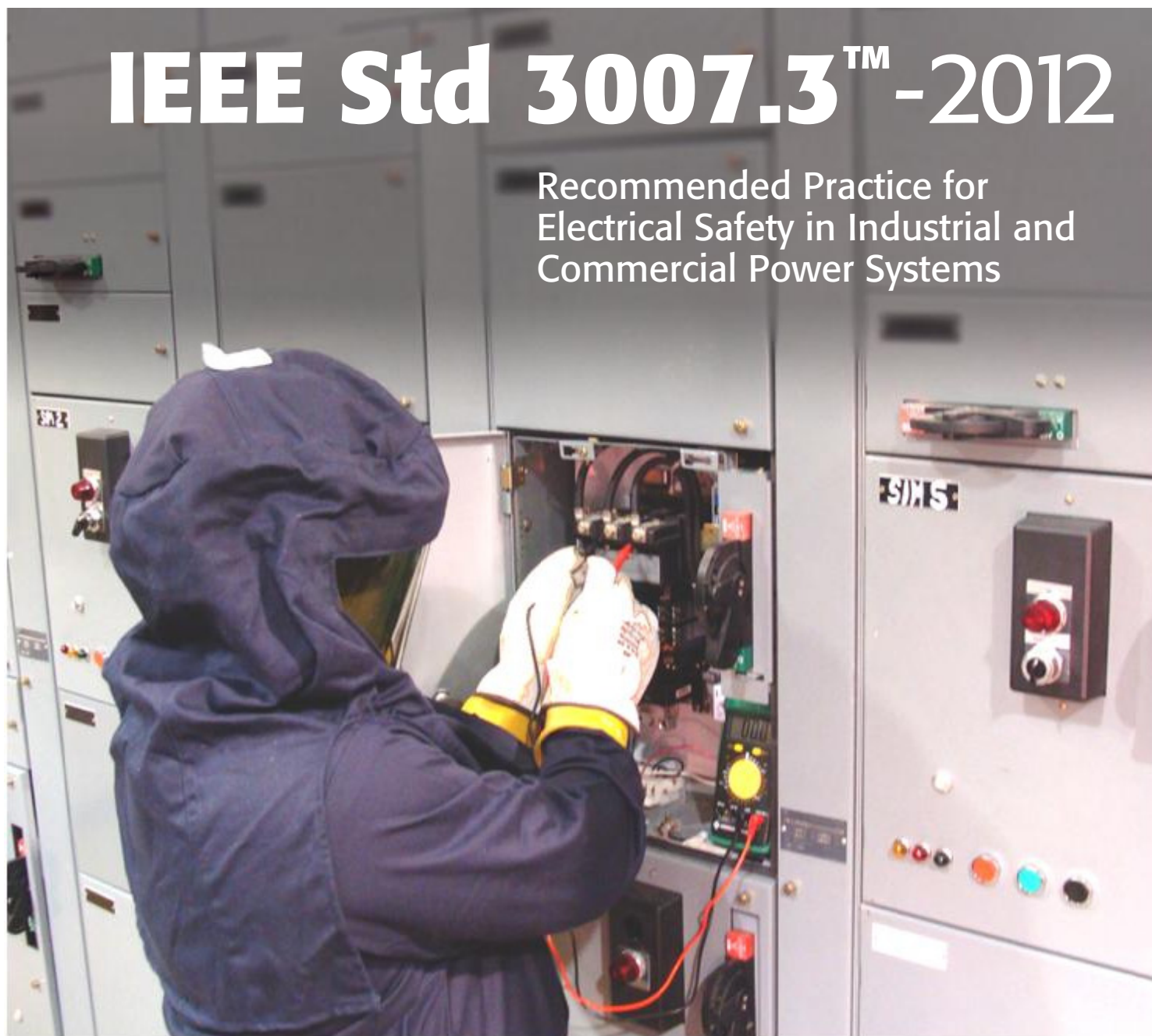


IEEE Std 3007.3™-2012

Recommended Practice for
Electrical Safety in Industrial and
Commercial Power Systems



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IEEE Recommended Practice for Electrical Safety in Industrial and Commercial Power Systems

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IEEE-SA Standards Board

Abstract: All aspects of electrical safety in industrial and commercial power systems are covered. This recommended practice provides personnel with guidelines for understanding the fundamental concepts of the hazards of electricity along with safety-related activities associated with the operation and maintenance of in-plant electrical power distribution systems.

Keywords: electrical hazards, electrical safety program, electrical safety-related maintenance, fire protection, grounding, IEEE 3007.3, personal protective equipment, safe electrical work practices, safety single-line diagram

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Introduction

This introduction is not part of IEEE Std 3007.3-2012, IEEE Recommended Practice for Electrical Safety in Industrial and Commercial Power Systems.

IEEE Std 902™-1998 [B27], also known as the *IEEE Yellow Book*™, has been an excellent resource for engineering, management, safety professionals, and maintenance personnel since it was published.^a The entire IEEE Color Books® series is in the process of being revised and reorganized into numerous “dot” standards, under the 3000 series of standards, with the *IEEE Yellow Book* being divided into three such “dot” standards. The new “dot” standards for operations and management, maintenance, and safety are as follows:

- IEEE Std 3007.1™-2010 [B29]
- IEEE Std 3007.2™-2010 [B30]
- IEEE Std 3007.3™-2012 (this standard)

IEEE Color Book reorganization

The thirteen recommended practices, known as the *IEEE Color Books*, have been industry-proven tools specifically developed for engineers, involved in all facets of industrial and commercial power systems, for many years. This set of recommended practices covers the many varied subjects dealing with all aspects of industrial and commercial power systems, including: analyzing, planning, calculating, coordinating, protecting, and assuring the safety of the power systems elements, equipment, and systems.

