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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.

Warranty

[a]The numbers in brackets correspond to those of the bibliography in Annex F.

Acknowledgments

Many organizations and individuals made cash or in-kind contributions that enabled the test program on which this guide is based. The IEEE Std 1584-2002 working group and IEEE gratefully acknowledge these contributions.

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Duke Energy

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SKM Systems

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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At the time this standard was completed, the working group had the following membership:

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When the IEEE-SA Standards Board approved this standard on 12 September 2002, it had the following membership:

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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.

[1]The 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 141™-1993, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants *(IEEE Red Book™)*.[4, 5]

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

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

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

IEEE Std C37.20.7™-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.

[2]ASTM 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/).
[3]U.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/).
[4]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).
[5]The IEEE standards referred to in Clause 2 are trademarks of the Institute of Electrical and Electronics Engineers, Inc.
[6]NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA.
[7]The 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.

[8]Information on references can be found in Clause 2.

[9]To 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.

[10] 37 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

[a]This 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

[a]Typical 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 J/cm^2 = 1.2 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.

[12] See Footnote 1

Convert from lg:

$$I_a = 10^{\lg I_a} \tag{3}$$

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.

$$\lg E_n = K_1 + K_2 + 1.081 \lg I_a + 0.0011\, G \tag{4}$$

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:

$$E_n = 10^{\lg E_n} \tag{5}$$

Finally, convert from normalized:[14]

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

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.

[13]Measurement utilized in test laboratories was cal/cm^2.
[14]See E.3.1 for calculation using cal/cm^2.
[15]See 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

[a]The 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.

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

where[17]

E is incident energy (J/cm^2)
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]

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

For the Lee method: [19]

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[16]See Footnote 1.
[17]See Footnote 14.
[18]See Footnote 14.

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

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 normalized[20]
E_B	is incident energy in J/cm^2 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/cm^2 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/cm^2).

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 kA ≤ I_{bf} ≤ 65.9 kA,

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

For I_{bf}, such that 65.9 kA < I_{bf} ≤ 106 kA,

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

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 kA ≤ I_{bf} ≤ 31.8 kA,

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

[19]See Footnote 14.
[20]See Footnote 13.
[21]5.0 J/cm^2 = 1.2 cal/cm^2

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

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

For I_{bf}, such that 44.1 kA ≤ I_{bf} ≤ 65.9 kA, E is 12.3 J/cm^2 [22]

For I_{bf}, such that 65.9 kA < I_{bf} ≤ 106 kA,

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

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

5.6.3 Equations for Class L fuses 801 A–1200 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 kA ≤ I_{bf} ≤ 22.6 kA,

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

For I_{bf}, such that 22.6 kA < I_{bf} ≤ 44.1 kA,

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

For I_{bf}, such that 44.1 kA < I_{bf} ≤ 106 kA, E = 1.63

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

5.6.4 Equations for Class L fuses 601 A–800 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 kA ≤ I_{bf} ≤ 44.1,

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

For I_{bf}, such that 44.1 kA < I_{bf} ≤ 106 kA, E = 1.046

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

5.6.5 Equations for Class RK1 fuses 401 A–600 A

For I_{bf} < 8.5 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 kA ≤ I_{bf} ≤ 14 kA,

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

For I_{bf}, such that 14 kA < I_{bf} ≤ 15.7 kA, E = 2.510

For I_{bf}, such that 15.7 kA < I_{bf} ≤ 22.6 kA,

[22]12.3 J/cm^2 = 2.93 cal/cm^2

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

For I_{bf}, such that 22.6 kA< I_{bf} ≤106 kA, E = 1.046

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

5.6.6 Equations for Class RK1 fuses 201 A–400 A

For I_{bf} < 3.16 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 kA ≤ I_{bf} ≤ 5.04 kA,

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

For I_{bf}, such that 5.04 kA < I_{bf} ≤ 22.6 kA,

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

For I_{bf}, such that 22.6 kA < I_{bf} ≤106 kA, E = 1.046

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

5.6.7 Equations for Class RK1 fuses 101A–200 A

For I_{bf} < 1.16 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 kA ≤ I_{bf} ≤ 1.6 kA,

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

For I_{bf}, such that 1.6 kA < I_{bf} ≤ 3.16 kA,

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

For I_{bf}, such that 3.16 kA < I_{bf} ≤ 106 kA, E = 1.046

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

5.6.8 Equations for Class RK1 fuses up to 100 A

For I_{bf} < 0.65 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 kA ≤ I_{bf} ≤ 1.16 kA,

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

For I_{bf}, such that 1.16 kA < I_{bf} ≤ 1.4 kA,

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

For I_{bf}, such that 1.4 kA < I_{bf} ≤ 106 kA, E = 1.046

For I_{bf} > 106 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]

			480 V and lower		575–690 V	
Rating (A)	Breaker type	Trip unit type	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]	$4.560\ I_{bf} + 27.230$	$47.20\ I_{bf} + 2660$	$6.860\ I_{bf} + 2.170$	$62.4\ I_{bf} + 2930$

[a]Refer to Annex E for Table 5 (Table E.1) in cal/cm^2.
[b]I_{bf} is in kA, working distance is 460 mm.
[c]Short 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.

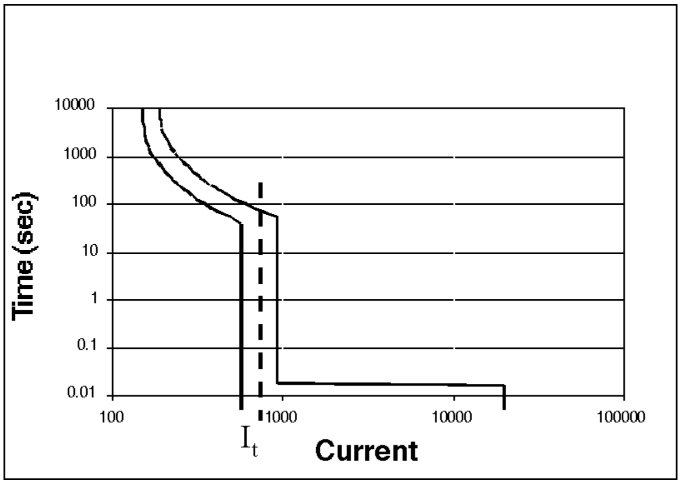


Figure 1—Typical circuit breaker time-current characteristic

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

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

$$\lg I_1 = 0.0281 + 1.09 \lg (1.3\, I_t) \tag{27}$$

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

$$\lg I_1 = 0.0407 + 1.17 \lg (1.3\, I_t) \tag{28}$$

$$I_{bf} = I_1 = 10^{\lg I_1} \tag{29}$$

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

[23]See 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

[24]See 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.

[25] See Footnote 1.
[26] See Footnote 1.

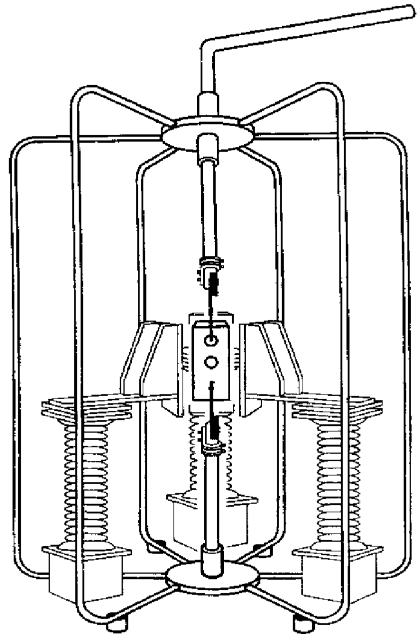


Figure 2—Test setup A—single-phase arc in air with electrodes in line and with partial faraday cage

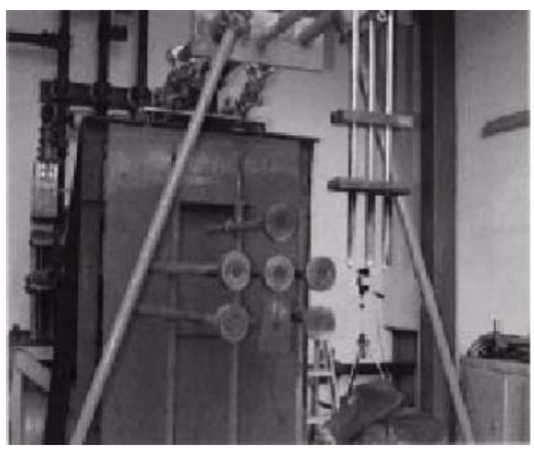


Figure 3—Test setup B—three-phase arc in air with electrodes in parallel

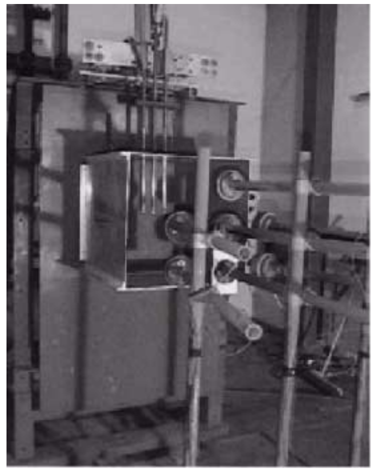


Figure 4—Test setup C—arc in box

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]

[27] 559 mm × 508 mm × 533 mm= 22" × 20" × 21"
[28] 508 mm × 508 × 508 mm = 20" × 20" × 20"
[29] See Footnote 28.
[30] 1143 mm × 762 × 762 mm = 45" × 30" × 30"
[31] 25.4 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/cm^2 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

[32]13.6 metric tons = 15 tons
[33]4.9 m× 4.9 m × 3 m = 16' × 16' × 10'
[34]508 mm = 20"
[35]356 mm × 305 mm × 191 mm = 14" × 12" × 7.5"
[36]6.35 mm × 19.05 mm = 0.250" × 0.750"
[37]19.05 mm = 0.750"
[38]152 mm = 6"
[39]To calculate incident energy in cal/cm^2, 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.

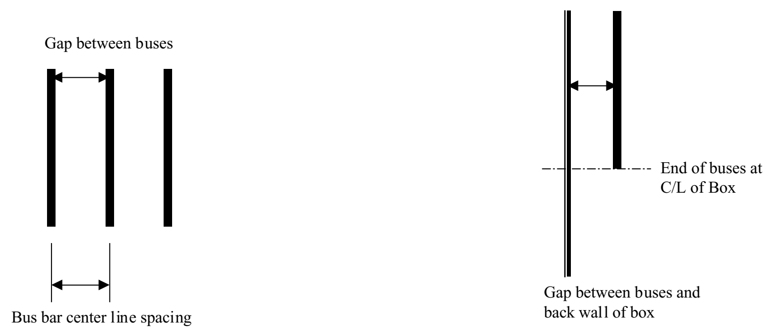
It was difficult to sustain an arc at the lower voltages. An arc was sustained only once at 208 V in a 508 mm × 508 mm × 508 mm box. In all other tests with that box and the 305 mm × 368 mm × 191 mm box, the arc blew itself out as soon as the fuse wire vaporized.[40] An arc was sustained several times 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.



Voltage Class	600 V	5 kV	15 kV
System voltages	208, 400, 600 V	2.4, 4.16 KV	13.8 kV
Bus thicknesses	6 x 19 mm and 19 mm D	19 mm D	19 mm D
Gaps between buses	3mm—40 mm	104 mm	13 and 152 mm
Gaps Box to buses	10 mm—104mm	152 mm	
Box sizes H/W/D in mm	508 x 508 x 508 mm 368 x 305 x 191 mm	1143 x 762 x 762 mm	

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.

[40] 508 mm × 508 mm × 508 mm = 20" × 20" × 20"
305 mm × 368 mm × 191 mm = 12" × 14" × 7.5"

[41] 100 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 (*Emax*) was then calculated, where maximum incident energy (*Emax*) was normalized for distance but not for time. The general linear model (GLM) was then used to fit a model for lg(*IEmax*) 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 (< 1kV) and high (> 1 kV) open circuit voltage cases. The statistical analysis is presented first, and then the equations for the model follow.

[42]See Footnote 1.

9.10.1 Regression analysis for lg of arc current for LV

The best way to find I_a is by finding lgI_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, lgI_a, 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):

$$\lg I_a = K + 0.662 \lg I_{bf} + 0.0966 V + 0.000526 G + 0.5588 V (\lg I_{bf}) - 0.00304 G (\lg I_{bf}) \quad (30)$$

In IEEE standard terms the equation is:

$$\lg I_a = K + 0.662 \lg I_{bf} + 0.0966 V + 0.000526 G + 0.5588 V (\lg I_{bf}) - 0.00304 G (\lg I_{bf}) \quad (31)$$

where

$\lg I_a$ is $\log_{10}$ of arc current (kA)
K is –0.153 for open configurations
is –0.097 for box configurations.
$\lg I_{bf}$ is log10 of bolted fault current (symmetrical RMS) (kA)
V is system voltage (kA)
G is distance between buses (mm)

This model had an R-square of 98.3%. R-square is a measure of the equation fit to the data; 100% is perfect.

Figure 7 and Figure 9 are plots of the $\log_{10}$ of the actual arcing fault current, compared to the values calculated by the equation model. Figure 7 shows the data points, for the lower voltage tests, and Figure 9 shows the data points with open circuit voltage over 5 kV. The plots show a very good fit of data to calculation values.

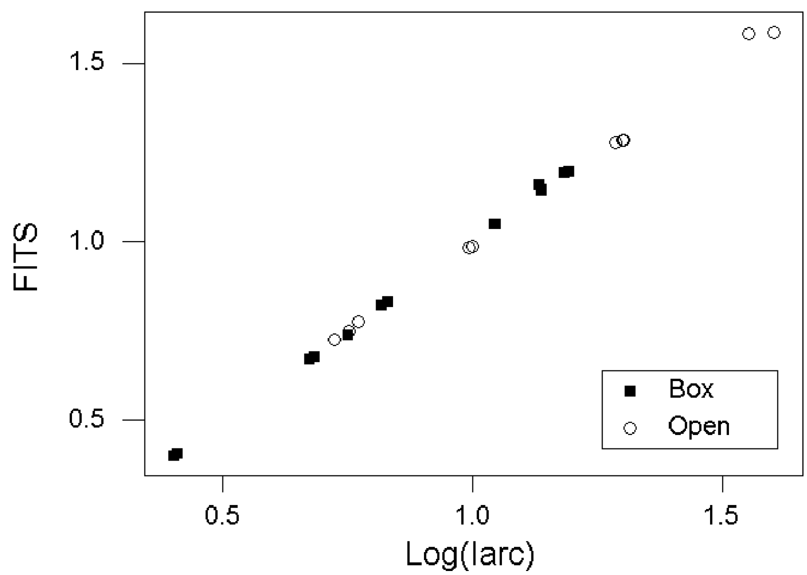


Figure 7—Log$_{10}$ of measured arcing fault current vs the fitted values (calculated values) for low-voltage test points

9.10.2 Regression analysis for lg of arc current for MV

A copy of the statistical analysis report that is used to find the $\log_{10}$ of arc current is presented in Figure 8.

```
PROGRAM OUTPUT 2.  REGRESSION ANALYSIS OF ARC CURRENT AT MEDIUM VOLTAGE

Program Output for:
Regression Analysis for Medium Voltage: logIarc versus logIbf

The regression equation is
logIarc = 0.00402 + 0.983 logIbf

Predictor        Coef     SE Coef         T       P
Constant     0.004025    0.008441      0.48   0.638
logIbf       0.983014    0.007874    124.84   0.000

S = 0.01258     R-Sq = 99.8%     R-Sq(adj) = 99.8%

Analysis of Variance

Source            DF         SS         MS         F        P
Regression         1     2.4676     2.4676  15585.94    0.000
Residual Error    24     0.0038     0.0002
Total             25     2.4714

Unusual Observations
Obs     logIbf    logIarc         Fit      SE Fit    Residual     St Resid
  5       1.61    1.55439     1.58347     0.00520    -0.02908       -2.54R
 26       1.18    1.13165     1.16014     0.00274    -0.02848       -2.32R

R denotes an observation with a large standardized residual
```

Figure 8—Program output 2—Regression analysis of $\log_{10}$ of arc current $\lg I_a$, for MV

The terms shown in the figure are illustrated in Equation (32):

$$\lg I_a = .00402 + 0.983 \lg I_{bf} \tag{32}$$

This model had an (R-square = 99.8%). The medium voltage case makes no distinction between open and box configurations—this was not a significant factor.

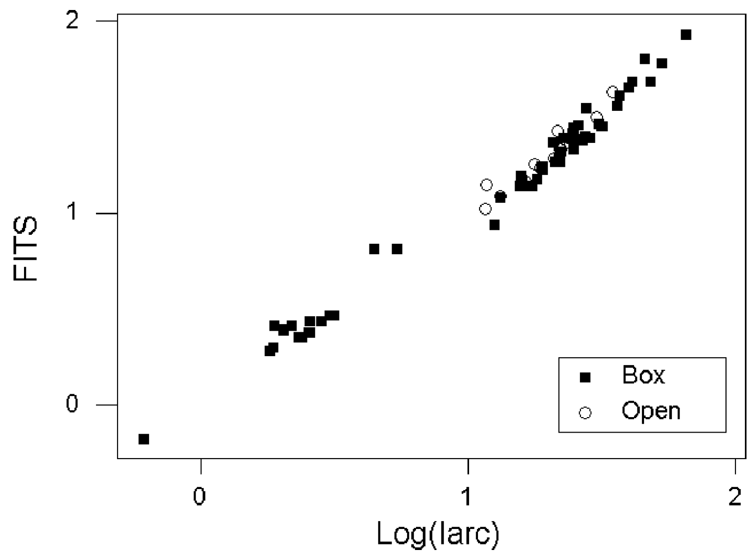


Figure 9—Log$_{10}$ of measured arc current vs the fitted values (calculated values) for medium voltage test points

9.10.3 Convert from lg

$$I_a = 10^{\lg I_a} \tag{33}$$

9.10.4 Effect of arc current variation on determination of clearing time

It is known that it is difficult to predict arc current accurately, so some analysis of the accuracy of the arc current model is essential. Arc current is used to determine protective-device operating time. For protective devices operating in the steep portion of their time-current curves, a small change in current causes a big change in operating time. Incident energy is linear with time, so arc current variation may have a big effect on incident energy.

The solution is to make two arc current and energy calculations; one using the calculated expected arc current and one using a reduced arc current that is 15% lower.

The model includes both calculations for each case considered, except where special methods are employed for certain circuit breakers or fuses. It requires that an operating time be determined for both the expected arc current and the reduced arc current. Incident energy is then calculated for both sets of arc currents and operating times and the larger incident energy is taken as the model result.

This solution was developed by comparing the results of arc current calculations using the best available arc current equation with actual measured arc current in the test database.

Arc current was calculated for each data point and the calculated currents were then compared to the measured currents. The best way to make the comparison was to take the difference between the calculated and measured value for each data point and group them by error levels. This is shown in Figure 10.

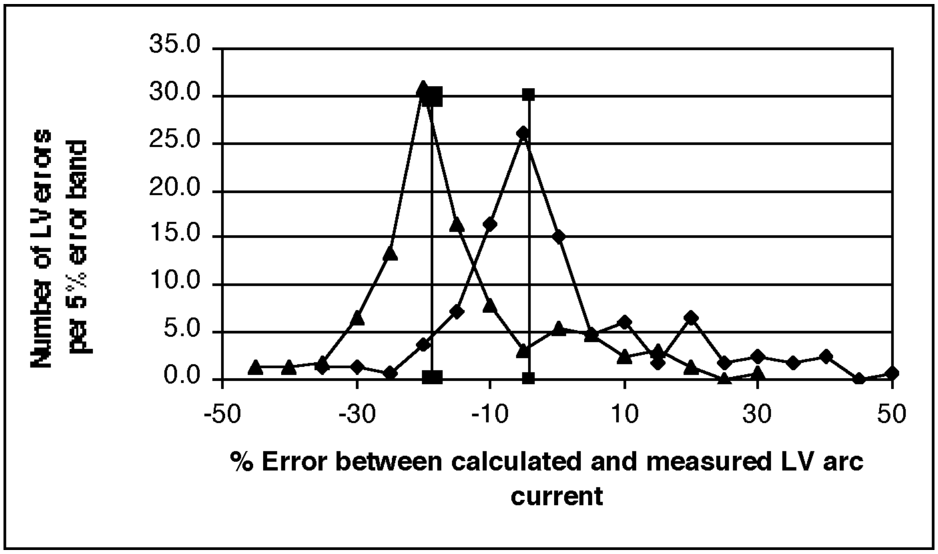


Figure 10—Histogram of LV arc current calculation error

Looking first at the black diamonds, the number of points shown as positive error are test points where the calculated current was higher than the measured current. For example, on the right hand side, there is one point shown at 50% indicating for one test point the calculated current was between 45% and 50% higher than the measured arc current. The black vertical line identifies the median, which is –4.2% of the measured arc current, an error on the safe side, because the calculated current is used to determine the protective-device operating time.

