation for arc current in 5.2 for box configurations by substituting I_t for arcing current. The 1.3 factor in Equation (26) adjusts current to the top of the tripping band.

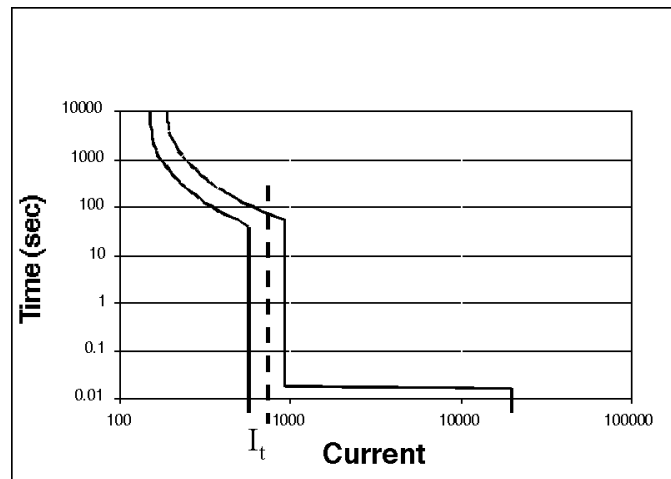


Figure 1—Typical circuit breaker time-current characteristic

$$\lg (1.3 I_t) = -0.084 + 0.096 V + 0.586 (\lg I_{bf}) + 0.559 V (\lg I_{bf}) \quad (26)$$

Solving for I_{bf} at the point I_1 for 600 V:

$$\lg I_1 = 0.0281 + 1.09 \lg (1.3 I_t) \quad (27)$$

Solving for I_{bf} at the point I_1 for 480 V and lower:

$$\lg I_1 = 0.0407 + 1.17 \lg (1.3 I_t) \quad (28)$$

$$I_{bf} = I_1 = 10^{\lg I_1} \quad (29)$$

6. Methods of applying the model

6.1 IEEE Std 1584-2002 arc-flash calculator

This is a program that is included with this guide, which is designed to calculate the incident energy and the flash-protection boundary.²³ The program may be used for simple radial systems or complex systems with multiple sources, many buses, and various plant operating modes. Input data is derived from the results of

²³See Footnote 1.

short-circuit and protective-device coordination studies. If a short-circuit program is not available, a bolted fault calculator, which is also included with this standard, may be used for simple radial systems.

6.2 Integrated system analysis method

Arc-flash calculations can be completely automated once software vendors integrate these models into their available short-circuit and protective-device coordination program.

IEEE offers licenses for this use of the models in software for commercial purposes.

7. Comparison of arc-flash calculation methods

Previously, a number of methods of performing arc-flash calculations have been used. Users must choose from the available methods. The empirically derived model in this guide is based upon data obtained from testing in four certified test laboratories over several years (see test data spreadsheets).²⁴

7.1 Table method in NFPA 70E-2000

The simplest method for determining PPE requirements for arc-flash protection is to use the tables in NFPA 70E-2000. These tables give instant answers and require almost no field data. It should be noted that these tables are for specific fault currents and specific clearing times, and the tables do not cover all applications or installations of electrical equipment. While these tables are intended to be conservative for most applications, they may not enable the user to select adequate protection.

7.2 Theory based model

Ralph Lee [B19] developed a theory based model of the arc flash. It served for many years as the only method available. Its biggest limitation is that it does not include a method of finding arc current, which is very important for cases under 1000 V. It also does not consider magnifying effects of arc in a box. For applications greater than 1000 V, it is quite conservative. This method is included in this guide and in the calculators for applications where the empirically derived model is not suitable, such as those in open air substations, and open air transmission and distribution systems.

7.3 Empirically derived models based on a curve fitting program

Empirically based methods developed by applying a curve fitting program to test data have been offered since the mid 1990s in published papers (see Bibliography in Annex F) and in the 1995 and 2000 editions of NFPA 70E. These methods are based on a limited amount of laboratory testing, as stated in the papers. They do not include the interaction between variables but do provide reasonably accurate results when compared to the model in this standard. The additional testing for the model in this guide allows application to a broader range of voltages, currents, enclosure sizes, and bus gaps. The model in this guide represents further development of the earlier models (see 7.5).