In 2002, the Industrial and Commercial Power Systems (I&CPS) Department of the Industry Applications Society (IAS) and the IEEE Standards Association (SA) initiated a major project to reorganize the IEEE Color Books series of standards. The primary goal of the project is to split up the recommended practices into a series of “dot” standards, such as IEEE Std 3007.1-2010 [B29], to allow each technical topic to be developed and balloted individually. A secondary goal of the project is to eliminate duplicate material that presently exists in the Color Book standards.

The decision to reorganize the Color Books standards was largely driven by the difficulty that exists today to review, revise, and ballot large standards (the “books”) in a timely manner. Technical material presented in smaller documents (via “dot” standards) can be more effectively and efficiently managed, and will facilitate more frequent updating.

The thirteen Color Books standards are being reorganized into a larger introductory book (the “base” book), plus approximately 60 individual “dot” standards covering various technical topics.

Much of the general power-systems information will be assembled into the new “base” book that will serve as a launching point to jump into the more detailed specifics of industrial and commercial power systems. Working Group subject matter experts are providing and maintaining the technical content and are focused on those areas that are changing with new technologies, while allowing the more basic areas to remain stable.

IEEE Std 3007.3-2012 provides a recommended practice for electrical safety of industrial and commercial power systems. It is likely to be of greatest value to the power-oriented engineer with limited experience in this area. It can also be an aid to all engineers responsible for the operation and maintenance of industrial and commercial power systems.

^a The numbers in brackets correspond to those of the bibliography in Annex A.

Due to the vital importance of electrical safety when working with industrial and commercial power systems, IEEE Std 3007.3-2012 provides more in-depth information to help ensure the safety of personnel working with electrical systems and equipment.

This standard is organized as follows:

Clause 1: Overview

Clause 2: Normative references

Clause 3: Definitions, acronyms, and abbreviations

Clause 4: Introduction to electrical safety

Clause 5: Establishing an electrical safety program

Clause 6: Providing and maintaining electrically safe facilities

Clause 7: Safe electrical work practices

Clause 8: Protective equipment, tools, and methods

Clause 9: Safety of use of electrical equipment

The new IEEE Std 3007.3-2012 provides a recommended practice for electrical safety of industrial and commercial power systems.

Contents

1. Overview	1
1.1 Scope	1
1.2 General	1
2. Normative references.....	2
3. Definitions, acronyms, and abbreviations	3
3.1 Definitions	3
3.2 Acronyms and abbreviations	3
4. Introduction to electrical safety	4
4.1 General discussion.....	4
4.2 Exposure to electrical hazards	5
4.3 Case histories.....	15
4.4 Reasons for practicing electrical safety	20
4.5 Summary.....	24
5. Establishing an electrical safety program	24
5.1 General discussion	24
5.2 Content of program.....	24
6. Providing and maintaining electrically safe facilities.....	30
6.1 General discussion	30
6.2 Design considerations.....	31
6.3 Installation safety requirements.....	36
6.4 Safety and fire protection inspections.....	36
6.5 Preplan for safe maintenance	37
6.6 Repairs and replacement parts	37
7. Safe electrical work practices	38
7.1 General discussion	38
7.2 Training	38
7.3 Electrical safety controls.....	40
7.4 Working on or near de-energized equipment.....	45
7.5 Working on or near equipment that is, or can become, energized.....	54
8. Protective equipment, tools, and methods	58
8.1 Introduction	58
8.2 Personal protective equipment.....	58
8.3 Other protective equipment	59
8.4 Protective methods	60
8.5 Drawings and other documentation	61
8.6 Safety audits	62
8.7 Safety morale and culture	65
9. Safety of use of electrical equipment.....	66
9.1 Introduction	66
9.2 Portable electrical equipment.....	66
9.3 Test instruments and equipment	66
9.4 Facilities infrastructure (power and light circuits).....	67
Annex A (informative) Bibliography	68

IEEE Recommended Practice for Electrical Safety in Industrial and Commercial Power Systems

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1. Overview

1.1 Scope

This recommended practice covers all aspects of electrical safety in industrial and commercial power systems. It provides personnel with guidelines for understanding the fundamental concepts of the hazards of electricity along with safety-related activities associated with the operation and maintenance of in-plant electrical power distribution systems.

1.2 General

An electrical safety program should address the needs of all employees, contractors, and visitors present at a facility. The size of the program depends upon the size and nature of the company, both in the number and complexity of facilities, and the number of personnel involved with electrical work. The guidance in this recommended practice presents the overall picture and expects that companies will consider their own specific needs. The program should be as simple and easy to understand as possible. At the same time, however, it should cover all the needs of each member of the organization.

An electrical safety program should define its objectives. The program objectives should consider the following:

- a) To familiarize workers with the details of each procedure associated with the intended task
- b) To familiarize workers with individual rights and responsibilities associated with the intended task
- c) To demonstrate the employer's intention to provide a safe working environment
- d) To document general requirements and guidelines intended to eliminate unauthorized exposure to electrical hazards
- e) To direct the activities of workers who could be exposed to an electrical hazard
- f) To enable each employee to take responsibility for his or her own safety through self-discipline

The electrical safety program should be formal, written, published, and available to all workers. The documented electrical safety program provides an indication that an employer intends to comply with regulatory requirements when requested to do so.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

Accredited Standards Committee C2, National Electrical Safety Code[®] (NESC[®]).¹

ANSI/ASSE Z244.1, Control of Hazardous Energy—Lockout/Tagout and Alternative Methods.²

ANSI/NEMA Z535.5, Safety tags and barricade tapes (for temporary hazards).³

ASTM F855, Standard Specifications for Temporary Protective Grounds to Be Used on De-energized Electric Power Lines and Equipment.⁴

Code of Federal Regulations Title 29 Part 1910 (29CFR1910), Occupational Safety and Health Standards.⁵

Code of Federal Regulations Title 29 Part 1926 (29CFR1926), Safety and Health Regulations for Construction.