There are still many error points shown to the right of the median and they are a concern. Taking 85% of the calculated arc current, recomputing the errors for the test data, and then plotting the results gave the points shown as gray triangles. The median for this data set is –18.4% of the measured arc current. A count of the number of points on the high side of zero error found 8.5% of the points were still high. If it is assumed that in half the cases encountered by users, the calculated arc current will fall on the horizontal portion of a device time-current curve, then more than 95% of the cases will have higher current than calculated. This is the best that could be done with the limited data available.

Table 6 shows gaps between conductors used in 9.10.3 and 9.11, and distance exponents developed in 9.11.1 and applied in 9.11.4. Users can select any gap within the range shown for open air for any application within the voltage class. For low-voltage applications, the difference between switchgear, MCCs and panels is based upon testing with text boxes of different dimensions, as described in 9.11.1. Users can select the equipment type that best matches their application.

Table 6—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	13–102	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

[a]The distance *x* factor is used in 5.3 as an exponent.

9.11 Incident energy

9.11.1 Distance exponents

For open air cases (exposed equipment) and cables in air, the incident energy is illustrated in equation (34) as follows:

$$E = \frac{4.184 E_n 610^2}{D^2} \tag{34}$$

where

D is distance from possible arc location to worker (mm)
E is incident energy (J/cm^2)
E_n is incident energy normalized for D = 610 mm[43]

In this case the distance exponent is two. For cases where the arc occurs in equipment the exponent is not two, and it is derived by applying the curve-fitting program in a spreadsheet program based on test data, which was taken from the database files.[44]

9.11.1.1 LV switchgear, 208 V–1000 V

The LV switchgear distance exponent is based on the 20" box test data described in “Predicting incident energy to better manage the electric arc hazard on 600 V power distribution systems” [B4], and shown in Table 7. See Figure 11 for the curve fitting equation and the distance exponent.

[43]See Footnote 13.
[44]See Footnote 1.

Table 7—Distance data for LV switchgear

D (mm)	E (J/cm^2)
457	101
610	67
762	42
914	35
1219	23
1524	17

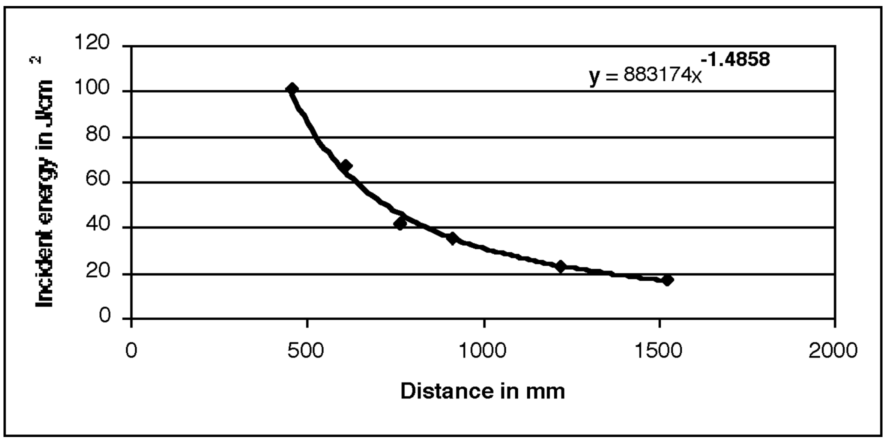


Figure 11—Distance exponent for low-voltage switchgear

9.11.1.2 LV MCCs and panelboards, 208 V–1000 V

The LV MCC and panelboard distance exponent is based on laboratory test results with the 305 mm × 356 mm × 191 mm as shown in Table 8. See Figure 6 for the curve fitting equation and the distance exponent.[45]

[45]305 mm × 356 mm × 191 mm= 12" × 14" × 7.5"

Table 8—Distance data for LV MCCs and panels

D (mm)	E (J/cm^2)
305.0	92
305.0	91
305.0	102
609.6	28
609.6	26
609.6	27
1829.0	3
1829.0	9
1829.0	5

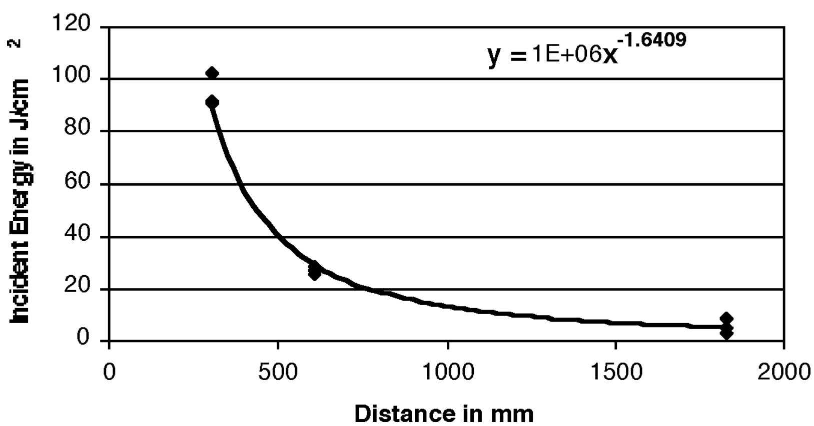


Figure 12—Distance exponent for LV MCCs and panelboards

9.11.1.3 MV switchgear, >1 kV–15 kV

The MV switchgear distance exponent is based on the 2400 V test data from laboratory 1. This test program used a 1143 mm × 762 mm × 762 mm box.[46] The data shown in Table 9 was applied in Figure 13 to develop a curve fitting equation and the distance exponent.

[46]1143 mm × 762 mm × 762 mm = 45" × 30" × 30"

Table 9—MV switchgear distance data

D (mm)	E (J/cm^2)
610	21.198
610	25.529
610	24.938
610	23.931
762	18.809
762	18.047
762	19.321
762	19.997
914	15.548
914	16.584
914	15.441
914	16.201
1219	11.269
1219	12.337
1219	13.457
1219	10.775
1524	8.756
1524	10.808
1524	10.191
1524	9.677

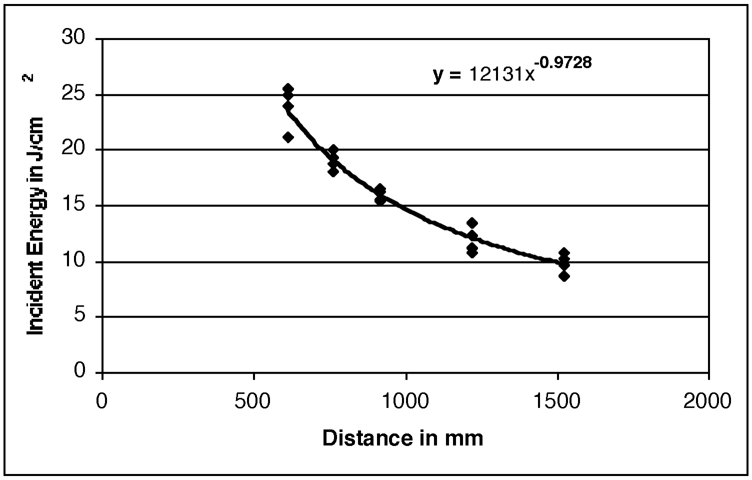


Figure 13—Distance exponent for MV switchgear

9.11.2 Incident energy statistical analysis

From extensive statistical analysis an equation was developed for the $\log_{10}$ of incident energy normalized for an arc duration of 200 ms and a distance from arc to calorimeters of 610 mm. This equation is:

$$\lg E_n = K_1 + K_2 + 1.081 \lg I_a + 0.00110\, G \tag{35}$$

where

E_n	is incident energy normalized
K_1	is –0.792 for open configurations (no enclosure)
	is –0.555 for box configurations (enclosed equipment)
K_2	is 0 for ungrounded and high-resistance grounded systems,
	is –0.113 for grounded systems.
$\lg I_a$	is $\log_{10}$ of arc current
G	is distance between arcing buses (mm)

The regression, R-square, is 89%, which is satisfactory.

A copy of the statistical analysis program report, the basis for developing LogIncEnergy, ($\lg E_n$) is presented in Figure 14.

```
Regression Analysis: logIncEnergy versus Box_code, Ground_code,...


The regression equation is
logIncEnergy = - 0.792 + 0.237 Box_code - 0.113 Ground_code + 1.08 fit_logIarc
           + 0.00110 ElectrGap

101 cases used 3 cases contain missing values

Predictor         Coef       SE Coef         T        P
Constant      -0.79196       0.07028    -11.27    0.000
Box_code       0.23736       0.04079      5.82    0.000
Ground_c      -0.11315       0.04125     -2.74    0.007
fit_logI       1.08124       0.03942     27.43    0.000
ElectrGa     0.0010963     0.0004633      2.37    0.020

S = 0.1614       R-Sq = 88.9%     R-Sq(adj) = 88.4%

Analysis of Variance

Source            DF          SS          MS          F        P
Regression         4     20.0122      5.0030     192.14    0.000
Residual Error    96      2.4998      0.0260
Total            100     22.5119

Source       DF      Seq SS
Box_code      1      0.0358
Ground_c      1      0.1939
fit_logI      1     19.6367
ElectrGa      1      0.1458
```

Figure 14—Program output 3—E_n regression analysis

Note that coded versions of the categorical factors open/box and grounded Y/N, labeled as “Box_code” and “Ground_c” were used. “Box_code” was 0 for Open, 1 for box; “Ground_c” was 0 for N (ungrounded), 1 for Y (grounded). As a result, it was possible to use the regression procedure rather than the general linear models procedure. Though mathematically the two approaches are equivalent, the regression procedure optionally provided the prediction limits sought, not available with the GLM. Note that the regression coefficients for the coded factors in the spreadsheet output represent the change in intercept as one goes from the 0 level of the factor to the 1 level.

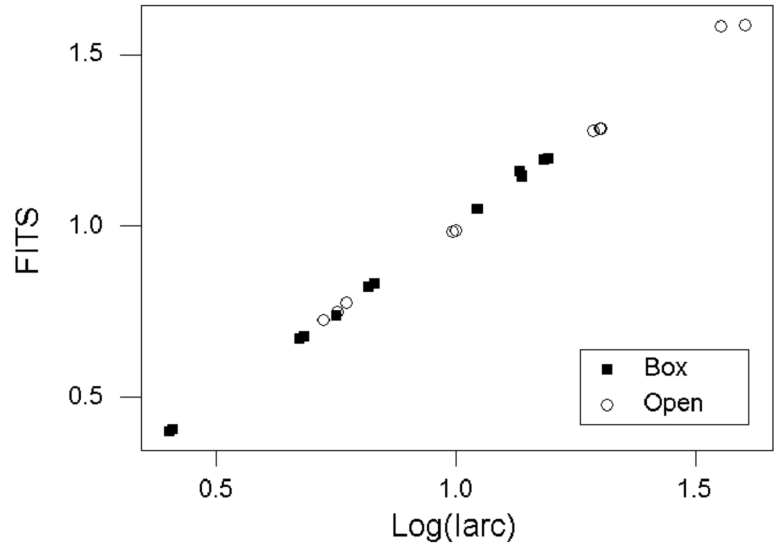


Figure 15—Log_{10} of measured incident energy vs the calculated (fitted) values for entire data set

9.11.3 Calculation factor

The formula gives a predicted value with a statistical 95% confidence limit. The calculation factor to achieve a numerical 95% confidence level for applications below 1 kV is 1.50 and is 1.0 for applications above 1 kV. This ensures that the resulting value is in line with the higher test results.

The basic model developed in the statistical analysis was further analyzed to compare the actual PPE required for each test point based on measured incident energy with the calculated PPE required. A calculation factor multiplier was included in the equations to allow a choice of most appropriate calculation factor. A calculation factor of 1 means no change in incident energy. The resulting tables for low and medium voltage are shown below. The test data is normalized to 0.2 seconds duration and distance of 610 mm, so variations in time and distance are not factors in this analysis. For this analysis, a set of incident energy levels was chosen as 1.2, 8, 25, 40, and 100 cal/cm^2. [47]

Table 10—Calculated versus actual PPE required for LV data

Calculation factor	Two high	One high	Same	One low	Two low
1.00	1	10	129	25	0
1.25	1	30	113	21	0
1.50	2	49	106	8	0
1.75	2	75	86	2	0
1.90	2	82	79	2	0

[47] See Footnote 13.

With a calculation factor of 1.50, there are 8 low-voltage test data points where the calculated PPE level is one layer too low; approximately 5% of the number of test points. That means there is 95% confidence the calculated PPE level will be adequate or more than adequate.

Table 11—Calculated versus actual PPE required for medium voltage data

Calculation factor	Two high	One high	Same	One low	Two low
1.00	0	7	131	8	0
1.25	0	35	109	2	0
1.50	0	57	89	0	0
1.75	0	76	70	0	0
1.90	0	76	70	0	0

With a calculation factor of 1.00, there are 8 medium voltage test data points where the calculated PPE level is one layer too low; approximately 5% of the number of test points. This gives a numerical 95% confidence the PPE level will be adequate or more than needed.

Combining this conservative approach with the conservatism in the arc current calculation, the model will be quite conservative for installations similar to those tested in the laboratory.

Some used equipment was also tested as shown in Annex D. Comparing these test results to the test results for the ideal box test setups shows that the laboratory test setups give very similar results. Therefore, the model is expected to be accurate for equipment in operation.

9.11.4 Conversion from normalized data to real cases

The preceding work was based on data which was normalized for t = 0.2 seconds and D = 610 mm. The equations had to be converted so they could be applied to real cases. The conversion process started with the $\lg E_n$ from above, here E_n is the incident energy normalized for time and distance.

$$\lg E_n = K_1 + K_2 + 1.081 \lg I_a + 0.00110 G \tag{36}$$

Then,

$$E_n = 10^{\lg E_n} \tag{37}$$

$$E = 4.184 C_f E_n \left(\frac{t}{0.2}\right)\left(\frac{610^x}{D^x}\right) \tag{38}$$

where

C_f *is calculation factor for a numerical 95% confidence (see 9.11.2) for*
LV use 1.5
MV use 1.0
E is the incident energy (J/cm^2)
t is time (seconds)

D	is the distance from the possible arc point to the person
x	is the distance exponent derived above and shown in Table 4.

9.11.5 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.

$$E = 2.142 \times 10^6 V I_{bf}\left(\frac{t}{D^2}\right) \tag{39}$$

where

E	is incident energy (J/cm^2)
V	is system voltage (kV)
t	is 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.

9.12 Flash boundary

The flash boundary can easily be calculated when the incident energy is known. Solve the same equation used to calculate incident energy for distance, D, with incident energy set for 5.0 J/cm^2. This equation can also be solved with other incident energy levels as data, such as the incident energy level with the rating of a particular set of PPE.

For the empirically derived model:

$$D_B = \left[4.184 C_f E_n\left(\frac{t}{0.2}\right)\left(\frac{610^x}{E_B}\right)\right]^{\frac{1}{x}} \tag{40}$$

where

E	is incident energy (J/cm^2)

For the Lee Method:

$$D_B = \sqrt{2.142 \times 10^6 V I_{bf}\left(\frac{t}{E_B}\right)} \tag{41}$$

where

D_B	is the distance of the boundary from the arcing point (mm)
E_B	is incident energy in J/cm^2 at the boundary distance

9.13 Current-limiting fuses

It was found to be difficult to calculate incident energy in circuits protected by current-limiting fuses because of the reduced arc time and limited let-through current. Therefore, tests were conducted to determine the effect of current-limiting fuses on incident energy.

Three fuses were placed between the laboratory's source and a switchgear sized enclosure 508 mm × 508 mm × 508 mm. [48] Arcs were initiated in the enclosure, and incident energy, arc current, and arc time were recorded. The circuit was calibrated for open circuit voltage and a range of bolted fault currents. The range of test currents was selected to enable development of a model of arc-flash characteristics, both within and below the fuses' current-limiting ranges. Three tests were performed for each fuse rating and each data point. The worst case was then selected. See [B1], [B2], [B3], [B5], [B6], [B7], [B8], [B9], [B10], [B12], [B13], [B15], [B16], [B17], [B18], [B19], [B20], [B21], [B22], [B24], [B26], [B27], and [B28] in the bibliography, and test data spreadsheets.[49]

Fuses from one manufacturer were used, but results with other manufacturers' fuses of the same class should be similar. The manufacturer should be consulted.

Actual field results could be different for various reasons, as follows:

a) Different system voltage
b) Different closing angle on the voltage wave
c) Different distance from the arc

The smallest fuse tested was a 100 A Class RK1 fuse. All data for lower amperage fuses is based upon the 100 A level. Incident energy values with actual 30 A and 60 A fuses would be considerably less than for 100 A fuses.

9.13.1 Development of curve fitting equations

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. They can be applied over the range of fuses below the tested fuse, e.g., the 200 A class RK1 fuse may be applied to fuses rated from 101 A to 200 A. The variables are as follows:

I_{bf} is bolted fault current for three-phase faults
E is incident energy (J/cm^2).

Table 12 through Table 19 show the test data used, and Figure 16 through Figure 42 show the application of a curve fitting program to develop equations.

[48] 508 mm × 508 mm × 508 mm = 20" × 20" × 20"
[49] See Footnote 1.

9.13.1.1 Class L 2000 A

Table 12—Incident energy as a function of bolted fault current for one manufacturer's 2000 A Class L current limiting fuses @ 600 V, 460 mm

Current limiting fuse	Bolted fault (kA)	Series average incident energy (J/cm^2)	Series mean max incident energy (J/cm^2)	Series maximum incident energy (J/cm^2)	Default for model[a]
Class L 2000 A	106.0	8.1	10.0	13.0	13
Class L 2000 A	65.9	27.0	34.0	100.0	100
Class L 2000 A	44.1	41.0	55.0	70.0	111
Class L 2000 A	22.6	97.0	121.0	123.0	123

[a]111.2944 was chosen as default value to linearize the values from 22.6 kA–65.9 kA.

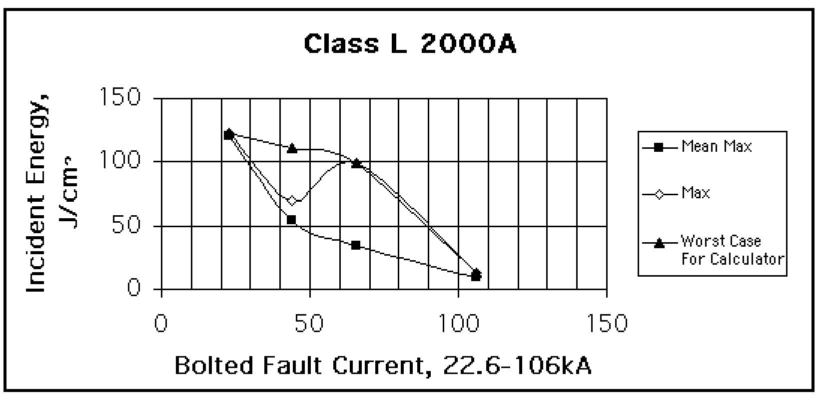


Figure 16—Class L 2000 A fuse—incident energy vs bolted fault current

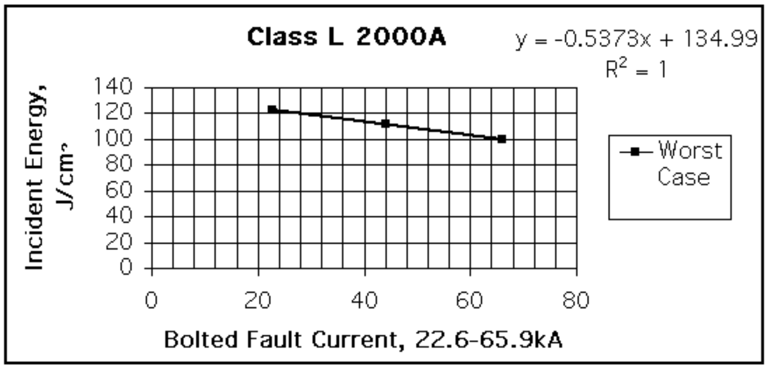


Figure 17—Class L 2000 A fuse—low current segment of model

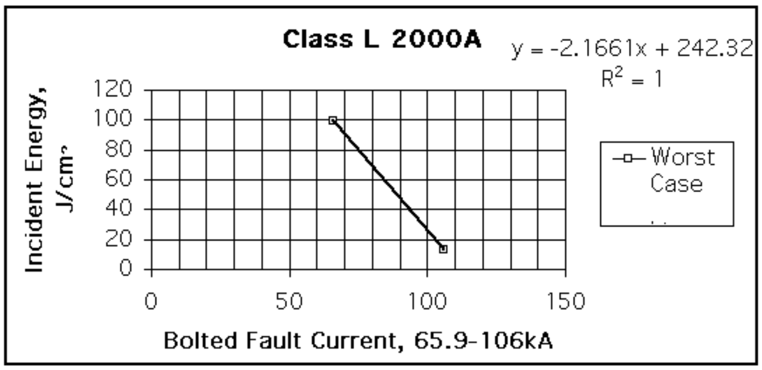


Figure 18—Class L 2000 A fuse—high current segment of model

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 kA ≤ I_{bf} ≤ 65.9 kA,

$$E = 4.184\ (-0.1284 I_{bf} + 32.262) \quad (42)$$

For I_{bf}, such that 65.9 kA < I_{bf} ≤ 106 kA,

$$E = 4.184\ (-0.5177\ I_{bf} + 57.917) \quad (43)$$

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

9.13.1.2 Class L 1600 A

Table 13—Incident energy as a function of bolted fault current for one manufacturer's 1600 A Class L current limiting fuses @ 600 V, 460 mm