7.4 Physical model based method with some verification testing

A physical model based method was developed and involves analysis of heat flow from each element of a theoretical arc in open air. The model has been verified by single-phase testing with electrodes spaced

²⁴See Footnote 1.

51 mm–305 mm apart and pointed toward each other. This is the only currently available method for electrode spacing greater than 152 mm having a verification database.

7.5 Empirically derived model based on statistical analysis and curve fitting programs

This guide is based on the extensive set of test data, shown in test data database spreadsheets.²⁵ The data includes all suitable data from previous testing and the programs conducted or witnessed by representatives of the IEEE Std 1584-2002 working group. The process of analyzing the data and developing the model is discussed in Clause 9. This model is designed for systems having:

- Voltages in the range of 208 V–15 000 V, three-phase.
- Frequencies of 50 or 60 Hz.
- Bolted fault current in the range of 700 A–106 000 A.
- Grounding of all types and ungrounded.
- Equipment enclosures of commonly available sizes.
- Cable and conductors in air, with gaps between conductors of 13 mm–152 mm.
- Faults involving three phases.

Use of this model is recommended for applications within the parameters stated in this subclause. The theory based and physical (see 7.2 and 7.4) models are still useful for some applications, such as those in open air substations, and open air transmission and distribution systems.

8. Laboratory test programs

Researchers have conducted a number of test programs at high power laboratories for the purpose of developing an understanding of the electrical characteristics of arc flashes and the resultant incident energy. Researchers have also endeavored to build a database that could be used to develop empirically based equations or to verify physical model based equations. This standard includes a description of all test programs (see 8.1) and a collection of the test data (see auxiliary spreadsheet files) that have been used in the development of this guide.²⁶

Three basic types of test setups were employed in the testing as follows:

- A) Single-phase arc in open air with electrodes in-line as shown in Figure 2.
- B) Three-phase arcs in open air with parallel electrodes as shown in Figure 3.
- C) Three-phase arcs in a box with parallel electrodes as shown in Figure 4.

²⁵See Footnote 1.

²⁶See Footnote 1.

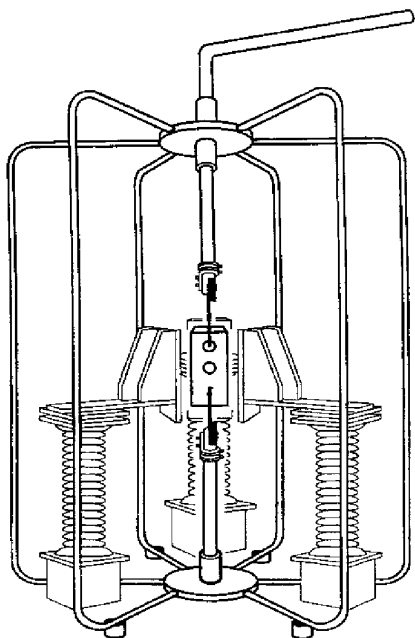


Figure 2—Test setup A—single-phase arc in air with electrodes in line and with partial faraday cage

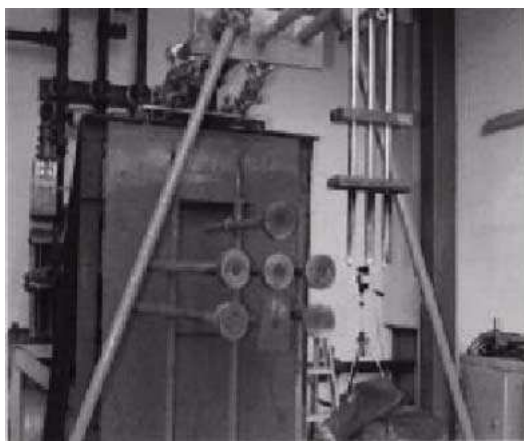


Figure 3—Test setup B—three-phase arc in air with electrodes in parallel

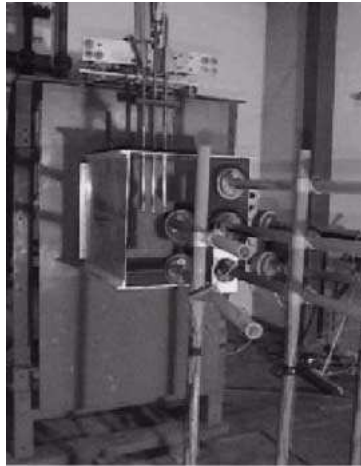


Figure 4—Test setup C—arc in box

8.1 Overview of test programs

The first test program to explore incident energy testing was reported in “Protective clothing guidelines for electric arc exposure” [B22]. Testing was conducted in laboratory 1 using all three of the basic test setups.