EN 50110-1,-2, Operation of electrical installations.⁶

IEEE Std 80[™], IEEE Guide for Safety in AC Substation Grounding.^{7, 8}

IEEE Std 1584[™], IEEE Guide for Performing Arc-Flash Hazard Calculations.

IESNA Lighting Handbook.⁹

¹ The NESC is available from The Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>).

² ANSI publications are available from the American National Standards Institute (<http://www.ansi.org/>).

³ NEMA publications are available from Global Engineering Documents (<http://global.ihs.com/>).

⁴ ASTM publications are available from the American Society for Testing and Materials (<http://www.astm.org/>).

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⁹ IESNA publications are available from the Illuminating Engineering Society of North America (<http://www.iesna.org/>).

NFPA 70[®], National Electrical Code[®] (NEC[®]).¹⁰

NFPA 70B, Recommended Practice for Electrical Equipment Maintenance.¹¹

NFPA 70E[®], Standard for Electrical Safety in the Workplace.

Parise, G., Moylan, W., and Sutherland, P. E., “Electrical safety for employee workplaces in Europe and in USA,” *IEEE Transactions on Industry Applications*, vol. 41, no. 4, July/August 2005.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

IEEE Standards Dictionary: Glossary of Terms and Definitions [B20] should be consulted for terms not defined in this clause.^{12, 13}

3.2 Acronyms and abbreviations

ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
CPR	cardiopulmonary resuscitation
D-N	Drouet-Nadeau
GFCI	ground fault circuit interrupter
IESNA	Illuminating Engineering Society of North America
NEC	National Electrical Code
NEMA	National Electrical Manufacturers Association
NESC	National Electrical Safety Code
NFPA	National Fire Protection Association
NRTL	nationally recognized testing laboratory
OSHA	Occupational Health and Safety Administration
PPE	personal protective equipment
UL	Underwriters Laboratories

¹⁰ The NEC is published by the National Fire Protection Association (<http://www.nfpa.org/>). It is also available from the IEEE at <http://www.techstreet.com/ieeegate.html>.

¹¹ NFPA publications are available from the National Fire Protection Association (<http://www.nfpa.org/>).

¹² *IEEE Standards Dictionary: Glossary of Terms and Definitions* is available at <http://shop.ieee.org>.

¹³ The numbers in brackets correspond to those of the bibliography in Annex A.

4. Introduction to electrical safety

4.1 General discussion

NFPA 70E-2009 defines an electrical hazard as “a dangerous condition such that contact or equipment failure can result in electric shock, arc-flash burn, thermal burn, or blast.”¹⁴ Electrical safety is defined as “recognizing hazards associated with the use of electrical energy and taking precautions so that hazards do not cause injury or death.”

Some explanation is necessary to fully appreciate the words of the two definitions. Personnel should understand the nature and consequences of electrical hazards and the reasons for practicing electrical safety. The nature of electrical hazards is discussed in 4.2. The consequences are demonstrated by some true case histories of injuries, deaths, and near-misses, as described in 4.3. Finally, 4.4 discusses the reasons for spending money and effort on electrical safety.

It is important to understand the four main phases of protection from electrical hazards.

- a) First, unless de-energizing is infeasible due to the nature of the task or creates a more hazardous situation, potentially energized electrical conductors and circuit parts must be placed in an electrically safe work condition before personnel work within the *limited approach boundary*. Safe practices must be used to establish an electrically safe work condition. An electrically safe work condition is discussed in Clause 7.
- b) Second, electrical installations should be designed and constructed to be safe by complying with the criteria as stipulated in national and international consensus standards and codes. This subject is discussed in Clause 6.
- c) Third, the integrity of electrical equipment must be maintained with particular emphasis on enclosures, insulation, operating mechanisms, grounding, and circuit protective devices. Maintenance is discussed in IEEE Std 3007.2™-2010 [B30], as well as in Clause 6.
- d) Fourth, safe work practices and adequate protective equipment, insulated and insulating tools, and test equipment must be understood and used when working on or near exposed energized conductors or parts of electrical equipment. Safe practices are covered in Clause 7. Personal protective equipment (PPE), appropriate tools, and other protective methods are discussed in Clause 8. The safety of use of electrical equipment is discussed in Clause 9.

The details of the above concepts should be implemented and documented into a cohesive electrical safety program. Clause 5 discusses establishing such a program.

These electrical safety sections (Clause 4 through Clause 9) provide overall guidance on how to minimize hazardous conditions, how to recognize hazardous conditions when they do exist, and take appropriate measures to avoid human injury from exposure to such conditions.

¹⁴ Information on references can be found in Clause 2.

4.1.1 Definition of safe

The term *safe* as used in this document is intended to describe a condition in which electrical safety risks are minimized to an acceptable level. The use of the term *safe* is not intended to suggest or guarantee that absolute electrical safety can be achieved in any situation and/or by compliance the recommended practices set forth herein.

