A High-Voltage Fuse Tutorial and Application Guide

or: how I learned to stop worrying and love the fuse protection

By John G. Leach

1. Introduction

It has been said that I have a strange love for fuses (movie buffs will get the connection…) but it is true that when I first learned what a current-limiting fuse was and how it worked, I felt a sense of wonder and an attraction that has lasted almost 50 years. This event happened in 1969, right after I read an internal job posting. I was working in the UK for a division of Hawker Siddeley called Brush (now part of Eaton Corporation). The posting was for someone to join the Fusegear division and conduct fuse research that, all being well, would lead to a Ph. D. The first thing I did was to look up what a current-limiting fuse was (in the UK it was actually called a “High Rupturing Capacity” fuse), and this, I think, goes to the heart of what I am going to talk about today. For many folks, even those in our industry, a fuse is something that is taken for granted, but not necessarily something to be really understood. As a recent graduate, I thought knew what a fuse was; we had them in our houses and cars after all, but I quickly discovered that there was a lot more to them than met the eye. I have spent a lifetime trying to understand them and I am still learning. But I don’t have a lifetime to talk to you - my aim is to keep at least half of you awake for 90 minutes or so while I bring you up to date on the latest developments in the attempt of both the IEEE and the IEC fuse committees to provide HV fuse education in the form of a Tutorial and Application Guide, the latest incarnation being IEEE Draft Guide PC37.48. I think it is quite an interesting story of how it came about, and in particular the circumstances surrounding the cooperation between the IEEE and IEC.

About 30 years ago, those of us in the fuse universe realized that that several of the pioneering fuse designers of the 60’s, 70’s and 80’s (a “golden age” of HV fuse development) were beginning to leave the industry, as were many knowledgeable utility engineers. Work began, therefore, initially in the IEEE but then in IEC to capture that knowledge before it was gone. The final result was the published IEC Technical report TR 62655 in 2013, which, with copyright approval from IEEE and others, incorporated information from IEEE documents, the “old” IEEE Std C37.48-2005, and IEEE Std C37.48.1-2011. Now we are at a late stage of developing the “twin” of the technical report, to be IEEE Std C37.48- “probably 2020”, a document to replace the “old” C37.48. We believe that the IEEE and IEC guides will be very useful reference documents, because no one can be expected to remember everything about everything all the time.

Today, I hope to answer some questions for you like, “So, how did we get where we are today” with the fuse guide and “what does it contain”? The IEEE document runs to around 140 pages and I estimate that to read it from start to finish, and without poring over the figures and equations for too long, would take about 7 hours. Clearly, I can only give you a brief overview. My plan therefore is to cover the following topics:

1) history behind the creation of the tutorial/guide;

2) structure of the document;
3) what the most common fuses are, and how they work;
4) an overview of some of the basic principles of fuse application and coordination.

2. History

2.1 IEEE Std C37.48.1:2002

Our story of the work to develop the first HV Fuse "tutorial" type of document (that became C37.48.1) begins in the 1970's when a new type of current-limiting fuse, the "full-range" fuse joined the existing CL types "backup" and "general-purpose". I will go into more detail concerning these fuse types when I discuss how fuses work, but for now it is sufficient to know that while CL fuses excel at interrupting very high currents, their limitations when it comes to interrupting lower currents results in various classifications. Backup current-limiting fuses can only interrupt currents higher than a defined value (rated minimum interrupting current). General-purpose fuses can interrupt quite low currents, compared to backup fuses, but for convenience they were tested at a low current corresponding to a melting time of one hour. This was fine for older designs, but design changes and new applications, particularly at elevated surrounding temperatures in enclosures, meant than a new category "full-range fuse" was introduced by several manufacturers with even lower current interrupting capability than specified for general-purpose fuses. Unfortunately, since there was no standard definition and testing in IEEE or IEC, designs from different manufacturers could have different capabilities. There was therefore some debate in the HV fuses Subcommittee as to whether a definition, and hence changes, was needed to the fuse standards, so a task force was set up in 1986 to investigate this. It may be noted that one of the driving forces behind setting up the task force was that the IEC was looking into a full-range fuse definition, and it was desirable for the US to have a position.

The first thing that the task force did was to commission a survey of users and specifiers to determine if there was indeed confusion concerning the different fuse types, to determine the level of general knowledge concerning fuse types, and to find whether an additional definition (and therefore testing requirements) was needed for a "full-range" fuse. The survey was sent, in 1988, to 180 potential users at investor owned utilities, electric cooperatives, municipal power distribution utilities and OEM suppliers. It was requested that those responsible for specifying fuses complete the survey, and 108 completed surveys were returned covering all of the general categories of user. Since the respondents had to note their role in specifying, using and applying CL fuses, it was possible to analyze their answers in light of their role. Questions covered definitions and application guidelines, with special emphasis on full-range fuses, and many questions were multiple choice to make answering simple. A typical question is shown in Figure 1.

The subcommittee was somewhat alarmed by the relatively low percentage of correct answers. For example, less than half (only 41.7%) of those answering the question in Fig. 1 were correct – "Current specified by the manufacturer and marked on fuse". Some questions designed to find the user's understanding of general-purpose and full-range fuses got even lower percentage correct answers.

For a back-up Current Limiting fuse, what is your understanding of the minimum current that the fuse is capable of interrupting?

- ○ Equal to the rated continuous current
- ○ 2 to 3 times the rated continuous current
- ○ Current which melts a fuse in 1 hr. – room temperature
- ○ Current which melts a fuse in 1 hr. – any temperature
- ○ Any current that melts the element
- X Current specified by the manufacturer and marked on fuse
- ○ Other

Figure 1, Typical survey question

As a result of the survey, all subcommittee members became convinced that work needed to be done. A Working Group was therefore formed and adopted two-pronged approach: a) full-range fuses needed to be covered in the definitions and testing sections of IEEE fuse standards, and b) we needed more education on the types of fuses and what they can do. The first led to the revision of existing standards with a full-range fuse definition in IEEE Std C37.40-1993, testing requirements in IEEE Std C37.41-1994 and application information in C37.48-1997. In parallel the second "prong" produced a fuse tutorial that would explain how fuses worked and the differences between CL fuse classes, as well as expanded application information.

The fuse tutorial and application information for current-limiting fuses was developed, and to ensure that the gathered information would not be lost and would be continued to be updated, a PAR was taken out and it became IEEE Std C37.48.1-2002 "IEEE Guide for the Operation, Classification, Application, and Coordination of Current-limiting Fuses with Rated Voltages 1-38 kV", and no, I did not choose the title! This document was notable for a number of reasons. In my early days of fuse standard work, almost 40 years ago, anytime I wrote anything that tried to explain *why* we were specifying something and did not simply say "do this and this", the "old timers" would complain that it was "too tutorial". It seemed that nothing in our standards should be tutorial in nature and here was a guide that was very tutorial. We already had an application guide in IEEE Std C37.48, but this assumed a quite high level of fuse knowledge to be able to understand it. The new guide started out assuming relatively little knowledge. While the document was to cover current-limiting fuses, because they are often used with expulsion fuses, a description of expulsion fuse operation was also included. Information on the coordination methods between the two types of fuses was expanded greatly compared to C37.48. Before being published as IEEE Std C37.48.1-2002, the guide was presented as a tutorial at, I believe, an IEEE PES meeting, and then over time the content of IEEE Std C37.48.1 was subsequently revised and improved and presentations of a tutorial based on the document occurred in 2003 at the T&D Conference and Exposition, and in 2012 at the PES annual meeting, as well as to the Switchgear Committee a number of years ago.

2.2 IEC TR 62655:2013

Turning now to IEC, things are done a little differently there. Standards for HV fuse requirements are developed by the subcommittee SC32A of Technical Committee TC32, a committee that covers high-voltage, low-voltage and miniature fuses. This is a separate technical committee to that which covers switchgear, although several IEC switchgear standards include fuse requirements for situations in which fuses are used with switchgear (more common in European practice than North American practice). I mention these differences in practice, because this plays a crucial role in what I have been trying to achieve over the last 25 years, while having one foot in the IEEE "camp" and the other in the IEC "camp". I have been representing the US at IEC plenary meetings for 25 years, although technically I was not representing the US last year at our SC32A meeting, as I am the current chair! During this time, I have been trying to get more recognition in IEC for fuses representing "North American" practice. While there are two tables for preferred voltages in IEC, Series I and Series II, covering European practice and North American practice, there was very little recognition of North American methods of using fuses, but a lot of emphasis on European Practice. I have been gradually introducing North American viewpoints into the IEC Fuse standards but it has not been easy. Once when I asked a member why the European viewpoint was more important than the US viewpoint during a "debate" over a particular issue, he said that it was because Europe was more important than the USA as they made more fuses! However, with persistence I have made some headway. It is said that a drip of water will wear away a stone – sometimes you have to be a drip.

Rather than have a separate fuse application guide such as we had in IEEE Std C37.48 (and then its supplement C37.48.1), each IEC fuse standard had a clause containing application information. Thus current-limiting fuses (IEC 60282-1), expulsion fuses (IEC 60282-2), fuses for motor circuits (IEC 60644), and fuses for capacitor protection (IEC 60549) had an applications clause and there was a freestanding guide for the selection of HV current-limiting fuse-links for transformer circuits (IEC 60787). While looking for ideas for future work, I suggested to the members of the HV fuses Maintenance Team 3 that collecting all application material together in one place, and including tutorial information about fuses, such as we had done in IEEE with C37.48.1 might be a worthwhile project. This was met with general agreement and a surprising level of enthusiasm, particularly from former SC Chair Phil Rosen. The IEC procedures are such that a formal project to develop a document has to be completed in a relatively short time (usually about a year to the first distributed committee draft document for international comment). Therefore in 2006 an ad hoc group was established to continue preparatory work on a General HV Fuse User's Guide. In 2009 this group became Working Group 6 of SC32A, to bring this work to the form of a Technical Report (all IEC guides are technical reports rather than standards). While the work was led by the convenor of WG6, Norbert Stein, as secretary I did most of the actual work of combining existing application information from both IEC and IEEE fuse standards. The scope of this document was much more than the IEEE Std C37.48.1 in that we wanted to include expulsion fuse information to the same extent as current-limiting fuse information. This required quite a lot of new material to be written. In addition to the existing IEC "European practice" application information I was able to include North American practice also, furthering my aim of having IEC recognize NA fusing practice as well as European practice. Including the content of IEEE C37.48.1 was therefore crucial to achieving this end, and so before we started the work, IEC sought copyright permission from IEEE to use material from IEEE Std C37.48 and C37.48.1. We were led to believe that this would not be a problem, but that we should request permission for the specific portions used, after the work was complete. In fact, a reasonable amount of C37.48.1 was actually being used by IEEE with my approval, i.e. using copyright material from Hi-Tech Fuses, Inc. a company I co-owned at the time C37.48.1 was being developed.

Copyright issues are complex and I am no attorney. However, I find copyrighting what is often little more than statements of fact somewhat problematical. In fact, from my reading I understand that it is not possible to copyright "facts, ideas, procedures, processes, systems, method of operation, concept, principle, or discovery", a pretty good description of most of our work. Only the "expression" of these things is copyrightable. While I can see where descriptive material (such as occurs in application guides) could be considered as copyrightable, it is difficult to see how most of our testing documents can contain much material that can be copyrighted (and most of the material in application guides has previously been published in the literature of the manufacturers who's employees make up most of the WG writing the guides). In our standards work, where different bodies are trying to develop descriptions of, and testing requirements for, components that are similar, we are bound to create conflicts of copyright if there is not enough give-and-take. For many years, I was told, the organizations worked on the principle that some duplication was acceptable, if no more that 10% of a given document was identical. The problems arise, however, when the same people work on both IEEE and IEC documents and write portions of both and use the same ideas back and forth. I am one of those people and often the same words that I have written appear in both IEEE and IEC standards, while each side claims copyright for what is in effect my intellectual property, based on which one happened to be published first! I have to say I find this rather offensive, but I suppose it is the price we pay for providing free information to organizations that then make money by selling our ideas, in return for providing us with some legal protection.