The next paper, “Testing update on protective clothing and equipment for electric arc exposure” [B3], used test setups B and C. In some cases only the back of a box was used—a flat panel. In others a test box of 559 mm × 508 mm × 533 mm dimensions deep was used.²⁷ Testing was conducted in laboratory 1.

“Predicting incident energy to better manage the electric arc hazard” [B4], was based on test setups B and C and employed a 508 mm × 508 × 508 mm box.²⁸ Testing was conducted in laboratory 1.

“The use of current limiting fuses to reduce arc flash energy” [B5], used test setup C, with the addition of current limiting fuses between the laboratory supply and the test box. Tests were also conducted without the fuses to establish a baseline. The box was 508 mm × 508 × 508 mm box.²⁹ Testing was conducted in laboratory 2.

A basis for incident energy calculations at 2400 V was developed jointly by 2 laboratories. Test setups B and C were used in both laboratories. The test box was 1143 mm × 762 × 762 mm, simulating a medium voltage equipment enclosure. This data was not previously published.³⁰

Testing was performed in laboratory 1 to develop a verification database for a proprietary analysis program. It used test setup A, two vertical electrodes inline or pointed at each other. They were mounted in a partial faraday cage of the type described in ASTM F-1959-99. The electrodes were 25.4 mm round hard drawn copper.³¹

²⁷559 mm × 508 mm × 533 mm = 22" × 20" × 21"

²⁸508 mm × 508 × 508 mm = 20" × 20" × 20"

²⁹See Footnote 28.

³⁰1143 mm × 762 × 762 mm = 45" × 30" × 30"

³¹25.4 mm = 1"

Testing was performed in laboratory 3 to investigate the effect of the pressure generated by an arc flash on ship compartments. Incident energy testing was included as part of that program and witnessed by representatives of the IEEE Std 1584-2002 working group. The laboratory used a test chamber that simulated a ship compartment for all tests. It was a 13.6 metric ton, 4.9 m × 4.9 m × 3 m enclosure made of steel plate with reinforcing channels and equipped with two naval bulkhead doors.^{32, 33} The doors were opened or closed as noted in the data sheet. The test setup was a slight modification of setup B, with the electrodes mounted horizontally and piercing the center of the side wall of the compartment. Tests were run at 450 V, 4160 V, and 13 800 V ac and at 1000 V dc.

Further testing was conducted by the IEEE Std 1584-2002 working group in laboratory 1 to extend the range of 508 mm box test data—test setup C, and thereby extend the range of current limiting fuse data available, and to test used equipment that had been donated.³⁴ The used equipment included circuit breakers, so that the effects of those circuit breakers on arc-flash energy were documented.

Testing was conducted by the IEEE Std 1584-2002 working group in laboratory 4. It used test setup C with a 356 mm × 305 mm × 191 mm enclosure.³⁵ For smaller bus gaps the electrodes were 6.35 mm × 19.05 mm copper bus bars.³⁶ For larger gaps they were the standard 19.05 mm diameter hard drawn copper wire.³⁷

8.2 Physical test methodology

The test method for determining the ability of materials to provide protection against electrical arc flashes is defined in ASTM F-1959-99. The ASTM standard is the basis for the incident energy testing described in this guide. It is intended by ASTM to enable determination of the incident energy that clothing material can withstand up to the point at which there is a 50% probability that skin under the material would receive a second degree burn. The test methodology works equally well to determine the incident energy to which a worker would be exposed in case of an arc in a specified electrical installation. The results of the two types of tests are complementary.