For example, use of terms such as *electrically safe*, *electrically safe work practices*, *safe work condition*, *safe work environment*, *safe design*, *safe distance*, *safe work method*, *safe work area*, *safe use*, etc., describe practices, conditions, etc., in which safety risks are minimized but are not intended to suggest that electrical safety can be or is guaranteed.

4.2 Exposure to electrical hazards

The definition of an electrical hazard indicates that hazards can result from poor physical condition of equipment or facilities, sometimes simply called *unsafe conditions*. It also indicates that injuries can result from the careless or inadvertent actions of people, sometimes simply called *unsafe acts*. Taking precautions to minimize electrical hazards implies that safety considerations regarding such conditions and actions should be given to all aspects of electrical work, including design, installation, commissioning, operating, and maintenance activities.

There are essentially three recognized hazards associated with electricity, as follows:

- a) Electrical shock
- b) Burns from contact, arcs, or flashes
- c) Impact from shrapnel or concussive waves from blasts

These injuries are described in detail in 4.2.1 through 4.2.2.

4.2.1 Electrical shock

Electrical shock hazard is the most common and known form of electrical hazard, and many electrical safety standards have historically been structured to address the shock hazard. Electrical shock affects human beings in the following ways:

- a) Electrical current as small as a few milliamperes through the heart can cause disruption of the natural electrical signals that the heart uses to perform its normal functions. Voltage levels as low as 50 V with low skin resistance and electrical current flowing through the chest area can cause fibrillation, which can result in death. This is why all personnel who routinely work on or near energized electrical conductors and circuit parts should be familiar with cardiopulmonary resuscitation (CPR). They may be required to perform CPR on a fellow worker who has experienced an electrical shock.
- b) Electrical shock can damage human tissue where the electrical current enters and exits the body. These types of injuries are under the broad category of burn injuries. Within the body, electrical current can also damage internal body parts in its path. The degree of damage is dependent on the amount of the electrical current, the condition of contact points, the duration of exposure to electrical shock, and the path of the electrical current through the body.

- c) Electrical shock normally causes the muscles to contract. Due to muscle contraction, the person experiencing the shock may not be able to release the conductor causing the shock. This involuntary grasping may lead to longer exposure to the electrical shock, as the exposed person may not be able to voluntarily let go of the hazard.

Several standards offer guidance regarding safe approach distances in order to minimize the possibility of shock from exposed electrical conductors and circuit parts of different voltage levels. One of the most commonly used and referenced standard is NFPA 70E. The limits of approach to exposed energized electrical conductors and circuit parts are discussed in Clause 7 of this standard.

Most electrical personnel are aware that electrical shock may result in electrocution and that by definition electrocution results in death. Just a small quantity of electric energy is required for electrocution. As an example, the current drawn by a 7.5 W, 120 V lamp, passed from hand-to-hand or hand-to-foot, is enough to cause electrocution. It should be emphasized that it is the electrical current, and not voltage, that causes physiological damage to humans.

The results of a sensitivity study from exposure to different values of 60 Hz ac current on a 68 kg (150 lb) human are listed in Table 1. This table provides a ready means of evaluating the physiological effects on a human body. In summary, under the right conditions any current of 6 mA or more may be fatal; those between 90 mA and 4 A can be fatal due to heart disruption. Those above 5 A may be fatal from severe internal or external burns. It is a fact, however, that shocks in this last current range are statistically less likely to be fatal than those in the 90 mA to 4 A range. In view of the diversity of injuries resulting from contact with electrical energy, it is only logical that, to minimize electrical shock or electrocution, exposure to energized conductors and circuit parts should be eliminated where possible, or at the very least minimized as much as possible.

Table 1—Current range and effect on a 68 kg (150 lb) human

Current (60 Hz)	Physiological phenomena	Feeling or lethal incidents
<1.0 mA	None	Imperceptible
1.0 mA	Perception threshold	—
0.5 mA to 2.0 mA	—	Mild sensation.
1.0 mA to 4.0 mA	—	Painful sensation.
6.0 mA to 22 mA	Paralysis threshold of arms	Cannot release hand grip. If no grip, victim may be thrown clear. (May progress to higher current and be fatal.)
18 mA to 30 mA	Respiratory paralysis	Stoppage of breathing (frequently fatal).
90 mA	Fibrillation threshold, 0.5% (greater than or equal to 3 s exposure)	Heart action discoordinated (probably fatal).
250 mA	Fibrillation threshold, 99.5% (greater than or equal to 3 s exposure)	Heart action discoordinated (probably fatal).

Table 1—Current range and effect on a 68 kg (150 lb) human (*continued*)

Current (60 Hz)	Physiological phenomena	Feeling or lethal incidents
4 A	Heart paralysis threshold (no fibrillation)	Heart stops for duration of current passage. For short shocks, heart may restart on interruption of current (usually not fatal from heart dysfunction).
≥ 5 A	Tissue burning	Not fatal unless vital organs are burned.

Reprinted with permission from: Dalziel, "Effects of electric shock on man," *IRE Transactions on Medical Electronics*, 5:44-62 (1956). See also Dalziel [B8].

As mentioned previously, the effects of shock are dependent upon the amount and path of current that flows through the human body. Typically the magnitude of electrical current established through the human body is a function of the applied voltage and the resistance of the path of the current. Table 2 shows some typical values of skin-contact resistance under various conditions. Table 3 shows typical resistance values of various materials.

