

IEEE Guide and Tutorial for the Application of High-Voltage (> 1000 V) Fuses and Accessories

IEEE Power and Energy Society

Developed by the
Switchgear Committee

IEEE Std C37.48™-2020
(Revision of IEEE Std C37.48™-2005
and IEEE Std C37.48.1™-2011)



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Abstract: Information for understanding the construction, operation, and application of high-voltage (> 1000 V) fuses and accessories, intended for use on alternating current (ac) electrical distribution systems is provided. Current-limiting, expulsion, electronic, and other non-current-limiting fuses and accessories are covered, as are North American, European, and other application practices.

Keywords: current-limiting fuses, expulsion fuses, fuse application, fuse coordination, high-voltage fuses, IEEE C37.48™, IEEE C37.48.1™, TCC, time-current characteristics, rated maximum voltage

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Introduction

This introduction is not part of IEEE Std C37.48™-2020, IEEE Guide and Tutorial for the Application of High-Voltage (> 1000 V) Fuses and Accessories.

This guide was prepared by the Revision of Fuse Standards Working Group of the IEEE Subcommittee on High-Voltage Fuses, and replaces IEEE Std C37.48-2005 and IEEE Std C37.48.1™-2011. Most of the structure and material in this guide is based on IEC TR 62655:2013, reprinted with permission from IEC. The IEC technical report, in turn, contains significant portions excerpted and reprinted with permission from IEEE Std C37.48.1-2011, IEEE Guide for the Application, Operation, and Coordination of High-Voltage (> 1000 V) Current-Limiting Fuses. IEC TR 62655:2013 frequently compares and contrasts IEC and IEEE practices, but with the primary emphasis on IEC practice. While this guide also compares and contrasts practices, because it is an IEEE guide it primarily emphasizes IEEE practice (e.g., using IEEE terminology in the body of the document, but with [Table 1](#) showing a comparison between IEEE and IEC terms). As with the IEC technical report, it is felt that including both sets of practices will particularly benefit users located in areas where both practices are used, and where fuses primarily tested to one or the other, or both, standards are available.

Acknowledgments

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IEEE Guide and Tutorial for the Application ~~, Operation, and Maintenance~~ of High-Voltage (> 1000 V) Fuses ~~, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches,~~ and Accessories

1. Overview

1.1 Scope

This guide provides ~~presents~~ information for understanding ~~on~~ the construction ~~application~~, operation, and application ~~maintenance~~ of high-voltage (> 1000 V) fuses , intended for use on alternating current (ac) electrical distribution systems. Current-limiting, expulsion, electronic, and other non-current-limiting fuses and accessories are covered, as are North American, European, and other application practices. As a guide, this document contains no requirements and is informative only. ~~(above 1000 V), distribution enclosed single-pole air switches, fuse disconnecting switches, and accessories for use on ac distribution systems. Devices with rated maximum voltages to 169 kV are covered. These guidelines apply to the following specific types of equipment:~~

- ~~a) Distribution and power class expulsion type fuses.~~
- ~~b) Distribution and power class current limiting type fuses.~~
- ~~c) Distribution and power class fuse disconnecting switches.~~
- ~~d) Items a) through c) used in fuse enclosure packages (see types listed in 1.3 and 1.4).~~
- ~~e) Fuse supports, and fuse mountings, of the type intended for use with distribution and power class fuses, and fuse disconnecting switches.~~
- ~~f) Removable switch blades of the type used exclusively with distribution class oil cutouts, power class fuses, and distribution class fuse disconnecting switches.~~
- ~~g) Fuse links of the type used exclusively with distribution class oil cutouts, power class fuses, and distribution class fuse disconnecting switches.~~

~~h) Distribution class oil cutouts.~~

~~i) Distribution class enclosed single pole air switches.~~

~~j) Distribution and power classes of expulsion, current limiting and combination external capacitor fuses used with a capacitor unit, groups of units, or capacitor banks.~~

1.2 Purpose

The purpose of this guide is:

- a) To help prospective users and protection engineers understand the basics of high-voltage (> 1000 V ac) fuse technology and applications involving high-voltage (HV) fuses¹
- b) To illustrate the particular and unique advantages of fuse protection for most service applications
- c) To reduce possible misapplications of fuses which could lead to problems in the field
- d) To list and describe the many types of fuse in use today, and the international standards that apply to them, including fuse types not specifically included in IEC, IEEE, or other recognized standards

This guide gathers information previously published in IEC, IEEE, and other publications, as well as new material.

1.3 How to use this guide

1.3.1 General

If read from start to finish, this guide will provide an in-depth study of HV fuses and their applications. It is essentially a tutorial covering all common (and some not so common) types of fuses and most fuse applications.

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However, it is assumed that few users will read the guide in this way, but rather read the appropriate sections covering fuses and applications for which they require information. Based on this assumption, there is therefore some inevitable duplication of information. To assist the user in making the best use of the document, a description of the content and relevance of each clause follows.

1.3.2 Fuse tutorial

After clauses on scope, references, and definitions, Clause 4 contains primarily tutorial-style information. The clause starts with a simple introduction to fuses, first with an explanation of how fuses work followed by information on basic fuse classifications and common fuse terms. Subclause 4.1.4 continues with lists of advantages gained by using fuses, and 4.1.6 provides a list of basic fuse types for which application information will be given later. An in-depth look at the most common types of fuses is given in 4.2 for current-limiting fuses and in 4.3 for expulsion fuses. The high level of detail given in 4.2 and 4.3, including information describing construction, operation, classification, and published ratings and characteristics, can, in some cases, be necessary in order to understand the application information that follows in Clause 5. For completeness, 4.4 gives an overview of less-common types of fuse (or fuse-related) devices that can require additional testing to the testing that is covered in existing standards, and for which no further application information is provided. Subclause 4.5 covers fuse supports.

1.3.3 Application material

Application information appears in Clause 5, Annex A, and Annex B, specifically:

- a) Subclause 5.1 covers information common to nearly all applications.
- b) Subclause 5.2 contains information on specific, typical applications.
- c) Subclause 5.3 covers installation, operation, maintenance, and replacement of fuses.
- d) Subclause 5.4 covers recycling of fuses.

- e) [Annex A reproduces the current-limiting fuse temperature de-rating information previously published in IEC 60282-1:2009.](#)
- f) [Annex B reproduces additional information on the coordination between reclosers and currentlimiting fuses from IEEE Std C37.48.1-2011.](#)

[If a knowledgeable user requires application information on a specific subject in 5.2 \(e.g., motor circuit fuses\), it is possible that only the relevant subclause needs to be read—however in most cases additional information from 5.1 will be required for satisfactory fuse selection. It should be emphasized that the information contained in this guide is intended to supplement information supplied by the manufacturer of a fuse and not replace it. If there is any doubt or conflict of information, the fuse manufacturer should be consulted.](#)

[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.](#)

[IEC 60038, IEC standard voltages.](#)

[IEC 60071-1, Insulation co-ordination – Part 1: Definitions, principles and rules.](#)

[IEC 60076-1, Power transformers – Part 1: General.](#)

[IEC 60076-7, Power transformers – Part 7: Loading guide for mineral-oil-immersed power transformers.](#)

[IEC 60076-12, Power transformers – Part 12: Loading guide for dry-type power transformers.](#)

[IEC 60282-1, High-voltage fuses – Part 1: Current-limiting fuses.](#)

[IEC 60282-1-2009, High-voltage fuses – Part 1: Current-limiting fuses.](#)

[IEC 60282-2, High-voltage fuses – Part 2: Expulsion fuses.](#)