For each incident energy test, an array of seven copper calorimeters was located in front of the test electrodes, at a distance D from the centerline of the electrodes. A set of three calorimeters was located in a horizontal row at the same height as the tip of the electrodes. A second set of three calorimeters was located in a horizontal row 152 mm below the elevation of the electrode tips. The middle calorimeters in each set were aligned with the center electrode. A single calorimeter was located 152 mm above the center electrode tip.³⁸

Incident energy was determined by calculation based on the temperature rise of the copper calorimeters mounted in front of the electrodes. Copper calorimeter temperature rise data in degrees Celsius was converted into incident energy in J/cm² by multiplying the temperature by 0.565.³⁹ Sensor absorption measurements have determined that absorbed energy is equal to or greater than 90% of incident energy for copper calorimeters. Therefore, incident and absorbed energy are considered as equivalent, and the term incident energy is used.

In order to simulate electrical equipment, hard drawn copper wire, 19.05 mm in diameter, was used for arc electrodes in all cases except where noted. Electrodes were typically vertically oriented in a flat configuration with a side-side spacing. Arcs were initiated by a 10 AWG wire connected between the ends of

³²13.6 metric tons = 15 tons

³³4.9 m × 4.9 m × 3 m = 16' × 16' × 10'

³⁴508 mm = 20"

³⁵356 mm × 305 mm × 191 mm = 14" × 12" × 7.5"

³⁶6.35 mm × 19.05 mm = 0.250" × 0.750"

³⁷19.05 mm = 0.750"

³⁸152 mm = 6"

³⁹To calculate incident energy in cal/cm², multiply temperature in degrees Celsius by 0.135.

the electrodes. For all tests it was necessary to install insulating support blocks between adjacent electrodes to prevent the electrodes from bending outward due to the extremely high magnetic forces created by the arc currents.

The bolted fault current available at the test terminals was measured by shorting the electrodes together at the top. The duration of all arc tests was selected to minimize damage to the test setup but to allow a measurable temperature rise on the calorimeters.

Phase currents and voltages were measured digitally and RMS values were computed. Arc power was computed by integrating the products of phase current and voltage and summing the results. Arc energy was computed by integrating arc power over the arc duration. Typically, all of the described data manipulation was performed using the menu/computation functions resident on the digital oscilloscope.

In order to reduce the impact of arc variability, multiple tests were run for each setup. Since arc duration varies slightly from test to test, a time duration correction factor was applied to the temperature rise data from the seven copper calorimeter sensors to ensure that each reported incident energy was based on an arc duration of 200 milliseconds. For the early test programs, the mean incident energy for the seven sensors and the mean maximum incident energy recorded by a single sensor were calculated for each test. In the testing monitored by the committee, each test was reported separately, so mean and maximum incident energy were reported.

8.3 Design of experiments (DOE) method of planning and analyzing tests

In all of the early testing, the test programs involved changing one variable at a time while keeping other variables fixed. This allowed easy development of equations but did not consider the possible interactions between variables. In the testing sponsored by the IEEE Std 1584-2002 working group at laboratory 1 and laboratory 4, the design of experiments (DOE) method was used to permit analysis of the impact of all possible variables.

The DOE method enables determining the effects that different variables can have when all are varied during the process over their ranges. It was important to determine if there are any interactions between the variables for arc-flash incident energy. The use of factorial experiments in the DOE method was the best known way to determine the existence of these possibly important interactions.

Factorial designs allow for the simultaneous study of the effects that several factors may have on a process. Efficiency is obtained by allowing the program to select the number of tests needed and the points for each variable at which each test must be run. The results of the factorial experiments can be analyzed with commercially available software to determine the relative importance of the variables and any interactions. The next step can be more detailed testing of the important variables and their interactions.

A partial factorial DOE was laid out that studied these variables: open-circuit voltage, system grounding, bolted fault current, X/R ratio, gap between electrodes, gap between electrodes and box, and box size

Statistical analysis programs, including regression analysis, were applied to analyze the test data and develop equations.

The curve-fitting program in spreadsheet program has been used to develop distance exponents, current limiting fuse equations, and circuit breaker equations.

9. Development of model

9.1 Range of model

The model is applicable for systems with:

- Voltages in the range of 208 V–15 000 V, three-phase.
- Frequencies of 50 or 60 Hz.
- Bolted fault current in the range of 700 A–106 000 A.
- Grounding of all types and ungrounded.
- Equipment enclosures of commonly available sizes.
- Gaps between conductors of 13 mm–152 mm.
- Faults involving three phases.