Table 2—Human resistance values for various skin-contact conditions

Condition (area to suit)	Resistance (Ω)	
	Dry	Wet
Finger touch	40 000 to 1 000 000	4000 to 15 000
Hand holding wire	15 000 to 50 000	3000 to 6000
Finger-thumb grasp ^a	10 000 to 30 000	2000 to 5000
Hand holding pliers	5000 to 10 000	1000 to 3000
Palm touch	3000 to 8000	1000 to 2000
Hand around 3.8 cm (1.5 in) pipe (or drill handle)	1000 to 3000	500 to 1500
Two hands around 3.8 cm (1.5 in) pipe	500 to 1500	250 to 750
Hand immersed	—	200 to 500
Foot immersed	—	100 to 300
Human body, internal, excluding skin ohms	200 to 1000	

^a Data interpolated.

Table 3—Resistance values for 130 cm² areas of various materials

Material	Resistance (Ω)
Rubber gloves or soles	>20 000 000
Dry concrete above grade	1 000 000 to 5 000 000
Dry concrete on grade	200 000 to 1 000 000
Leather sole, dry, including foot	100 000 to 500 000
Leather sole, damp, including foot	5 000 to 20 000
Wet concrete on grade	1 000 to 5 000

Reprinted with permission from: Lee [B32].

In fibrillation, the victim may not recover consciousness. On the other hand, the victim may be conscious, deny needing help, walk a few feet, and then collapse. Death may occur within a few minutes, or may take hours with vulnerability possible up to a week later. Detection of the fibrillation condition requires medical skill and training. Portable heart defibrillators are often available at the work place or in public buildings, which can be used to stabilize the heartbeat of a victim who has gone into fibrillation. Many of these units provide vocalized step-by-step directions on their use and are suitable for use by non-professionals.

In Figure 1, note the fibrillation line for an exposure time of 5.0 s or more is shown at 75 mA. For shorter times, the threshold current is higher. It should be noted that, if the duration of shock is only 0.004 s, or one-quarter cycle of 60 Hz, the fibrillation threshold current is determined by the energy in the impulse, i.e., $\text{Energy} = VI(t)$. Dalziel has determined that the safe limit for impulse shock is 50 Joules (J). For an impulse shock of 4 A at 4 msec from a 120 V source, the impulse shock energy is only 2 J and is unlikely to be harmful to a human. When the impulse shock is 4 A at 4 ms from a 4000 V source, the impulse shock energy is 64 J, so then it is more likely that a harmful injury will occur.

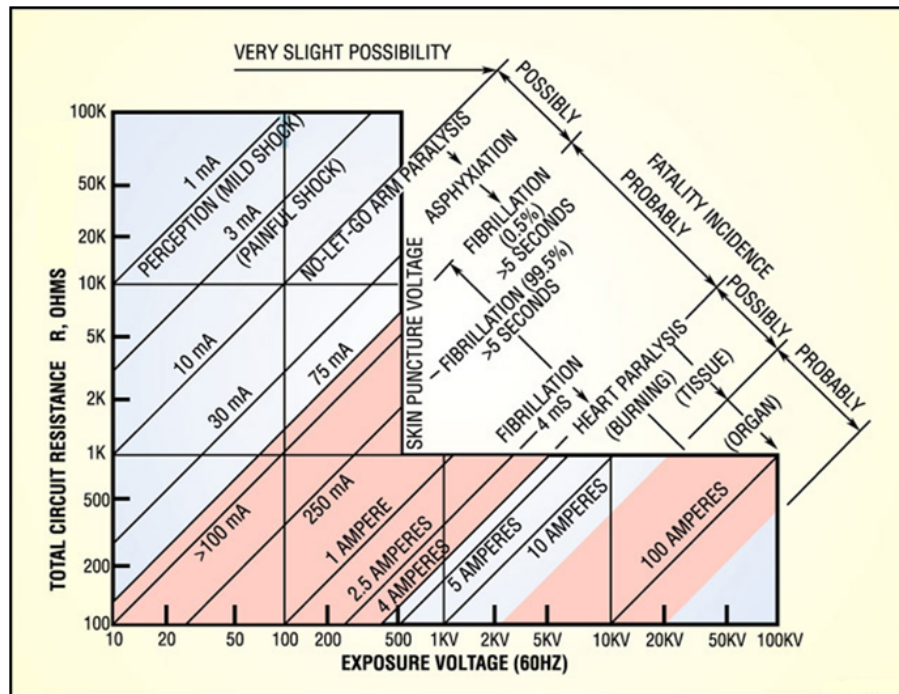


Figure 1—Resistance—voltage—current effect appraisal chart

This sensitivity, increasing with time, explains why a victim who is “frozen” to a current source is much more likely to be electrocuted than one whose contact does not involve hand grasp. A full hand grasp can immobilize the victim such that he cannot let go; hence, the exposure time may extend to many seconds, placing it in range of the 90 mA threshold. In comparison, a casual contact (such as with a fingertip) causes a reflexive retraction of the arm, thereby interrupting the shock current path. In this case, the victim is exposed for only a few thousandths of a second and is much less likely to sustain an injury.

In addition, data has been compiled that shows the corresponding voltage required to force certain current values through a person who has a circuit resistance of 500 Ω . Although this value appears to be rather low for human body resistance, it can be approached by someone who has sweat-soaked cloth gloves on both hands and a full hand grasp of a large energized conductor and a grounded pipe or conduit. Moreover, cuts, abrasions, or blisters on hands can negate the skin resistance, leaving only internal body resistance to oppose current flow. A circuit value as low as 18 V could be dangerous in this instance. For a person with a resistance of 1000 Ω , 90 V could be dangerous; 120 V would be dangerous for a human body with a resistance of 1333 Ω or less.