[IEC 60549, High-voltage fuses for the external protection of shunt capacitors.](#)

[IEC 60644, Specification for high-voltage fuse-links for motor circuit applications.](#)

[IEC TR 60890:1987, A method of temperature-rise assessment by extrapolation for partially type-tested assemblies \(PTTA\) of low-voltage switchgear and controlgear.](#)

[IEC 60909-0, Short-circuit currents in three-phase a.c. systems – Part 0: Calculation of currents.](#)

[IEC 62271-100:2012, High-voltage switchgear and controlgear – Part 100: Alternating-current circuit-breakers.](#)

[IEC 62271-103, High-voltage switchgear and controlgear – Part 103: Switches for rated voltages above 1 kV up to and including 52 kV.](#)

[IEC 62271-105:2012, High-voltage switchgear and controlgear – Part 105: Alternating current switch-fuse combinations for rated voltages above 1 kV up to and including 52 kV.](#)

[IEC 62271-106, High-voltage switchgear and controlgear – Part 106: Alternating current contactors, contactor-based controllers and motor-starters.](#)

[IEC 62271-107, High-voltage switchgear and controlgear – Part 107: Alternating current fused circuit-switchers for rated voltages above 1 kV up to and including 52 kV.](#)

[IEEE Std 4TM-2013, IEEE Standard Techniques for High-Voltage Testing.](#)

[IEEE Std 141TM-1993 \(R1999\), IEEE Recommended Practice for Electric Power Distribution for Industrial Plants \(*IEEE Red Book*TM\).](#)

[IEEE Std 399TM-1997, IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis \(*IEEE Brown Book*TM\).](#)

[IEEE Std C37.41TM, IEEE Standard Design Tests for High-Voltage \(> 1000 V\) Fuses and Accessories.](#)

[IEEE Std C37.42™, IEEE Standard Specifications for High-Voltage \(> 1000 V\) Fuses and Accessories.](#)

[IEEE Std C37.99™, IEEE Guide for the Protection of Shunt Capacitor Banks.](#)

[IEEE Std C57.91™, IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators.](#)

3. Definitions, acronyms, and abbreviations

3.1 Definitions

[For the purposes of this document, the terms and definitions contained in IEEE Std C37.41™² apply.](#)
[For a comparison of terms according to IEEE usage compared to IEC usage, see Table 1. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in IEEE Std C37.41.³](#)

3.2 Acronyms and abbreviations

[The following acronyms and abbreviations are used in this document:](#)

[A²s amperes-squared-seconds, also A² × s, the unit of I²t \(Joule integral\), see 4.2.5.4](#)

[BIL basic impulse insulation level](#)

[CL current-limiting](#)

[CLF current-limiting fuse](#)

[FEP fuse-enclosure package](#)

[HV high-voltage](#)

²[Information on references can be found in Clause 2.](#)

³[IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.](#)

I_{encl} de-rated current (of a fuse in an enclosure)

I_r rated current (of a fuse)

I_t crossover current, where the primary current interruption function in a fuse transfers from one series mechanism to another

u_c TRV peak voltage in kV (IEC)

t_3 time in microseconds to voltage u_c (IEC)

I_1 prospective current in Test Series 1, as specified for current-limiting fuses and expulsion fuses in IEEE Std C37.41

I_2 prospective current in Test Series 2, as specified for current-limiting fuses and expulsion fuses in IEEE Std C37.41

I_3 prospective current in Test Series 3, respectively, as specified for current-limiting fuses and expulsion fuses in IEEE Std C37.41

R_{MAT} rated maximum application temperature

TCC time-current characteristic

TRV transient recovery voltage

Table 1—Comparison of IEEE and IEC terms

IEEE term	IEC term	Notes
Ambient temperature	Surrounding temperature	In IEC, ambient temperature is the temperature outside of any enclosure.
Backup current-limiting fuse	Back-Up fuse	
Clearing	Operating	Clearing time and clearing Ft are used.
Cutout fuse support	Cut-out fuse base	
Dropout	Drop-out	
Full-range current-limiting fuse	Full-Range fuse	
Fuse, or fuse and fuse support	Fuse	In IEC, a fuse is the whole device necessary to be inserted into a circuit.
Fuse, fuse unit	Fuse-link	In IEC, the fuse-link is the part replaced to return the device to functionality after an operation.
Fuse link	Fuse-link	A fuse link is the replaceable part of an expulsion fuse, typically used in a fuseholder.
Fuse support	Fuse-base (fuse-mount)	
Fuseholder	Fuse-carrier	
Fuseholder and fuse support	Fuseholder	
Fuse cutout	Distribution fuse-cutout	
General-purpose current-limiting fuse	General-Purpose fuse	
Ground	Earth	
Guide	Technical report	
Interrupting (current)	Breaking (current)	
Ft	Joule integral, Ft	
Maximum permissible continuous current I_{sc} (of a fuse)	Maximum enclosure current I_{sc}	It is a current that, in some cases, and with agreement between the manufacturer and user, is permitted to cause the normal maximum temperatures to be exceeded.
Melting	Pre-arcing	Used for time (of a fuse), Ft , current, etc.
Minimum fusing current	Minimum melting current	The lowest current that causes a fuse to melt.
Peak let-through current	Cut-off current	
Peak overvoltage	Switching voltage	A maximum value. In IEEE, applies just for current-limiting fuses. In IEC, can also be expulsion fuses as transient recovery voltage is included.
Rated maximum application temperature (RMAT)	Maximum application temperature (MAT)	
Wye connected	Star connected	Three-phase circuit connection

(New)

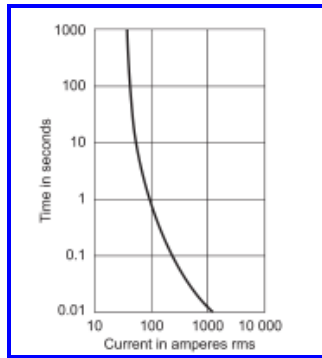
4. Tutorial section

4.1 A simple introduction to fuses

4.1.1 General

Fuses have been in use since the very beginnings of electrical power distribution. While the true inventor of the fuse is not known, pioneers of electrical distribution soon incorporated them as “weak points” in their circuits to prevent overheating of wiring due to excessive current, and to prevent damage to fragile lamps from fluctuations in voltage. Fuses rapidly developed into devices able to sense a current higher than normal and quickly interrupt (break) that current, all in a self-contained, easily replaceable unit. Although the variety and complexity of fuses has grown to the point where user’s guides, such as this one, are necessary, fuses still provide the highest degree of protection for the lowest initial cost.

The simplest definition of a *fuse* is that it is a device that carries current through a conductive part called the *fuse element* that, when the fuse is subjected to an excessive current, melts due to self-heating and initiates the interruption of the current. All conventional fuses interrupt current after some arcing across breaks in the element produced by the melting process. The melting time of a fuse is therefore also termed the *pre-arcing* time. A characteristic of fuses is that, because a melting process initiates current interruption, there are almost no “mechanical” aspects involved in their arc initiation. Fuses therefore have a very inverse time-current relationship (higher currents giving much shorter melting times), as illustrated in Figure 1. This enables extremely short melting times at high currents, virtually without limit. This apparently simple phenomenon is primarily responsible for the universal success fuses have enjoyed for a very long time.