Current limiting fuse	Bolted fault (kA)	Series average incident energy (J/cm^2)	Series mean maximum incident energy (J/cm^2)	Series maximum incident energy (J/cm^2)	Default for model
Class L 1600 A	106.0	1.2	1.5	1.5	1.7
Class L 1600 A	65.9	4.1	5.2	12.3	12.0
Class L 1600 A	44.1	3.1	3.8	4.9	12.0
Class L 1600 A	31.8	84.0	87.0	92.0	92.0
Class L 1600 A	22.6	29.0	40.0	49.0	99.0
Class L 1600 A	15.7	77.0	79.0	85.0	105.0

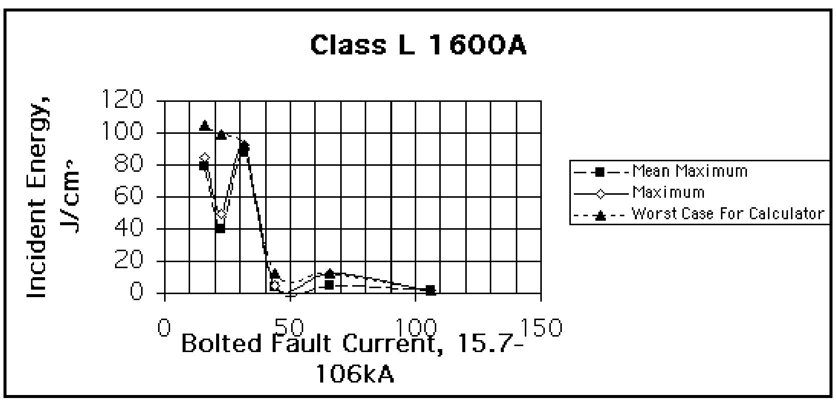


Figure 19—Class L 1600 A fuse—incident energy vs bolted fault current

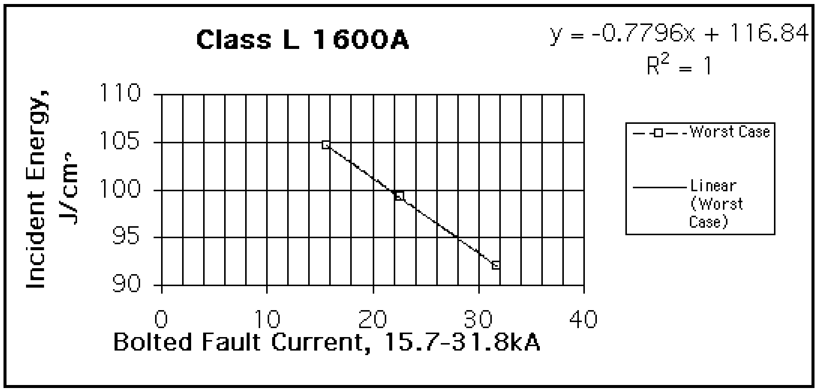


Figure 20—Class L 1600 A fuse—low current segment of model

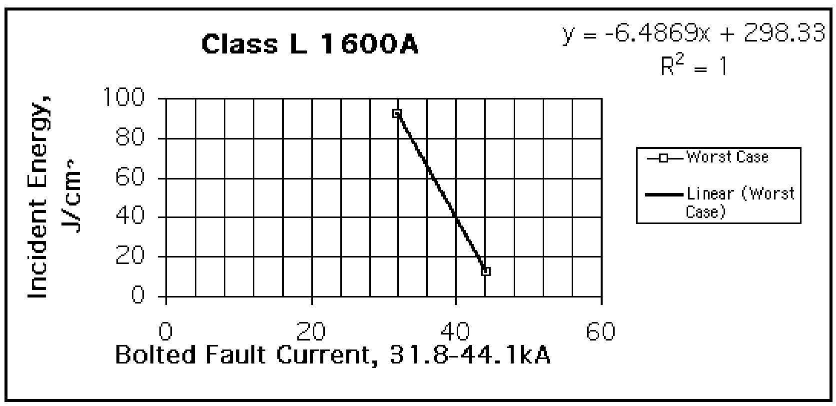


Figure 21—Class L 1600 A fuse—lower-middle current segment of model

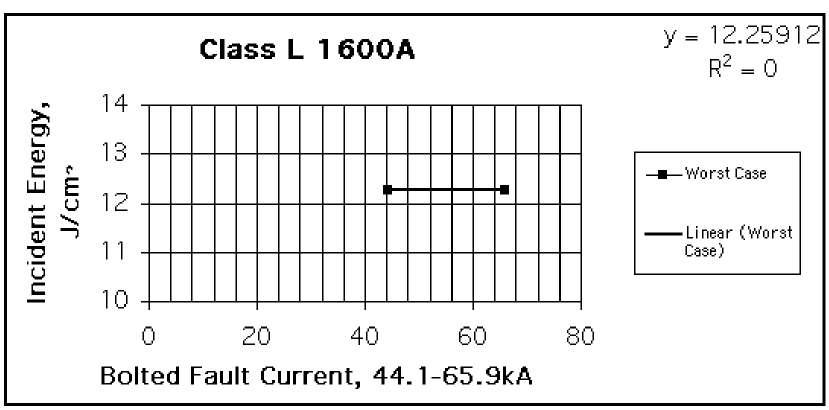


Figure 22— Class L 1600 A fuse—upper-middle current segment of model

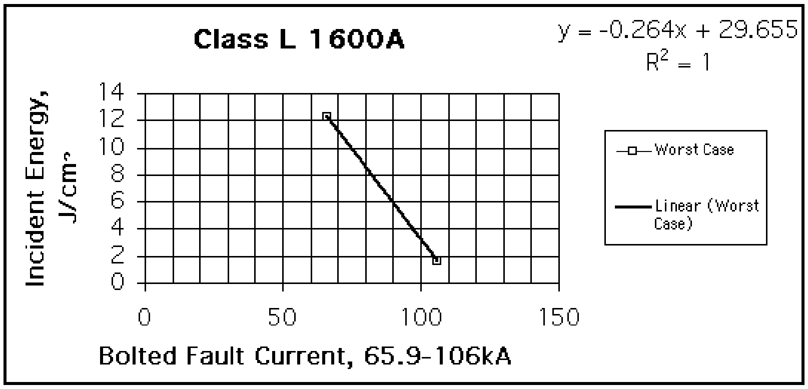


Figure 23— Class L 1600 A fuse—upper current segment of model

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 kA ≤ I_{bf} ≤ 31.8 kA,

$$E = 4.184\ (-0.1863\ I_{bf} + 27.926) \tag{44}$$

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

$$E = 4.184\ (-1.5504\ I_{bf} + 71.303) \tag{45}$$

For I_{bf}, such that 44.1 kA ≤ I_{bf} ≤ 65.9 kA, E is 12.259 J/cm^2 [50]

For I_{bf}, such that 65.9 kA < I_{bf} ≤ 106 kA,

$$E = 4.184\ (-0.0631\ I_{bf} + 7.0878) \tag{46}$$

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

9.13.1.3 Class L 1200 A

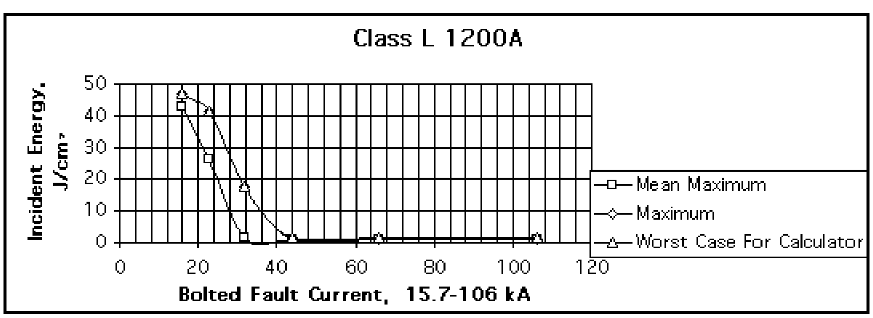


Figure 24—Class L 2000 A fuse—incident energy vs bolted fault current

[50]12.259 J/cm^2 = 2.93 cal/cm^2

Table 14—Incident energy as a function of bolted fault current for one manufacturer's 1200 A Class L current limiting fuses @ 600 V, 460 mm

Current limiting fuse	Bolted fault (ka)	Series average incident energy (J/cm^2)	Series mean maximum incident energy (J/cm^2)	Series maximum incident energy (J/cm^2)	Default for spreadsheet calculation
Class L 1200 A	106.0	0.6	0.8	1.0	1.6
Class L 1200 A	65.9	0.8	1.0	1.0	1.6
Class L 1200 A	44.1	1.0	1.3	1.6	1.6
Class L 1200 A	31.8	7.1	1.7	18.0	18.0
Class L 1200 A	22.6	19.0	26.0	41.0	41.0
Class L 1200 A	15.7	37.0	43.0	47.0	47.0

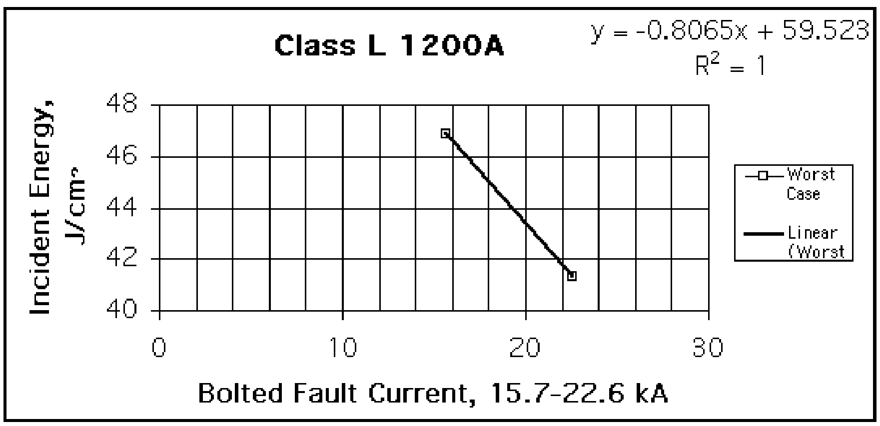


Figure 25—Class L 1200 A fuse—lower current segment of model

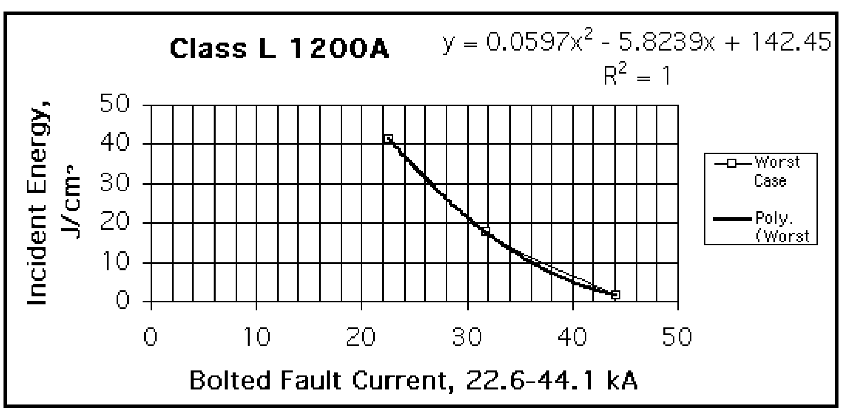


Figure 26—Class L 1200 A fuse—middle current segment of model

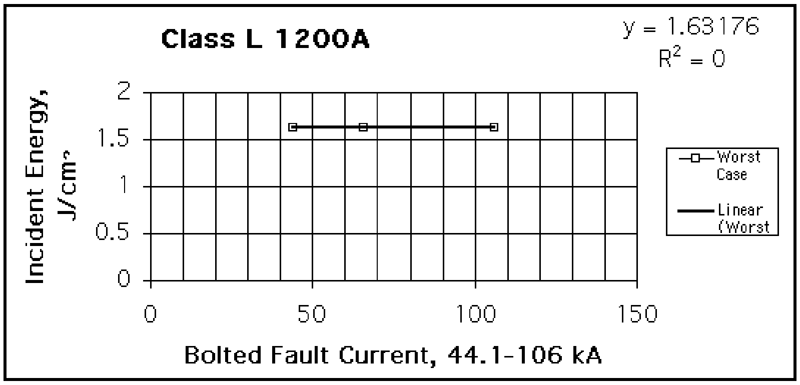


Figure 27—Class L 1200 A fuse—upper current segment of model

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 kA ≤ I_{bf} ≤ 22.6 kA,

$$E = 4.184\ (–0.1928\ I_{bf} + 14.226) \tag{47}$$

For I_{bf}, such that 22.6 kA < I_{bf} ≤ 44.1 kA,

$$E = 4.184\ (0.0143\ I_{bf}^2 –1.3919\ I_{bf} + 34.045) \tag{48}$$

For I_{bf}, such that 44.1 kA < I_{bf} ≤ 106 kA, E = 1.631

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

9.13.1.4 Class L 800 A

Table 15—Incident energy as a function of bolted fault current for one manufacturer's 800 A Class L current limiting fuses @ 600 V, 460 mm

Current limiting fuse	Bolted fault (ka)	Series average incident energy (J/cm^2)	Series mean maximum incident energy (J/cm^2)	Series maximum incident energy (J/cm^2)	Default for model
Class L 800 A	106.0	0.75	0.92	1.00	1.0
Class L 800 A	65.9	0.59	0.71	0.75	1.0
Class L 800 A	44.1	0.38	0.63	0.75	1.0
Class L 800 A	22.6	2.60	3.50	6.40	6.4
Class L 800 A	15.7	4.10	4.20	4.60	8.2

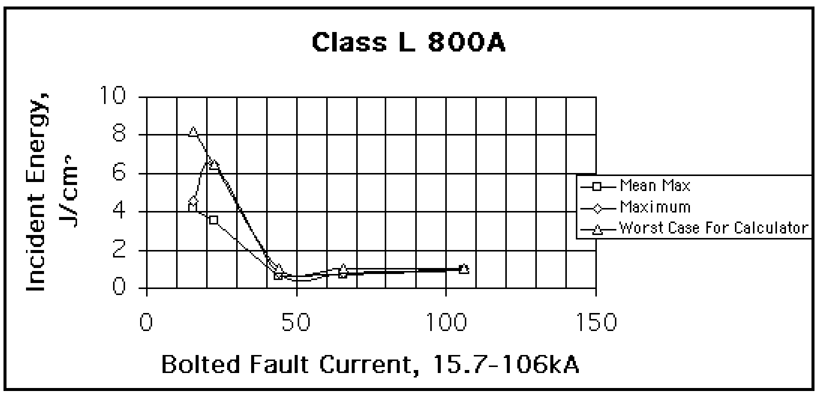


Figure 28—Class RK1 800 A fuse—incident energy vs bolted fault current

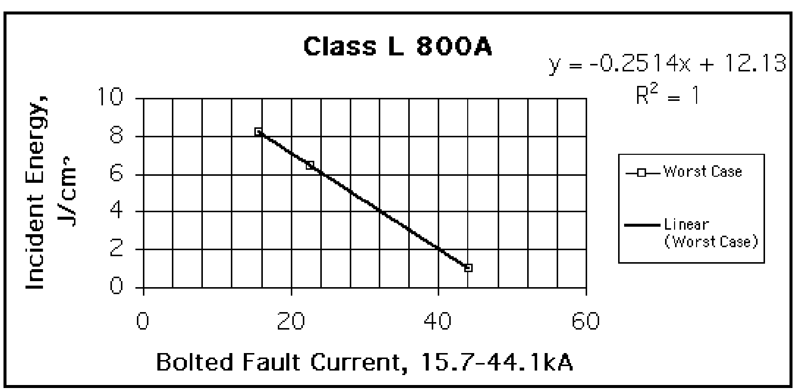


Figure 29—Class RK1 800 A fuse—lower current segment of model

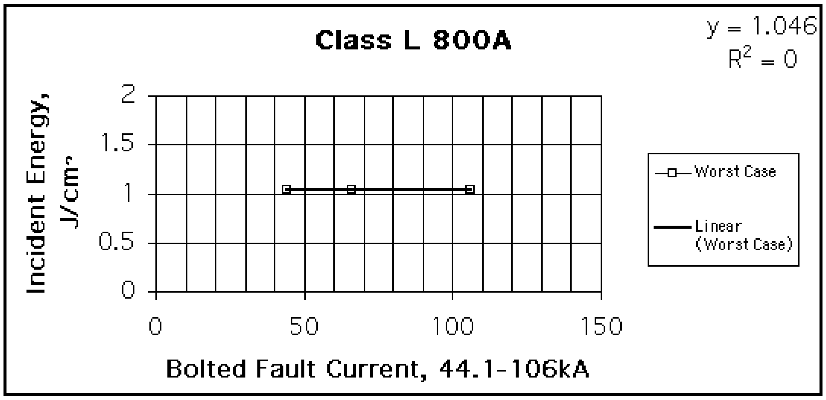


Figure 30—Class RK1 800 A fuse—middle current segment of model

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 kA ≤ I_{bf} ≤ 44.1,

$$E = 4.184\ (-0.0601\ I_{bf} + 2.8992) \qquad (49)$$

For I_{bf}, such that 44.1 kA < I_{bf} ≤ 106 kA, E = 1.046

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

9.13.1.5 Class RK1 600 A

Table 16—Incident energy as a function of bolted fault current for one manufacturer's 600 A Class RK1 current limiting fuses @ 600 V, 460 mm

Current limiting fuse	Bolted fault (ka)	Series average incident energy (J/cm²)	Series mean maximum incident energy (J/cm²)	Series maximum incident energy (J/cm²)	Default for model
Class RK1 600 A	106.0	0.13	0.17	0.17	1.0
Class RK1 600 A	65.9	0.21	0.38	0.46	1.0
Class RK1 600 A	44.1	0.21	0.29	0.33	1.0
Class RK1 600 A	22.6	0.42	0.63	0.63	1.0
Class RK1 600 A	15.7	1.50	1.30	2.10	2.5
Class RK1 600 A	14.0	1.50	1.30	2.50	2.5
Class RK1 600 A	8.5	53.00	52.00	73.00	73.0

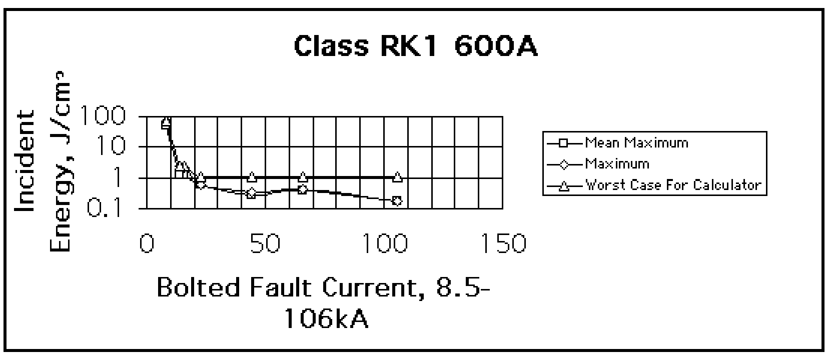


Figure 31—Class RK1 600 A fuse—lower current segment of model

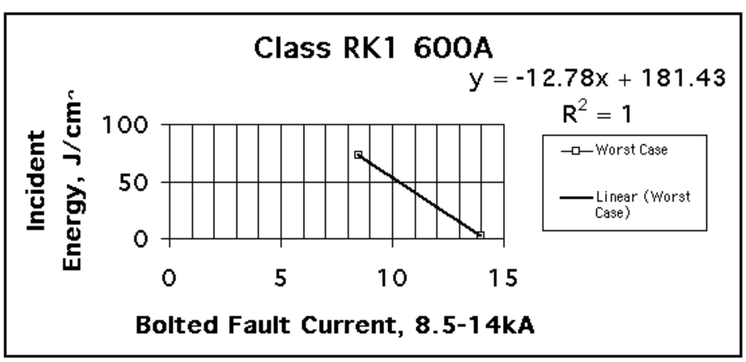


Figure 32—Class RK1 600 A fuse—middle current segment of model

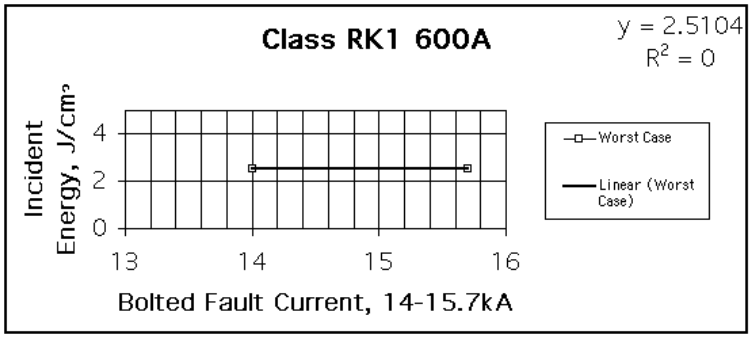


Figure 33—Class RK1 200 A fuse—upper current segment of model

For I_{bf} < 8.5 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 kA ≤ I_{bf} ≤ 14 kA,

$$E = 4.184\ (-3.0545\ I_{bf} + 43.364) \quad (50)$$

For I_{bf}, such that 14 kA < I_{bf} ≤ 15.7 kA, E = 2.510

For I_{bf}, such that 15.7 kA < I_{bf} ≤ 22.6 kA,

$$E = 4.184\ (-0.0507\ I_{bf} + 1.3964) \quad (51)$$

For I_{bf}, such that 22.6 kA< I_{bf} ≤106 kA, E = 1.046

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

9.13.1.6 Class RK1 400 A

Table 17—Incident energy as a function of bolted fault current for one manufacturer's 400 A Class RK1 current limiting fuses @ 600 V, 460 mm