Defibrillation involves placing electrodes and conductive jelly on the chest. A pulse of over 1000 V dc is applied; this results in current flow up to a few tens of amperes, but only for several milliseconds. These numbers vary with the type of instrument, settings, and other factors. This pulse of dc causes a violent muscle contraction in the chest. Such defibrillation places the heart in asystole: a complete stoppage of electrical activity of the heart. Within a few seconds, the heart will usually resume a normal pattern of beating.

Once the heart goes into ventricular fibrillation it usually does not spontaneously revert to a normal heart rhythm, though it may do so.

4.2.2 Burns from contact, arcs, or flashes

Electrical shock can be a hazard to life. Many people, however, have experienced minor shocks with no dire consequences—not even skin burns. This tends to make people somewhat complacent around electricity. What most people do not know is that approximately half of the serious electrical injuries involve burns. Electrical burns include not only burns from contact, but also radiation burns from the extreme temperatures of electric arcs that result from short circuits due to poor electrical contact or insulation failure. The electric arc between metals is, next to the laser, the hottest thing on earth. It is about four times as hot as the sun’s surface, or 20 000 $^{\circ}\text{K}$ (35 000 $^{\circ}\text{F}$). Where high arc currents are involved, burns from such arcs can be fatal, even when the victim is some distance from the arc. Serious or fatal burns can occur at distances of more than 304 cm (10 ft) from the source of a flash. In addition to burns from the flash itself, clothing is often ignited. Fatal burns can result because the clothing cannot be removed or extinguished quickly enough to prevent serious burns over much of the body. Wearing clothing made of meltable fibers will also add to the problem. Because of this Occupational Safety and Health Administration (OSHA) 29CFR1910.269(l)(6)(iii) requires the employer to have employees who are exposed to flames or electric arcs wear only clothing that will not increase the extent of injury. Clothing that is made of acetate, nylon, polyester, or rayon is prohibited unless the employer can demonstrate that the fabric has been treated to withstand the conditions that may be encountered.

Visible skin burns from direct contact electrical shock are caused by the I^2R heating of body tissue and vary according to many factors such as voltage, contact resistance, skin conditions, contact duration, and bodily current path. It has been estimated by various researchers that the minimum current necessary to produce first-degree skin burns is an exposure of approximately 100 mA for 1.0 s to 9.0 s for a skin area of 1.0 cm^2 .

Even at what a person may believe to be a large and safe distance, serious or fatal injuries can occur to a person’s bare skin or skin covered with flammable clothing as a result of a high energy electric arc. Electrical workers are frequently in the vicinity of energized electrical conductors or circuit parts. It is only the relative infrequency of such arcs that has limited the number of injuries. Examples of exposure are

working on open panelboards, switchboards, or motor control centers, racking in or out circuit breakers or contactors, hook-stick operation of medium-voltage fuses, testing of cable terminals, grounding before testing, or working in manholes near energized cables.

Several studies, tests, and technical papers have been written on the subject of electrical shock and arc-flash hazards (see Annex A). Safety standards and procedure requirements are continuing to be developed to recognize the fact that arcs can cause serious injuries at significant distances from energized sources. Equally important in these new safety standards is the fact that only trained and qualified people with shock and arc-rated protective equipment are permitted to approach energized electrical conductors or circuit parts. Spectators, or unqualified persons, should stay away because, even though they think they are far enough away, they generally do not have an understanding of what is a safe approach distance. The *arc-flash protection boundary* (defined as when an arc flash exists, an approach limit at a distance from a prospective arc source within which a person could receive a second degree burn if an electrical arc flash were to occur) can be calculated using the equations given in IEEE Std 1584 or guidance can be found in NFPA 70E. Depending upon the fault energy available, spectators can be seriously injured or killed at great distances from the initiation point of an arc.

4.2.3 Nature of arcs

Electrical arcing is the term that is applied to the passage of substantial electrical currents through what had previously been air. It is initiated by flashover or the introduction of some conductive material. Current passage is through ionized air and the vapor of the arc terminal material, which is usually a conductive metal or carbon. In contrast to current flow through low-pressure gases such as neon, arcing involves high temperatures of up to, or beyond, 20 000 °K (35 000 °F) at the arc terminals. No materials on earth can withstand these temperatures; all materials are not only melted, but vaporized. The vapor of the terminal material has substantially higher resistance than solid metal, to the extent that the voltage drop in the arc ranges from 29.53 V/cm (75 V/in) to 39.37 V/cm (100 V/in), which is several thousand times the voltage drop in a solid conductor. Since the inductance of the arc path is not appreciably different from that of a solid conductor of the same length, the arc current path is substantially resistive in nature, thus yielding unity power factor. Voltage drop in a faulted large solid or stranded conductor is about 0.016 V/cm to 0.033 V/cm (0.042 V/in to 0.083 V/in).

For low-voltage circuits, an arc length of 29.53 V/cm to 39.37 V/cm (75 V/in to 100 V/in) consumes a substantial portion of the available voltage, leaving only the difference between source voltage and arc voltage to force the fault current through the total system impedance, including that of the arc. This is the reason for the “stabilization” of arc current on 480Y/277V circuits when the arc length is of the order of 10.16 cm (4 in), such as with bus spacing.

For higher voltages, the arc lengths can be substantially greater, e.g., 2.54 cm (1 in) per 100 V of supply, before the system impedance starts to regulate or limit the fault current. Note that the arc voltage drop and the source voltage drop add in quadrature, the former resistive, the latter substantially reactive. The length or size of arcs in the higher voltage systems thus can be greater and can readily bridge the gap from energized parts to ground or other polarities with little drop in fault current.