(New)

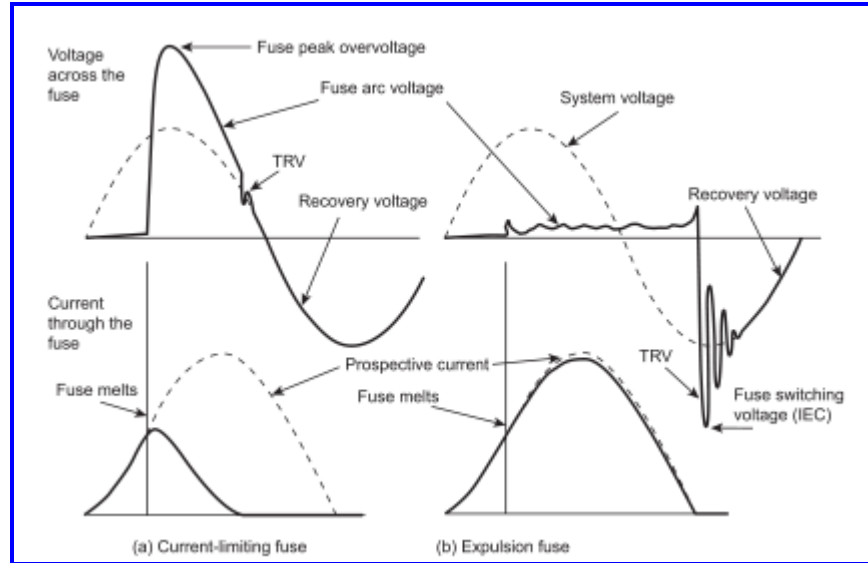
Figure 1—Fuse melting time–current characteristic curve

In general, high-voltage fuses (defined as fuses rated above 1000 V ac) are physically larger and generally more complex than low-voltage fuses due to their need to operate at much higher voltages. Some standards, (e.g., ANSI C84.1 [B1]⁴) classify system voltages as low-voltage, medium-voltage, or high-voltage. *Medium-voltage* is classified as a nominal system voltage of greater than 1000 V and less than a specified value. This value is 100 000 V or less, depending on the standard, and *high-voltage* is then equal to or higher than this specified value. *HV fuses* are used on medium-voltage and high-voltage systems but, technically, there is no recognition of “medium-voltage fuses” in IEEE and IEC fuse standards. HV fuses can perform one or both of two primary functions. The first function is to respond to moderately excessive currents, typically termed *overload* currents. In this case, the rated current of the fuse (the current it is designed to be capable of carrying indefinitely without deterioration) is exceeded by a relatively modest amount (typically less than 10 times). Such currents can be caused by too much load being connected to a circuit, or by a fault that bypasses only part of the load. It should be noted that not all types of fuses are designed to have the ability to operate successfully if melted by an overload current as some types are intended only for operation at currents above a specified value (see 4.1.2.2). If melted by a low current, it is possible that such fuses can arc until a series device interrupts, possibly resulting in physical damage to the fuse and its surroundings. However, some fuses of this type can quickly initiate another device to interrupt such current, containing the arcing without damage until the second device interrupts.

⁴The numbers in brackets correspond to those of the bibliography in Annex C.

The second function, which virtually all fuses are designed to perform, is to respond to overcurrents that are much higher, and that are usually termed *short-circuit currents*. In this case substantially all of the load is bypassed by a major fault and the available current (which, when not limited by a protective device, is termed the *prospective current*) can be very high. However, different types of fuse vary widely in exactly how high a current they can interrupt, and this could be a significant factor in choosing a fuse type for a particular application. The ways in which fuses respond to high and low overcurrents, as well as the ways in which they actually interrupt the current, causes HV fuses to be classified in various ways.

The first main classification is into *current-limiting* and *non-current-limiting* types (although because almost all commonly used non-current-limiting fuses are expulsion fuses, *expulsion fuse* is usually the term used in preference to *non-current-limiting*). *Current-limiting (CL)* describes a class of fuses defined by the behavior that occurs when the current is so high that the fuse element melts before the first peak of the fault current (i.e., in less than a few ms). Upon melting, this type of fuse introduces resistance into the circuit so rapidly (due to factors including multiple series arcs quickly producing a significant arc length, and arc constriction by the fuse filler) that the current stops rising and instead is forced quickly to zero (before a natural current zero would occur). Because the maximum prospective peak current is not reached, the fuse limits the current in magnitude as well as duration, hence the *current-limiting* name. The current-limiting action is shown in Figure 2(a). Note that during operation, the current-limiting fuse introduces a “spike” of overvoltage (the fuse peak overvoltage) into the system during the current-limiting action as shown in Figure 2(a). The lowest current at which a particular current-limiting fuse exhibits a current-limiting effect is termed its *threshold current* and typically occurs at a current of about 20 to 30 times its current rating.



(New)

Figure 2— High-current interruption by current-limiting fuse and expulsion fuse

An expulsion fuse, melting under the same circumstances, introduces only a small resistance into the circuit (primarily due to the relatively large diameter and low resistivity of its arc compared to a current-limiting fuse), so the current continues to virtually the same peak as would occur if the fuse had not melted. An expulsion action (i.e., where gas is generated by the arc and expelled along with ionized material) produces a physical gap such that, at a natural current zero, the arc does not reignite and the current is interrupted. This type of fuse therefore limits the duration of a fault but not its magnitude. This action is illustrated in Figure 2(b). The figure shows the effect of circuit transient recovery voltage (TRV). This is the brief transient oscillatory voltage that appears across an opened circuit, in this case across the fuse, after current interruption, and is due to damped current oscillation in the circuit inductance and intrinsic parallel capacitance.

For detailed information about the arcing processes and their relationship to fuse resistance during arcing, see *Electric Fuses* by Wright and Newbery [B7].

A second classification, for fuses tested to IEEE Std C37.41, relates to where on the distribution network a fuse is likely to be suitable for use, based on testing severity. Both current-limiting and expulsion fuses are termed *Class A* or *Class B* (in IEEE standards before 2016 these were called *distribution class* and *power class*, respectively). Generally speaking, Class B fuses are applied in closer proximity to a major supplying substation than Class A (see 4.1.2.1 for a more thorough explanation).

While, based on testing, expulsion fuses are only divided into Class A and Class B. Current-limiting fuses are further divided into classes based on their low current-interrupting ability. This is discussed in 4.1.2.2 and 4.2.2.

4.1.2 Fuse classifications and terms

4.1.2.1 General

Both current-limiting and expulsion fuses can be of *Class A* or *Class B* (these were formerly called *distribution class* and *power class* in IEEE standards before 2016). This classification relates to where, on a distribution network, the fuses are suitable for use, based on various testing requirements. Class A fuses are generally applicable for the protection of small transformers, and small capacitor banks for power-factor correction or voltage control, located on power distribution systems of overhead line type or cable type, and remotely placed from major substations. They are also applicable as protective devices at sectionalizing points on such systems. TRV conditions are described by TRV test parameters, having lower values of frequency and peak factor (lower values of u_c and longer values of t_3 in IEC standards) than those for Class B fuses. They are generally used in single-phase applications, but are suitable for use in three-phase applications where the higher capabilities of the Class B (formerly power class) fuse are not required and other application requirements are met.

Class B fuses are generally applicable to protect similar equipment as Class A fuses, but in closer proximity to a major supplying substation and feeder circuits leaving such substations. TRV conditions and X/R values are more severe than those for Class A fuse applications, and therefore Class B fuses have more severe test parameters specified. They are more likely to be used in three-phase applications and in substations, cabinets, or vaults where a large amount of electrical power is being supplied to a distribution system or some facility that requires large quantities of energy. They are generally used in that part of a system where high dielectric properties are required for all equipment. Alternatively, they are sometimes used in single-phase applications in an area where distribution Class A fuses would normally be used, but where severe faults, high X/R, or severe TRV is anticipated. Class B expulsion fuses are generally available with higher maximum interrupting currents than Class A expulsion fuses, and designs are available having higher rated maximum voltages.