Stepping down from my soapbox, I will continue to tell my tale. Anyway, armed with my semi-promise from IEEE I started the process of combining all existing application information I could find, together with descriptions of common (and not so common) fuses and fuse-like devices.

The resulting IEC Technical Report was finished in 2012 and in October, copyright permission was requested from IEEE. After an exchange of information concerning what sentences were the same (actually a relatively small percentage, probably no more than 5%, particularly as IEC uses a lot of different terminology) IEEE then decided that they did *not* want to give their permission! This was after almost seven years of work, and with snippets of IEEE material liberally sprinkled throughout the IEC material in the report. Over the next week I sent e-mails to various folk and did my best to persuade IEEE management that this was not a smart move if they in turn wanted to use material from IEC in future IEEE fuse standards (and since our fuse documents have the same basic testing requirements, and so use essentially similar text, this was a distinct possibility). Eventually IEEE “re-evaluated” copyright permission and apologizing “for the confusion” granted the permission. However, courtesy of the IEEE, I had a very uncomfortable week. IEC TR 62655 was published in 2013.

2.3 Revision of IEEE C37.48

Now we come to the requirement of IEEE to update our standards within a 10-year period. Our application guide C37.48 had to be replaced by the end of 2020, and C37.48.1 by the end of 2021. It seemed to the HV Fuses Subcommittee that with much of the information in these documents contained in the IEC Technical Report, with the report covering tutorial information for expulsion fuses, and with European application practice as well as North American practice covered, we should be able to use the IEC document to replace the IEEE standards. However, as it stood, the document did not lend itself to use by those familiar with North American practice. The first reason was that there are significant differences in terminology between IEC and IEEE standards. Secondly, the IEC document was obviously written with other IEC standards in mind and IEEE standards only being referenced somewhat parenthetically (or not at all). Thirdly, additional changes were required because one of the referenced documents, IEC 60282-1 the current-limiting fuse standard, was being revised itself, and would require that the TR be subsequently modified also. As an example of the terminology differences see Figure 2, a modified form of a table from the revised C37.48. The HV Fuses subcommittee therefore proposed that a revision of IEC TR 62655 be done to make it more suitable for use in North America, and that it be published as a revision of C37.48. Of course, this would require that IEC give permission for the document to be used almost “as is” but with numerous revisions. IEEE therefore approached IEC for copyright permission. I argued that the TR already contained substantial IEEE material and, somewhat surprisingly, IEC agreed to the copyright permission, and this time I got it in writing before we started! The Revision of Fuse Standards Working Group was therefore tasked by the subcommittee (and at the time I chaired both) to take the IEC TR and make such modifications as were required to make it suitable for IEEE use as IEEE Std C37.48-20XX. We decided that the primary focus would be North American practice regarding terminology, but that we would include an equivalence table. In the same way, where equivalent or similar IEEE and IEC standards exist, the IEEE standard would be mentioned first. However, we deliberately left in place references to IEC practice since we felt it important to compare and contrast areas where we were similar and different, as well as taking the opportunity to educate readers as to other methods of achieving protection using fuses – after all, almost all North American fuse manufacturers have plants and affiliates overseas. In the introduction we state “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.”

So that is my story as to how I managed to get cooperation between IEEE and IEC, and I have to say it was not without a certain amount of blood-pressure, sweat and tears, not to mention sleepless nights! This all, therefore, explains the somewhat unusual appearance and very substantial revision of IEEE Std C37.48, which I hope the Switchgear Committee membership will be seeing in a ballot before October as "PC37.48-D4".

IEEE term	**IEC term**
ambient temperature	surrounding temperature
backup current-limiting fuse	Back-Up fuse
clearing	operating
cutout fuse support	cut-out fuse base
drop out	drop-out
full-range current-limiting fuse	Full-Range fuse
fuse, or fuse and fuse support	fuse
fuse, fuse unit	fuse-link
fuse link	fuse-link
fuse support	fuse-base (fuse-mount)
fuseholder	fuse-carrier
fuseholder and fuse support	fuse-holder
fuse cutout	distribution fuse-cutout
general-purpose current-limiting fuse	General-Purpose fuse
ground	earth
guide	technical report
interrupting (current)	breaking (current)
I^2t	Joule integral, I^2t
melting	pre-arcing
minimum fusing current	minimum melting current
Peak let-through current	Cut-off current
peak overvoltage	switching voltage
Rated Maximum Application Temperature (RMAT)	Maximum Application Temperature (MAT)
wye connected	Star connected

Figure 2 – Comparison between IEEE and IEC terms

3. The structure of the Document

The PC37.48 document's title is "Draft Guide and Tutorial for the Application of High-Voltage (> 1 000 V) Fuses and Accessories", to line up with the other standards in the series. As with all IEEE standards the document starts with an overview. Of course, first comes the scope, which emphasizes that as a guide it contains no requirements and is informative only. The purpose states that it is to help prospective users and protection engineers to understand HV fuses, to illustrate the unique advantages of fuses, to minimize misapplication than could cause problems in the field, and to describe the many types of fuses in use and standards that apply to them, as well as types not covered by IEEE and IEC standards. Finally, there is a section on how to use the guide. The first point to be made is that if one were to read the whole guide start to finish, it provides an in-depth study of HV fuses. However, it is recognized that most readers will look at the section that contains information they desire. This leads to some duplication of material. To assist the user in making best use of the guide, there then follows a brief description of each clause.

After the scope, references, and definitions, Clause 4 contains primarily "tutorial" style information, starting with a simple introduction to fuses pointing out that the most basic division of types is into “current-limiting” and “non-current-limiting”. In IEEE both types are further classified into “Class A” and “Class B” (formerly in IEEE “Distribution Class” and “Power Class”), which generally indicates where, on an electrical distribution system, the fuses have been designed and tested to be used. Finally, the sub-classes of CL fuses are mentioned “backup”, “general-purpose”, and “full-range” together with common terminology. There then follows lists of the advantages afforded by using fuses in general and then current-limiting fuses in particular.

After the overview, the next clauses look at individual types of fuse in much more depth. They are “4.2 Current-limiting fuses”, “4.3 Expulsion fuses”, “4.4 Other related protective devices”, and “4.5 Fuse supports”. This depth inevitably repeats some of the information previously given in the overview but the level of detail is needed if one is to understand the reasons for the application information that follows in Clause 5.

Descriptions of the most common fuse types are included, but also some of the less common types including some obsolete designs that may still be found in service. However, for fuses not covered by standards, no application information is given later in the guide.

Clause 5 and Annexes A & B provides application information. It is split into 4 sections. The first covers application information common to nearly all applications, the second contains information on specific, typical, applications while the third covers installation, operation, maintenance, and replacement of fuses. The annexes reproduce the current-limiting fuse temperature de-rating information previously published in the IEC current-limiting fuse standard and additional coordination information for reclosers from IEEE Std C37.48-2005. The overview finishes with the important observation that “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.” It may be noted that the tutorial section covers about 40 pages while the application section covers about 100 pages.

4 The most common fuses and how they work

4.1 Introduction to HV fuses

4.1.1 Simple explanation of how a fuse works

The Tutorial and guide begin this part with a simple explanation as to how fuses work, and then go into more detail for different fuse types. I am therefore going to have to combine these into just one section of the presentation

Fuses have been in use since the very beginning of electrical power distribution. One of their first usages was to protect fragile (and expensive) lamps from being damaged due to fluctuations in voltage. From a simple “weak point” in the circuit they quickly became devices able to sense a current higher than normal and quickly interrupt (or break, using European terminology) that current, all in a self-contained easily replaceable unit. Fuses still provide the highest degree of protection for the lowest initial cost. A simple definition of a fuse is that it is a device that carries current through an “element” that melts by self-heating at an excessive current and initiates current interruption. All conventional fuses interrupt the current after some arcing across breaks formed in the element when it melts. Because there are few “mechanical” aspects to the melting process, fuses can have a very inverse time-current relationship as illustrated in Figure 3. This enables extremely short melting times almost without limit (while time-current characteristic - TCC – curves are normally drawn down to 0.01 s, there is no fundamental reason they could not be drawn to 0.001 s, or even less) and it is this apparently simple phenomenon that is primarily responsible for the universal success fuses have enjoyed for a very long time.

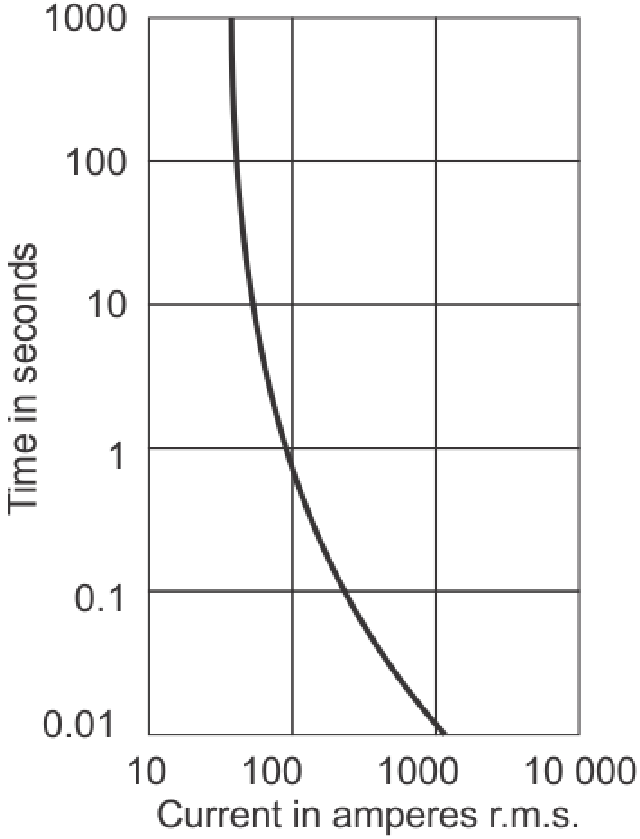


Figure 3— Fuse melting time-current characteristic curve

Fuses covered by standards all have three ratings, rated current, rated maximum voltage, and rated maximum interrupting current, all determined under prescribed conditions as set out in the standards. As we have seen backup current-limiting fuses also have a rated minimum interrupting current but more about that later.

4.1.2 An aside

Now a few paragraphs ago I said “apparently simple” phenomenon in relation to fuse melting, but in fact, it is not simple at all. Like many aspects of fuses, it belies the common view that a fuse is a simple device. Now feel free to forget everything I am about to cover next, because my aim is just to illustrate that, again, there is much more to fuses than meets the eye!

What is the “melting process”? The Europeans more correctly call the melting time of a fuse the “pre-arcing” time, because it is possible to determine when an arc begins from the abrupt rise in voltage across the fuse (whatever the circuit voltage) but this period can contain much more than just “melting”. The pre-arcing process is not fully understood, particularly for wire elements, but the basic principle is that an element melts when more heat is input by I^2R self-heating than is lost by conduction, convection and radiation. Most element materials have non-linear resistances, higher at higher temperatures, which speeds the process significantly. If there are no unusual effects, simple theory has the element rising to its melting temperature, latent heat of melting is then absorbed, the liquid temperature rises to vaporization temperature, latent heat of vaporization is then absorbed, and finally vapor is formed. This is illustrated in Figure 4.