The hazard of the arc is not only due to the level of voltage. Under some cases it is possible to generate a higher energy arc from a lower voltage than from a higher voltage. The amount of arc energy generated is dependent upon the amount of short-circuit current available and the amount of time before the fault causing the arc is cleared (removed from the power source) by a circuit breaker or fuse. This highlights the need for workers to be cognizant of the arc hazards not only on higher voltages, but on 600 V rated equipment as well.

4.2.4 Arc as a heat source

The electric arc is widely recognized as a very high-level source of heat. Common uses are arc welding of metals, electric arc furnaces to produce molten steel, and even electric cauterizing of wounds to seal against infection while deeper parts are healing. The temperatures at the metal terminals are extraordinarily high, being reliably reported at 20 000 °K (about 35 000 °F) and special types of arcs can reach 50 000 °K (about 90 000 °F). The only higher temperature source known on earth is the laser, which can produce 100 000 °K (about 180 000 °F).

4.2.5 Development of arc size

In a bolted fault there is no arc, so in this instance comparatively little heat will be generated. Should there be appreciable resistance at the fault point, temperatures could rise to the melting and boiling points of the metal, and an arc could be started. The longer the arc becomes, the more of the available system voltage it consumes. Consequently, less voltage is available to overcome the supply impedance, and the total current decreases.

4.2.6 Effect of temperature and incident energy on human tissue and clothing

The human body can exist in only a relatively narrow temperature range that is close to normal blood temperature, which is around 36.5 °C (97.7 °F). Survival much below this level requires insulation with clothing. Temperatures that are slightly above this level can be compensated for by perspiration. Studies show that at skin temperature as low as 44 °C (110 °F), the body temperature equilibrium mechanism begins to break down in about 6 h, and cell damage can occur beyond 6 h at that temperature. Between 44 °C (110 °F) and 51 °C (124 °F), the rate of cell destruction doubles for each 1.0 °C (1.8 °F) temperature rise. Above 51 °C (124 °F), the rate of cell destruction is extremely rapid. At 70 °C (158 °F), only a one second duration of exposure is sufficient to cause total cell destruction.

NFPA 70E-2009 defines incident energy as “the amount of energy impressed on a surface, a certain distance from the source, generated during an electrical arc event. One of the units used to measure incident energy is calories per centimeter squared (cal/cm^2).” It is estimated that for systems of 600 V or less, a 4 ft arc-flash protection boundary should be established based on the product of a clearing time of 2.0 cycles (0.033 s) and an available bolted fault current of 50 kA or any combination that does not exceed 100 kA cycles.

Where the voltage is greater than 600 V the arc-flash protection boundary shall be the distance at which the incident energy equals $5.0 \text{ J}/\text{cm}^2$ ($1.2 \text{ cal}/\text{cm}^2$). For situations where fault-clearing time is equal to or less than 0.1 s, the arc-flash protection boundary shall be the distance at which the incident energy level equals $6.24 \text{ J}/\text{cm}^2$ ($1.5 \text{ cal}/\text{cm}^2$).

Arc-flash protection boundary is defined as “when an arc flash exists, an approach limit at a distance from a prospective arc source within which a person could receive a second degree burn if an electrical arc flash were to occur.”

4.2.7 Impact from blasts

The rapid expansion of air caused by a fault current has been recognized for some time as one of the electrical hazards. What was not recognized previously was the fact that this blast and its effects could be calculated, and precautions against its effects could be taken.

As in shock and arc damage, the first hazard mitigation technique to employ to avoid the blast hazard is to stay away from energized conductors and circuit parts. Unfortunately, electrical work is a profession that

sometimes requires exposure to this hazard. The total exposure can be reduced, however, by not using electrical rooms for offices, warehouses, or break rooms. Sometimes electrical equipment must be maintained and operated while it is energized. The risk of a fault occurring while people are in close proximity to this equipment shall be taken into account.

4.2.8 Pressures developed by arc blasts

People are exposed to two dangers from electrical arcs: burns and blasts. The blast can cause falls and other injuries, as well as damage nearby structures. A relationship is developed between arc current and pressure for an applicable range of distance.

For familiarization with some units used for pressures in the SI (metric) system, the following may be useful:

- 1 newton (N) = 0.2248 lb force (lbf)
- 1 newton/m² = 0.0209 lb/ft²
- 1 atmosphere (atm) = 14.7 psi = 2 116 lb/ft² = 1.0125×10^5 N/m²

4.2.9 Arc forces defined

Reports of the consequences of electrical power arcs in air include descriptions of the rearward propulsion of personnel who were close to the arc. In many cases, the affected people do not remember being propelled away from the arc, often failing to remember the arc occurrence itself. The relative infrequency of power arcs has tended to distract interest from determining the nature and magnitude of this pressure.

Also, the heat and molten metal droplet emanation from the arc can cause serious burns to nearby personnel, a fact that has also tended to reduce interest in the rearward propulsion and pressures generated.

Another consequence of arcs is structural damage. One power arc in a substation of the Quebec Hydroelectric System caused collapse of a nearby substation wall. To determine the magnitude of pressure that is generated by the arcing fault, M. G. Drouet and F. Nadeau of the Institut de Recherche de l'Hydro-Québec were assigned to develop theoretical and practical bases for this phenomenon. The results of their work are described in a 1979 paper (see Drouet and Nadeau [B14]).