Current limiting fuse	Bolted fault (ka)	Series average incident energy (J/cm^2)	Series mean maximum incident energy (J/cm^2)	Series maximum incident energy (J/cm^2)	Default for model
Class RK1 400 A	22.60	0.08	0.13	0.13	1.0
Class RK1 400 A	5.04	1.20	1.50	3.30	3.3
Class RK1 400 A	3.16	92.00	92.00	153.00	153.0

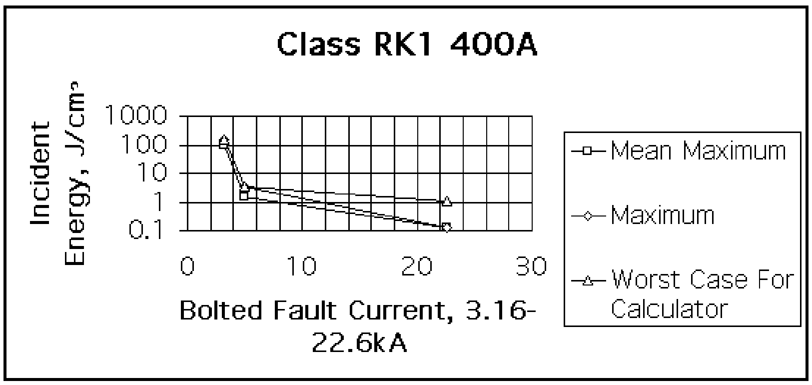


Figure 34—Class RK1 400 A fuse—incident energy vs bolted fault current

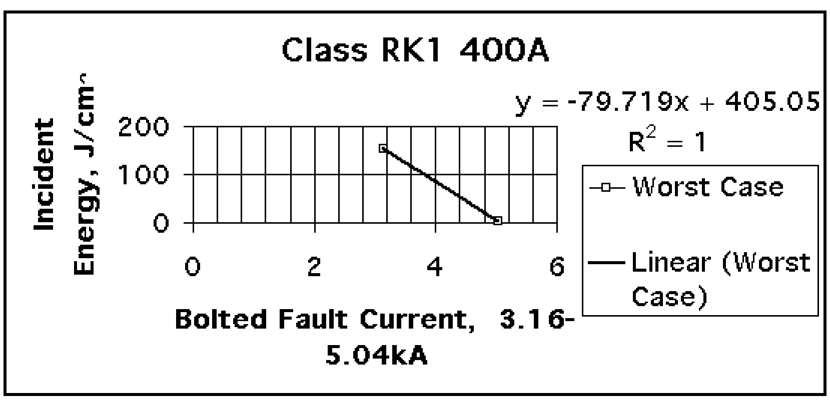


Figure 35—Class RK1 400 A fuse—lower current segment of model

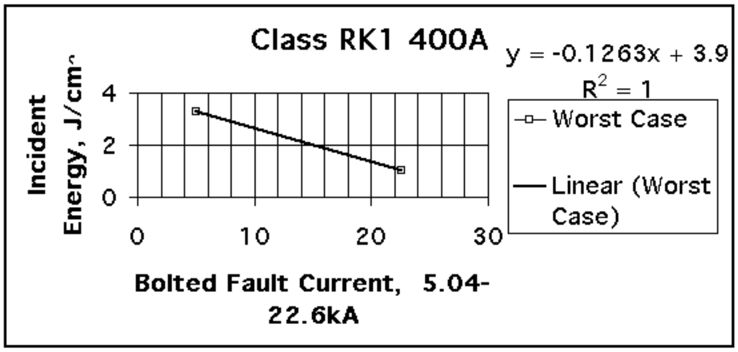


Figure 36— Class RK1 400 A fuse—middle current segment of model

For I_{bf} < 3.16 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 kA ≤ I_{bf} ≤5.04 kA,

$$E = 4.184\ (-19.053\ I_{bf} + 96.808) \tag{52}$$

For I_{bf}, such that 5.04 kA < I_{bf} ≤ 22.6 kA,

$$E = 4.184\ (-0.0302\ I_{bf} + 0.9321) \tag{53}$$

For I_{bf}, such that 22.6 kA < I_{bf} ≤106 kA, E = 1.046

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

9.13.1.7 Class RK1 200 A

Table 18—Incident energy as a function of bolted fault current for one manufacturer's 200 A Class RK1 current limiting fuses @ 600 V, 460 mm

Current limiting fuse	Bolted fault (ka)	Series average incident energy (J/cm^2)	Series mean maximum incident energy (J/cm^2)	Series maximum incident energy (J/cm^2)	Default for model
Class RK1 200 A	3.16	0.21	0.21	0.21	1.0
Class RK1 200 A	1.60	5.40	0.63	29.00	29.0
Class RK1 200 A	1.16	63.00	63.00	63.00	63.0

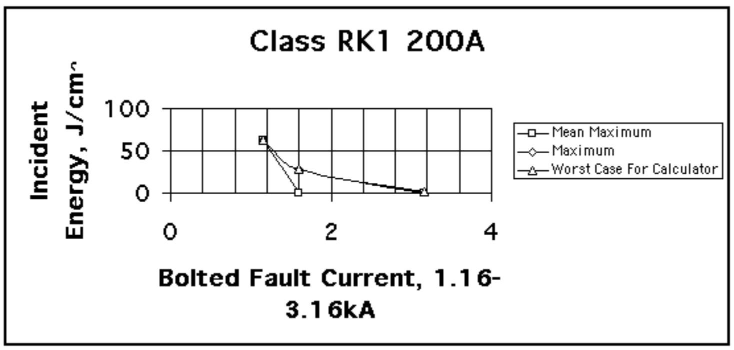


Figure 37—Class RK1 200 A fuse—incident energy vs bolted fault current

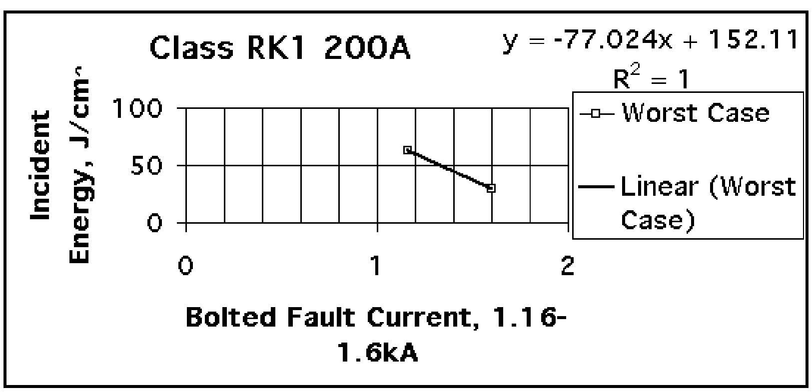


Figure 38—Class RK1 200 A fuse—lower current segment of model

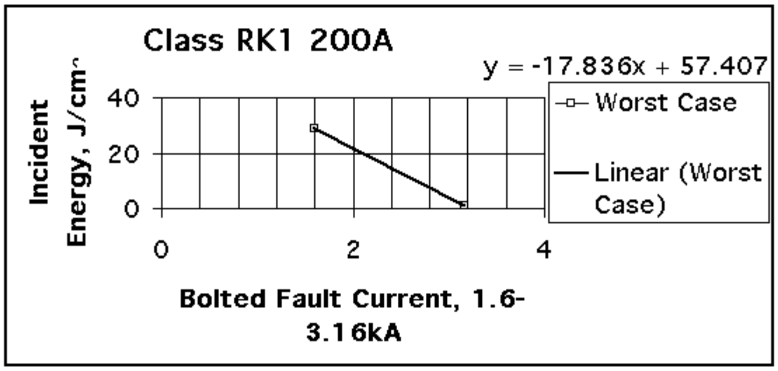


Figure 39—Class RK1 200 A fuse—upper current segment of model

For I_{bf} < 1.16 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 kA ≤ I_{bf} ≤ 1.6 kA,

$$E = 4.184\ (-18.409\ I_{bf} + 36.355) \tag{54}$$

For I_{bf}, such that 1.6 kA < I_{bf} ≤ 3.16 kA,

$$E = 4.184\ (-4.2628\ I_{bf} + 13.721) \tag{55}$$

For I_{bf}, such that 3.16 kA < I_{bf} ≤ 106 kA, E = 1.046

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

9.13.1.8 Class RK1 100 A

Table 19—Incident energy as a function of bolted fault current for one manufacturer's 100 A Class RK1 current limiting fuses @ 600 V, 460 mm

Current limiting fuse	Bolted fault (ka)	Series average incident energy (J/cm^2)	Series mean maximum incident energy (J/cm^2)	Series maximum incident energy (J/cm^2)	Default for model
Class RK1 100 A	1.60	0.42	0.21	0.84	1.0
Class RK1 100 A	1.40	0.92	0.84	1.05	1.0
Class RK1 100 A	1.16	2.00	1.70	2.50	2.5
Class RK1 100 A	0.65	21.00	21.00	26.00	26.0

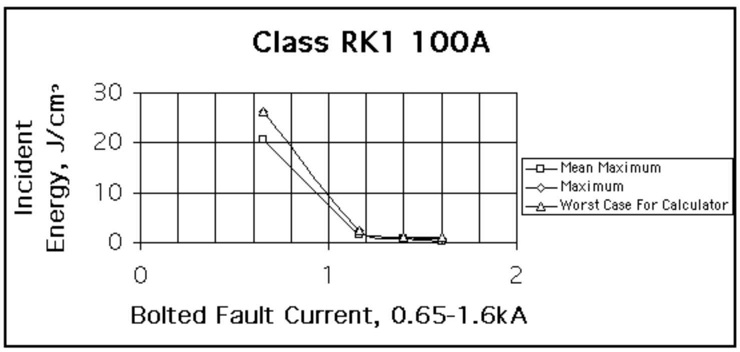


Figure 40—Class RK1 100 A fuse—lower current segment of model

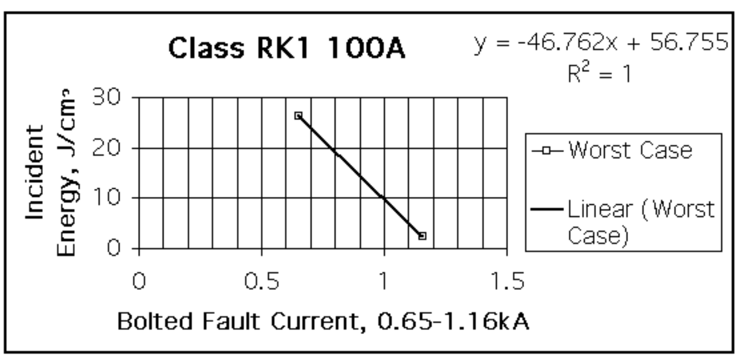


Figure 41—Class RK1 100 A fuse—upper current segment of model

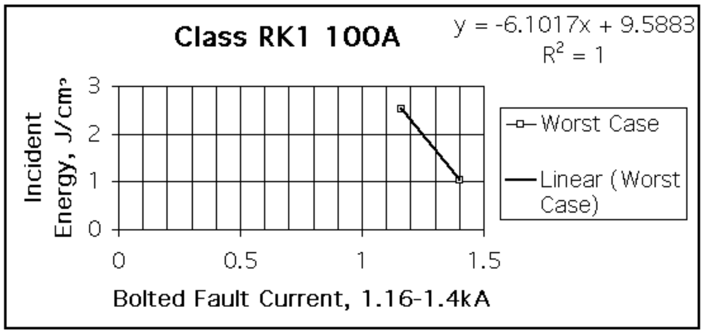


Figure 42—Class L 100 A fuse—upper current segment of model

For I_{bf} < 0.65 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 kA ≤ I_{bf} ≤ 1.16 kA,

$$E = 4.184\,(-11.176\,I_{bf} + 13.565) \tag{56}$$

For I_{bf}, such that 1.16 kA < I_{bf} ≤ 1.4 kA,

$$E = 4.184\,(-1.4583\,I_{bf} + 2.2917) \tag{57}$$

For I_{bf}, such that 1.4 kA < I_{bf} ≤ 106 kA, E = 1.046

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

9.14 Circuit breakers

Study has shown that in some cases a shortcut can be taken in analysis of the incident energy on equipment protected by upstream circuit breakers. The incident energy calculator included with this standard contains the shortcut. It allows a calculation of incident energy if the potential arc current falls in the instantaneous trip range of the circuit breaker. See Gregory, Lyttle, and Wellman [B11].

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. For conditions of bolted fault current below the range indicated for Table 20, the arc current and incident energy equations in 5.2 and 5.3 must be used.

Calculations were performed for a broad range of low-voltage circuit breakers in order to find those with the highest values for incident energy and flash-protection boundary. The output provided a range of information as indicated in Figure 43 for one grouping of circuit breakers. The calculations were performed using the model equations for arc current and incident energy with time-current characteristic curves for various ranges of circuit breakers for four manufacturers. Similar calculations were run for various groupings of circuit breaker types and ratings, as shown in Table 20.

Table 20—Equations for incident energy and flash-protection boundary by frame[a]

			480 V and lower		575–690 V	
Rating (A)	**Breaker**	**Trip unit type**	**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]	$4.560\ I_{bf} + 27.230$	$47.20\ I_{bf} + 2660$	$6.860\ I_{bf} + 2.170$	$62.4\ I_{bf} + 2930$

[a]Refer to Annex E for Table 20 (Table E.1) in cal/cm^2.
[b]I_{bf} is in kA, working distance is 460 mm.
[c]Short time delay is assumed to be set at maximum.

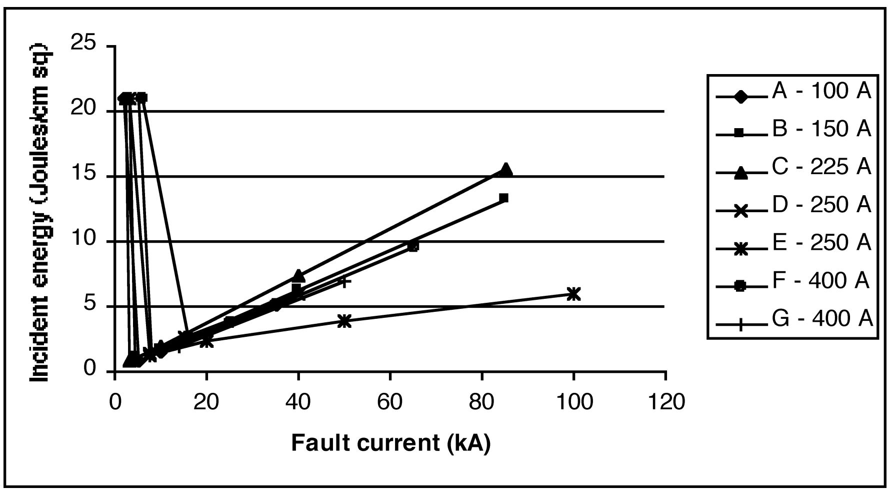


Figure 43—Incident energy vs fault current for 100 A–400 A frame circuit breakers

The format for both incident energy and flash-protection boundary appeared as indicated in Figure 44 for each grouping of circuit breakers in Table 20.

Even though the curves developed in this manner represent various designs from multiple manufacturers, the curves are somewhat bundled. This makes it practical to generate a single maximum energy or maximum distance curve representing each group of frames. The equations in Table 20 were formed by taking the highest curve calculated using model equations for any circuit breaker found and by calculating the line $E = M\ I_{bf} + N$ for the portion between I_1 and I_2. These represent the highest values for any equipment class regardless of whether solidly grounded or resistance grounded.

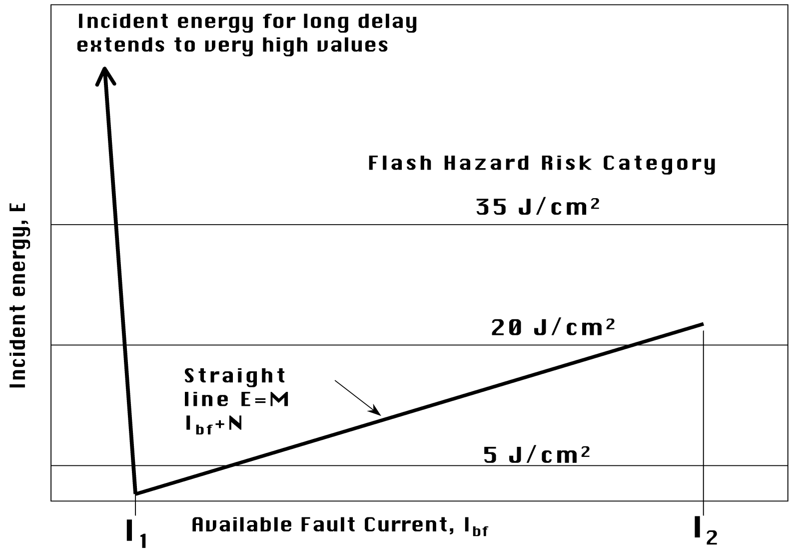


Figure 44—Incident energy vs available fault current generalized for circuit breakers

Note that the curve reaches a low energy value at the bottom of the "V" at a fault current point labeled I_1. Finding this current point is an essential part of calculating the incident energy because the user must be assured that the application is at a fault current above I_1. The high current point on the line is the interrupting rating of the CB and is labeled I_2. From I_1 on the chart to the highest current point, I_2, the curve is roughly a straight line due to the fact that manufacturers represent instantaneous clearing times as a straight line. This line, E = M I_{bf} + N represents the equation in Table 20. It is taken from a least squares regression of values calculated.

In the low current region (below I_1), in which the MCCBs are operating on their long-time characteristic, incident energy elevates quickly and may go above 100 cal/cm^2.

NOTE—I_{bf} is bolted fault current in kA.

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 trip under short-circuit conditions instantaneously, with no intentional delay. Below the instantaneous trip current, they have a long-time delay established to protect conductors while allowing momentary current surges such as for motor starting and transformer inrush. In many cases they have adjustable instantaneous trip current settings.
— M: Magnetic (instantaneous only) trip units are used for short-circuit protection only, usually in motor circuits. They have no long-time characteristic and will not trip below the instantaneous trip current, which is usually an adjustable setting.
— 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.

— L: The long-time setting is for lower overcurrent conditions to allow for momentary current surges. It usually has a current pick-up adjustment and a time-delay adjustment.
— S: The short-time setting is for coordination purposes through the overload and short-circuit current levels. It usually has a current pick-up and a time-delay adjustment.
— I: The instantaneous feature sets a current level above which tripping occurs with no intentional delay. It is usually turned off or is absent when the short-time function is used.

The range of these equations is 700 A–106 000 A and for the voltages mentioned in the Table 18. 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 arcing fault current at which this method can be applied. It is the lowest bolted fault current level that generates arcing current great enough for instantaneous tripping to occur.

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 45. 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.

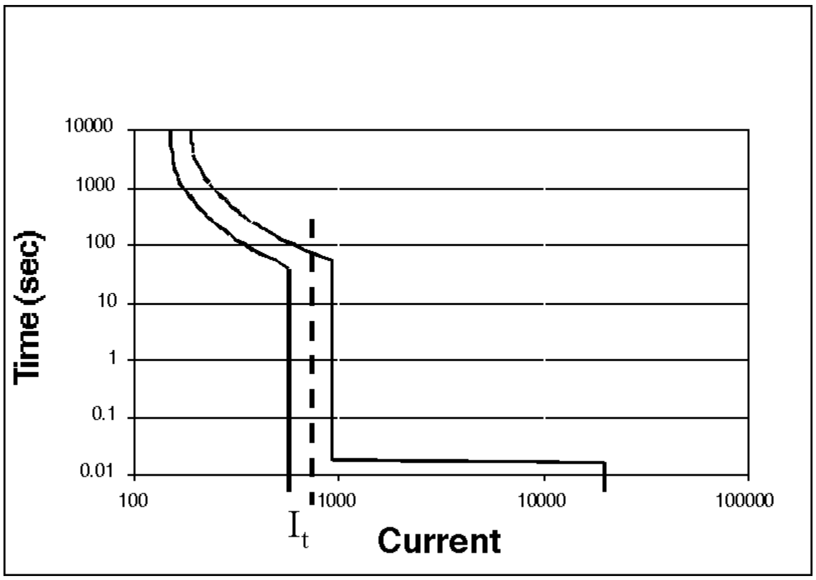


Figure 45—Typical circuit breaker time-current characteristic

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

$$\lg I_1 = 0.0281 + 1.09 \lg (1.3\, I_t) \tag{58}$$

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

$$\lg I_1 = 0.0407 + 1.17 \lg (1.3\, I_t) \tag{59}$$

$$I_{bf} = I_1 = 10^{\lg I_1} \tag{60}$$

10. Background on the arc-flash hazard

10.1 Early papers

10.1.1 "Arcing fault protection for low-voltage power distribution systems—nature of the problem" [B18]

This paper identified the potential for personal injury from arcing faults caused by such things as tools contacting bare buses, rodents, dust, insulation failure, or loose connections. The focus was on the nature of arcing faults and the protective equipment and relaying schemes that could be used to extinguish the arc.