When selecting the class and type of fuse that should be used at a particular location, factors such as power being supplied, dielectric properties of the equipment being protected, X/R ratios, fault currents available, and transient recovery voltage (TRV) severity require consideration.

It should be noted that current-limiting fuses tested to IEC 60282-1 do not differentiate between Class A and Class B since CL fuses are somewhat insensitive to X/R and TRV. The IEC testing requirements tend to be similar to those for Class A fuses in IEEE standards.

A fuse, or fuse unit, comprises all of the parts needed to produce current interruption, to open the circuit, and to, at least initially, withstand the recovery voltage. However, it may, or may not, be the complete device that is necessary to connect into an electrical circuit. A fuse support of some type could be needed also. After operation, at least some part of a device has to be replaced to return the protection to “as new,” and this can be called a fuse or a fuse unit. It should be noted that in IEC terminology, a fuse is defined as all the parts that form a complete device, which is everything needed to connect it into a circuit. After operation, that which is replaced after operation is called the *fuse-link*, and is the part that performs the active function of current carrying and interruption. However, in IEEE standards, *fuse link* refers only to the replaceable part of a fuse cutout (see 4.3.2.1.1). The terms *fuse* and *fuse unit* in IEEE standards have carried the same definition since 2003. However, in this document, the term *fuse unit* is normally used for an assembly of parts, requiring replacement after each operation, which would normally require additional reusable parts to enable it to connect to the fuse’s contacts or into the electrical circuit, sometimes in addition to a fuse support. However, a fuse unit does contain all of the necessary parts to enable it to perform the desired interrupting function, but not necessarily additional functions such an ability to fit into a fuse support, or perform a dropout action in the fuse support.

There now follows an explanation of additional classifications and common terminology used in fuse standards and in this guide. An explanation of some differences between IEEE and IEC terminology is included (see also Table 1).

4.1.2.2 Additional current-limiting fuse classifications

The ability of different types of CL fuse to interrupt currents lower than those that produce a current-limiting action result in different classes of CL fuse. Some CL fuses are designed to interrupt only high currents (i.e., their primary function is to provide a current-limiting action). They therefore have a limited low-current- interrupting ability and are termed *backup fuses*. They are usually used in conjunction with another device in series; such devices include switches (most commonly tripped by a striker in a *switch-fuse combination*, see 5.2.8.2), contactors, circuit breakers, or another fuse having a lower current-interrupting ability. They can be considered to be “backing up” another device, and in addition to the important current-limiting function, they usually provide increased interrupting capability. This is because the series device frequently has a limited interrupting capability, while backup fuses can normally interrupt very high currents, i.e., they have a very high rated maximum interrupting current.

High-voltage fuses having the ability to interrupt low values of overcurrent as well as high short-circuit currents are classed as either *general-purpose* or *full-range* types. The term *general-purpose* (which has historical origins, being used before full-range fuses were introduced) does not mean that the fuse can be used for any sort of application, but merely means that the fuse is designed to clear low values of fault/overload current. Testing is performed by the fuse manufacturer to show that fuses classed as general-purpose can clear currents down to at least a value that causes melting of the fuse element in 1 h. This means that general-purpose fuses can be used with overload currents that cause them to melt in times of up to 1 h, but no longer. The term *full-range* is used for the class of fuse designed to clear even lower values of fault/overload current; in fact, it is intended that such a fuse can interrupt any continuous current that causes the fuse element to melt. Full-range fuses are often used in enclosures, sometimes with the enclosure at elevated temperatures; both factors can reduce the lowest current that causes them to melt, and full-range fuse test methods reflect this.

4.1.2.3 Current-limiting fuse terminology

Current-limiting fuses are often termed *cartridge fuses*. This is because they are almost always cylindrical in shape and contain the fuse element surrounded by an arc-absorbing filler, usually quartz sand (see 4.2.2 for illustrations of typical current-limiting fuse designs). They have also been called *high rupturing capacity (HRC) fuses* and *silver-sand fuses* (as elements were traditionally made from silver, although other element materials are now also common).

A complete CL fuse device can employ a fuse support (see 4.5 and 4.2.2.1). The traditional form of support usually consists of clips and spade terminals, which are in turn mounted on insulators. They are used with a fuse/fuse unit having ferrules that fit in the clips. Cables or bus-bars attach to the terminals. This type of fuse is still extensively in use, normally in “live-front” gear (i.e., equipment that would have live conductors accessible if the access doors can be opened with the equipment live). Alternatively, fuse units can be found installed in canisters (i.e., relatively tight-fitting enclosures) or be molded into rubber or epoxy for use with cables in submersible/dead-front installations (“dead-front” meaning that no live conductors are exposed). CL fuses are also used under insulating liquid, either in quite elaborate fuse supports (for ease of replacement) or in simple cradles inside transformers when they do not have to be replaced by the user (see 5.2.2.6.4).

In some cases, a fuse unit can include all of the components necessary for connection into a circuit, e.g., if the fuse unit has tags or spade/eyebolt terminals. An example of this method of mounting is an external CL fuse that can be hung from an overhead line or mounted on a fuse cutout or transformer insulator (in which case the cutout or insulator substitutes for the fuse support).

4.1.2.4 Expulsion fuse classifications and terminology

For expulsion fuses, in most cases the construction and interrupting mechanisms differ between Classes A and B (unlike current-limiting fuses). See 4.3.2 for illustrations of typical expulsion fuse designs. The majority of Class A fuses are of a specific fuse type called *fuse cutouts* (formerly *distribution fuse cutouts*). They are characterized by a *cutout fuse support* that uses an insulator or insulators having a single-point mounting bracket, generally located centrally between the terminals that are mounted at each end of the insulator(s). The support holds a fuseholder that is lined with arc-quenching material and holds a fuse link. The link initiates the arcing and the fuseholder provides for arc elongation and most of the expulsion gas produced at high currents. After the expulsion operation, the fuseholder hangs open giving indication and isolation ("dropout action"). Only the fuse link, comprising a fuse element attached to a flexible cable (termed *leader*, *tail*, or *pig tail*) and surrounded by a small gas-evolving (arc-quenching) tube (sometimes called the *auxiliary tube*), has to be replaced. There are also designs, called *open-link cutouts*, that use no fuseholder, but rather the fuse link contains all the parts necessary to connect to the fuse support. They have quite low maximum interrupting currents. There is a third type of Class A expulsion fuse common in some countries. It is termed an *enclosed fuse cutout*. It has all of the live parts enclosed in a housing (usually made of porcelain). An enclosed fuse cutout can have a dropout design but commonly do not. Additional types of Class A expulsion fuses include those intended for capacitor applications, and those that surround the fuse element with a liquid.

Class B fuses (formerly termed *power fuses* and still commonly known this way) are designed for circuits having a higher X/R (lower power factor) and higher transient recovery voltage (TRV, see 4.1.1) values than Class A, and the fuses normally have higher maximum interrupting currents. The fuse unit tends to be more elaborate than that of a fuse cutout and in some cases can constitute most, if not all, of the fuseholder. Some designs use a renewable fuse unit that, after operation, can be restored by means of installing a refill unit (containing an element and arc-quenching material). Unlike fuse cutouts, not all Class B expulsion fuses drop to an open position after operation. The most common type of Class B fuses uses boric acid as part of its interruption mechanism, and so the fuses are often termed *boric acid fuses* (see 4.3.2.2).