9.2 Summary of conclusions from studies

Analysis of the data allowed the following conclusions:

- Arc time has a linear affect on incident energy.
- Distance from the arc to the calorimeters has an inverse exponential affect, with the exponent depending on the enclosure size.
- The inclusion of system grounding had the effect of improving the R-square of the incident energy equation by 1% [R-square is a measure of the equation fit to the data (see 9.10.3 and 9.11.2)].
- System X/R ratio, frequency, electrode material, and other variables that were considered were found to have little or no effect on arc current and incident energy, and so they are neglected.
- Arc current depends primarily on available fault current. Bus gap (the distance between conductors at the point of fault), system voltage, and grounding type are smaller factors.
- Incident energy depends primarily on calculated arc current. Bus gap is a small factor.

9.3 Results by variable

9.3.1 Bolted fault current

Tests were done over the following ranges of bolted fault currents.

- At 13.8 kV: 5.7 kA–40.8 kA
- At 4.16 kV: 5.4 kA–40.4 kA
- At 2.3 kV: 2.6 kA–16.6 kA
- At <1 kV: 0.7 kA–106 kA

These ranges cover the majority of bolted fault currents that are found in industrial and commercial systems. Some 208 V, 2.3 kV, and 4.16 kV systems can have much higher bolted fault currents than were tested, but the model can still be used for these systems and will give conservative results.

9.3.2 Voltage

Testing covered the range 208 V–13 800 V.

It was difficult to sustain an arc at the lower voltages. An arc was sustained only once at 208 V in a 508 mm × 508 mm × 508 mm box. In all other tests with that box and the 305 mm × 368 mm × 191 mm box, the arc blew itself out as soon as the fuse wire vaporized.⁴⁰ An arc was sustained several times at 215 V in a device box (100 mm × 100 mm × 50 mm size).⁴¹ It appeared from the arc-flash photos from the

305 mm × 368 mm × 191 mm box that testing arcs usually jumped from the electrodes to the box wall and from another point on the box wall back to another electrode. The magnetic forces created by these arc currents forced them away from each other and into the box wall.

Arc faults can be sustained at 208 V and have caused severe injuries with very high short-circuit current applications in meter enclosures. A meter enclosure is small and tends to confine an arc more than laboratory test boxes with no door. Used equipment at 208 V was not tested, but it is recognized that many types of equipment have relatively small open spaces between components, such as the space in a panelboard between the circuit breakers and the wall of the enclosure.

While the accuracy of the model at 208 V is not in the same class with the accuracy at 250 V and higher, it will work and will yield conservative results. The arc-flash hazard need only be considered for large 208 V systems: systems fed by transformers smaller than 125 kVA should not be a concern.

The model is based on testing at voltages of 208, 400, 450, 480, 600, 2400, 4160, and 13 800 V. Enclosure sizes and electrode or bus gaps were appropriate relative to the voltages as shown in Figure 5.