10.1.2 "Predicting damage from 277-V single phase to ground arcing faults" [B28]

This paper proposed a method of approximating the degree of burning damage to metal that could be expected from various arcing current values and considerations for coordinating the time and current settings of ground fault protection devices with phase overcurrent protection equipment.

10.1.3 "The other electrical hazard—electric arc blast burns" [B19]

The electrical arc-flash hazard was highlighted. The paper described the electrical arc blast as the other electrical hazard. The thermal hazard was described as second degree burns up to 10 ft from the arc and third degree burns up to 5 ft. It also presented theoretical methods of evaluating the open air arc hazard and gave information on protective measures that should be taken to avoid serious injury.

10.1.4 "The escalating arcing ground-fault phenomenon" [B7]

The possible consequences of arcing ground faults were described in this paper. The phenomena of how low-voltage arcing phase-to-ground faults migrate to three-phase arcs was presented. The observation that the maximum arcing three-phase fault current is considerably less than the three-phase bolted fault value in 480 V equipment was discussed. The conditions where arcing becomes self-sustaining were described.

10.1.5 "Predicting incident energy to better manage the electric arc hazard on 600 V power distribution systems" [B4]

A method of estimating incident energy on a 600 V, three-phase power distribution system is presented. The effect on incident energy of the arc in a cubic box was considered in developing equations to estimate available bolted fault currents and incident energy at various distances. Benefits of using an estimate of the incident energy in the management of the electrical arc hazard was discussed.

10.1.6 "Report on enclosure internal arcing tests" [B12]

This paper focuses on high-energy arcing faults in enclosures with the compartment door closed. It reports the results of tests in 600 V class MCCs. The need for equipment testing standards in the low-voltage class is identified. Users should identify and provide PPE to personnel working near equipment that can not contain nor safely vent the arcing hazard.

10.1.7 "Arc and flash burn hazards at various levels of an electrical system" [B15]

This paper presents information from a survey of petrochemical facilities on the PPE used for electrical arc-flash protection. It focuses on the effect of high-energy electrical arcs on humans and presents calculations of distances for curable burn injury at typical industrial/large commercial electrical installations.

10.2 History of regulation and standards

10.2.1 U.S. Occupational Safety and Health Administration (OSHA)

On 4 August 1991, OSHA included language in its Title 29 Code of Federal Regulations, Subpart S, for the electrical safe work practices for general industry that added arc flash as an additional hazard to the shock hazard of electricity.

On 31 January 1994, OSHA included language in Title 29 Code of Federal Regulations, Subpart R, for the electric power generation, transmission, and distribution industry that protected the employee exposed to an arc flash by stating that the clothes worn by workers must not increase the extent of injury should the employee be exposed to an arc flash on the job.

10.2.2 National Fire Protection Association (NFPA)

The fifth edition of the NFPA Standard 70E, Electrical Safety Requirements for Employee Workplaces, published in 1995, established a flash-protection boundary. This action recognized the hazard of arc flashes and required employee protection from the flash hazard. The sixth edition, published in 2000, expanded on the requirement for flash-protection boundaries and the use of PPE. The flash-protection boundary is defined for 600 V and below electrical systems based on the bolted fault current and the clearing time. For systems above 600 V, the flash-protection boundaries must be calculated based on the distance at which the incident energy level from the flash equals 5.0 J/cm^2. [51] The onset of second degree burns is at the 5.0 J/cm^2 level. [52] If an employee works within the established flash-protection boundary, the standard requires either a flash hazard analysis be conducted or the protective clothing and equipment matrix be used to determine the level of protection required.

10.3 The reality of arc-flash injuries and deaths

The arc-flash hazard was not widely recognized nor identified prior to the publication of NFPA 70E-1995 as a separate electrical hazard. To the date of this standard, records do not identify arc-flash burn injuries as a separate category. However, numerous injuries and deaths have occurred. In retrospect, one large utility has discovered an average of 1 arc-flash injury every 18 months for the past 54 years. In preparation of this guide, a list of typical arc-flash incidents was compiled (see Annex C).

Following is the story of Vernon Peter Wiebe (see description of incident 1 in Table C.1 and Figure 46, Figure 47, and Figure 48), one survivor of an arc-flash burn injury.

“My name is Vernon Peter Wiebe. I received a note from Dr. Mary Capelli-Schellpfeffer, M.D. asking if I would be willing to share my story as to how I was seriously burned by an electrical arc flash/arc blast. I would be pleased to let you use whatever part of my story if it would help prevent other electrical workers from being severely injured or killed as a result of simply trying to do their job...The arc flash burned the shirt off my body. I was severely burned from the waist up, 28% of my body was skin grafted. I have lost the excellent eyesight and hearing I took for granted. My hearing is deteriorating. I must use hearing aids and have severe tinitus as a result of the arc blast. My vestibular function is damaged as well. I have no sense of smell, either good smells or bad. I suffer from severe headaches when I try to focus on anything close up (one meter or less).”

[51] See Footnote 11.
[52] See Footnote 11.

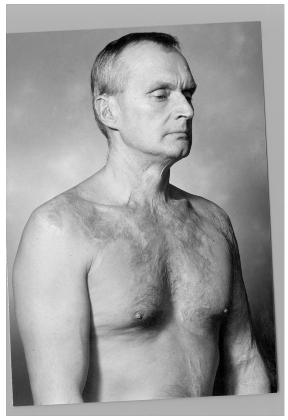


Figure 46—Peter Wiebe healed with scar tissue

Figure 47—Low-voltage class circuit isolation equipment (front view) where Peter Wiebe was engulfed in the discharge of the arc-flash products (heat, spatter, plasma)

Figure 48—Low-voltage class circuit isolation equipment (top view) where Peter Wiebe was engulfed in the discharge of the arc-flash products (heat, spatter, plasma)

Annex A

(informative)

Typical required equipment information data collection form

Table A.1—Typical required equipment information data collection form

Equipment information data	Study or task			
	Detailed single-line diagram	**Short-circuit study**	**Relay coordination**	**Arc-flash calculation**
1. Generator				
Manufacturer’s data				X
ID name	X	X	X	X
Rated kV	X	X	X	X
Nominal MVA or kVA	X	X	X	
Type of driver (steam, gas, etc.)	X	X	X	
Power factor	X		X	
Efficiency			X	
RPM			X	
X/R		X		
MW output	X	X	X	
MVAR output		X	X	
MVAR (minimum and maximum)			X	
MW output	X	X	X	
MVAR output		X	X	
MVAR (minimum and maximum)			X	
X″dv	X	X		
X′dv	X	X		
Xov	X	X		
Locked rotor impedance		X	X	X
Ground resistance (neutral ground resistance)	X	X	X	
Ground jX (neutral ground reactance	X	X	X	
Capability curves				
K value / I^2t characteristics				
Volts/Hz limit curves (unit generators only)				

Table A.1—Typical required equipment information data collection form *(continued)*

Equipment information data	Study or task			
	Detailed single-line diagram	**Short-circuit study**	**Relay coordination**	**Arc-flash calculation**
2. Utility				
ID name	X	X	X	X
Nominal kV	X	X	X	X
Three-phase short circuit MVA		X	X	X
Three-phase short circuit *X/R*		X	X	
Line-to-ground short circuit MVA		X	X	
Line-to-ground short circuit *X/R*		X		
Positive sequence fault impedance		X		
Zero sequence fault impedance		X		
3. Transmission line				
ID name		X	X	X
Number of conductors per phase	X	X	X	
Conductor material	X	X	X	
Conductor size	X	X	X	
Conductor circuit length	X	X		
Temperature of loaded conductor		X	X	
Conductor geometric mean distance spacing		X		
Rating of conductor (A)	X		X	
Impedance		X		
X1		X		
Xo		X		
Xc		X		
Xc0		X		
Overcurrent protective-device operating time				X
Available fault current				X
4. Transformer, power				
Note 1: Use only manufacturer's nameplate data and transformer's test report for % Z	X	X	X	
ID name		X	X	
Type (oil, gas, dry, etc.)		X	X	

Table A.1—Typical required equipment information data collection form *(continued)*

Equipment information data	Study or task			
	Detailed single-line diagram	**Short-circuit study**	**Relay coordination**	**Arc-flash calculation**
Class (type of cooling)	X		X	
Self-cooled rating	X	X	X	
Forced cooled rating	X	X	X	
% impedance	X	X	X	
R0, X0 (zero sequence impedance)		X	X	
R1		X	X	
X1		X	X	
Rated kV of a winding	X	X	X	
Winding connection	X	X	X	
Tap changer (NL-no load, or OLTC-on load)	X			
Quantities of taps (above and below normal)	X		X	
Tap changer step size (%)	X		X	
Available fault current				X
Tap changer max tap kV			X	
Tap setting	X	X		
Overcurrent protective-device operating time				X
Available fault current				X
5. Bus duct				
ID name		X	X	
Manufacturer	X	X	X	
Type	X	X	X	
Length	X	X	X	
Material	X	X	X	
Ampacity rating	X		X	
R1 positive sequence resistance		X	X	
X1 positive sequence reactance		X	X	
R0 zero sequence resistance		X	X	
X0 zero sequence reactance		X	X	
short-circuit withstand rating	X	X		

Table A.1—Typical required equipment information data collection form *(continued)*

Equipment information data	Study or task			
	Detailed single-line diagram	**Short-circuit study**	**Relay coordination**	**Arc-flash calculation**
Overcurrent protective-device operating time				X
Available fault current				X
6. Cables, power				
ID name		X	X	
Voltage rating	X	X	X	
Circuit or operating voltage	X	X	X	
No. of conductor per phase	X	X	X	
Conductor size (AWG or KCMIL)	X	X	X	
Circuit length	X	X	X	
Conductor material	X	X	X	
Conductor insulation type (for new installation only)	X	X	X	
Ampacity of conductors	X		X	
Cable routing (magnetic, nonmagnetic metal, or nonmetallic)	X	X	X	
Cable geometry (triangular, triplexed, etc.)	X	X	X	
Shielded or non-shielded	X	X		
Conductor shield material / construction (for new installations only)	X	X	X	
Available fault current				X
Overcurrent protective-device operating time				X
Available fault current				X
Overcurrent protective-device operating time				X
Rated continuous amperes	X	X		
7. Switchgear, medium voltage				
Medium-voltage circuit breakers (above 600 V)				
ID name	X	X		X
Normal state (if not closed)	X	X	X	

Table A.1—Typical required equipment information data collection form *(continued)*

Equipment information data	Study or task			
	Detailed single-line diagram	**Short-circuit study**	**Relay coordination**	**Arc-flash calculation**
Circuit and utilization description (incoming feeder to motor, transformer, or another equipment, as needed, bus tie, etc.)	X	X		
Year manufactured	X	X		
Interrupting rating at operating voltage	X	X		
Close and latch rating	X	X		
Rated kA at maximum kV	X	X		
Interrupting time		X		
K-factor		X		
Operating kV		X	X	X
Manufacturer	X	X		
Type	X	X		
Year manufactured	X	X		
Type (oil, vacuum, air magnetic, SF_6, other)	X	X	X	
Draw-out or fixed-mounted	X			
Voltage rating	X	X		
Operator (manual or electrical)	X			
8. Switchgear, low voltage (600 V and below) A—Circuit breaker (continued)				
Close and trip voltage (125 V dc etc.)	X			
Fuse size, manufacturer and type (if applicable)	X	X		
Normal state (if not normally closed)	X	X	X	
Interrupting rating at operating voltage	X	X		
Continuous current rating	X	X		
Trip unit information	X	X		
Available fault current				X
Overcurrent protective-device operating time				X

Table A.1—Typical required equipment information data collection form *(continued)*

Equipment information data	Study or task			
	Detailed single-line diagram	**Short-circuit study**	**Relay coordination**	**Arc-flash calculation**
B—Switchgear, low voltage (600 V and below)				
Manufacturer	X			
Type of switchgear	X			
Year manufactured	X	X		
Main bus material and continuous rating	X		X	
Main bus short-circuit withstand rating	X	X		
Vertical bus continuous rating	X		X	
Vertical bus short-circuit withstand rating	X	X		
9. Motors (all medium-voltage motors 151 HP and above operated at 600 V and above)				
ID name	X	X		X
Unit (HP or kW)	X	X		
Rated voltage	X	X	X	
Service factor	X	X	X	
Type (induction; synchronous; etc.)	X	X	X	
Full-load amp (at 1.0 service factor rating	X		X	
RPM		X	X	
Operating power factor and efficiency		X		
Acceleration time at 80% voltage			X	
Locked rotor amps at rated voltage		X	X	
Locked rotor withstand time (hot and cold)			X	
X/R (for all new motors, and for existing motors 3000 HP and above)		X		
X″dv (for all new motors, and for existing motors 3000 HP and above)		X		

Table A.1—Typical required equipment information data collection form *(continued)*

Equipment information data	Study or task			
	Detailed single-line diagram	**Short-circuit study**	**Relay coordination**	**Arc-flash calculation**
Available fault current				X
Overcurrent protective-device operating time				X
10. Motors (150 HP and below)				
Rated voltage	X	X		
Service factor	X			
Type (induction; synchronous, etc.)	X	X		
Full-load amp (at 1.0 service factor rating)	X			
RPM		X		
Operating power factor and efficiency				
Locked rotor amps	X	X	X	
11. Motor control center (Medium-voltage with fused contactors)				
ID name	X	X		X
Manufacturer and type	X	X	X	X
Year manufactured	X	X		
Contactor type (vacuum or air break)	X	X	X	
Bus short-circuit rating kA	X	X	X	
Horizontal bus continuous-rating amps	X	X	X	
Contactor rating (enclosed) continuous	X		X	
Fuse size, type, and manufacturer	X	X	X	
protective-device information	X		X	
Available fault current				X
Overcurrent protective-device operating time				X
12. Motor control center (low voltage)				
ID name	X	X	X	X

Table A.1—Typical required equipment information data collection form *(continued)*

Equipment information data	Study or task			
	Detailed single-line diagram	Short-circuit study	Relay coordination	Arc-flash calculation
Manufacturer	X	X	X	X
Year manufactured	X			
Short-circuit protective-device information (type, size, range of adjustment, fuse size, and type)	X	X	X	
Bus short-circuit rating	X	X	X	
Horizontal bus continuous rating Amps	X		X	X
Vertical bus continuous rating amps	X			X
Overload protective-device information (type, setting)	X		X	
Available fault current				X
Overcurrent protective-device operating time				X

Annex B

(informative)

Instructions and examples using IEEE Std 1584-2002 calculators

Clause 4 of this guide contains detailed information on the process of conducting an arc-flash study. It should be studied by anyone conducting an arc-flash study. The calculators included with this guide include some instructions, cautions, and disclaimers, which should also be studied. The instructions in B.1 and B.2 will walk a user through use of the calculators. Use of the bolted fault calculator is shown in B.3. This calculator was provided by Porcaro and Porcaro [B23]. The incident energy calculator contains pre-entered data for illustrative purposes.[53]

B.1 IEEE Std 1584-2002 Arc-Flash Hazard Calculator

B.1.1 Basic information tab

Go to the basic information tab and review all information on this page. Enter the case or location and the date.

B.1.2 Data-normal tab

Go to the data-normal tab and note that the information in the green cells has transferred automatically to this worksheet from the basic information tab.

Enter the information in the yellow cells.

— In row 2, indicate the appropriate mode for the analysis being performed. See B.1.5 for information on multiple modes.
— In row 19, enter the desired boundary energy if different from the default. It can be in either J/cm^2 or cal/cm^2. Results will be in both units in either case.
— In row 21, enter the estimate of the motor contribution factor, which is the fraction, of bolted fault current coming from motors or alternate feeds and not passing through the protective device that will interrupt most of the fault current. Zero is acceptable. The default is 0.03 (i.e., 3%).
— Beginning on row 24, enter the bus identification, the voltage, and the bolted fault current in columns A, B, and C, respectively. If the portion of bolted fault current in kA that flows through the protective device is known, enter that number in column D. When entering data, overwrite the example cases shown. Inserting rows will disrupt the cross-sheet references.

Enter the equipment class in column M. Based on equipment class and voltage, the calculator will select a distance exponent and a bus gap from the reference tables tab and will immediately calculate the arcing fault current in column F.

NOTE—If the calculator does not calculate, go to tools/options/calculation or tools/preferences/calculations and see if manual or automatic is selected. Select preference.

For low-voltage applications, under 1 kV, it will also calculate a reduced arcing fault current in column I. that will be 85% of the current in column F. This will allow a second calculation, which is needed due to

[53]See Footnote 1.

variation in arc current. For those cases where the arc current falls on the steep part of the time-current curve or falls near a step change, the variation in arc current could cause a significant error in protective-device tripping or operating time.

Enter the grounding type in column N.

Enter the protective-device type in column O. If none of those listed is applicable, leave the zero default entry. This column is optional.

If a protective-device type number for a circuit breaker is entered and the arcing current is high enough, a time-current curve to find trip time is not necessary for use. The calculator can automatically determine incident energy. Recognize that using the time-current curve would give a more accurate result.

Find and insert the instantaneous trip setting, It, using the procedure in 5.7. If the arc current is high enough, the calculator will turn the cells in columns G and H white, indicating no entry is required and “not required” will show in column I.

If the arcing current is too low compared to the instantaneous trip setting, the calculator will change several cells to orange, column O and on the calculations—normal tab columns M and N. It will then be necessary to change the protective-device type to 0, find the time-current curve, and input the circuit breaker trip times as described below.

If the protective-device type number for a fuse is entered, the calculator will assess the applicability of the fuse equations and if the current is neither too high nor too low—beyond the test range, the fuse equations will be applied. As an indicator, the cells in columns G and H will turn white, indicating no trip time need be entered and “not required” will show in column I.

If outside the range of the equations, column O and the calculations—normal tab columns M and N will turn orange and the protective-device type will have to be changed to 0.

For available short-circuit currents outside the range of the protective devices or for other types of protective devices, find the time-current curves for the protective device of concern. Find the trip and opening time for the arcing fault current by following the guidance in 4.5, and enter the times in columns G and H. Repeat for the reduced arcing fault current for low-voltage cases, and enter the times in columns J and K.

Note that if an arcing fault can be initiated on the line side of a main protective device in an enclosure, that protective device should not be utilized for the calculations, instead, the upstream protective device should be used. That is because only an upstream protective device can be considered to provide protection for an arcing fault on the line side of the main protective device in a downstream enclosure.

If the time is longer than two seconds, consider how long a person is likely to remain in the location of the arc flash. It is likely that a person exposed to an arc flash will move away quickly if it is physically possible and two seconds is a reasonable maximum time for calculations. A person in a bucket truck or a person who has crawled into equipment will need more time to move away.

Insert working distance in mm in column L (see 4.8 for guidance).

Additional entry instructions are shown on the data—normal worksheet of the calculator.

B.1.3 Reference tables and CB reference tabs

The calculator uses the tables on these worksheets as look-up tables.

If desired, change any of the gaps on the references tables tab to any gap within the range covered by the test database and shown in Clause 5 of IEEE Std 1584-2002. The calculator will not give an error indication if a number outside of that range is used, but there will be no test basis for the result. The PPE levels can also be changed to the site preference or to new NFPA 70E levels.

B.1.4 Calculations—normal tab

Go to the calculations—normal tab for results. Read off incident energy, flash boundary, and the PPE level recommended in NFPA 70E-2000.

Equations can be viewed by selecting the columns on both sides of the hidden columns, accessing format/columns, and selecting unhide.

Recognize that the calculators are not locked, so always make a copy of the calculators before changing any defaults.

B.1.5 Summary tab

This calculator can be expanded to allow as many modes of operation as necessary. Select the data—normal and calculations—normal tabs at the same time and then copy the sheets by selecting *move or copy sheet* from the edit menu, checking the *create a copy* box, and then selecting OK. Rename the sheets as a different mode such as one utility feeder, parallel secondary ties, or parallel primary ties. The results of the new worksheets can be added manually to the summary page.

When using this calculator with multiple mode sheets, it is recommended that each bus be shown in the same row on all sheets.

B.2 IEEE Std 1584-2002 Bolted Fault Calculator

The calculator for bolted fault current calculates the short-circuit current for simple systems consisting of a radial feeder, which can then be used as input data for the incident energy calculator.