4.1.3 Basic principles of fuse operation

The following basic principles of fuse operation are common to all types of fuse, both current-limiting and non-current-limiting varieties.

In its passive or current-carrying mode, a fuse is expected to carry load current and permissible cyclic or transient overloads without deterioration essentially indefinitely (with a service life often measured in decades, see 5.1.1.7). When load current is passing through the fuse, its element temperature rises but as heat is dissipated to its surroundings, the temperature stabilizes at some value below that at which the element material and connections to the power system would deteriorate. Under these conditions, the heat lost through conduction, convection, and radiation exactly balances the heat generated by the current flowing through the fuse resistance.

In its active or fault-interrupting mode, more heat is generated in the fuse element than can be dissipated before its melting temperature is reached. The relationship between current and melting time is described with a time- current characteristic (TCC) curve. An example of a fuse melting TCC curve is shown in Figure 1. For most fuses, the melting current becomes asymptotic to the time axis at very long times, and is termed the *minimum fusing current* (*minimum melting current* in IEC). Standards specify the time to which curves are required to be drawn, depending on the type of fuse. Not all curves are drawn to a time that shows the minimum fusing current, and not all fuses are capable of interrupting this current (see 4.1.2.1).

Upon melting, a current-interrupting (breaking) process occurs that is different according to whether the fuse in question is of the current-limiting or non-current-limiting type. The interrupting process is described for each type of fuse in the appropriate section of the guide.

After the interrupting process, fuses have to be capable of withstanding normal system voltage. To assist with this phase of operation, some fuses drop open, providing a visual and physical gap. This is relatively common with expulsion type fuses, but much less common with current-limiting types.

4.1.4 Advantages of fuse protection

While fuses and other forms of protective devices (such as circuit breakers) all have their own advantages and disadvantages for a given application, fuses do have some unique benefits:

- a) Because their operation is initiated by the melting of an element, there is no theoretical limit on how fast they can initiate the interruption process (the faster heat is generated in a fuse element, the faster it melts). Generally, there are no moving parts that require separation before the interrupting process can be initiated.
- b) Rapid operation of fuses under short-circuit fault conditions reduces voltage dips on the system and provides more effective protection of lines and equipment, often allowing equipment connected to adjacent circuits to ride through the fault-clearing operation.
- c) Fuses cannot be re-set when “blown,” thus the user is encouraged to identify and correct the fault condition before re-energizing the circuit.
- d) Fuses have no, or very few, moving parts that could become damaged by dust, oil, or corrosion.
- e) Fuse replacement after operation restores protection to its original operational state of integrity after circuit interruption, unlike typical mechanical switching devices.
- f) Use of fuses usually gives the most economical solution for a high degree of system protection.
- g) Specific types of fuse are available for almost every service application.

4.1.5 Advantages of current-limiting fuses

4.1.5.1 General

In addition to the advantages detailed in 4.1.4, fuses of the current-limiting type offer additional important advantages:

- a) Limitation of current and energy let-through into the location of the fault provides significant protection and limits the risks of possible fire damage, explosion, or injury to persons.
- b) Very high maximum interrupting current enables such fuses to be employed on a given system even where the system is later modified to give a higher prospective fault level. Hence there is no need to incur capital cost in installation of new, more expensive protection equipment.
- c) Silent operation with no emission of gas, flame, or arcing products.
- d) Compact size and much lower comparable cost than alternative forms of protection.
- e) Ability to reduce the size of cables due to reduced short-circuit stresses.
- f) By reducing the I^2t (see 4.2.5.4 for an explanation of I^2t) flowing due to a fault, thermal stresses on all equipment in the fault circuit are reduced.
- g) Since the peak current is reduced, the electro-dynamic forces, resulting from the magnetic fields surrounding the conductors of transformers and other equipment in the fault circuit, are reduced.
- h) Because a current-limiting fuse reduces both the peak current and forces the current to zero before the natural current zero of the circuit, the fuse has a specific maximum-clearing I^2t . Since upstream protective devices (see 5.1.4.1) require a minimum I^2t to initiate the interrupting process, it is possible to coordinate the devices such that a failure at one point in a system does not cause operation of an upstream device, thereby reducing the extent of the overall outage and helping to maintain service reliability.

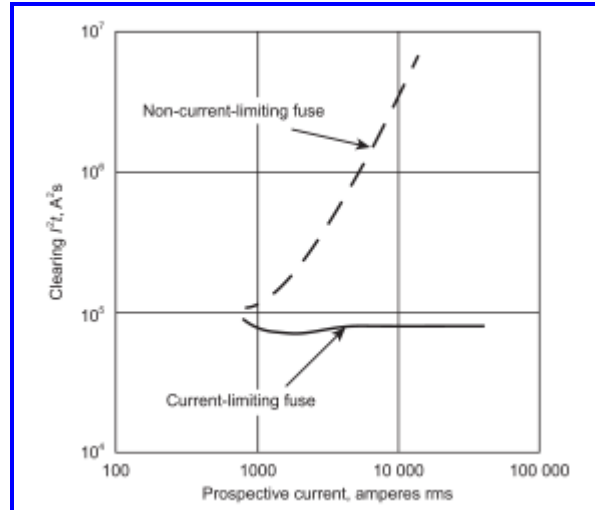
4.1.5.2 Transformer protection

The most common application of high-voltage current-limiting fuses is for transformer protection. The use of such fuses for the primary side protection of distribution transformers provides significant advantages due to their current-limiting action. Under most short-circuit conditions, they are able to interrupt fault currents within a few milliseconds after fault initiation. Hence, the prospective peak of the fault current is not reached and the resulting let-through current and energy is significantly reduced. This feature, that cannot be achieved by any other relay/switching device combination, makes current-limiting fuses particularly suited for distribution transformer protection since they are able to prevent or significantly reduce any major consequences of internal transformer faults.

Figure 3 illustrates the clearing I^2t versus prospective current for a non-current-limiting fuse, which interrupts after one fully asymmetrical loop of current, and a current-limiting fuse. In principle, the lowest current rating of current-limiting fuse that meets the coordination requirements of 5.2.2 should be chosen. This is because a smaller fuse of a given design will generally have a lower clearing I^2t . In the case of a low impedance internal transformer fault that produces a current-limiting action by the fuse, the I^2t limitation significantly reduces the likelihood of a disruptive failure, particularly with oil-filled transformers.

Experience has shown that the I^2t associated with a current-limiting fuse interruption is often an order of magnitude less than that causing a disruptive transformer failure, hence the effectiveness of current-limiting fuses in reducing the likelihood of such serious incidents.

It should be noted that the disparity in protection ability is even greater when the non-current-limiting device is a circuit breaker, due to the time delay introduced by the processes necessary to achieve current interruption. These are the time needed for relay/current sensing, the time needed for the circuit-breaker contacts to open, and the time needed for the current to be extinguished. Therefore, in addition to the first loop I^2t , shown in Figure 3, I^2t from additional loops of current, which flow until the fault is interrupted, have to be added. This has the effect of shifting the non-current-limiting fuse curve in Figure 3 upward, typically increasing I^2t by a factor of approximately 2.5 times that shown.



(New)

Figure 3—Comparison of clearing I^2t (Joule integral) versus prospective current for current-limiting fuses and non-current-limiting fuses

Current-limiting fuses are available for the protection of distribution transformers up to approximately 5 MVA. For larger transformers with rated currents up to several thousand amperes, commutating current-limiting devices (see 4.4.2.1 for a description) with high rated current can be applied. They are operated by an electronic sensing and triggering unit, which can be adapted to the required protection function. The electronics need to be able to distinguish between the fault current and the inrush current of the transformer.