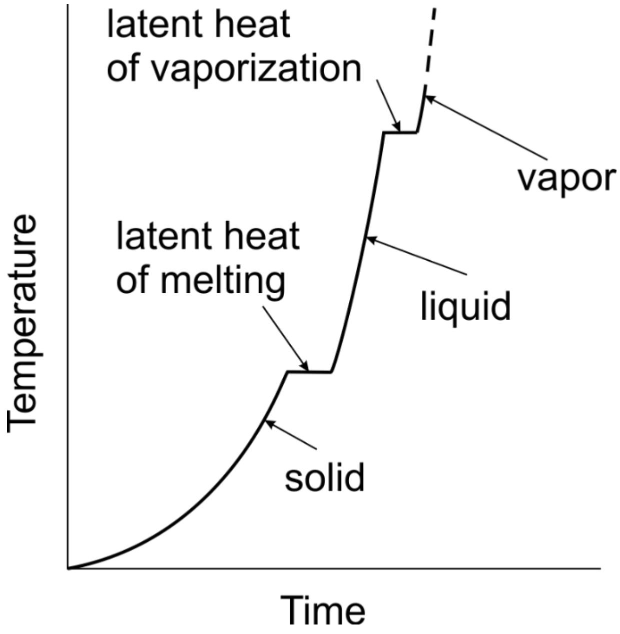


Figure 4 – Pre-arcing (“melting”) process

Everyone agrees that an element temperature rises to the melting point of its material but what happens next is subject to various theories, which depend on the current density and hence melting time (minutes or microseconds). Consider a relatively short melting time, say 1 ms. The addition of the specific heat of melting will then enable what was a solid material to then start melting. However, the full cross-section of the element does not usually melt simultaneously, because other factors affect the uniformity of the current density in its cross-section. One of the simpler ones is skin effect, whereby more current flows just under the surface of a conductor. Consider first a simple wire element (and simple strip elements show some of the same phenomenon). The surface layer melts before the core of the wire. Magneto-hydrodynamic vibration effects, electromagnetic pinch effect, and surface tension produce phenomenon in wires that result in multiple series arcs and a high arc voltage (voltage across the fuse) per length of element, as each arc has a minimum ignition voltage (typically observed as 30-50 volts per arc in a fuse). At longer melting times, one theory proposes this is caused by unduloid formation (liquid metal “beads” form on the wire as molten material gathers together under surface tension). At shorter times in sand, the wire breaks up and arcs in much shorter lengths called “striations”, as shown in Figure 5 which is an X-ray photograph of an arcing wire, and electromagnetic pinch effect is thought to be responsible by some.

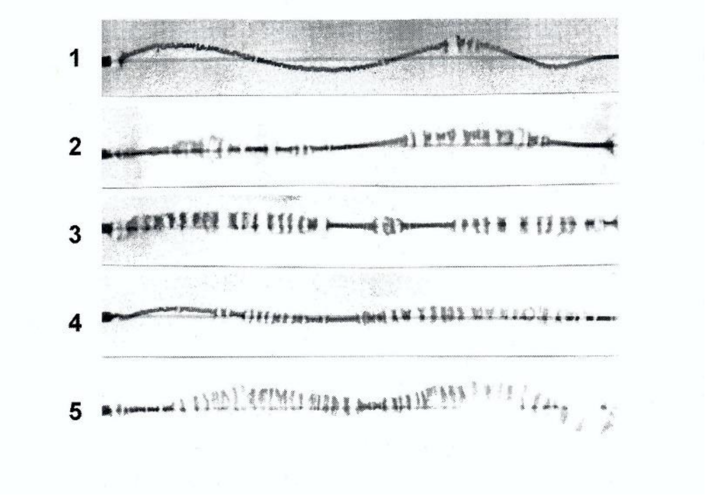


Figure 5 – Striation formation (from K. Jakubiuk [1])

Many papers have been written about melting and arcing in wires, termed “exploding wire phenomenon” and while relatively few HV fuses now use wire elements (mostly just very low current ratings) there is still significant interest in this phenomenon. Perhaps this because exploding wires are used in setting off atomic bombs. One of the “ICEFA” (International Conference on Electric Fuses and their Applications) that are held every 4 years under the auspices of “The Fuse Club”, was enlivened when a gentleman who worked for the UK agency responsible for their nuclear weapons started asking questions about, and discussing issues they had, with exploding wire phenomenon!

Most modern higher current rating CL fuses use notched strip elements in order to control the number of series arcs, and hence the peak overvoltage. Here, the current density is never uniform across the restriction (unless it is long, in which case the striation phenomenon again occurs). The current is “squeezed” adjacent to the restriction; in Figure 6 the current between each line is one eighth of the total element current, so the narrower the gap between lines the higher the current density. The restriction shown is functionally equivalent to the common method of punching a hole in the center of the strip. Such restrictions therefore begin melting from the outside edge in towards the center (figure 7). Having established some molten material, various mechanical and electro-mechanical forces act on the molten material. When some molten material reaches vaporization temperature, latent heat of vaporization is supplied and then vapor starts to form. This adds even more mechanical action into the phenomenon. At some point a “gap” occurs filled with non-conducting element vapor, and the voltage supplied from the system, plus di/dt effects in the circuit inductance, provide enough voltage to break down the gap(s). Ok, fuses are simple right?

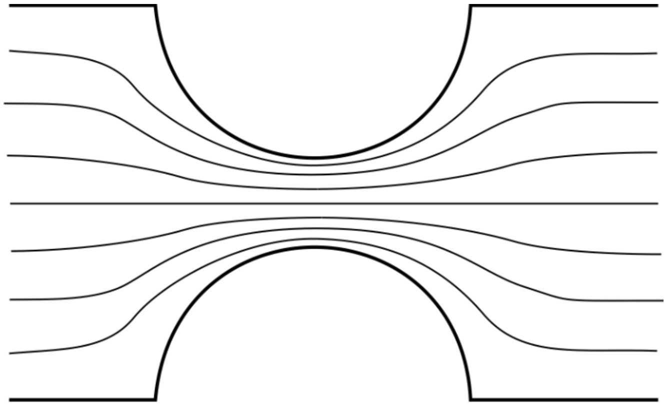


Figure 6 – Current flow in notched strip

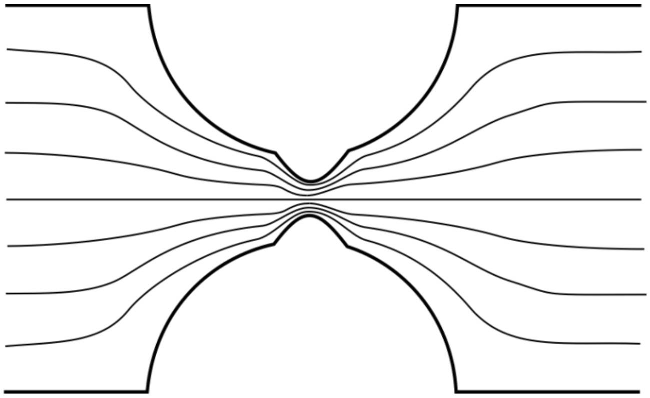


Figure 7 – Melting of notched strip

4.1.3 Fuse classifications

4.1.3.1 High-Voltage/Medium-Voltage

Before progressing further, clarification between “high-voltage” fuses and “medium-voltage” fuses should perhaps be explained. High-voltage fuses are defined as fuses rated above 1 000 V a.c. but some standards (e.g. ANSI C84.1) classify system voltages as medium-voltage or high-voltage with both being over 1 000 V. However, “medium-voltage” is classed as being below a certain value. This is 100 000V, or sometimes less depending on the standard, with high-voltage above this value. “HV fuses” are therefore used on medium-voltage and high-voltage systems but, technically, there is no recognition of “medium-voltage fuses” in IEEE and IEC fuse standards.

4.1.3.2 High and low current interruption

HV fuses perform one or both of two primary functions. The first which virtually all types of fuse are designed to perform is to respond to quite high currents, normally termed “short-circuit” currents. In this case virtually all of the load has been bypassed, and the current can be very high. Fuses vary greatly in exactly how high a current they can interrupt, and this can be a significant factor in what fuse to select for a given task. It is high-current behaviour that causes fuses to be classified as “current-limiting” or “non-current-limiting”. Because almost all commonly used non-current-limiting fuses are expulsion fuses, “expulsion fuse” is usually the term used rather than “non-current-limiting”.

The second function, is to respond to moderately excessive currents, often called “overload” currents, up to about 10 times the rated current of the fuse. However not all fuses are designed for this type of operation, some are designed only to operate at quite high currents and may arc at low currents until a second device interrupts the current, possibly resulting in physical damage to the fuse. They are therefore coordinated with a second device to interrupt low currents. The ways fuses respond to high and low currents, as well as the ways they actually interrupt the current causes them to be classified in various ways.

While all current-limiting fuses excel at high-current operation, their ability to interrupt lower currents leads to sub-classifications of “backup”, general-purpose” and “full-range”.

4.1.3.3 Class A and Class B

In IEEE standards, both CL fuses and expulsion fuses are further divided into two classes, “Class A” and “Class B” (in IEEE standards before 2016 these were called “distribution class” and “power class” respectively). The class is based on where in an electrical distribution system they are likely to be suitable for use and affects testing severity. Generally speaking, Class B fuses are applied in closer proximity to a major supplying substation than Class A and so have more severe test parameters for TRV and X/R. Class B expulsion fuses will generally be available with higher maximum interrupting currents than Class A expulsion fuses, and designs are available having higher rated maximum voltages.

4.1.3.4 Current-limiting fuse and expulsion fuse

Current-limiting (CL) describes a class of fuse characterized by their behaviour when the current is sufficiently high to cause them to melt before the first peak of a fault waveform. When a CL fuse melts in this way, the arcing process introduces resistance so rapidly into the circuit that the current stops rising and is forced quickly to zero before it would naturally do so. Because the maximum prospective current is not reached, the fuse limits the magnitude as well as the duration of the fault which is where the “current-limiting” name comes from. The action is shown in Figure 8a. The current-limiting action also produces a “spike” of voltage (the fuse peak overvoltage) into the system, and a maximum is specified by standards. However, this does help support the system, reducing the duration of a voltage dip caused by the fault just to the melting time of the fuse. The lowest current at which a fuse shows this current-limiting effect, called its “threshold current”, is usually about 20 to 30 times the fuse’s current rating.