B.2.1 Basic information tab

Go to the basic information tab and review all information on this page. Enter the case or location and the date.

B.2.2 Bolted fault tab

Collect application data. Minimum needed data is as follows:

a) Available fault MVA and *X/R* ratio, which the utility can provide
b) Feeder lengths, copper or aluminum conductors, number of conductors per phase, and sizes
c) Transformer MVA rating, primary and secondary voltages, and percent impedance and *X/R* ratio

Enter the data in the calculator bolted fault tab, as applicable.

This calculator is intended to enable calculation of the available fault current and *X/R* ratio. It neglects the motor contribution if present. If there are motors, 37 kW (50 hp) or larger connected to a bus shown on the bolted fault calculation tab, this calculator cannot be used.

B.2.3 Transformer impedance tab

If the transformer impedance or *X/R* ratio are not available, go to the transformer impedance tab for the information. Transformer impedance data should be obtained from nameplates wherever available to ensure accuracy.

B.2.4 Conductor impedance tab

Go to the conductor impedance tab and find the cable resistance and reactance per 1000 ft. Enter the data on the bolted fault tab.

B.2.5 Bolted fault tab again

The bolted fault calculator will then provide the bolted fault current in the three pink fields. Manually enter these bolted fault currents, the bus designations, and the voltages on the data—normal tab of the incident energy calculator.

If the calculator does not calculate, go to tools/options/calculate and see if manual or automatic is selected. Select preference.

B.3 Example

Consider a radial distribution system consisting of a utility service, a 13.8 kV feeder, a 2000 kVA transformer, and a 480 V feeder to an MCC. The bolted fault calculator can find the available three-phase short-circuit current at the transformer primary, transformer secondary, and MCC. This example is provided in the calculator.

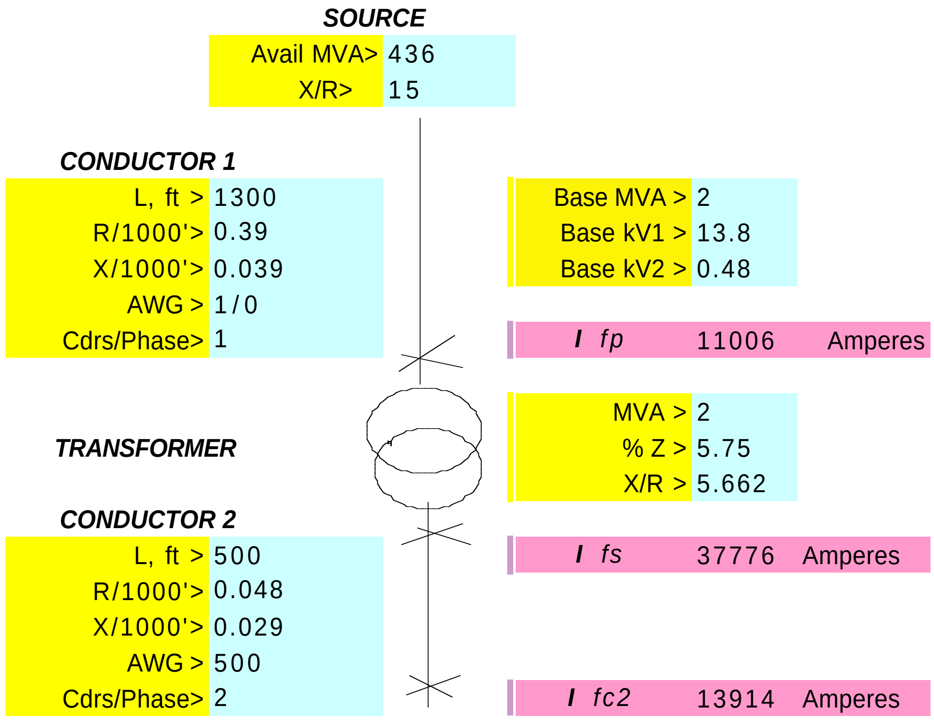


Figure B.1—Example—Part of bolted fault tab

Annex C

(informative)

Description of arc-flash incidents

Table C.1—Case histories of arc-flash incidents

Setting	Electric system	Equipment	Activity	Event	Apparel	Outcome
1. Commercial site—1998	600/347 V ac	XFMR 1500 kVA, 12.47 kV—600/347 V Grounding Secondary ground Fault relay protected Primary fuse protected	Electrician installing a 400 A fuse in a panel module. Switch had been opened to isolate the fuse mount	Arc flash occurred in the panel directly in front of the employee. 	Hard hat Safety glasses	Third degree burns to 28% of the employee's body. Significant loss of sight, hearing, and smell. Ground fault relay did not open. Primary fuse operated.
2. Industrial site, power distribution—1994	Unit substation	Unit feeder circuits	Electrician was circuit testing on deenergized feeder circuits.	An arc flash occurred when the feeder circuits were reenergized at main substation while electrician was connecting test lead to fuse holder.	HV gloves Safety glasses	No injury.
3. Laboratory—1997	480 V ac	480 V ac electric panel MCC	Connecting temporary lighting and heat circuits from an MCC to a 480 V electrical panel in another room. Electrician was removing the upper bus bar cover that shields the line side connections in the panel.	While moving the cover, it contacted the C-phase of the bus bar causing an arc flash.	Unknown	The electrician had burns to his face and hands.
4. Industrial site, outdoor substation—1998	13.8 kV ac	HV switch	Electrician was using a paint brush to clean inside the switchgear cabinet in close proximity to energized equipment.	Debris or other material fell and contacted the energized C-phase knife blade creating an arc flash.	T-shirt	Second and third degree burns to the right arm and left hand.

Table C.1—Case histories of arc-flash incidents *(continued)*

Setting	Electric system	Equipment	Activity	Event	Apparel	Outcome
5. Industrial site—1998	480 V ac	MCC	Electrician removed the door operating mechanism from a spare circuit breaker and was reinstalling the spare breaker to the mounting plate.	While reinserting screws into the spare breaker mounting plate, a screw penetrated a line side conductor causing a 480 V, three-phase arc flash.	Unknown	Second degree burns.
6. Industrial site—1992	480 V ac	480 V bus bar	One electrician was holding a ground lead in place while the other was tightening the lug with a “taped” Allen wrench near a 480 V bus shielded with an insulation blanket.	The Allen wrench slipped and contacted the 480 V bus.	Unknown	Burns to the hands of both electricians.
7. Utility generation plant	2400 V ac, three-phase, ungrounded, delta-connected	Motor starting circuit breaker (1950’s vintage) 2400 V ac feeder bus had no main overcurrent protection of its own of any kind. Interlock that prevented breaker from being “racked in” while closed was missing. Breaker was in the “closed” position. Breaker feeds a 700 HP motor.	Operator racked the breaker “in” with it in the closed position, and then started to rack it out.	The 700 HP motor was accelerating and the breaker being backed out caused a significant arc flash to occur. The arcing fault continued until an overcurrent relay operated a breaker on the primary side of the 13.8 kV–2.4 kV transformer	Hard hat Leather gloves Safety glasses	No injuries.

Table C.1—Case histories of arc-flash incidents *(continued)*

Setting	Electric system	Equipment	Activity	Event	Apparel	Outcome
8. Utility, outdoor substation—2000	13.2 kV ac	13 k V vacuum circuit breaker 200 A fused dropouts between the breaker bus and the main bus Maximum fault currents: 8 kA phase-to-ground 6 kA phase-to-phase	Electrician was reaching with a combination wrench for a stinger conductor bolt of C-phase on the energized breaker from a step ladder.	The wrench bridged C and B phases causing a phase-to-phase arc flash. The fuse dropouts cleared the fault in 27 cycles.	Cotton T-shirt	The burning T-shirt caused second and third degree burns to 60% of the upper torso.
9. Industrial site—1997	480 V ac	480 V MCC main breaker Placed lock and tag to isolate the MCC main breaker Unisolated feed existed to breaker that was out-of-service when work began	The circuit tested deenergized the day before accident. On second workday, electrician assumed (no test) circuit was still deenergized.	Electrician started to connect line side leads to the MCC main breaker when an arc flash occurred.	Unknown	The electrician suffered arc-flash burns from this incident.
10. Utility generation plant—1997	480 V ac	MCC	Racking in breaker.	An electrical connector touched a brace bar as the breaker was racked in and the phase was grounded causing an arc flash.	Unknown	Burns to both wrists.
11. Utility generation plant—1995	480 V ac	480 V feeder board 480 V breaker (reconditioned)	Racking in a reconditioned replacement breaker, but was unable to close the door due to incompatible components (incorrect part).	Standing to the left of the compartment, the electrician closed the breaker with just his hand in front of the compartment. The breaker malfunctioned causing an arc flash.	Unknown	Serious burns to hand.

Table C.1—Case histories of arc-flash incidents ***(continued)***

Setting	Electric system	Equipment	Activity	Event	Apparel	Outcome
12. Utility generation plant—1994	Precipitator power substation	480 V ac breaker	Trouble shooting for a ground indicator light problem. Inserted volt ohmmeter lead into the 1200 V ac socket of the meter.	When placing the meter probes across A and B phase buses the meter shorted causing an arc flash, which migrated to the panel above the work area and caused a phase-to-phase arc in panel.	Unknown	Second and third degree burns to both hands.
13. Industrial site—1994	480 V ac	480 V ac, 200 A panel	Turning breakers on and off to locate equipment feeds in machine shop.	The beaker shorted causing an arc flash between phases.	Unknown	Burn to right hand.
14. Utility generation plant—1992	440 V ac	440 V ac, molded frame breaker Distribution board	Electrician was removing a 440 V ac breaker, which had been out of service since 1982.	When cutting the leads to the 440 V ac breaker, an arc flash occurred.	Unknown	Serious burns to both hands.
15. Utility generation plant—1991	Less than 600 V ac	Motor rotation indicator	Performing a phase sequence check on a new bus and was using a motor rotation indicator issued by the tool room and not the phase sequence indicator.	When the power was applied to the bus, the motor rotation indicator shorted causing an arc flash.	Unknown	Corneal burn to both eyes.
16. Utility generation plant—1990	480 V ac	480 V ac breaker Feeder board	Was placing breaker in cubicle, the breaker was closed and did not open due to mechanical failure.	The closed breaker caused an arc flash.	Unknown	Burn to shoulder.
17. Utility transmission—1990	Outdoor substation	4160 V ac conductors	Testing to determine if the conductors were energized to the transformer bank.	When the electrician placed the Simspon 260 m probe on one phase and the other probe on the second phase the meter shorted causing an arc flash.	Unknown	Burns to both hands.

Table C.1—Case histories of arc-flash incidents ***(continued)***

Setting	Electric system	Equipment	Activity	Event	Apparel	Outcome
18. Utility generation plant—1989	480 V ac	Panel board 480 V ac breaker	Two electricians were taking current readings in the breaker compartment with a clamp-on type ammeter on the motor phase conductor from the breaker.	A fault occurred that caused an arc flash in the breaker compartment.	Unknown	Second and third degree burns to both employees' faces.
19. Utility generation plant—1988	161 kV ac	Plant switchyard Disconnect switch	Two electricians were inspecting lightning arrestors and disconnect switch insulators from a non-insulated aerial lift bucket.	While moving bucket to a new position, there was an arc flash from an energized 161 kV switch to the bucket.	Non-flame resistant winter clothing Hard hat Safety glasses	Two employees had second and third degree burns from the arc flash and burning clothing. One employee died from burn injury complications.
20. Utility generation plant—1988	480 V ac	480 V ac breaker board	Electrician was testing for voltage on the 480 V ac breaker studs with an HV probe.	When the studs were contacted, an arc flash occurred in the breaker compartment.	Hard hat Safety glasses	Second degree burns to hands and first degree burns to face and forearms.
21. Industrial site—1986	2400 V ac	2400 V ac breaker board that feeds a 1250 HP pump	Opening a breaker.	Electrician opened a 2400 V breaker under load.	Cotton clothing	Electrician had second and third degree burns from the arc flash and burning clothing to 70% of body. Second electrician had first and second degree burns to hands from rescue efforts.

Table C.1—Case histories of arc-flash incidents *(continued)*

Setting	Electric system	Equipment	Activity	Event	Apparel	Outcome
22. Utility, transmission—1970	13 kV ac	Energized 13 kV substation bus 13 kV potential transformer	Lineman was in an insulated aerial lift maneuvering an energized “stinger” during the installation of a potential transformer with help of an electrician using a “hot stick” from a ladder.	The electrician caused an arc flash between the bucket and the substation steel setting fire to the lineman’s shirt. The assistant superintendent climbed onto the structure to aid the injured. When he touched the bucket a second arc flash occurred setting his clothing on fire.	Unknown	Both the lineman and superintendent died from injuries from their burning clothing.
23. Utility, transmission—1967	13.8 kV ac	13.8 kV oil-filled circuit breaker (OCB) 13 kV synchronous condenser	Periodic inspection of the condenser had been performed with the circuit deenergized. The circuit was reenergized and a substation control alarm went off. The operator and electrician went to the switchhouse breaker room to investigate.	The employees attempted to close the 13.8 kV OCB causing an arc flash. The arc flash caused the OCB to explode throwing flaming oil throughout the room.	Unknown	The electrician was able to exit the room with his clothing on fire. The operator did not get out of the room. Both died of burn injuries.
24. Utility, transmission—1981	46 kV ac	46 kV gang operated three-phase switch 46 kV OCB	Completed testing B and C phases. Conducting resistance test on the A-phase OCB insulator using a “micrometer.”	“When the employee applied the test probe to the insulator, an arc flash occurred because the A-phase of the 46 kV gang operated switch did not open when the circuit was cleared.	Polyester/cotton shirt	Second and third degree burns on two-thirds of the upper torso. Polyester melted on his skin.
25. Utility, transmission—1973	46 kV ac	46 kV transmission line switch structure, wood poles 46 kV switch	Lineman was dead-ending a conductor on a switch structure working from a ladder.	The lineman’s head contracted the energized 46 kV switch above him causing him to fall.	Unknown	Lineman had burns over two-thirds of his body, which resulted in his death.

Table C.1—Case histories of arc-flash incidents ***(continued)***

Setting	Electric system	Equipment	Activity	Event	Apparel	Outcome
26. Utility transmission—1984	161 kV ac	Double circuit 161 kV steel transmission tower 161 kV jumper Zinc based paint	Lineman was painting a steel transmission tower with energized jumpers above and below the tower arm where he was working.	Dripping paint from the bucket to the 161 kV energized jumper caused an arc-flash explosion.	Unknown	Lineman was blown off the tower, but had on a “safety” which prevented his fall. He received first degree burns to his forearms
27. Utility transmission substation—1969	161 kV ac	161 kV OCB OCB phase bushing on bus side	The OCB was cleared on the line side, but not the bus side. The electrician climbed on the breaker to attach temporary safety grounds.	The electrician contacted the energized OCB bushing on the bus side of the breaker causing an arc flash that blew him off the breaker.	Unknown	Electrician had third degree burns to his arms and a fractured skull.
28. Mine site—2000	995 V ac	1 kV ac breaker panel.	Replacing a 480 V ac breaker panel with a 1 kV ac breaker panel. With new panel installed, the 7200 V ac transformer was reenergized. At first the AMR-type ground check circuit prevented the new panel from energizing. The electrician started removing the 1.0 kV panel when the ground check circuit shorted and energized the panel.	While moving the panel, it contacted the line side connections which were energized at 995 V causing an arc flash.	Unknown	Electrician had serious burns to both hands and face.

Table C.1—Case histories of arc-flash incidents *(continued)*

Setting	Electric system	Equipment	Activity	Event	Apparel	Outcome
29. Industrial site, substation—1996	35.4 kV ac	Substation main 34.5 kv overhead switch support column Cable support bracket 34.5 kv bus substation bus insulator	Employee was installing an HV cable support bracket on the support column. Supervisor was holding the bracket in place while employee stood on fiberglass step ladder. This operation was next to an energized 34.5 kV bus.	The employee reached out and contacted the bus insulator causing an arc flash.	Unknown	Employee had burns on his face, hands, waist, and upper back. He also had electrical internal burn injuries. He died from these injuries.
30. Industrial site—1994	480 V ac	480 V secondary circuit breakers 480 V power distribution panel Below-pier electrical vault	Three employees were reinstalling 480 V breakers into an energized distribution panel in an electrical vault. The crew installed one breaker.	While installing the second breaker, an arc flash occurred. The cause of the arc was excessive moisture in the glass fiber reinforced polyester (GFRP) molded insulating material between the 480 V phases during breaker installation.	Non-fire resistant clothing	One employee was engulfed in flames and died from burn injuries. The other two had serious burn injuries.
31. Industrial site—1992	2.3 kV ac	MCC 250 V multimeter 2.3 kV fuses	An electrical worker (nine months experience) and a Journeyman electrician were performing operation checks on MCC. Compartment heater found inoperative. Journeyman went to get single-line drawing.	Worker thought a set of fuses was low voltage (could not read fuse label). He touched the meter probes to fuses which were energized at 2.3 kV causing an arc flash.	Eye and face protection Electrical hazard safety shoes	The worker had first, second, and third degree burns over 30% of his body.

Table C.1—Case histories of arc-flash incidents *(continued)*

Setting	Electric system	Equipment	Activity	Event	Apparel	Outcome
32. Mine site—1997	480 V ac	MCC 480 V main circuit breaker 480 V feeder circuit breaker	The main breaker in the MCC would not reset. The electrical supervisor had all the 480 V load shut down and then shut off all the breakers in the MCC. He tried again to reset the main breaker.	Supervisor opened the panel door to take readings on the main breaker with a multi-meter. The probe simultaneously touched the energized terminal and a grounded nut that was used to mount the breaker in the MCC (the breaker was improperly mounted). This caused an arc flash to occur.	Non-flame resistant clothing	The supervisor's clothing ignited and he had second degree burns over 75% of his body. He died the following day. Two other supervisor who were assisting to trouble shoot the MCC received arc-flash burns to the face, arms, and hands.
33. Industrial site—1987	2.4 kV ac	2.4 kV draw-out, fused-contactor assembly in a motor starter	An electrician taking reading with a multimeter. The meter operating range was set at 500 V ac. The fused-contactor was energized at 2.4 kV.	When the meter probe contacted the 2.4 kV fused-contactor, it exploded causing a three-phase arc flash in the assembly.	Unknown	The electrician sustained massive burn injuries and subsequently died. There was no evidence of electrical shock.
34. Industrial site—1994	480 V ac	480 V ac main breaker	Moving a no. 6 AWG ground wire in a 480 V cabinet.	The electrician allowed the ground wire to contact an energized phase lug of the main breaker resulting in a three-phase arc flash.	Unknown	The electrician sustained third degree burns to neck, arms, and torso.

Table C.1—Case histories of arc-flash incidents *(continued)*

Setting	Electric system	Equipment	Activity	Event	Apparel	Outcome
35. Industrial site—1998	480 V ac	480 V frame type KC breaker with solid state trip unit	Employee was trouble shooting the “trip” button on the breaker. The button was stuck behind the panel it normally stuck through and was located just below the hole. He opened the cubicle door, squatted down, and attempted to realign the button.	The button came apart and the linkage dropped down into the energized bus bar initiating an arc flash.	Safety glasses. HV switching gloves.	Employee sustained second degree burns to his arms and face.
36. Industrial site—1995	480 V ac	480 V circuit breaker Air conditioner unit 13.2 kV–480 V transformer fed directly to the breaker	The system was not deenergized. Two employees approached the breaker panel board which already had its cover and door removed. One employee either reset the breaker or started to remove it.	As the employee started to reset/work on the breaker, an arc flash occurred which caused a second arc flash at the block connection at the switchgear.	Unknown	One employee nearest breaker sustained burns over 87% of his body. The second employee sustained burns over 50% of his body and later died.
37. Industrial site—1993	12 kV ac	12 kV circuit breaker Circuit breaker cubicle	Electrician was working inside the energized 12 kV breaker cubicle without insulating barriers. He was working on the breaker controls.	An arc flash occurred on the exposed phases of the supply side of the breaker.	Unknown	The electrician suffered third degree burns to his face, body, and arms.
38. Industrial site—1991	480 V ac	480 V circuit breaker Rotary switch to wind turbine	Electrician was replacing a 480 V breaker serving a wind turbine. He turned a rotary switch to what he thought was the open position to isolate the breaker.	When he touched the breaker terminals to discharge stored energy, an arc flash occurred because of the backfeed from a transformer.	Unknown	The electrician’s shirt ignited and he suffered deep burns to his face and arms.