4.1.6 Types of high-voltage fuses

4.1.6.1 General

High-voltage fuses of one type or another are available to meet almost every application for protection of high-voltage circuits or equipment. It may be said that such fuses usually provide the simplest and most economical solution. There follows a listing of the most common types of fuse and fuse-related devices that receive coverage in this guide. They are grouped under four headings: current-limiting fuses, expulsion fuses, non- current-limiting fuses (that are not expulsion fuses), and fuse-related devices (devices that incorporate fuses into their operation, or are mounted in fuse supports). A brief description is added for each device and places in the guide where they are addressed can be found in the index. It is believed that some types of device listed are obsolete and/or either not being currently manufactured, or manufactured in very small quantities. Such devices are followed by the word *obsolete*. They are covered (if somewhat briefly) in this document because examples could still be found in service, and because they might require replacement by more modern devices.

4.1.6.2 Current-limiting fuses

When this type of fuse melts with a current high enough to cause it to melt before the first natural peak (the threshold current for a particular fuse), it introduces a sufficient resistance into the circuit that the current is quickly reduced to zero. They are enclosed fuses, normally filled with quartz sand, and the higher the fault current above the threshold current, the greater is the percentage reduction in let-through current peak and energy. Table 2 lists the most common types covered by this guide.

Table 2— Common types of current-limiting fuse

	Type of CL fuse	Brief description
1	Full-range	Fuses intended to interrupt all currents that cause the fuse to melt, up to the rated maximum interrupting current of the fuse.
2	General-purpose	Fuses intended to interrupt all currents from a low value, equal to a current that causes the fuse to melt in one hour, up to the rated maximum interrupting current of the fuse.
3	Backup	Fuses intended to interrupt currents from their rated minimum interrupting current, up to their rated maximum interrupting current.
4	Types 1 through 3 using an indicator or striker	Indicators provide indication of fuse operation; strikers operate on fuse element melting (or at high temperature) typically causing a pin to emerge from the fuse end ferrule and trip associated switching equipment.
5	Motor circuit applications ("motor-starter fuses")	Fuses used in circuits that supply motors, and that are subjected to repeated starting surges higher than their rated current.
6	Voltage transformer fuse	Fuses used in the HV circuits of voltage transformers (and typically having very low current ratings).
7	Capacitor fuse	Fuses used to protect capacitors and that are required to interrupt capacitive currents.
8	Types 1 through 7 for use indoors, outdoors, or immersed in an insulating liquid	Outdoor fuses can have special dielectric requirements compared to indoor fuses and also requirements for UV protection and/or moisture ingress. Fuses immersed in a liquid have special sealing requirements to avoid liquid ingress.
9	Exothermically-assisted triggered fuse (obsolete)	A full-range-type fuse that used exothermic material to provide multiple element breaks at low currents.

(New)

4.1.6.3 Expulsion fuses

These are fuses that work through an expulsion action. After the fuse element melts, an arc is formed, during which ionized material is expelled from a housing with the assistance of gas generated as a result of the arc interacting with components of the fuse. This enables the "gap" so produced to withstand circuit recovery voltage at a current zero. They do not significantly reduce the magnitude of a fault current, only its duration, and so are also called *non-current-limiting fuses*. Table 3 lists the most common types covered by this guide.

Table 3— Common types of expulsion fuse

	Type of expulsion fuse	Brief description
1	Fuse cutout (Class A expulsion fuse) (open cutout)	A Class A expulsion fuse that uses a replaceable fuse link in a fuseholder that drops open after interruption. Used outdoors.
2	Enclosed fuse cutout	An expulsion fuse in which live parts are enclosed. They may or may not be of a type that drops open after operation. Used outdoors.
3	Open-link cutout	A cutout that does not use a fuseholder but a special type of fuse link attached to spring loaded arms. Used outdoors.
4	Boric acid fuse (Class B expulsion fuse)	A Class B expulsion fuse that uses boric acid to generate expulsion gases. May or may not be of a type that drops open. Indoor versions are available.
5	Liquid-submerged expulsion fuse	Fuse immersed in a dielectric liquid with the element in contact with the liquid.
6	Liquid fuse (liquid-filled fuse)	Sealed fuse containing a dielectric liquid. Used outdoors.
7	Capacitor fuses	Fuses used to protect capacitors and that are required to interrupt capacitive currents.
8	Distribution oil fuse cutout (obsolete)	Small oil-filled tank containing rotating switch device that includes a fuse link.

(New)

4.1.6.4 Non-current-limiting fuses (non-expulsion-type fuses)

Like expulsion fuses, non-current-limiting fuses produce little resistance during arcing and rely on achieving a “gap” having dielectric conditions such that when the arc is extinguished at a natural current zero, it is not re-established and current flow ceases. Types of non-current-limiting fuses mentioned in this guide are listed in Table 4.

Table 4—Types of non-current-limiting fuse

	Type of non-current-limiting fuse	Brief description
1	Horn gap fuse (arcing-horn fuse)	Fuse that uses a wire between two arcing horns.
2	SF ₆ fuse (obsolete, see 4.4.3.2)	Fuse uses a short element between two electrodes, in a small, sealed enclosure with SF ₆ gas.
3	Vacuum fuse (obsolete, see 4.4.3.3)	Fuse uses a short element between two electrodes, in a small, sealed enclosure with vacuum.

(New)

4.1.6.5 Fuse-related devices

These devices use fuses as part of their operation or employ fuse supports as part of their construction. Common types referenced in this guide are listed in Table 5.

Table 5—Fuse-related devices

	Type of fuse-related device	Brief description
1	Commutating current-limiting devices with integral fuses	Device incorporates low-resistance conductor, capable of very quickly transferring current to a parallel current-limiting fuse upon a signal supplied by a separate sensing device.
2	Electronic automatic sectionalizing link (ASL)	A device, mounted in a cutout fuse support that can sense fault current and drop open, providing isolation during the “off” time of a recloser or similar device.
3	Cutout mounted recloser	Single-phase automatic circuit recloser mounted in a cutout fuse support or base as defined in IEEE Std C37.41 and IEC 60282-2. It is a self-controlled device for making, carrying, and automatically interrupting and reclosing an alternating-current circuit, with a predetermined sequence of opening and reclosing followed by resetting, hold-closed, or lockout operation. It may also perform drop open and isolation functions.
4	Disconnecting cutout	A cutout fuse support fitted with a solid blade in place of the fuseholder.
5	Fuse support with load-break means	A fuse support with an integral load-break device used with a special fuse unit or fuseholder, or a fuse cutout fitted with a link-break mechanism.

(New)

4.1.7 Application of fuse types

Some applications commonly use just one type of fuse (e.g., motor circuit applications almost always use current-limiting fuses designed for the application). However, in other applications, more than one type of fuse is often found. This could be either as alternatives (e.g., an expulsion fuse or a current-limiting fuse) or a combination of fuses (e.g., a fuse cutout in series with a current-limiting backup fuse). Combination fuses are available in which a current-limiting fuse is attached to an expulsion fuse (e.g., for capacitor applications). Particular advantages and disadvantages of different fuse types drive the selection process. While this guide will compare and contrast different fuse types, it is not the intention to suggest that any one fuse type is better or worse than another, but rather that some fuse types are better suited for certain applications than others, depending on the desired protection requirements and the budget available.