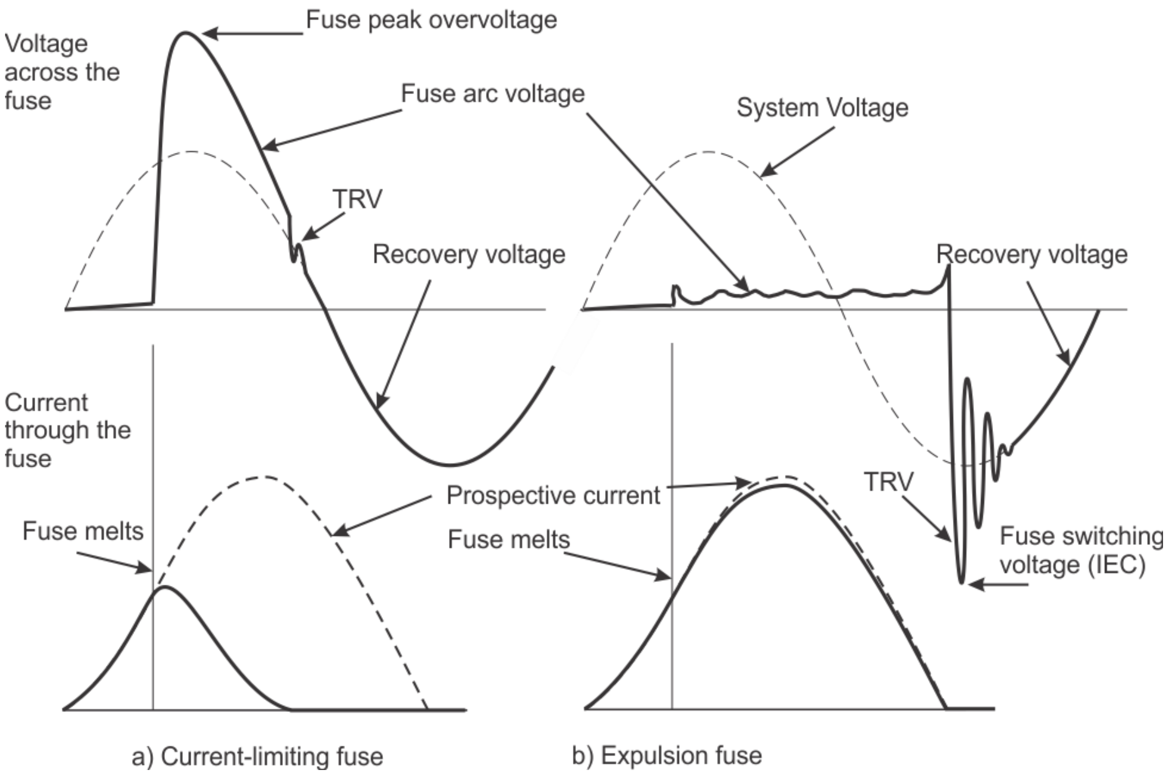


Figure 8— High current interruption by current-limiting fuse and expulsion fuse

An expulsion fuse, melting under the same circumstances as described, introduces only a small resistance into the circuit, so the current continues almost unchanged to the same peak as without the fuse. An expulsion action, that is where gas is generated by the arc and is expelled along with ionized material, produces a physical gap so that, at a natural current zero, the arc does not re-ignite and the current is interrupted. This type of fuse therefore limits the duration of a fault but not its magnitude, as shown in Figure 8b. The figure shows the effect of 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. TRV is quite significant for expulsion fuses, but less so for CL fuses.

The mechanisms that produce the characteristics described will be covered in the individual sections on current-limiting fuses and expulsion fuses.

4.1.3.5 Basic principles of fuse operation

The basic principles that apply to all types of fuses are as follows.

a) In its passive or current carrying mode a fuse must be able to carry load current and permissible cyclic or transient currents without deterioration. The standards limit temperature rises.
b) In its active, or fault-interrupting mode, more heat is generated than can be dissipated and the element melts. The relationship between a particular constant current and the minimum time required to melt the fuse is published in the form of a time-current

characteristic curve (TCC curve). Upon melting a current interrupting process occurs that depends on the type of fuse, and a maximum clearing time-current characteristic curve is also published.

c) After interruption, a fuse must be capable of withstanding normal circuit voltage. Some fuses drop open to form a visible and physical "gap".

4.1.3.6 Terminology

Current-limiting fuses are often called "cartridge fuses" as they are usually cylindrical in shape and contain the fuse element surrounded by an arc absorbing filler, usually quartz sand. They have also been called "silver-sand" fuses as elements were traditionally made from silver, although other element materials are now also common

In the case of expulsion fuses, the construction and interrupting mechanisms differ between Class A and Class B fuses (unlike CL fuses). Most Class A fuses are of a type called "fuse cutouts" (formerly "distribution fuse cutouts") characterized by a "cutout fuse support" that uses an insulator or insulators having a single point mounting bracket. Class B fuses, formerly termed "Power Fuses" (and still widely known this way) or "boric acid fuses", have a more elaborate fuse unit than that of a fuse cutout.

4.1.3.7 Advantages of fuses

a) Non-mechanical so faster at higher currents
b) Minimizes voltage dips
c) Non-resettable encourages correction of fault
d) No or few moving parts to degrade
e) Fuse replacement restores protection to 100%
f) Most economical for high degree of system protection
g) Many types available.

4.1.3.8 For current-limiting fuses in addition

a) Current limitation reduces energy let-through
b) Very high maximum interrupting current
c) Silent operation, no gas emission
d) Compact size and lower comparable cost than other forms of protection
e) Allows smaller cables due to reduced short-circuit stresses
f) Reduced I^2t equals reduced thermal stress on circuit components
g) Reduced electro-dynamic forces from peak current-limitation
h) Fuse has specific maximum clearing I^2t for easier coordination to minimize an outage

4.1.3.9 Types of HV fuse

The guide goes into detail concerning Current-limiting fuses, Expulsion fuses, other related protective devices, and fuse supports. The guide makes the important observation that its intention is not to suggest 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

While there are many types of CL fuse, their general characteristic is that they are non-vented devices with the ability to limit the prospective current before its first peak value is reached, if the current is sufficiently high. Unlike expulsion fuses, the basic construction and operating principles between Class A and Class B fuses are usually similar. This is because the primary operating conditions that differentiate the two classes (*X*/*R*, TRV, and maximum interrupting current) are all of much less importance to current-limiting fuse operation. Construction and operation differences are therefore primarily related to their ability (or lack of ability) to interrupt lower currents, which determines their class.

4.2.2 Construction

Figure 9 shows the construction of a typical backup fuse having “DIN” dimensions (a European style fuse) and many features are common to other CL fuses. Fuses intended for outdoor use, or submerged in an insulating liquid will have special attention paid to sealing. 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. The fuse elements are made of a very conductive metal, usually silver or copper, but aluminum has been used extensively as well as a few other metals. They 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". Element design is critical; its length 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. Figure 9 shows a striker, and while that are seldom used in North American practice, they are commonly used in European practice to trip a series connected switch to interrupt low currents. Thermally operated strikers are also available to trip the switch before the fuse actually melts. By using a backup fuse and striker together with a switch, “full-range” current interruption is possible (i.e. from overload to short-circuit).

Full-range performance is also available from some types of CL fuse and one such is shown in Figure 10. This is of the “dual-element” type and pairs a “backup” type element for high currents with an “expulsion” type element for low currents in series. The expulsion section includes a low melting point material, and special testing is specified to show that the two sections working separately or together can interrupt all currents that cause the fuse to melt. Figure 11 shows a current-limiting fuse mounted in a typical traditional fuse support. Figure 12 shows a cutaway drawing of a full-range current-limiting fuse mounted under liquid in a “dry-well” canister.