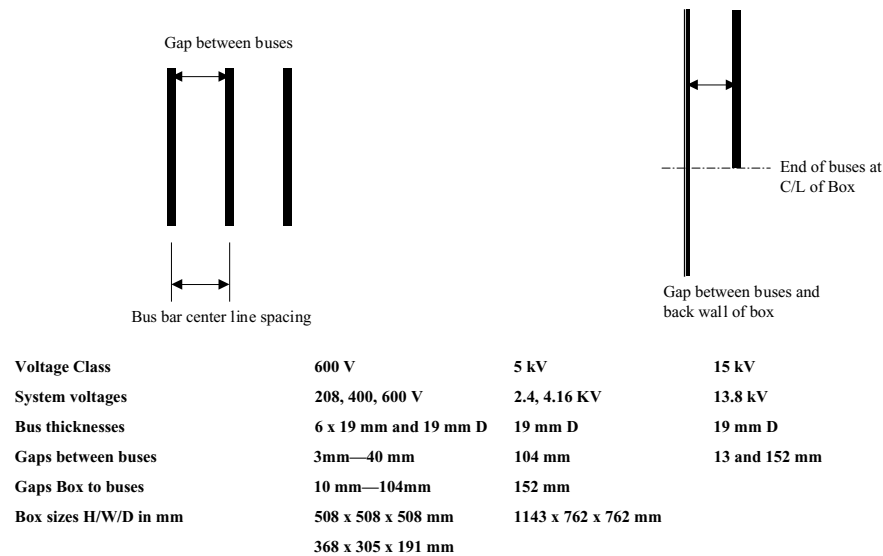


Figure 5—Bus spacing and box sizes tested

9.4 Electrode gap and box gap

In all testing used in the model, electrodes were parallel and in a flat configuration, the same as typical equipment buses. The gap between the electrodes (buses) and between the electrodes and the back wall of the boxes was as shown in Figure 5. These gaps are intended to be typical gaps found in equipment. Gaps in 400 V IEC equipment can be as small as 10 mm. In attempts to sustain arcs at 208 V even smaller gaps were tested. Gaps of 13 mm were used for low voltage and 13.8 kV testing to simulate gaps between conductors in cables.

⁴⁰508 mm × 508 mm × 508 mm = 20" × 20" × 20"
305 mm × 368 mm × 191 mm = 12" × 14" × 7.5"
⁴¹100 mm × 100 mm × 50 mm = 4" × 4" × 2"

9.5 Grounding

Medium voltage testing involved ungrounded systems. Low-voltage testing involved grounded, ungrounded, and high-resistance grounded systems.

Grounding turned out to be statistically significant for incident energy and increases the R-square of the fit (statistical alignment between measured and calculated values) by about 1% for low-voltage systems.

Two grounding classes are applied in the equations considered, as follows:

- a) Ungrounded, which included ungrounded, high-resistance grounding and low-resistance grounding.
- b) Solidly grounded.

There was no basis for further differentiating results.

9.6 Fault types

All testing used in the basic incident energy model was three-phase testing because three-phase arcs produce the greatest possible arc-flash hazard in ac equipment. Open bus switchyards and open conductor lines where single-phase faults are likely can only be addressed as three-phase faults using the models in this guide.

Consider the other possibilities.

- Line-to-line faults: It is widely recognized that line-to-line faults in equipment or cables quickly escalate into three-phase faults.
- Low-voltage (LV) solidly grounded system ground faults: These faults also escalate very quickly into three-phase faults.
- LV ungrounded and high-resistance system ground faults: These faults will not result in a significant release of energy, as long as the first fault to ground is cleared before a second phase faults to ground. As this does not always occur, three-phase fault must still be considered a possibility.
- Medium voltage (MV) low resistance or reactance grounded system ground faults: These faults should be cleared quickly with only a limited release of energy. However, worst case three-phase faults must still be considered.

9.7 Time

Incident energy (E) is proportional to arc duration (time), all other factors being fixed. All data points where a given configuration of factors, other than time and distance, were run at more than one level of time were considered. Each set of “replicate points” (i.e., points that had the same configuration of factors, other than time and distance) was assigned a unique “replicate group” identification number. This included the tests points where time was considered as a variable as well as some additional points were tested specifically. $Lg(E_{max})$ was then calculated, where maximum incident energy (E_{max}) was normalized for distance but not for time. The general linear model (GLM) was then used to fit a model for $lg(IE_{max})$ consisting of the terms “replicate group” and $lg(time)$, as a covariate. The “replicate group” factor then accounts for any differences due to other variables, and the coefficient of the $lg(time)$ factor then indicates the slope of the effect of time (in the log scale). It turned out that the estimated coefficient of $lg(time)$ was very close to 1 and not statistically different from 1, thus supporting the assumption that incident energy is proportional to time.

9.8 Frequency

Nearly all the testing was done at 60 Hz. Some tests were done at 50 Hz to compare the incident energy values at this lower frequency. The results of the incident energy tests were the same statistically as identical tests at 60 Hz. The system of equations for calculating arcing current and incident energy should be accurate over the range of 50 Hz to 60 Hz.

There is ongoing testing at dc, but it was not used in this analysis. Therefore dc and other frequencies of operation such as 400 Hz are not included in the IEEE Std 1584-2002 empirically derived model.

9.9 Electrode materials

Most of the three-phase testing was done with hard-drawn copper as the electrode material. Some testing with soft copper was done. The effect of the electrode material was insignificant compared to the other variables.