Table C.1—Case histories of arc-flash incidents *(continued)*

Setting	Electric system	Equipment	Activity	Event	Apparel	Outcome
39. Industrial site—1991	600 V ac	600 V circuit breaker	Electrician was measuring voltage on the load side of a 125 A, 600 V breaker.	Something caused an arc flash in the breaker.	Unknown	Electrician was burned over 60% of his body and died.
40. Utility generation plant—1985	4160 V ac	4160 V circuit breaker	Three employees were going to remove a 4160 V breaker. They went to the wrong breaker, which was energized.	When the breaker contacts were opened, an arc flash occurred.	Unknown	One electrician suffered second and third degree burns. The other two suffered burns to their face and hands. All were hospitalized.
41. Industrial site—1984	6.9 kV ac	6.9 kV transformer bank 6.9 kV OCB	Three employees were in the OCB building to inspect equipment, change the OCB oil, and clean transformer bushings. Number 1 employee was isolating the equipment. He removed the load from the secondary side of the transformer, then used an ammeter to measure current to the transformer, which showed no load.	He then opened the OCB, which caused an arc flash and the building ignited.	Unknown	Employees no. 1, 2, and 3 were in the building when the arc flash occurred. All suffered burns, but employee no. 1 died from the injuries.

Table C.1—Case histories of arc-flash incidents *(continued)*

Setting	Electric system	Equipment	Activity	Event	Apparel	Outcome
42. Industrial site—1998	2.3 kV ac	2300 V, 1000 Hp motor Temporary protective grounds	Electrician had swapped the motor leads at the contactor to change the rotation of the motor. Then, operator was to return motor to service. He closed the no-load switch.	The no-load switch arc flashed phase-to-phase because grounds were not removed. Hot gases pushed the door open where operator was standing. 	Safety glasses Fire resistant pants and shirt Arc flash suit including hood	PPE prevented burn injury.
43. Utility generation plant—2002	4160 V ac	4 kV ac breaker. Temporary protective safety grounds.	Electrician was to install a safety ground on the load side copper stabs of the 4 kV breaker. Electricians two and three were assisting by holding the breaker's arc shield to expose the stabs. While attempting to attach the first ground, he approached the high-side, energized, stabs of the breaker with the safety ground.	An electrical arc flash occurred from the energized breaker stab to the grounded safety ground. The fault migrated into a three-phase arcing fault.	The employee handling ground: FR switching jacket, safety glasses, leather gloves, and hard hat Employee on left side of cubicle: 100% cotton shirt, safety glasses, leather gloves, hard hat Employee on right side of cubicle: 65/35 polyester/ cotton shirt, safety glasses, leather gloves, and hard hat	Employee handling ground: first and second degree burns to neck and face (3% total body). Employee on left: first and second degree burns to his arm (3% total body). Employee on right: second and third degree burns to arm and upper body (13% total body).

Table C.1—Case histories of arc-flash incidents *(continued)*

Setting	Electric system	Equipment	Activity	Event	Apparel	Outcome
44. Utility generation plant—1985	13.8 kV ac	13.8 kV disconnect Temporary safety grounds Step-ladder	Employee was to attach grounds to the generator side of the disconnect from a step-ladder.	As he started to attach the ground on the deenergized bus, the ladder tipped causing the ground conductor to contact the energized side of the disconnect. An electrical arc flash occurred.	Unknown	Employee had second and third degree burns to hand, arm, and face.
45. Utility generation plant—1991	480 V ac	480 V breaker	.Employee was “racking-in” the 480 V breaker with it in the “closed” position.	An electrical arc flash occurred.	Unknown	Employee was burned on the arm.
46. Utility generation plant—1948	Unknown	Compensator Disconnect switch	The employee switched a ventilating fan switch to start the fan.	An electrical arc flash occurred in the compensator, and it blew up.	Unknown	Employees clothing ignited and burned. He had over 50% total body burns and died.
47. Utility transmission—1963	13 kV	13 kV substation bus	The employee was removing temporary jumpers on a 13 kV line.	The employee contacted the C-phase bus with his body causing an arc flash to occur.	Unknown	Burns caused death of the employee.
48. Utility transmission—1968	13 kV	13 kV bus	A hydraulic press was being moved and it fell into a 13 kV energized bus.	An electrical arc flash occurred.	Unknown	The employee was burned.

Table C.1—Case histories of arc-flash incidents *(continued)*

Setting	Electric system	Equipment	Activity	Event	Apparel	Outcome
49. Utility generation plant—2002	4160 V ac	4 kV breaker.	The employee was racking the breaker and it would not completely rack-in, lacking about an inch. The employee removed the arc shield from the breaker to observe the shutter levers. He reached in to check whether the levers were “free.”	An electrical arc flash occurred when the employee’s hand contacted the A-phase shunt which was energized.	Polyester/cotton shirt.	80% of his shirt burned away. He received third degree burns to his right hand, arm, and right shoulder and second degree burns to face, neck, left arm, and hand.

Annex D

(informative)

Test results database

Please refer to auxiliary files: Data_set.xls, Test_results_database.xls, and CL_Fuse_test_data.xls supplied with this standard (on CD ROM with the printed version and spreadsheet files bundled with PDF version).[54]

[54]See Footnote 1.

Annex E

(informative)

Units of measure

E.1 IEEE metric policy

In 1995, the IEEE implemented a new metric policy (IEEE Policy 9.20), which calls for measured and calculated values of quantities to be expressed in metric units [SI (Systéme International d'Unites)] in IEEE publications as of January 2000. (See IEEE/ASTM SI 10-1997 for guidance in metric practice.) This means that all new standards and revised standards submitted for approval shall now use metric units exclusively in the normative portions of the standard. Inch-pound data may be included, if necessary, in footnotes or annexes that are informative only.

E.2 Incident energy

Incident energy is measured in Joules per square centimeter (J/cm^2) in the SI system. A joule is defined as a watt second. To convert from the CGS system unit of calories per square centimeter (cal/cm^2) to J/cm^2, multiply by 4.184 (see IEEE/ASTM SI10-2002 [B14]).

To understand these units, the incident energy that will cause a just curable burn or a second degree burn is 5.0 J/cm^2 (1.2 cal/cm^2.) If a butane lighter is held 1 cm away from a person's finger for one second and the finger is in the blue flame, a square centimeter area of the finger will be exposed to about 5.0 J/cm^2 or 1 cal/cm^2.

E.3 Equations, tables and figures using cal/cm^2 for incident energy

E.3.1 Basic equations using cal/cm^2

Using the empirically derived model to calculate incident energy in cal/cm^2 Equation (6) becomes:[55]

$$E = C_f E_n \left(\frac{t}{0.2}\right)\left(\frac{610^x}{D^x}\right) \tag{E.1}$$

where

E is incident energy (cal/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 [56]
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.

[55]See Equation (6) for calculation in J/cm^2.
[56]See Footnote 1.

Using the Lee method to calculate energy in cal/cm^2, Equation (7) becomes:

$$E = 5.12 \times 10^5 V I_{bf}\left(\frac{t}{D^2}\right) \quad \text{(E.2)}$$

where

- E is incident energy (cal/cm^2)
- V is system voltage (kV)
- t is arcing time (seconds)
- D is distance from possible arc point to person (mm)

Using the empirically derived model to find the flash protection boundary, Equation (8) becomes:[57]

$$D_B = \left[C_f E_n\left(\frac{t}{0.2}\right)\left(\frac{610^x}{E_B}\right)\right]^{\frac{1}{x}} \quad \text{(E.3)}$$

Using the Lee method to find the flash protection boundary, Equation (9) becomes:[58]

$$D_B = \sqrt{5.12 \times 10^5 V I_{bf}\left(\frac{t}{E_B}\right)} \quad \text{(E.4)}$$

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 normalized[59]
- E_B is incident energy in cal/cm^2 at the boundary distance
- t is time (seconds)
- x is the distance exponent from Table 4.
- I_{bf} is bolted fault current

[57] Refer to Equation (8) for calculation in J/cm^2.
[58] Refer to Equation (9) for calculation in J/cm^2.
[59] See Footnote 13.

E.3.2 Circuit breakers

Table E.1—Equations for incident energy and flash-protection boundary by frame[a]

			480 V and lower		575–690 V	
Rating (A)	**Breaker**	**Trip unit type**	**Incident energy (cal/cm²) [b]**	**Flash boundary (mm)**	**Incident energy (cal/cm²)**	**Flash boundary (mm)**
100–400	MCCB	TM or M	$0.045\ I_{bf} + 0.13$	$9.16\ I_{bf} + 194$	$0.065\ I_{bf} + 0.040$	$11.8\ I_{bf} + 196$
600–1200	MCCB	TM or M	$0.053\ I_{bf} + 0.38$	$8.45\ I_{bf} + 364$	$0.080\ I_{bf} + 0.090$	$11.4\ I_{bf} + 369$
600–1200	MCCB	E, LI	$0.090\ I_{bf} + 0.324$	$12.50\ I_{bf} + 428$	$0.112\ I_{bf} + 11.000$	$14.3\ I_{bf} + 568$
1600–6000	MCCB or ICCB	TM or E, LI	$0.107\ I_{bf} + 0.72$	$11.10\ I_{bf} +696$	$0.164\ I_{bf} + 0.040$	$16.7\ I_{bf} + 606$
800–6300	LVPCB	E, LI	$0.150\ I_{bf} + 0.88$	$14.50\ I_{bf} + 786$	$0.230\ I_{bf} + 0.070$	$19.1\ I_{bf} + 864$
800–6300	LVPCB	E, LS[c]	$1.090\ I_{bf} + 6.51$	$47.20\ I_{bf} +2660$	$1.640\ I_{bf} + 0.519$	$62.4\ I_{bf} + 2930$

[a]Refer to Table 5 and Table 20 for J/cm^2.
[b]I_{bf} is in kA, working distance is 18 inches.
[c]Short time delay is assumed to be set at maximum.

E.3.3 Current limiting fuses

E.3.3.1 Class L 2000 A

Table E.2—Incident energy as a function of bolted fault current for one manufacturer's 2000 A Class L current limiting fuses @ 600 V, 18 inches

Current limiting fuse	Bolted fault (kA)	Series average incident energy (cal/cm²)	Series mean max incident energy (cal/cm²)	Series maximum incident energy (cal/cm²)	Default for model
Class L 2000 A	106.0	1.94	2.39	3.04	3.04
Class L 2000 A	65.9	6.48	8.24	23.80	23.80
Class L 2000 A	44.1	9.90	13.05	16.79	26.60 [a]
Class L 2000 A	22.6	23.12	28.89	29.36	29.36

[a]26.60 was chosen as default value to linearize the values from 22.6 kA–65.9 kA.

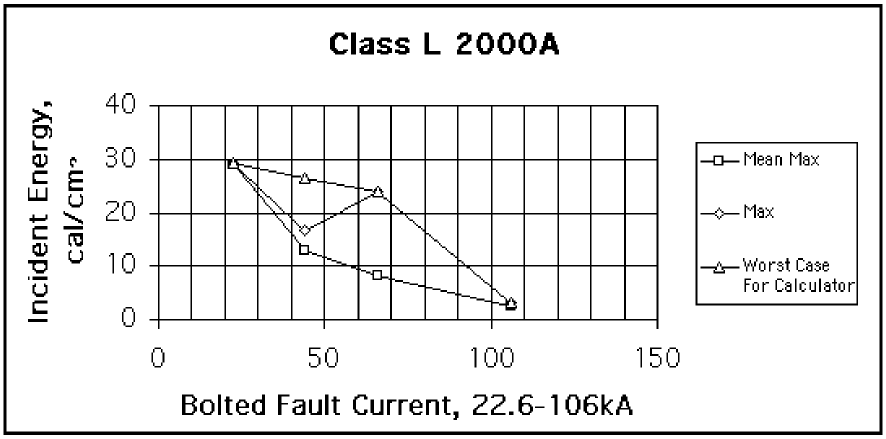


Figure E.1—Class L 2000 A fuse incident energy vs bolted fault current

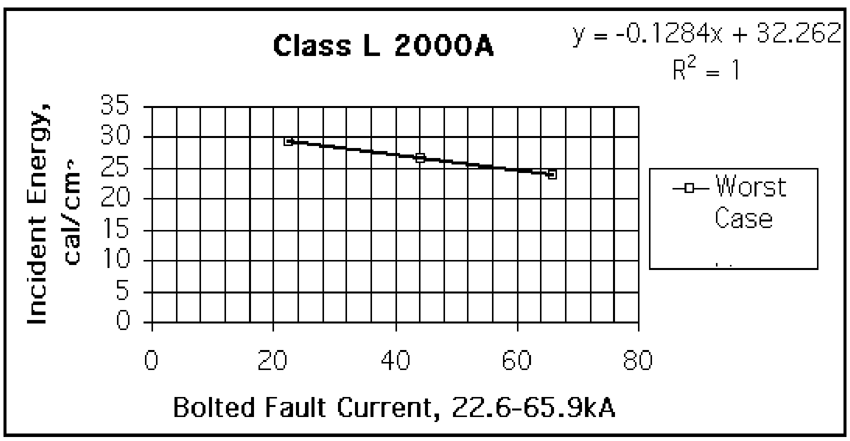


Figure E.2—Class L 2000 A fuse—low segment

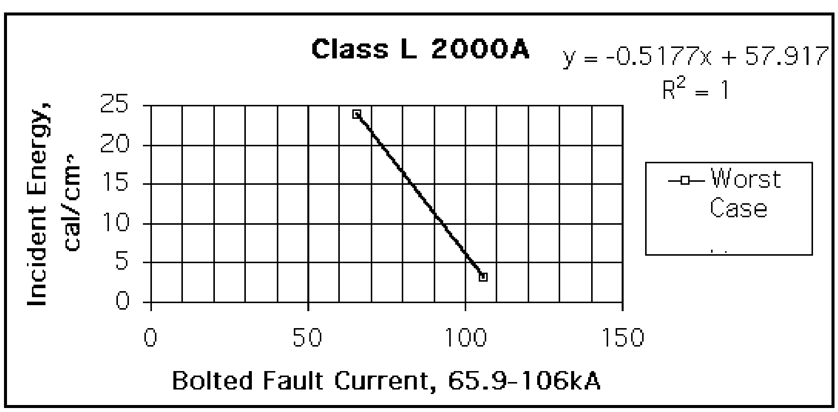


Figure E.3—Class L 2000 A fuse—high segment

E.3.3.2 Class L 1600 A

Table E.3—Incident energy as a function of bolted fault current for one manufacturer's 1600 A Class L current limiting fuses @ 600 V, 18 inches

Current limiting fuse	Bolted fault (kA)	Series average incident energy (cal/cm^2)	Series mean maximum incident energy (cal/cm^2)	Series maximum incident energy (cal/cm^2)	Default for model
Class L 1600 A	106.0	0.29	0.36	0.36	0.400
Class L 1600 A	65.9	0.99	1.24	2.93	2.930
Class L 1600 A	44.1	0.73	0.92	1.16	2.930
Class L 1600 A	31.8	20.00	20.90	22.00	22.000
Class L 1600 A	22.6	7.01	9.47	11.76	23.715
Class L 1600 A	15.7	18.50	18.90	20.20	25.000

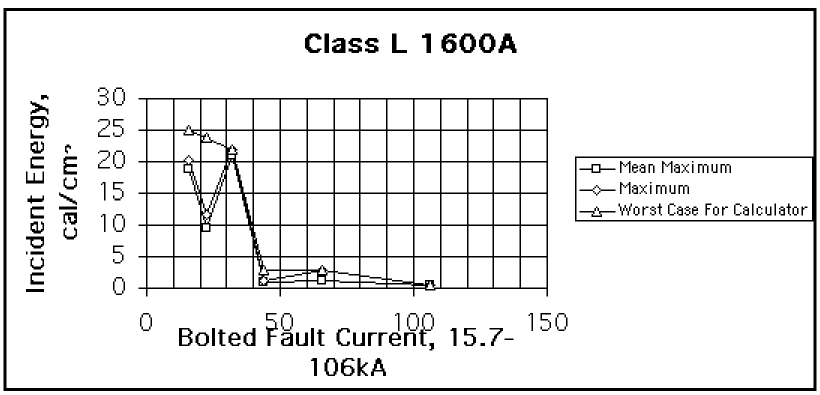


Figure E.4—Class L 1600 A fuse—incident energy vs bolted fault current

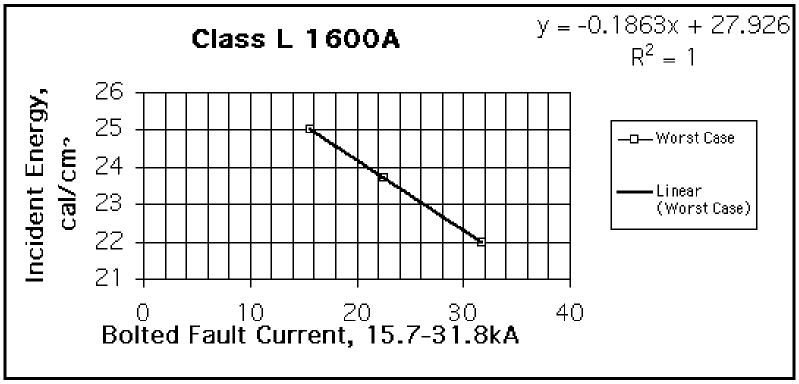


Figure E.5—Class L 1600 A fuse—low current segment of model

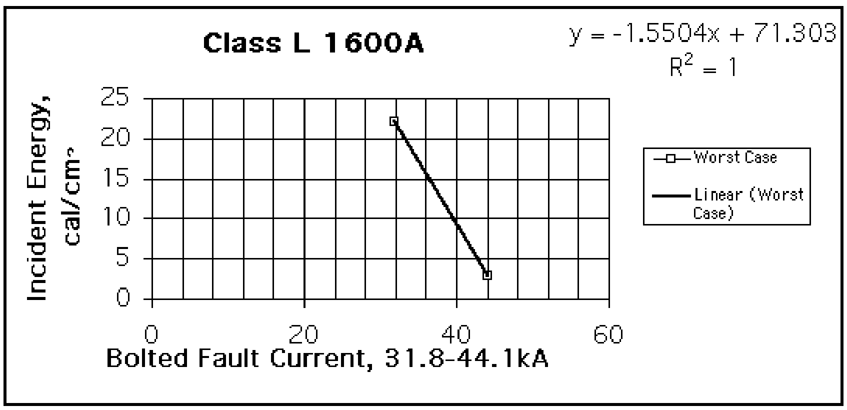


Figure E.6—Class L 1600 A fuse—lower-middle current segment of model

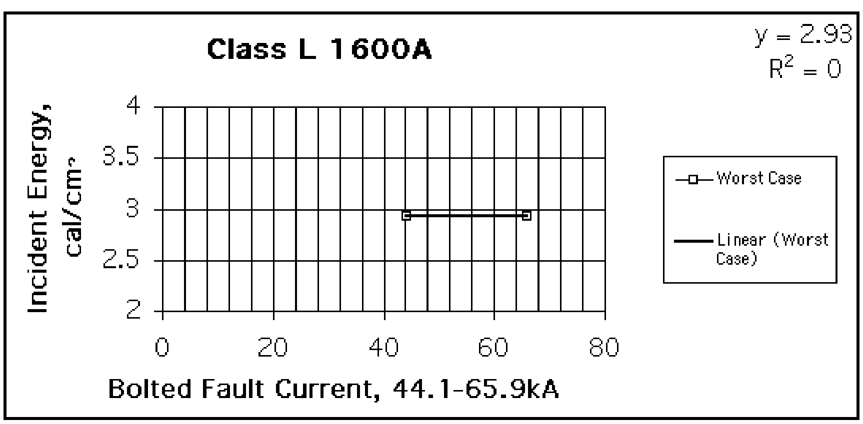


Figure E.7—Class L 1600 A fuse—upper-middle current segment of model

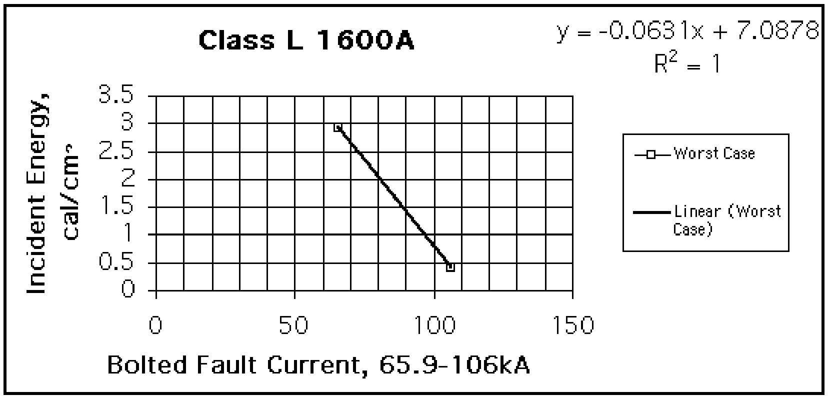


Figure E.8—Class L 1600 A fuse—upper current segment of model

E.3.3.3 Class L 1200 A

Table E.4—Incident energy as a function of bolted fault current for one manufacturer's 1200A Class L current limiting fuses @ 600 V, 18 inches

Current limiting fuse	Bolted fault (kA)	Series average incident energy (cal/cm^2)	Series mean maximum incident energy (cal/cm^2)	Series maximum incident energy (cal/cm^2)	Default for model
Class L 1200 A	106.0	0.14	0.20	0.23	0.39
Class L 1200 A	65.9	0.18	0.24	0.24	0.39
Class L 1200 A	44.1	0.24	0.30	0.39	0.39
Class L 1200 A	31.8	1.70	0.40	4.20	4.20
Class L 1200 A	22.6	4.65	6.33	9.87	9.87
Class L 1200 A	15.7	8.90	10.30	11.20	11.20