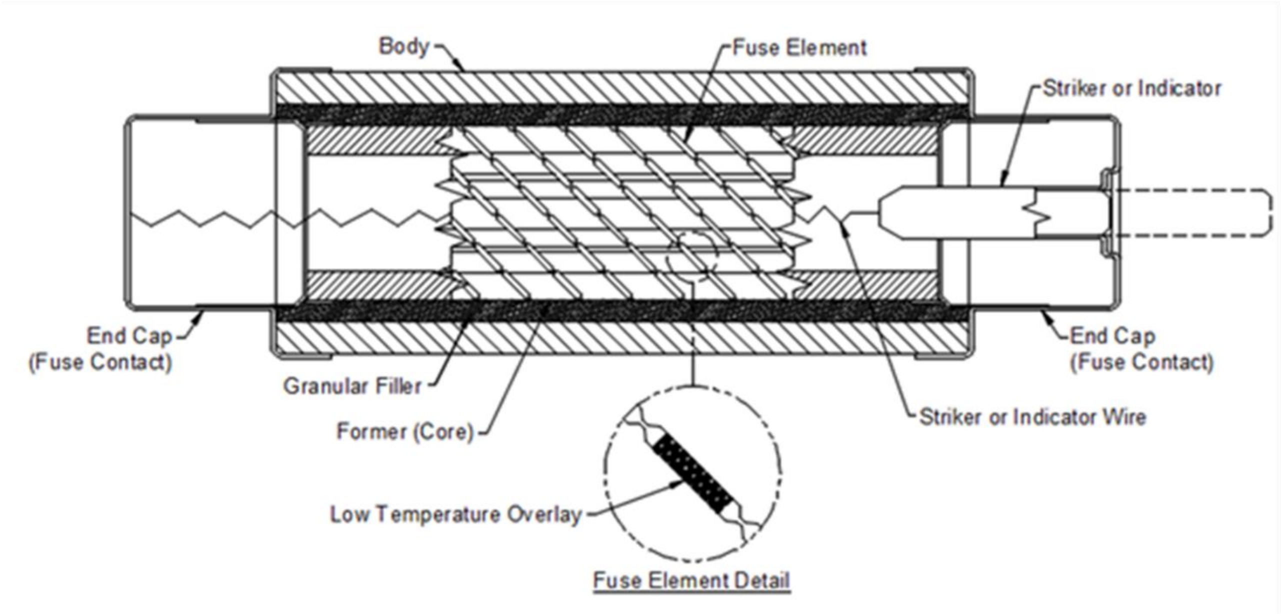


Figure 9 – Construction of typical backup fuse

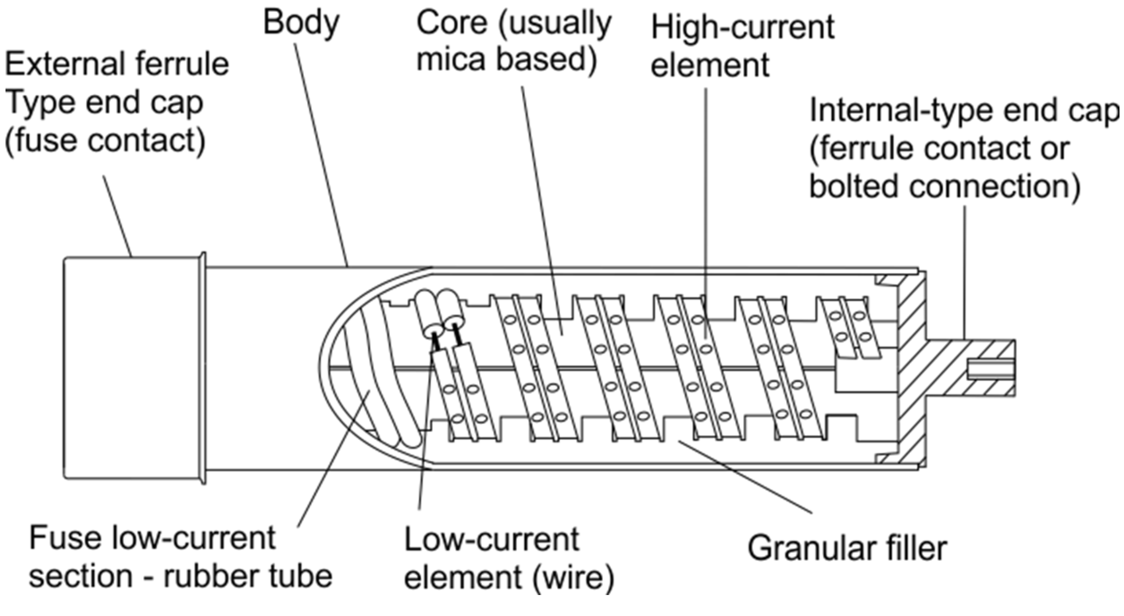


Figure 10 – Construction of a typical full-range fuse

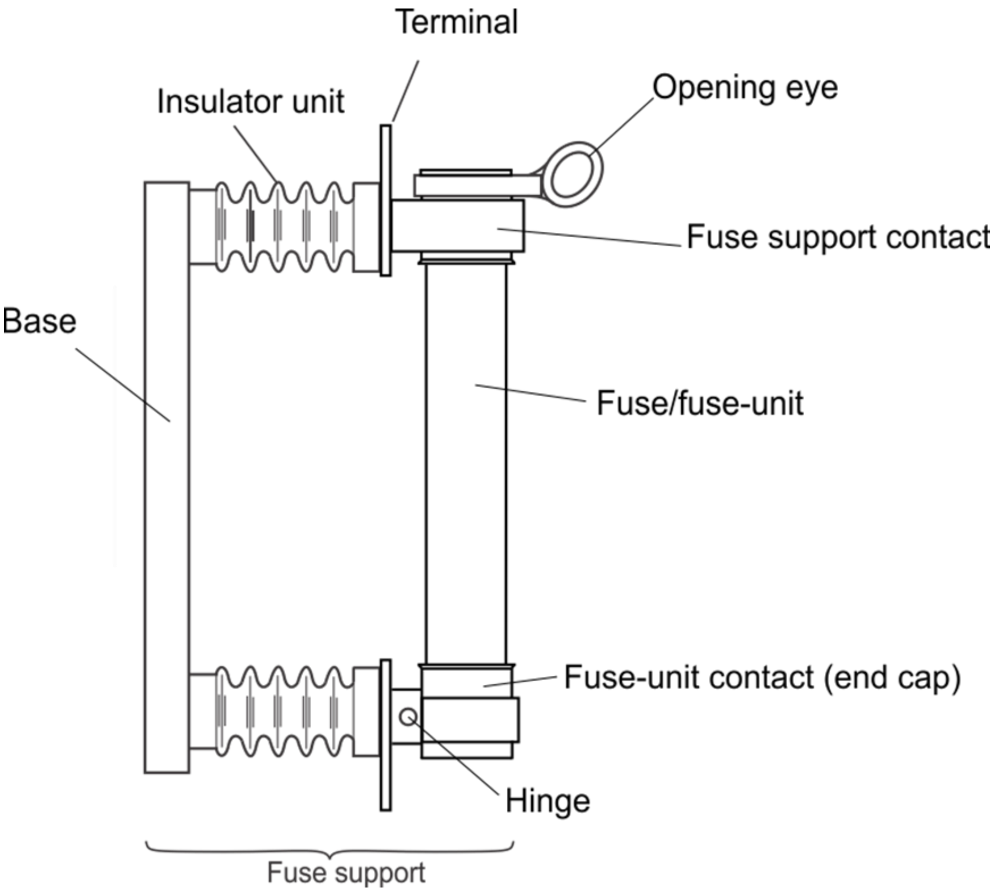


Figure 11 – Traditional fuse support

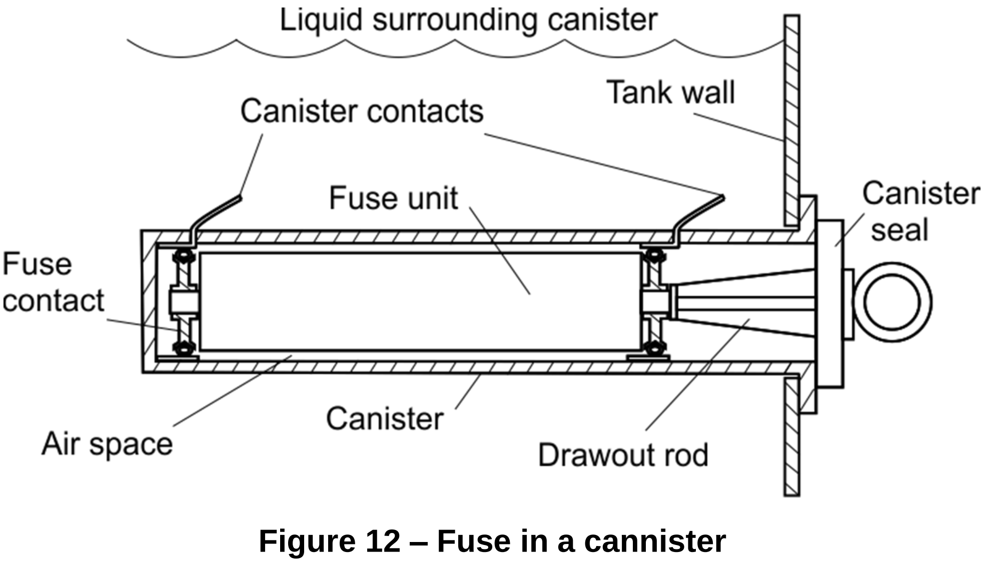


Figure 12 – Fuse in a cannister

4.2.3 Operation under high-fault current conditions

A current-limiting fuse introduces significant resistance into the circuit by having a long element with multiple pre-determined places where melting is initiated (Figure 6). At high currents all the restrictions melt simultaneously producing a controlled number of arcs. With continued current flow, the arcs elongate increasing the resistance and arc voltage. Eventually the arcs merge but by that time the current is low and close to zero. The combination of melted sand and element material is called “fulgurite” and is an insulator. Figure 13 shows a “before and after” shot. It is of a full-range fuse but a backup fuse looks like the left-hand side.

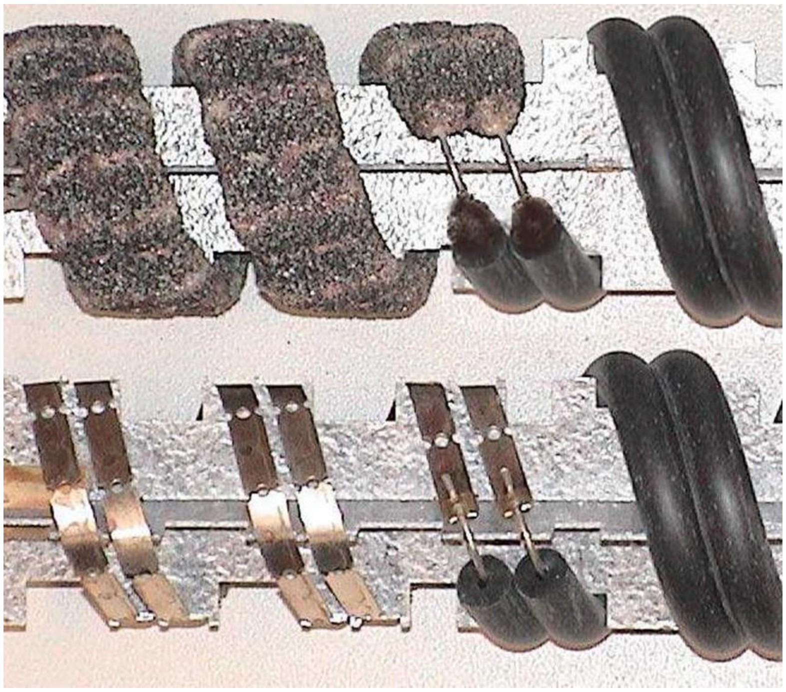


Figure 13 – Fulgurite formation due to high current interruption.

If the fuse were to try and interrupt against a slightly higher voltage than that seen in the illustration, the fulgurite would be much larger. A modest increase in fulgurite size can lead to failure (breakdown between the turns for example) so a CL fuse should never be called upon to interrupt a voltage higher than its rated maximum voltage (this is true also for low currents, for different reasons).

4.2.4 Additional CL 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. There are some primarily designed to provide a current-limiting action at high currents and they have a limited low current interrupting ability. They are termed “backup” fuses and are usually used in conjunction with another device in series. In North America this is usually an expulsion fuse, although in Europe a series switch is more common (normally tripped by a striker in a "switch-fuse combination"). Alternatives include contactors and circuit breakers. It may be considered that they are "backing up" this other device and in addition to the important current-limiting function, they also 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 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 will cause them to melt in times of up to one hour, but no longer. When the term “general-purpose” was first used, fuses often used wire elements, and the melting TCC became asymptotic to the time axis around one hour, so this was a convenient time to demonstrate that the fuse could clear almost any current that causes it to melt. With the introduction of ribbon elements, this was no longer true, longer melting times became possible at significantly lower currents than the “one-hour” melting current. Also, the use of fuses in high ambient temperatures in enclosures further reduced the current that could cause the fuse to melt at long times. The term “full-range” is used for the Class of fuse designed to clear these lower values of fault/overload current; in fact, any continuous current that causes the fuse element to melt must be interrupted by such a fuse. Because full-range fuses are often used in enclosures, sometimes with the enclosure at elevated temperatures test methods reflect that significantly lower melting currents than a “one-hour” current are possible.

4.2.4 Operation under low-fault current conditions

4.2.4.1 General

As current increases above the rated current of the fuse, the elements reach their melting temperature over seconds, minutes or (for full-range fuses) hours. Since typical element materials of silver and copper melt around 1 000 °C, if the melting time is too long and if the whole fuse were to reach a high temperature, damage to the fuse and its surroundings would result. Various means are therefore used to alleviate this problem. Some designs use a spot of low melting point material on the element, and when its melting temperature is reached an “M effect” occurs in which the base element material diffuses into the molten M-spot. Other techniques include the incorporation of a low melting point section in series with the element, elongated restrictions, and thermal insulation of part of the element. The object, again, is to ensure that fuse element melting occurs without the strip as a whole having to reach an excessively high temperature. An alternative approach uses a thermally activated striker to trip a series switch as previously explained (4.2.2).

The lowest current that a current-limiting fuse has to be shown to be capable of interrupting (IEEE Std C37.41) is termed its I_3 or Test Series 3 current, and its value depends on the rated current of the fuse and its class.

When a fuse has more than one parallel element, they do not melt and arc simultaneously at lower currents like they do at high currents, but rather each element melts at one place until the last element melts.

4.2.4.2 Backup fuses

Backup fuses have a minimum current below which they cannot interrupt. Why is this? For typical backup fuses using plain notched strip elements, if the system voltage is more than a few thousand volts, more than one series arc is needed to interrupt relatively low currents (about 3 to10 times rated current). Consider a single element. At high currents all the restrictions melt simultaneously. At very low currents, only one restriction will melt and the fuse cannot interrupt. However, at an intermediate current where the current density is sufficient, enough restrictions will melt simultaneously to enable interruption to occur. This current would be the Rated minimum interrupting current for the fuse. In the case of a multi element fuse, if the current density in the last element to melt is sufficiently high to achieve multiple series melting, the arcing can cause another parallel fuse element to re-strike and create multiple series arcs that, in turn, are extinguished when another element re-strikes. This process continues until all fuse elements have arced sufficiently to be able to withstand recovery voltage (including any TRV present). This is the principle used with most backup fuses. Below its “rated minimum interrupting current” satisfactory circuit clearance cannot be assured. Such fuses may only have a minimum interrupting current corresponding to a melting time of a few seconds or less, and they are intended to be used in conjunction with another device that interrupts currents below their minimum I/C. Every backup fuse design and rating will have its own minimum interrupting rating based on the number and thickness of the elements as well as element design. The minimum I/C is required to be marked on the fuse (see Figure 1).

4.2.4.3 General-purpose and full-range fuses

Current-limiting fuse designs exist that are capable of interrupting currents that take a long time to melt the fuse. They are termed general-purpose or full-range fuses (see 4.2.4 "Additional CL fuse classifications"). In one version, an improved very low minimum interrupting current capability is obtained by use of a large number of parallel fuse elements, each of small cross-section so that each fuse element when arcing on its own, has a high enough current density to break up into full multiple arcing and clear the fault current. In other cases, gas-evolving materials are used to increase the effectiveness of series arcs and improve low current interrupting ability. Manipulation of the length of a limited number of restrictions is another technique as is insulating portions of the element. In another popular version, each current-limiting fuse element is connected in series with a fuse element working on the expulsion principle (see Figure 10 and Figure 13). In this arrangement, the expulsion fuse elements handle any low-level faults. For higher fault levels, the current-limiting fuse elements take over to clear the short-circuit fault current. Fuses using this principle (sometimes called "dual-element" fuses) will have been tested using special tests, I_t, specified in IEEE Std C37.41. This checks operation in the cross-over region from the current-limiting fuse element to the low-current fuse element. General-purpose and full-range fuses can usually be employed as sole protection for all fault levels without the need of associated equipment to handle the lower fault currents.