4.2 Current-limiting fuses

4.2.1 General operating principles

There are many types of current-limiting fuse, but their primary characteristic is that they are non-vented devices which have the ability to limit the prospective current before its first peak value is reached, if the current is sufficiently high (see 4.2.2.2). They are therefore suitable for use in enclosures and vaults, and versions exist that can be immersed in an insulating liquid and/or are suitable for use outdoors. Individual classes of current-limiting fuse are further distinguished by their ability (or lack of ability) to interrupt currents less than those that cause a current-limiting effect (see 4.2.2.3).

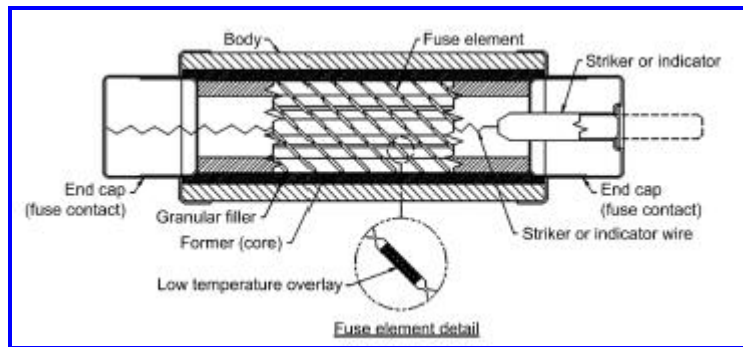
Unlike expulsion fuses (see 4.3.2) the basic construction and operating principles of Class A and Class B fuses are usually similar. This is because the main operating conditions that differentiate expulsion fuses of the two classes (X/R, TRV, and maximum interrupting current) are all of much less importance to current-limiting fuse operation (see 4.2.2.2). The construction and operation of current-limiting fuses are therefore much more related to the ability of a fuse to interrupt lower currents and physical operational requirements. The information in 4.2 therefore does not differentiate between Class A and Class B current-limiting fuses.

4.2.2 Construction and operation of current-limiting fuses

4.2.2.1 General

In its passive or current-carrying role, the fuse is required to carry load current and permitted cyclic or other transient overloads for an indefinite time without deterioration (see 4.2.5.7 and 5.1.1.7). In its active or overload/fault current interrupting role, the fuse has to disconnect the circuit, either relatively slowly, based on its pre-determined melting or clearing time-current characteristics, or very quickly with high fault currents, absorbing perhaps many kiloJoules of resultant arc energy within itself and limiting the energy passed into the protected faulty circuit as much as possible.

Figure 4 shows the construction of a typical backup fuse having DIN dimensions (European-style fuse). While other types of current-limiting fuse will show differences in construction, this figure illustrates the primary characteristics of such fuses. An insulating tube (the fuse body) of ceramic or organic resin/glass fiber material encloses parallel fusible current-carrying fuse elements. These are connected at each end to metal caps, normally copper or brass, which seal the body and act as the electrical connections to the fuse. The body and caps are required to have the attributes of a pressure vessel, capable of withstanding the combination of high pressure and very high temperature that occurs at the instant of fuse operation. If the fuse is designed for use outdoors or under oil (or another dielectric liquid or gas, such as synthetic or seed-based oil, or SF₆), special additional sealing is usually included to prevent ingress of moisture or fluid. For outdoor use, the manufacturer should use a material selection or special coating to help prevent damage from weather and solar radiation over time.



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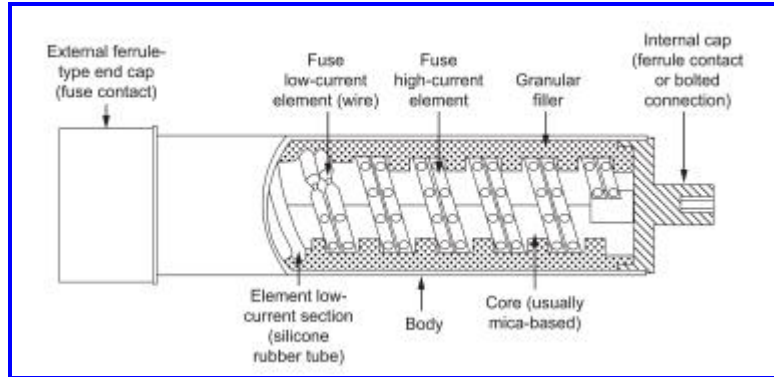
Figure 4—Cut-away drawing of typical current-limiting fuse of the DIN dimensioned type

The fuse elements are surrounded by granular insulating material, almost always compacted quartz sand of high purity and closely-controlled grain size. The fuse shown, like many ratings, requires a fuse element length greater than the body length and so the fuse elements are wound in a spiral pattern around an inert former or *core*, often, from its shape, known as a *star core*. Other designs of fuse require fuse elements only of similar length to the body, and so are mounted parallel to the body (notably motor circuit fuses) as with low-voltage fuses. Low current ratings often have only one fuse element, while high current ratings will usually have many parallel fuse elements.

The fuse elements are the heart of the fuse, and are manufactured to a high degree of precision, normally from pure silver or copper wire or strip. The length of the fuse elements is proportional to the voltage rating of the fuse, while the total cross-section and number of parallel fuse elements determine the current rating. The shape of the fuse elements together with their spacing and configuration determine many of the electrical characteristics of the fuse. They have a strong influence on the shape of the time-current characteristics, the degree of current limitation, and the peak overvoltage during high-current operation (also termed *switching voltage* or *peak arc voltage*—see 4.2.5.5).

Where fitted, strikers (often used to trip an auxiliary device) or indicating devices (to show that the fuse has operated), are wired in parallel with the fuse-element system. During fuse operation, when the main fuse elements are melted, the current transfers into the striker circuit, before quickly switching back to the main elements. Current IEEE standards do not address striker operation, but there is extensive information and test requirements for strikers in IEC 60282-1. Depending on the design, the current either ignites a small pyrotechnic charge to expel the pin (typically British Standard type fuses or fuses that require a striker of the “heavy” type), or else melt a small latch wire (typically DIN-type fuses) to release a coil spring that expels the striker pin. In some designs, the latch is made thermally sensitive so that the striker is released and trips the associated switchgear once the fuse has reached a given temperature, irrespective as to whether the fuse itself has actually operated. In the case where an indicating device rather than a striker is used, a relatively weak spring-loaded indicator device can operate in a similar manner to a striker, or it could use a non-conducting filament, released by heat from the fuse arcing.

Figure 5 shows the construction of a typical full-range fuse that employs a “dual-element” method of achieving lowcurrent operation (essentially a backup fuse in series with an expulsion fuse in the same body). Such fuses are subject to special testing requirements to demonstrate operation when one series element passes the interruption duty to the other. The low-current section in this type of fuse typically uses a rubber tube containing a wire element that incorporates a low melting point material. This type of design is discussed in 4.2.2.3.2. Two common types of end cap are shown (typically used in North American practice): an external ferrule on the left, and a cap with smaller diameter ferrule, or bolted connection, on the right. These types of cap arrangement are also used with other types of fuse (general-purpose and backup). Caps used with spring-loaded clips are typically silver or tin plated, at least on their contact surfaces, while fuses that are immersed in liquid are normally unplated. When this type of fuse is used immersed in liquid, or used outdoors, it is sealed, and special testing requirements (see 5.1.1.2.2 and 5.1.1.2.6) apply to verify the ability of the fuse to remain sealed over the anticipated lifetime of the fuse.