Another test database that was made available to the working group included tests with electrode materials of stainless steel, aluminum, and copper. These tests were single-phase arcs, and so the data could not be combined with the other test points in the database. However, the data can be used to compare the materials of construction of the electrodes where a fault might occur. An analysis of variance on the data, with incident energy values normalized for arc duration and distance from the arc, shows no significant difference between copper and aluminum. The arcing current and incident energy values for the tests with steel electrodes were lower as a group than the aluminum/copper electrodes, but it was unclear whether this was because of lower arcing current due to the steel electrodes or to lower bolted fault current.

Since typical equipment buses are copper and/or aluminum, it is reasonable to ignore the electrode materials when predicting incident energy for an arc flash. Some part of the arc-flash hazard, such as droplets of molten metal ejected from the faulted equipment, will depend on the electrode material; but this would be very difficult to measure and predict. It seems reasonable to ignore the materials at this time. Perhaps in the future, more detailed testing will be done to help in understanding the smaller effects of all the other variables in an arc-flash incident.

9.10 Arc current

The predicted three-phase arcing current must be found so the operating time for protective devices can be determined. First the equations are presented, then the statistical analysis used to develop them is shown (see auxiliary files).⁴²

For arc current, separate models were developed for the low ($< 1\text{ kV}$) and high ($> 1\text{ kV}$) open circuit voltage cases. The statistical analysis is presented first, and then the equations for the model follow.

⁴²See Footnote 1.

9.10.1 Regression analysis for I_g of arc current for LV

The best way to find I_a is by finding $\lg I_a$. A copy of the statistical analysis report that is used to find $\log_{10}$ of arc current is presented in Figure 6.

PROGRAM OUTPUT 1. REGRESSION ANALYSIS OF ARC CURRENT AT LOW VOLTAGE

Program Output for:

logIarc versus Variables for LV Data Points

Analysis of Variance for logIarc, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Open/Box	1	0.5510	0.0319	0.0319	8.30	0.005
logIbf	1	14.3291	0.2046	0.2046	53.28	0.000
Voltage	1	0.4683	0.0005	0.0005	0.13	0.716
logIbf*Voltage	1	0.0295	0.0438	0.0438	11.40	0.001
ElectrGap	1	0.0941	0.0004	0.0004	0.10	0.749
logIbf*ElectrGa	1	0.0242	0.0242	0.0242	6.30	0.014
Error	70	0.2688	0.2688	0.0038		
Total	76	15.7650				

Term	Coef	SE Coef	T	P
Constant	-0.1249	0.1486	-0.84	0.404
Open/Box				
Box	0.028274	0.009814	2.88	0.005
logIbf	0.66200	0.09069	7.30	0.000
Voltage	0.0966	0.2642	0.37	0.716
logIbf*Voltage	0.5588	0.1655	3.38	0.001
ElectrGap	0.000526	0.001637	0.32	0.749
logIbf*ElectrGa	-0.003043	0.001213	-2.51	0.014

Unusual Observations for logIarc

Obs	logIarc	Fit	SE Fit	Residual	St Resid
1	1.66257	1.80071	0.01652	-0.13814	-2.31R
17	1.09945	0.93623	0.02730	0.16322	2.93R
18	0.64994	0.81099	0.01973	-0.16106	-2.74R
32	1.07041	1.14803	0.03508	-0.07763	-1.52 X
68	0.25840	0.28119	0.03766	-0.02280	-0.46 X
70	0.27753	0.41699	0.01652	-0.13946	-2.33R
72	0.27257	0.29872	0.03829	-0.02616	-0.54 X
76	1.31917	1.36642	0.03337	-0.04725	-0.90 X
77	1.81398	1.93033	0.02758	-0.11635	-2.10R

R denotes an observation with a large standardized residual.

X denotes an observation whose X value gives it large influence.

Figure 6—Program output 1—Regression analysis of $\log_{10}$ of arc current, I_g , for LV

The equation can be extracted from this program output. The terms are in the “Term” column and coefficients are in the “Coef” column. Most are straightforward, but the “Open/Box” coefficient is subtracted from the constant coefficient for open configurations and added to the constant coefficient for enclosed or box configurations. The terms shown in the figure are illustrated in Equation (30):