Figure 14 illustrates the current ranges over which the different classifications of fuse are intended to be used, and for which they are tested. In the Figure, I_{ACC} represents the maximum continuous current permitted by the application and the fuse will have been chosen to be able to carry this current, indefinitely.

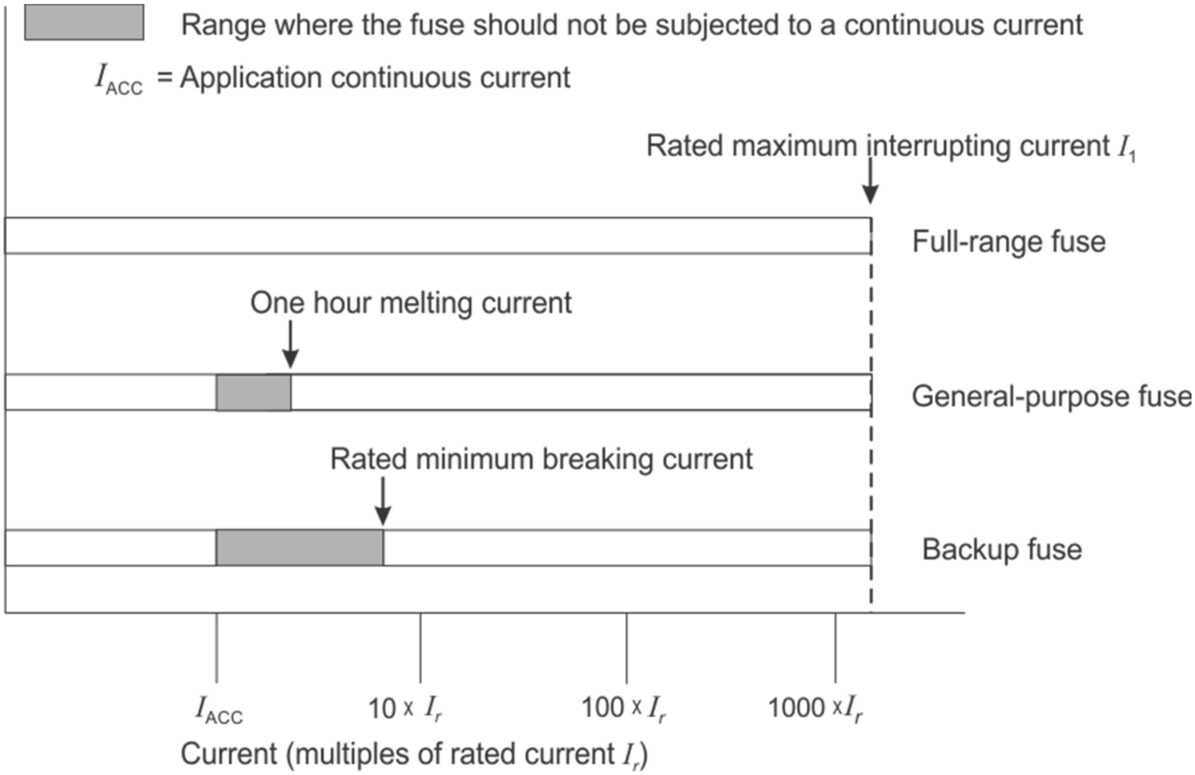


Figure 14 – Operation ranges for different CL fuse types

4.3 Expulsion fuses.

4.3.1 General

While there are many types of expulsion fuse, their primary characteristic is that they are vented devices in which, after their fuse element melts and arcs, the expulsion effect of the gases produced by the interaction of the arc with other parts of the fuse results in the current interruption in the circuit. Another common characteristic is that they are essentially non-current-limiting, having a low arc voltage. They extinguish current at a natural current zero so that anything that increases the magnitude of the first major loop of an asymmetrical fault current makes interruption harder. They are therefore very sensitive to fault current magnitude, system *X*/*R*, and degree of asymmetry. Because current is extinguished at a natural current zero, they are also very sensitive to TRV. While expulsion fuses are not significantly affected by system voltage during arcing, it has a significant effect on recovery voltage so like CL fuses should never be used at a voltage higher than their rated voltage.

Because of their typical applications, expulsion and other types of non-current-limiting fuses have been designed to interrupt any current from the overload current at which the fuse element melts up to their maximum fault rating.

In common with all fuses, expulsion fuse elements have a defined melting characteristic. However, because their fuse elements are relatively short, and the interrupting process relatively independent of the fuse element size and construction, it is possible for a single expulsion fuse to be available with many different melting time-current characteristics. Thus, for example, a fuse cutout may accept, and be compatible with, a number of fuse links that have different curve shapes but the same current rating.

Because all of the features that make Class A and Class B different significantly affect the performance of expulsion fuses, the construction and operation of Class A fuses and Class B fuses tends to be different and so are treated separately in the guide.

4.3.2 Construction and operation

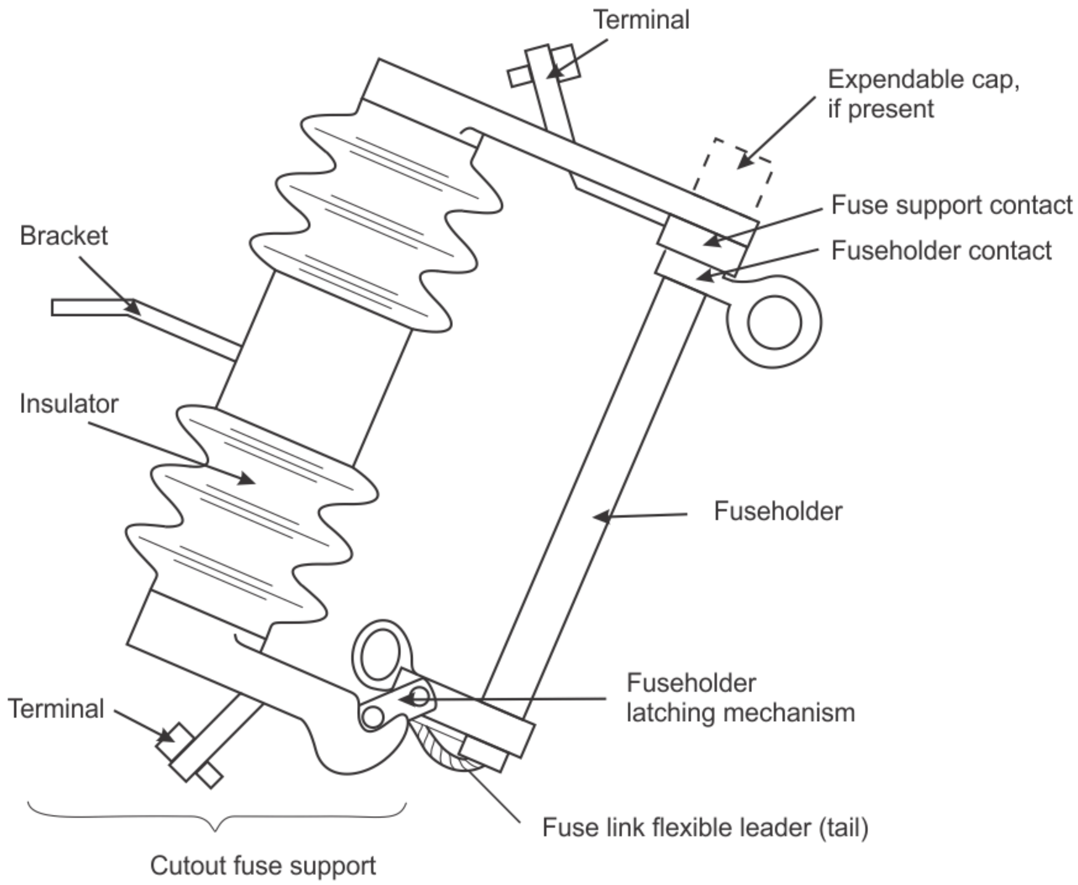
4.3.2.1 Class “A” expulsion fuses

4.3.2.1.1 Fuse cutouts

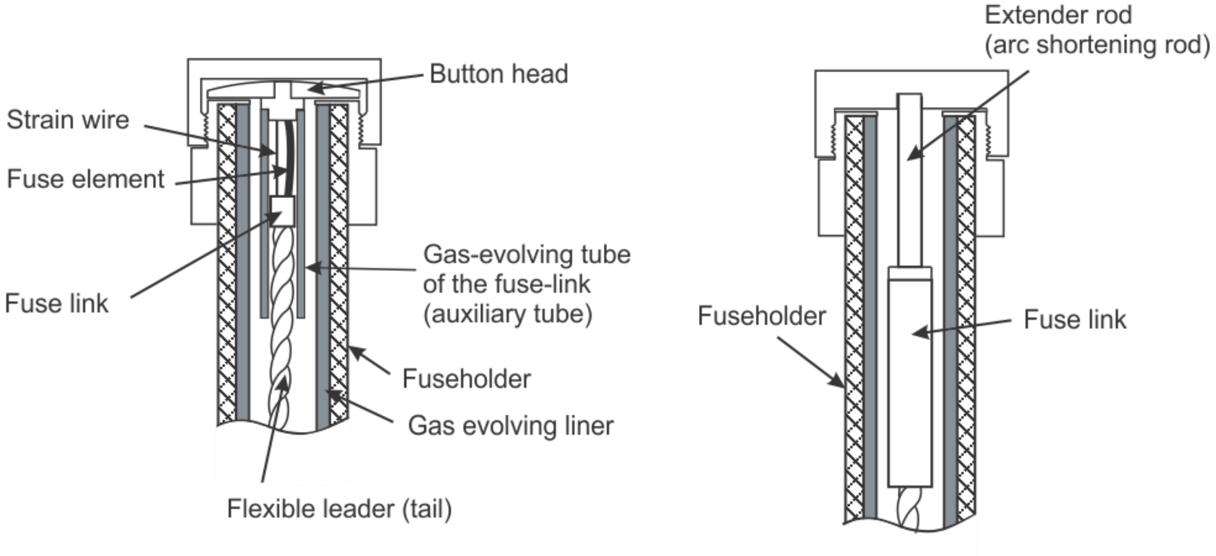
The most common type of "Class A" expulsion fuses are open fuse cutouts normally just termed fuse cutouts (and previously called “distribution fuse cutouts”). Figure 15A shows the components of a typical fuse cutout. The normal fuse support used with cutouts, and consequently called a “cutout fuse support”, consists of an insulator (traditionally ceramic but increasingly made from polymer material) with a bracket in its middle. Two separate insulators mounted to a central bracket are also used. The pivoted fuseholder includes a tube lined with gas-evolving material, which contains the fuse element, typically mounted in a replaceable fuse link.

Figure 15B) shows a typical fuse link construction, mounted in a fuseholder, in which a small gas-evolving tube (also termed arc quenching tube or auxiliary tube) surrounds the fuse element. This tube handles interruption at low currents while at high currents the auxiliary tube bursts and the main tube supplies the expulsion products. The fuse element in this type of fuse is normally quite short (e.g. 30 mm) and is attached to a contact at the top of the fuse link, and a flexible cable ("tail" or "leader") at the bottom attached to a contact, holding in place a latching mechanism that releases when the fuse element melts, enabling the fuseholder to swing open after current interruption. This provides an isolating distance (making it a “dropout” fuse) and also visual indication of fuse operation. The current rating and melting characteristics of the fuse are governed mainly by the design of the replaceable link.