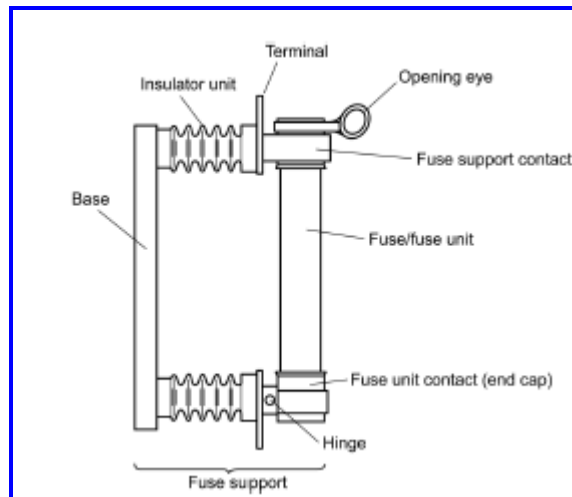


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Figure 5—Partial cut-away drawing showing typical full-range current-limiting fuse features

Fuses can be designed as simple ferrule fuses to fit into suitably-shaped contact clips, or they can be fitted with terminal tags for bolting onto bus-bars, etc. Some, intended for outdoor use, incorporate eye bolts for attaching cables or studs for mounting in eye-bolt terminals.

Figure 6 shows a current-limiting fuse mounted in a typical “traditional” fuse support. What is shown is a fuse- disconnecting switch. The upper fuse-unit ferrule fits into contact clips and the lower attached hardware fits into a hinge and contact mechanism on the fuse support. The upper attached hardware, with an opening eye, then permits the fuse to be swung open with a switch stick. If the hardware components were removed, and the lower fuse support contact was the same as the upper contact, then it would be a non-disconnecting device, which is the more common arrangement. Note that unless additional load-break components are attached, a fuse-disconnecting switch has no load-breaking ability.

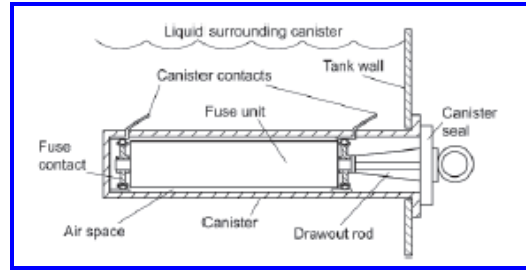


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Figure 6— Fuse unit in typical fuse support

When a current-limiting fuse is mounted in a cutout fuse support (see 4.3.2.1.1) it is termed a *cutout-mounted current-limiting fuse*. After operation it automatically drops into the open position (i.e., it is a *dropout fuse*).

Figure 7 shows the cutaway drawing of a full-range current-limiting fuse mounted under liquid in a “dry-well” canister fuseholder. In this arrangement, the fuse is surrounded by air and so fuse replacement is possible without unsealing the tank. Designs are available that include a load-break feature at the inner end of the fuse (usually based on separable connector technology). In addition to unsealed canisters, designs are available that are sealed to prevent liquid leaking into the inside of the canister from outside the tank, making them suitable for tanks that could sometimes be immersed in water, for example in vaults subject to flooding.



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Figure 7—Fuse mounted in a canister-type fuse support

Other designs exist in which the CL fuse is intentionally surrounded by insulating liquid in a similar manner to expulsion *bayonet* fuses (see 4.3.2.1.5). These are sometimes called *wet-well* fuse holders.

The high-voltage current-limiting fuse has two distinct modes of interrupting fault currents, which are described in 4.2.2.2 and 4.2.2.3. For a theoretical treatment of fuse interrupting phenomenon, see *Electric Fuses* by Wright and Newbery [B7].

4.2.2.2 Operation under high fault current conditions

At high fault currents (say more than 10 to 20 times load current), all elements in a fuse reach melting temperature virtually simultaneously in only a few milliseconds or less. They break up along their length into multiple small series arcs. Strip fuse elements usually include a pattern of holes or notches along their length to limit the number of these separate arcs, providing control over peak overvoltages (see also 4.2.5.5). Wire fuse elements also break up into multiple series arcs, due to complex thermal/magnetic forces. Since, for wires, the number of arcs tends to be very high, high peak overvoltages can result, so wire-fuse elements are normally used only for relatively low-current ratings (see 4.2.5.5). The arcing, in effect, introduces a high resistance into the circuit and causes the current to be driven down long before the peak of the prospective fault current is reached (known as the *cut-off effect*). This is illustrated in Figure 2(a). The arcs elongate, further increasing resistance. When the current has been driven down to a low value, the arcs are extinguished almost simultaneously within the first loop of fault current. Because the forced current zero occurs close to the circuit voltage zero, current-limiting fuses are much less sensitive to TRV than expulsion fuses; see Figure 2(a).

Since both the peak value of the fault current and its duration are greatly reduced as compared with the operation of a non-current-limiting device, the energy released into the location of the fault or into the circuit being protected is very greatly reduced. The rapidity with which the fuse operates results in the appearance of a transient overvoltage in the circuit—also known as the *arc voltage*. This is due to the collapse of the field associated with the circuit inductance and is more pronounced in circuits of high X/R (low power factor). This peak overvoltage, appearing across the fuse, can be appreciably higher than the system voltage and should be allowed for when designing equipment clearances and creepage, and selecting lightning arresters.

The energy of the arcs within the fuse is dissipated in the formation of nodules of fulgurite from the sand filler surrounding the fuse elements. *Fulgurite* is the term used by fuse engineers to denote the mixture of sintered and fused sand grains together with globules of metal from the melted fuse elements. The amount of fulgurite produced during fuse operation is directly related to the quantity of arc energy absorbed by the fuse. Approximately 0.5 g of fulgurite are produced per kiloJoule of arc energy. Small increases in system voltage (above the rated voltage for the given fuse) cause a large increase in the arc energy and hence in the quantity of fulgurite produced. The fuse envelope has a definite upper limit to the mass of hot fulgurite it can accommodate. Thus, in general, current-limiting fuses can only correctly interrupt short-circuit currents at system voltages not in excess of the fuse rated voltage.

4.2.2.3 Operation under low fault current conditions

4.2.2.3.1 Temperature considerations

In the case of low fault currents, say up to around five times the fuse rated current, the fuse elements reach melting temperature gradually over a period of many seconds or minutes (or, for full-range fuses, even hours). The melting temperature of silver is approximately 960 °C, that of copper, approximately 1080 °C. If the melting time of a fuse is more than a few seconds (or for some types a few minutes), and the fuse as a whole had to reach such a high temperature during operation, damage to the fuse itself or its associated equipment could result. Various means are therefore employed to overcome this problem. Some fuse designs include a spot of low-melting-point alloy on the fuse element, to produce an *M-effect* (after its discoverer Prof. Metcalf) as shown in Figure 4. If a typical tin alloy is used for the M-effect, at about 230 °C the alloy melts and the base fuse element material diffuses into it. This causes the fuse element to melt open at a lower temperature than its normal melting temperature, and initiate the process of current interruption. Where M-effect is not employed, other techniques include the incorporation of a low-melting-point section in series with a fuse element (common in some types of full-range fuse), the formation of a hot spot on the fuse element by creating a long narrow neck in the strip, or by enclosing part of the fuse element in thermal insulating material. The object, again, is to produce fuse element melting without the strip as a whole having to reach an excessively high temperature.

An alternative solution, employed where the fuse is mounted in a striker-tripped switching device, is to use a thermal striker which is designed to operate and trip the associated switching device, when the temperature of the fuse reaches a pre-determined value. In this particular case, it is the switching device, and not the fuse, which performs the current interruption.