Drouet and Nadeau's work shows that actual pressures are an order of magnitude greater than theoretical values. According to a reviewer, Dr. Nettleson, this phenomenon is attributed to a very high frequency component of pressure that is not recorded by measuring apparatus. Regardless of this, the measured amplitudes of pressures from a 100 kA, 10 kV arc reached about 2×10^4 N/m² (400 lb/ft²) at a distance of 1 m (3.3 ft). This pressure is about ten times the value of wind resistance that walls are normally built to withstand, so such an arc could readily destroy a conventional wall at distances of about 12 m (40 ft) or less. A 25 kA arc could similarly destroy a wall at a distance of 3 m (9.5 ft).

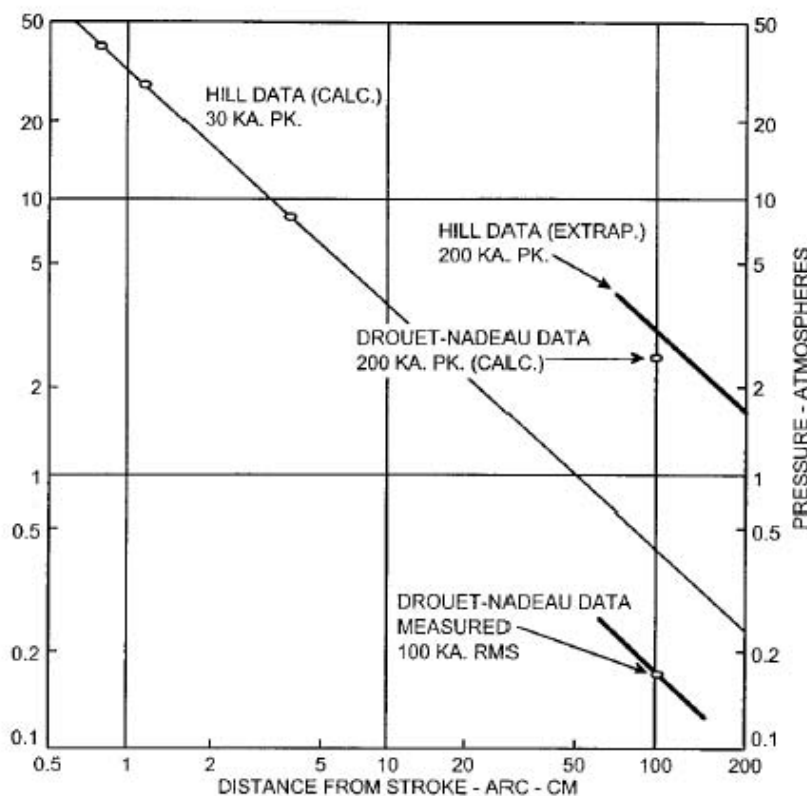
Pressures on projected areas of individuals at 0.6 m (2 ft) from a 25 kA arc would be about 7 750 N/m² (160 lb/ft²). This is sufficient to place a force on the front of a person's body of about 2100 N (480 lbf). Such pressures are also found to be damaging to human ears. Mandatory hearing protection, as in other high noise-level locations, should be considered during the hazard analysis (see 7.3.5 and 7.3.6.).

Additional research as to the effects of electric arcs and their resultant acoustic forces is being performed under a collaborative effort between the IEEE and NFPA; they have formed the Arc Flash Collaborative Research and Testing Project. In 2006 the fund-raising for this project was initiated. The principle purpose of this joint research and testing initiative is to provide information to update both IEEE Std 1584 and NFPA 70E. It is expected that much new information will be brought forth as the research progresses.

4.2.10 Development of arc pressure

The pressures from an arc are developed from two sources: the expansion of the metal when boiling and the heating of the air by passage of the arc through it. Copper expands by a factor of 67 000 in vaporizing, similar to the way that water expands about 1670 times when it becomes steam. This accounts for the expulsion of near-vaporized droplets of molten metal from an arc. These are propelled for distances of up to about 3 m (10 ft). It also generates plasma (ionized vapor) outward from the arc for distances proportional to the arc energy. With copper, 53 kW/s vaporizes 0.328 cm^3 (0.05 in^3), thereby producing $54\,907 \text{ cm}^3$ ($3\,350 \text{ in}^3$) of vapor. Therefore, 16.39 cm^3 (1 in^3) of copper vaporizes into 1.098 m^3 (38.8 ft^3) of vapor.

The air in the arc stream expands in warming up from its ambient temperature to that of the arc, or about $20\,000 \text{ °K}$ ($35\,000 \text{ °F}$). This heating of the air is related to the generation of thunder by the passage of lightning current through it. Dr. R. D. Hill developed theoretical pressures at distances of 0.75 cm to 4 cm (0.295 in to 1.575 in) from a 30 kA peak lightning strike. These pressures ranged from 40 atm down to 9 atm. Dr. Hill's data are plotted in Figure 2, on log-log scale, and the straight-line of these points is extrapolated to 100 cm (39.37 in) distance, at which distance the pressure would have been 0.45 atm. Multiply this 0.45 by $200/30$, to match the peak power of the Drouet-Nadeau (D-N) tests, and the Hill data becomes 3.3 atm, rather close to the D-N theoretical value of 2.7 atm.



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Figure 2—Pressure vs. distance from stroke or arc

The actual measured pressure by D-N from a 200 kA peak, 100 kA rms current was 0.19 atm or 0.07 times the calculated theoretical pressure. Since this is the only available measured pressure level, it is used to generate a family of lines, shown as Figure 3. In this figure, pressures are shown for arc currents from 1 kA to 100 kA rms, for a range of distances of 15 cm to 30 m (0.5 ft to 100 ft), from the arc center to the point