Expulsion fuses, under some conditions, expel solid materials at high velocities upon fault current interruption. This should be considered in the mounting location of the device.



15A - Open fuse cutout components



15B - Typical fuse link arrangement

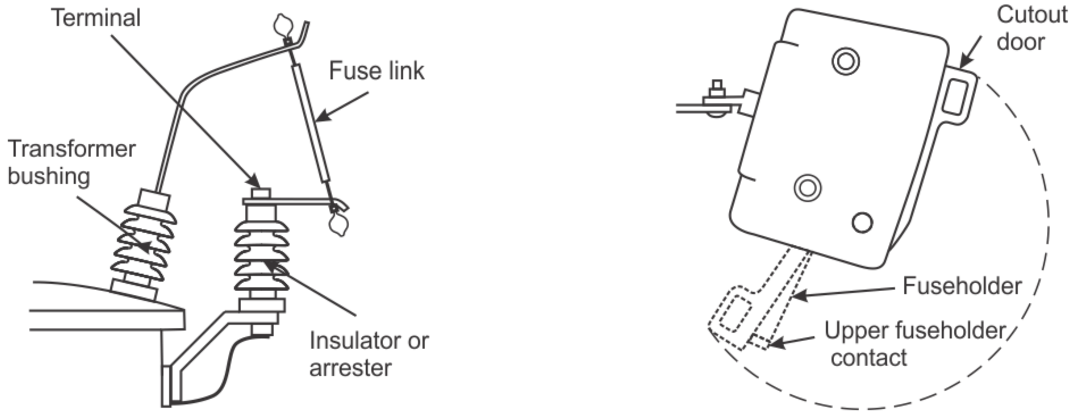
15C - Fuseholder with extender rod

Figure 15—Fuse cutout construction

Techniques to increase the maximum interrupting current of the fuse includes expendable caps (making the fuse "double vented") and an extender rod to reduce the arc length and pressure (Figure 15C).

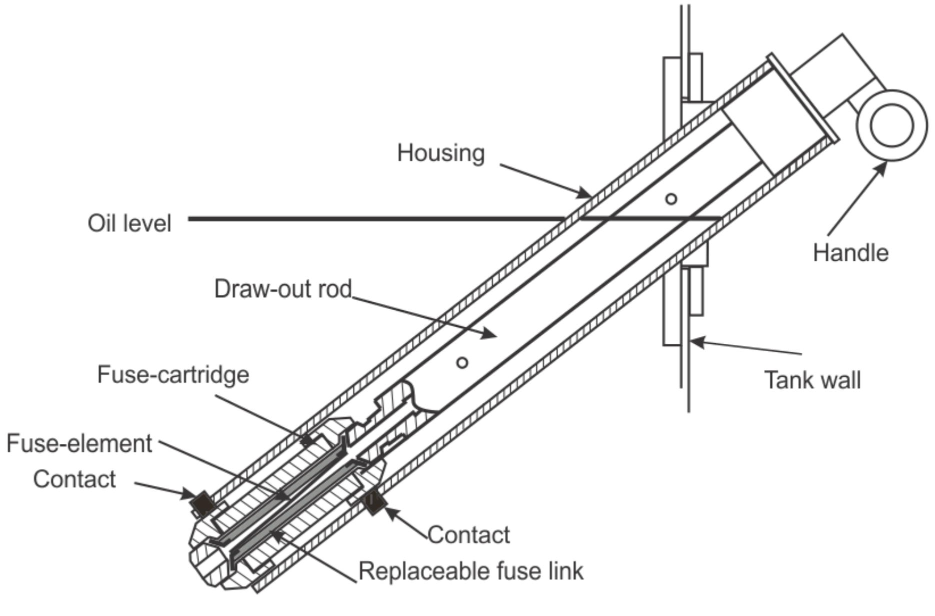
4.3.2.1.2 Open-link cutouts

Open-link cutouts (Figure 16A) suspend an open-link fuse link in air with no fuseholder. They work much as a fuse cutout but with reduced interrupting capability. They are often used with a backup current-limiting fuse.



16A - Typical open-link cutout arrangement

16B - Typical enclosed fuse cutout



16C - Typical "bayonet fuse" assembly

Figure 16—Types of expulsion fuse

4.3.2.1.3 Enclosed fuse cutouts

An enclosed cutout (see Figure 16B) is similar to an “open” fuse cutout, but has all of the live parts enclosed in a housing (usually made of porcelain). A hinged "door" supports the fuseholder. They may be of a drop out design but commonly are not, this feature often being selectable by the user. They operate in a similar manner to fuse cutouts described in 4.3.2.1.1.

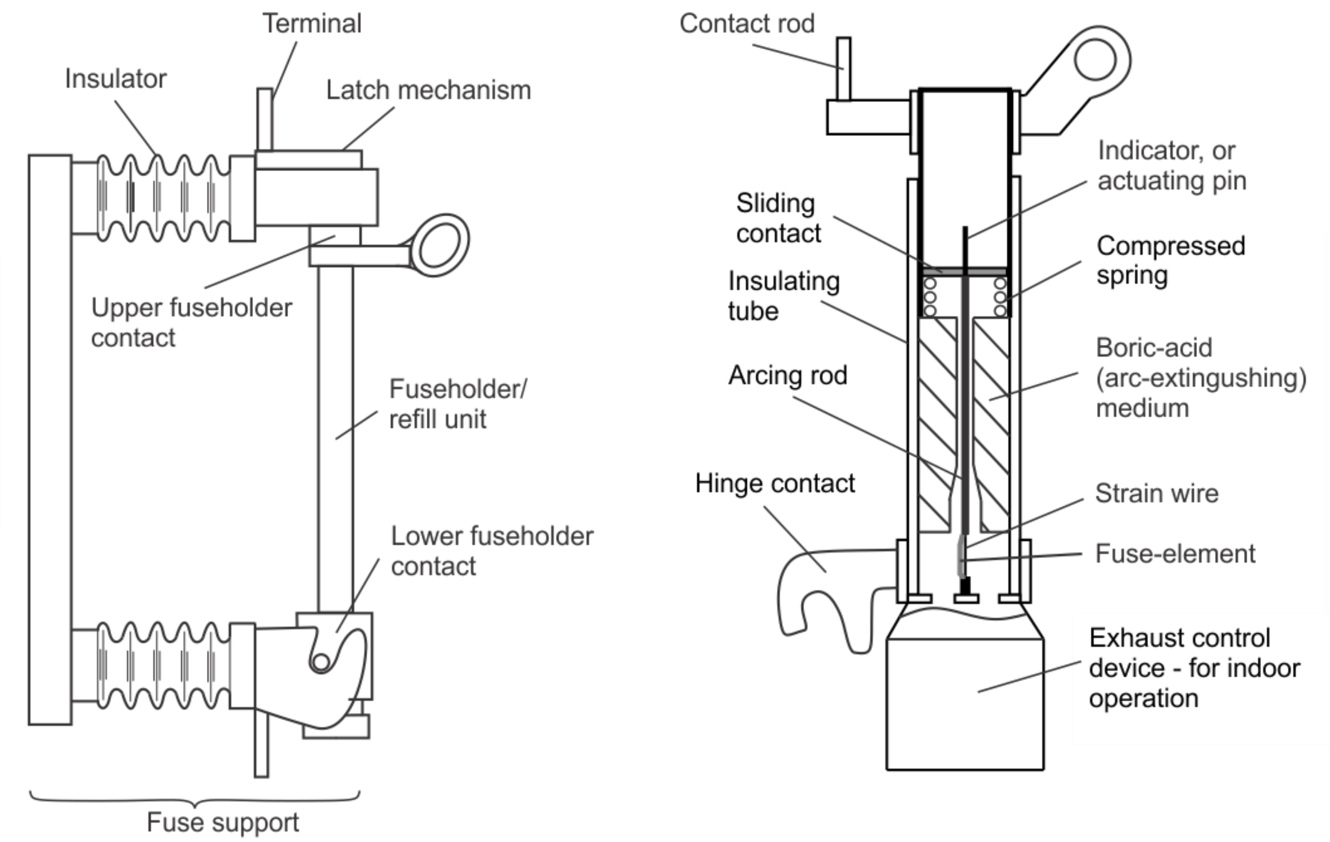
4.3.2.1.5 Liquid-submerged expulsion fuses

These are expulsion fuses in which arc extinction is effected by having the melting fuse elements immersed in an arc quenching liquid. They employ a strong, small diameter, tube with a fuse element suspended between terminals at each end. They operate on a similar principle to fuse cutouts (described in 4.3.2.1.1), except that insulating liquid (usually oil) is used as the dielectric medium. After the fuse element melts, the resulting arc heats, vaporizes, and dissociates the liquid. At higher currents, the fuse tube wall also supplies gas to facilitate the interruption process. They have a very limited maximum interrupting current. A common variant of this type of fuse positions the fuse in a fuseholder at the end of a draw-out rod, suspended in a supporting housing containing electrical contacts, as shown in Figure 16C. After operation the fuseholder can be withdrawn from the liquid, and the fuse link replaced. This type of fuse is commonly known as a "bayonet fuse".

4.3.2.2 Class “B” expulsion fuses

The most common type, shown in Figure 17A, are expulsion fuses in which arc interruption is effected by use of a boric acid liner to the fuseholder tube. This gives them a higher interrupting capability, under more onerous circuit conditions, than Class A expulsion fuses. They have a more complex internal structure than cutouts, see Figure 17B, that includes a main bore for high-current interruption and, in some designs (not shown), a smaller, parallel, bore for low current interruption. They have a rather short fuse element with parallel strain wire connected to an arcing rod attached to a compressed spring. When the fuse element and strain wire melts, the arcing rod draws the arc through the boric acid block. This increases the arc length and length of boric acid exposed to the arc. Gasses produced by the arc are primarily water vapor, which cools the arc and produces a deionizing effect. Some power-class expulsion fuses can be provided with an exhaust-control device to condense the water vapor and virtually eliminate the effect of these gases allowing their use indoors and in enclosures.

Boric-acid fuses typically use a replaceable refill unit, which contains the fuse element and associated parts necessary to restore a fuse to its original condition after an operation. Class B fuses can be drop out fuses, like fuse cutouts, or remain in the fuse clips after operation like most current-limiting fuses.



17A - Typical Class"B" expulsion fuse

17B - Cutaway of typical boric acid power fuse

Figure 17—Class B expulsion fuse

4.3.2.3 Application considerations

Fuse cutouts, or other types of fuses fitted with removable fuseholders have no inherent load-break ability when manually opened unless fitted with a load-break means.

4.3.4 Ratings of expulsion fuses

Rated frequency: Standardized values of rated frequency are 50 Hz, 50/60 Hz and 60 Hz. Expulsion fuses are suitable for use at higher frequencies than they are rated, but not lower frequencies. This is because expulsion fuses are sensitive to the I^2t flowing before a current zero is reached. The I^2t of the first loop of a fully asymmetrical current waveform, having the same r.m.s. symmetrical current value, is 20 % higher for 50 Hz than for 60 Hz.

4.4 Other related protective devices

4.4.1 General

While all fuses can, in theory, be tested to IEEE or IEC standards, there are devices that are fuse-like or fuse-related but are not recognized in standards. In fact, it is believed that several of devices referred to in 4.4 are no longer being manufactured. They are mentioned because they may still be in service (and may require replacement by more modern devices).