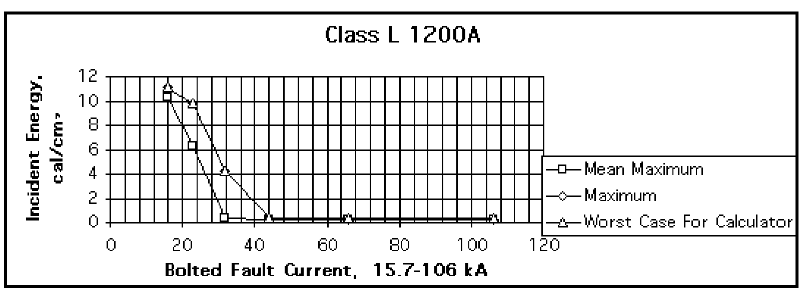


Figure E.9—Class L 2000 A fuse—incident energy vs bolted fault current

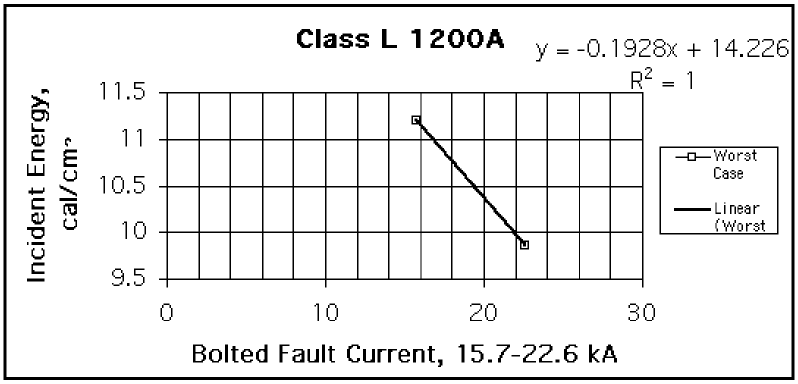


Figure E.10—Class L 1200 A fuse—lower current segment of model

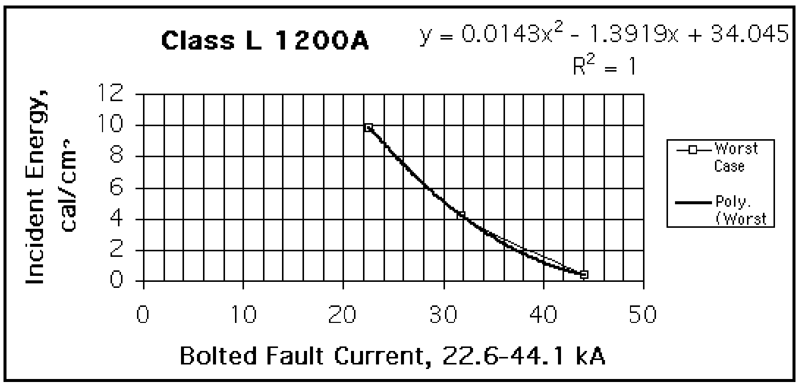


Figure E.11—Class L 1200 A fuse—middle current segment of model

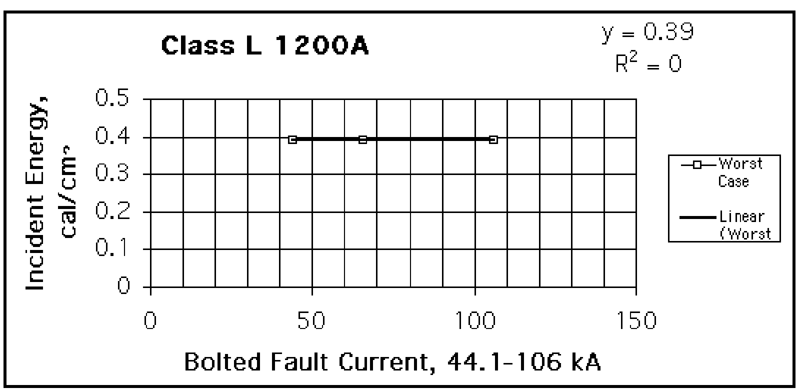


Figure E.12—Class L 1200 A fuse—upper current segment of model

E.3.3.4 Class L 800 A

Table E.5—Incident energy as a function of bolted fault current for one manufacturer's 800A Class L current limiting fuses @ 600 V 18 inches

Current limiting fuse	Bolted fault (kA)	Series average incident energy (cal/cm^2)	Series mean maximum incident energy (cal/cm^2)	Series maximum incident energy (cal/cm^2)	Default for spreadsheet calculation
Class L 800 A	106.0	0.18	0.22	0.24	0.250
Class L 800 A	65.9	0.14	0.17	0.18	0.250
Class L 800 A	44.1	0.09	0.15	0.18	0.250
Class L 800 A	22.6	0.63	0.84	1.54	1.540
Class L 800 A	15.7	0.97	1.00	1.10	1.957

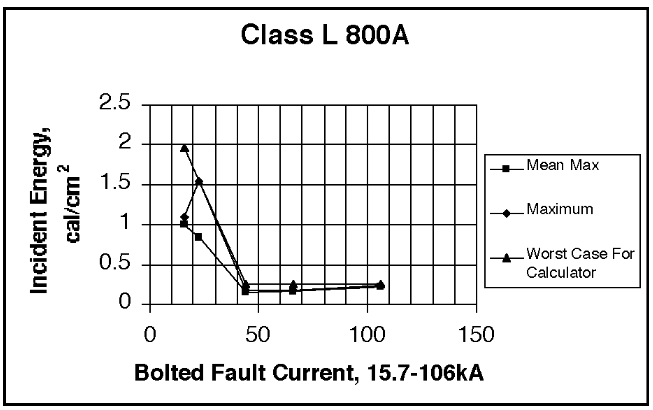


Figure E.13—Class RK1 800 A fuse—incident energy vs bolted fault current

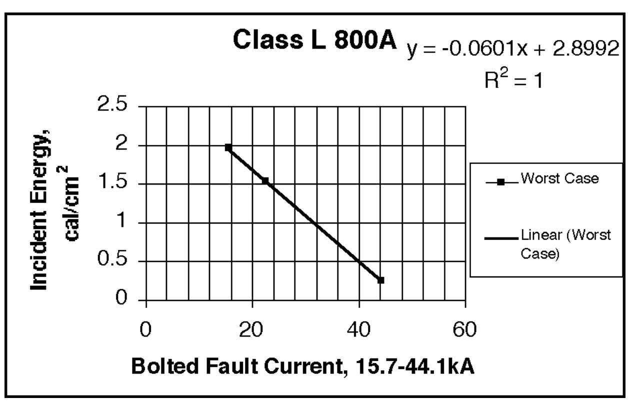


Figure E.14—Class RK1 800 A fuse—lower current segment of model

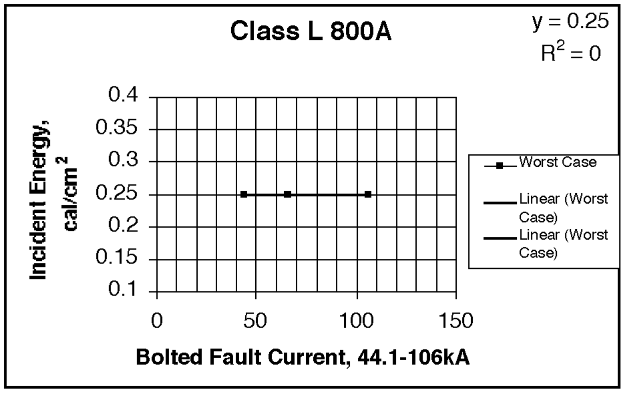


Figure E.15—Class RK1 800 A fuse—middle current segment of model

E.3.3.5 Class RK1 600 A

Table E.6—Incident energy as a function of bolted fault current for one manufacturer's 600A Class RK1 current limiting fuses @ 600 V, 18 inches

Current limiting fuse	Bolted fault (kA)	Series average incident energy (cal/cm^2)	Series mean maximum incident energy (cal/cm^2)	Series maximum incident energy (cal/cm^2)	Default for model
Class RK1 600 A	106.0	0.03	0.04	0.04	0.25
Class RK1 600 A	65.9	0.05	0.09	0.11	0.25
Class RK1 600 A	44.1	0.05	0.07	0.08	0.25
Class RK1 600 A	22.6	0.10	0.15	0.15	0.25
Class RK1 600 A	15.7	0.37	0.30	0.50	0.60
Class RK1 600 A	14.0	0.37	0.30	0.60	0.60
Class RK1 600 A	8.5	12.70	12.50	17.40	17.40

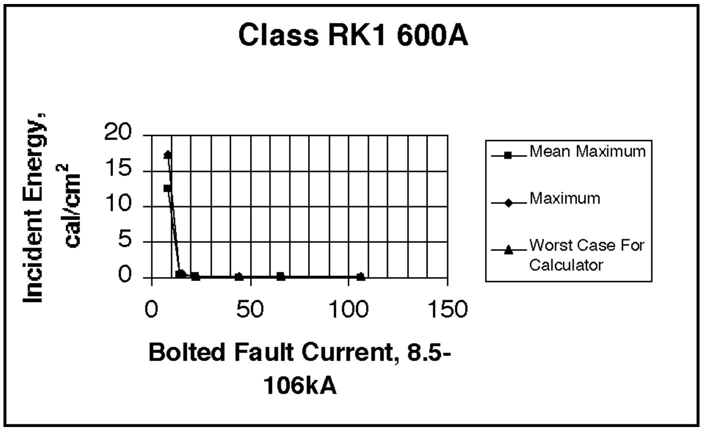


Figure E.16— Class RK1 600 A fuse—lower current segment of model

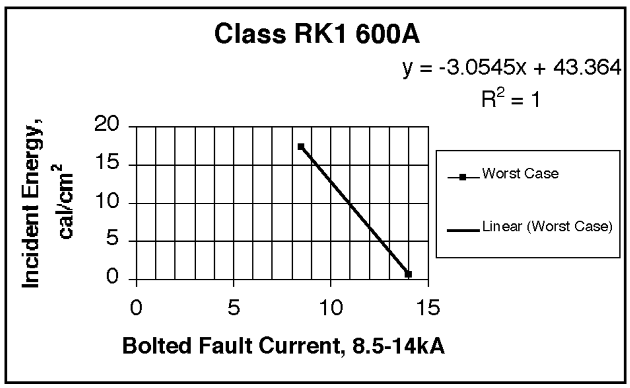


Figure E.17—Class RK1 600 A fuse—middle current segment of model

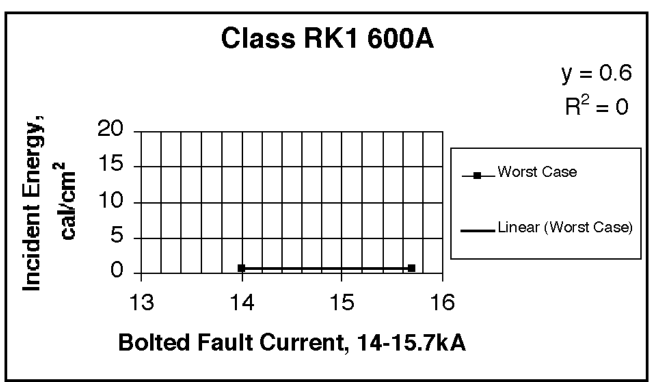


Figure E.18—Class RK1 200 A fuse—upper current segment of model

E.3.3.6 Class RK1 400 A

Table E.7—Incident energy as a function of bolted fault current for one manufacturer's 400A Class RK1 current limiting fuses @ 600 V, 18 inches

Current limiting fuse	Bolted fault (kA)	Series average incident energy (cal/cm^2)	Series mean maximum incident energy (cal/cm^2)	Series maximum incident energy (cal/cm^2)	Default for model
Class RK1 400 A	22.60	0.02	0.03	0.03	0.25
Class RK1 400 A	5.04	0.29	0.35	0.78	0.78
Class RK1 400 A	3.16	22.10	22.10	36.60	36.60

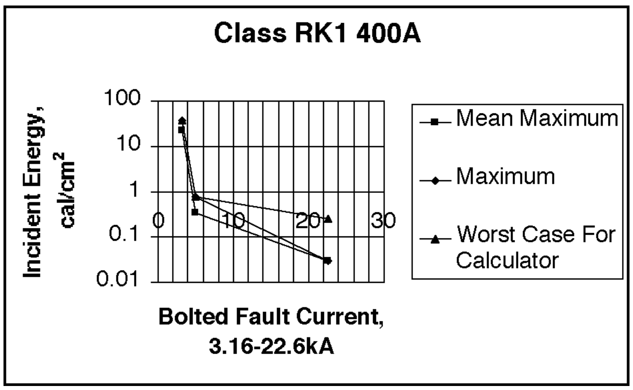


Figure E.19—Class RK1 400 A fuse—incident energy vs bolted fault current

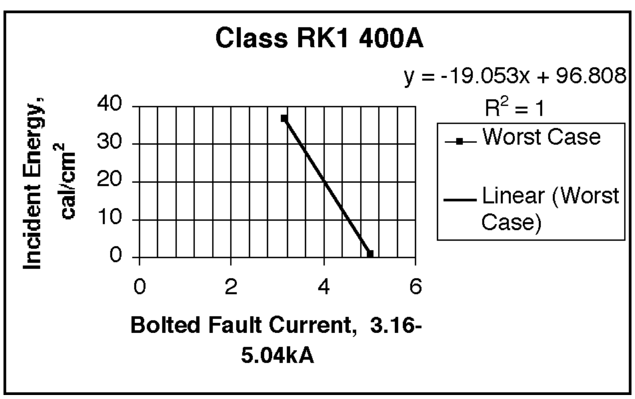


Figure E.20—Class RK1 400 A fuse—lower current segment of model

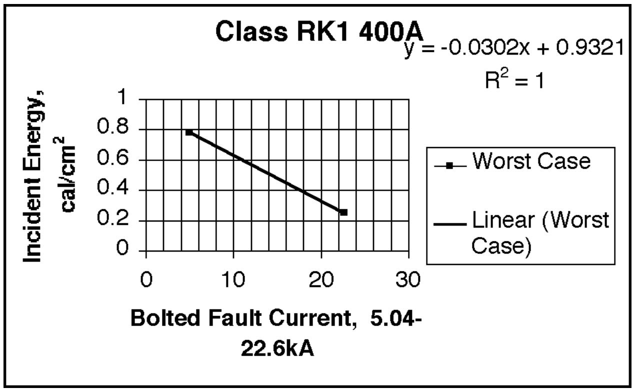


Figure E.21—Class RK1 400 A fuse—middle current segment of model

E.3.3.7 Class RK1 200 A

Table E.8—Incident energy as a function of bolted fault current for one manufacturer's 200A Class RK1 current limiting fuses @ 600 V, 18 inches

Current limiting fuse	Bolted fault (kA)	Series average incident energy (cal/cm^2)	Series mean maximum incident energy (cal/cm^2)	Series maximum incident energy (cal/cm^2)	Default for spreadsheet calculation
Class RK1 200 A	3.16	0.05	0.05	0.05	0.25
Class RK1 200 A	1.60	1.30	0.15	6.90	6.90
Class RK1 200 A	1.16	15.00	15.00	15.00	15.00

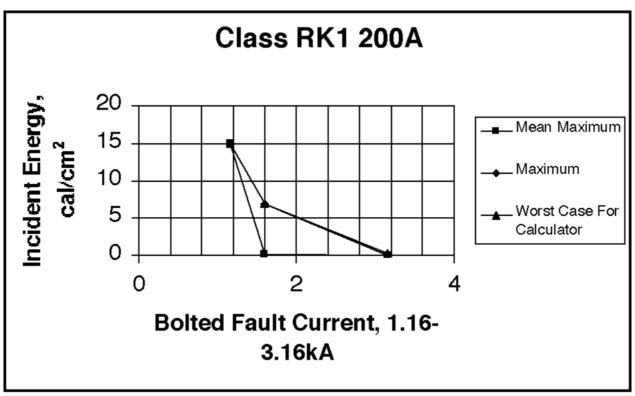


Figure E.22—Class RK1 200 A fuse—incident energy vs bolted fault current

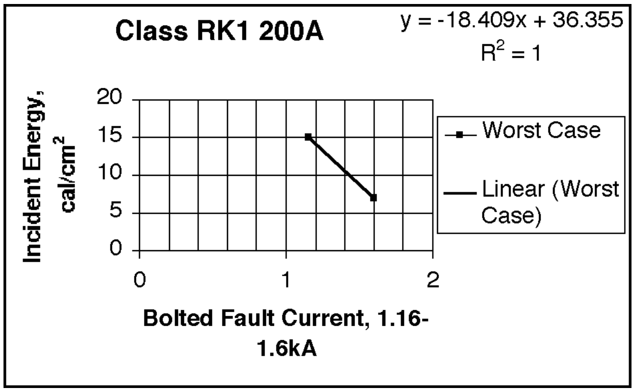


Figure E.23—Class RK1 200 A fuse—lower current segment of model

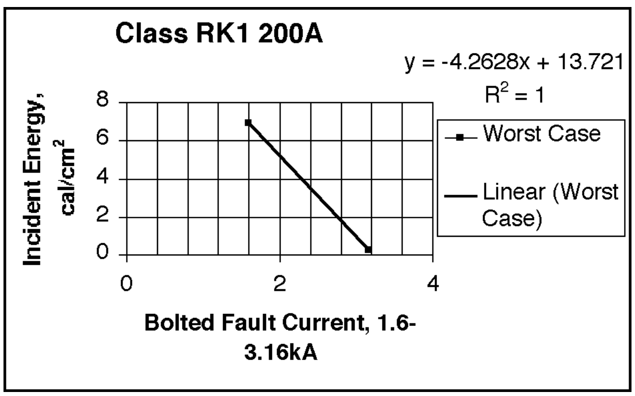


Figure E.24—Class RK1 200 A fuse—upper current segment of model

E.3.3.8 Class RK1 100 A

Table E.9—Incident energy as a function of bolted fault current for one manufacturer's 100A Class RK1 current limiting fuses @ 600 V, 18 inches

Current limiting fuse	Bolted fault (kA)	Series average incident energy (cal/cm^2)	Series mean maximum incident energy (cal/cm^2)	Series maximum incident energy (cal/cm^2)	Default for model
Class RK1 100 A	1.60	0.10	0.05	0.20	0.25
Class RK1 100 A	1.40	0.22	0.20	0.25	0.25
Class RK1 100 A	1.16	0.47	0.40	0.60	0.60
Class RK1 100 A	0.65	4.90	4.90	6.30	6.30

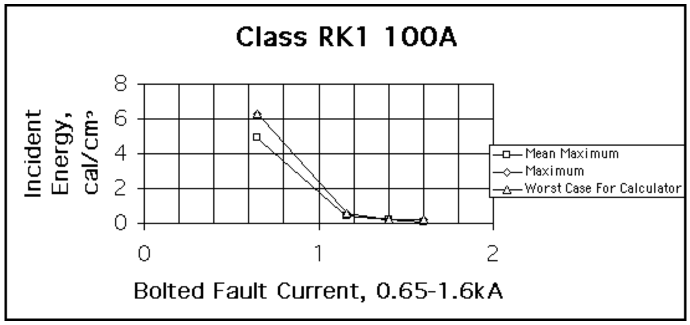


Figure E.25—Class RK1 100 A fuse—lower current segment of model

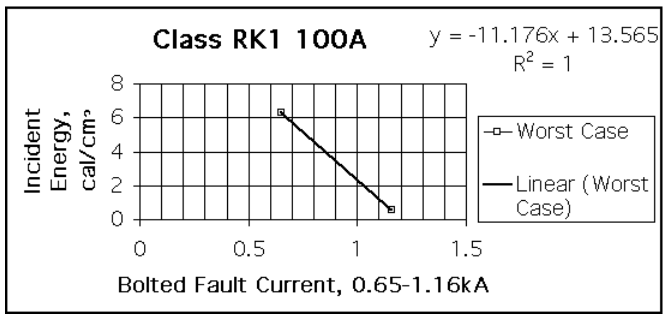


Figure E.26— Class RK1 100 A fuse—upper current segment of model

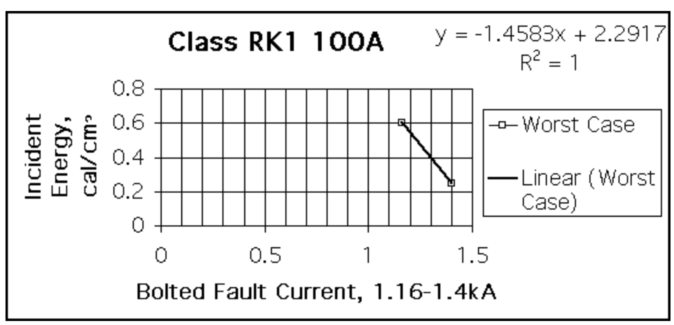


Figure E.27—Class L 100 A fuse—upper current segment of model

Annex F

(informative)

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