4.4.2 Electronically activated devices

4.4.2.1 Fuses and fuse-like devices

One type is referred to as a commutating current-limiter, triggered current-limiter or electronically activated fuse. Under normal circumstances the current is carried through a very low impedance path, allowing higher currents ratings than is possible with a conventional fuse. A schematic of this type of fuse is shown in Figure 18. Upon occurrence of a fault, this main current path is opened (for example by a pyrotechnic charge) and the fault current is commutated to a parallel traditional current-limiting fuse, before the first peak. The shunt fuse interrupts the circuit. These devices typically employ electronic sensing to initiate a means of achieving high-speed switching of the main conductor. The electronics may also be used to selectively initiate interruption in a non-current-limiting fashion. Compared to conventional fuses, such devices are relatively complex and expensive, but have applications where very large current ratings are required along with some degree of current limitation.

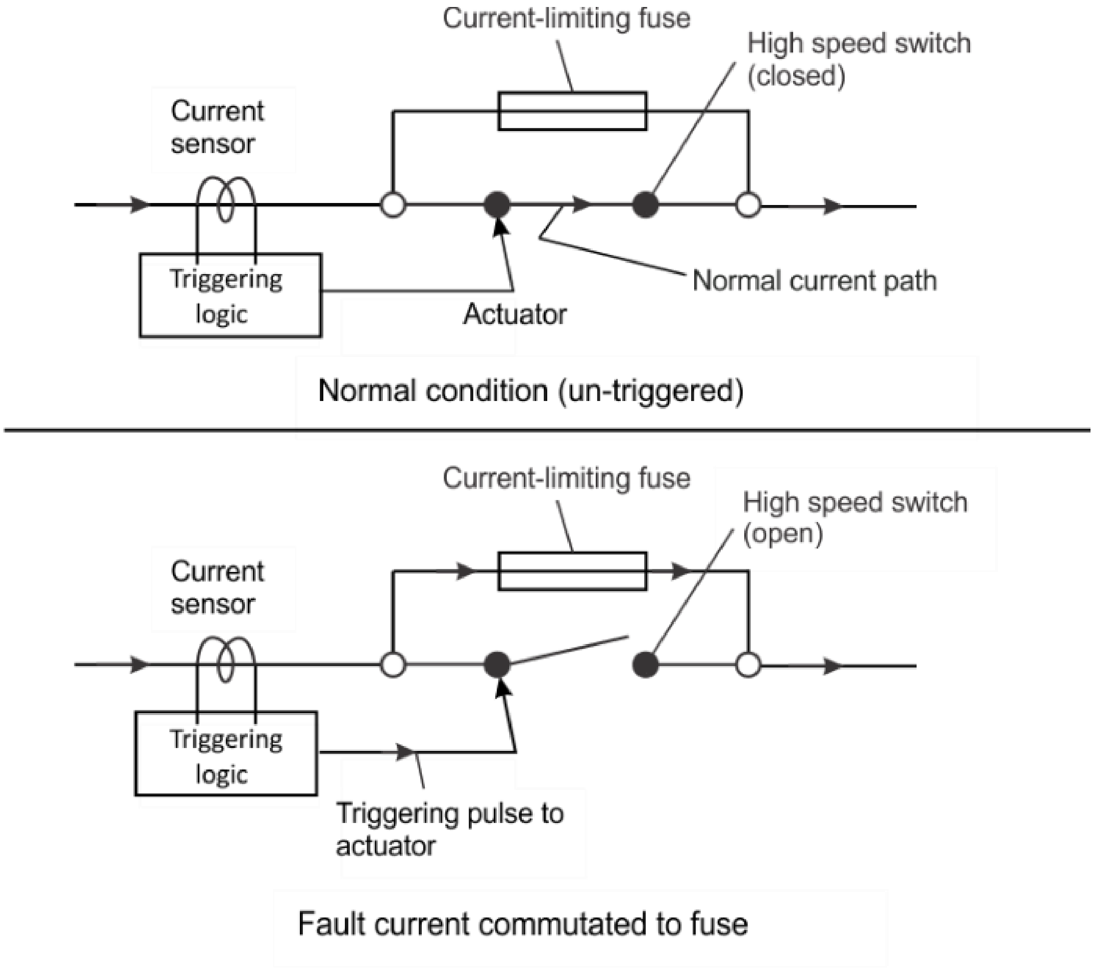


Figure 18—Schematic of a commutating type of current-limiter

4.4.3 Additional types of non-current-limiting fuses

4.4.3.1 Horn gap fuses

Horn gap fuses are very simple devices in which two curved or angled metal strips are mounted on insulators and connected by a fuse wire (fuse element). The wire may be open to the air, or be enclosed in a glass tube for environmental protection. Each strip is connected to the circuit so that under overload conditions the fuse element melts and produces an arc. The natural interaction of the arc and the magnetic field produced by the current propels the arc up the "horns", elongating the arc (Jacob's ladder). When the arc is long enough, it is extinguished at a natural current zero. Since quite long high-current arcs are relatively stable, these devices have a very low maximum interrupting current. Although not generally tested to IEC or IEEE standards, they are widely used in developing countries because of their low cost.

4.4.3.2 SF_6 fuses

SF6 fuses employ a tube filled with sulfur hexafluoride gas dielectric, and axial contacts joined by the fuse element. SF6 fuses have circuit interrupting capabilities similar to those of expulsion fuses. It is believed that this type of fuse is no longer being manufactured.

4.4.3.3 Vacuum fuses

Vacuum fuses typically have a very short fusible element attached to two opposing arc rotating plates that are mounted inside of a vacuum bottle. Vacuum fuses have circuit interrupting capabilities similar to those of expulsion fuses. It is believed that this type of fuse is no longer being manufactured.

4.4.3.4 Distribution oil cutouts

Distribution oil fuse cutouts are devices that operate in a manner similar to liquid-submerged expulsion fuses. The oil fuse cutout typically contains a fuse carrier (tube) mounted on a rotating structure with contacts on each end, so that it may be used as a load interrupting switch as well as a protective device. The contacts, fuse carrier, and fuse element are under oil in a vessel capable of withstanding very substantial pressures. It should be noted that these devices, while still possibly in service, are considered obsolete in some areas. While formerly recognized in IEEE standards, for example, references to testing these devices have been eliminated from current standards.

4.5 Fuse supports

A fuse support, includes all of the parts required to hold a replaceable fuse, fuse unit or fuseholder together with insulators and terminals. The fuse support provides the dielectric properties of a fuse. It should be noted that some types of fuse are supplied for mounting by the user, as for example some liquid-submerged expulsion and current-limiting fuses and some external current-limiting fuses mounted on bushings, fuse cutouts, or attached directly to overhead distribution conductors. The insulation properties of fuses are based on those of the fuse support so when only the fuse is provided, because a fuse has no inherent dielectric properties, the manufacturer can perform no dielectric testing of a fuse/fuse unit alone.

5 Application of fuses

5.1 General

Now it would take me a long time to do justice to the application section I intend to just pick out a few isolated issues, together with an example of fuse-to-fuse coordination.

5.2 Current rating of a fuse

A fuse's rated current is the nameplate value; it is based on a current the fuse can carry continuously without deterioration and without exceeding maximum contact temperature rises specified in IEEE Std C37.41, and in an ambient temperature of up to 40 °C (in IEEE ambient temperature is the temperature of the fluid surrounding, and cooling, a fuse). Because the fuse must not suffer deterioration at rated current, in practice the maximum temperatures could be less than specified, as it may be the element temperature that is critical, particularly with lower current rating CL fuses and full-range current-limiting fuses. Temperature surrounding the fuse may be more than 40 °C, and this is usually when the fuse is in an enclosure. The combination of fuse and enclosure is called a "fuse enclosure package" or FEP. In the case of an FEP, the performance characteristics of the total system should be evaluated. The fuse, or FEP, will be assigned a rated maximum application temperature (RMAT), the highest ambient temperature for which it is suitable for use. The manufacturer will supply information concerning the acceptable current-carrying capability in an enclosure. The rated current of the fuse does not change (it is the number stamped on the fuse) but instead a fuse is assigned an "allowable continuous current". This is the current that a fuse can carry continuously, at a particular ambient temperature, without deterioration, and without exceeding the temperatures specified in IEEE Std C37.41.

If a current-limiting fuse is used in a canister (close fitting container) the relevant ambient temperature is that of the fluid outside the container, while if a fuse is in a vault it is the temperature of the air in the vault.

Current-limiting fuses intended for use under oil or other liquids have to be specially designed and tested for this application. Liquid tightness testing for transformer applications are included in C37.41, with the tests at the fuse's RMAT. It should be noted that the RMAT may be chosen to cover, for example, transformer overload conditions, and a fuse may not be suitable for continuous operation at its RMAT.

Fuses in an enclosure may experience a shift in their time-current characteristics (characteristics used for fuse-to-fuse or fuse-to-device coordination). The effect depends on the fuse construction. Elements that melt at a relatively low temperature will experience a more significant shift (to the left, or to lower current) than a high melting temperature element. The FEP manufacturer should provide information on any shift to the TCC based on the enclosure itself, and for the temperature of the fluid surrounding the enclosure.

The general rule of thumb coordination factor, that the maximum clearing time of the load side device should not exceed 75% of the minimum melt time of the source side device generally provides sufficient allowance for TCC shift in the 0.01 s to 1 000 s region. However, for general-purpose and full-range fuses, this rule may be insufficient for times longer than 1 000 s.

5.3 Coordination between fuses and fuses and other protective devices

The primary aim of coordination is to isolate faults and keep as much load connected as possible. In general, therefore, one wants the "down-stream" device to operate leaving the "up-stream" device intact and undamaged. Figure 19 explains these terms.

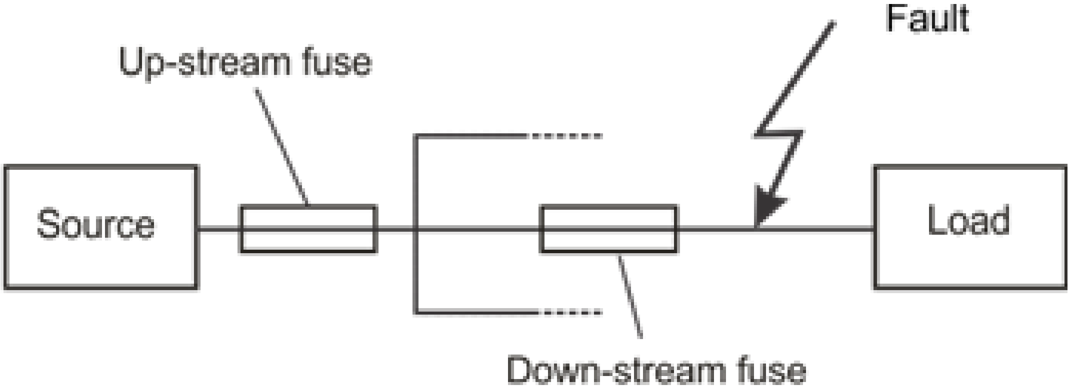


Figure 19 – Description of the terms "up-stream" and "down-stream" fuses

The fuse characteristics that are primarily used for coordination purposes are time-current-characteristic (TCC) curves (minimum melting and maximum clearing) and I^2t characteristics. The primary method is to compare TCC curves for the minimum melting (pre-arcing) of the upstream fuse to the maximum clearing (operating) characteristics of the downstream (smaller) fuse. Both curves take into account variations resulting from manufacturing tolerances and represent performance under specific conditions. If nominal curves are published, they must be shifted to take account of the manufacturer's tolerances.

Generally speaking, curves are used for times greater than 0.01 s, the lower limit that curves are normally plotted to, while I^2t is used for shorter times. At high currents and very short melting times, the clearing I^2t of current-limiting fuses tends to a minimum value (the fuse's maximum clearing I^2t) that is published, and may be used in determining coordination with other devices.

For non-current limiting fuses, clearing at high currents cannot occur until a current zero, so cleating curves for such devices are horizontal at a time corresponding to the duration of one loop (the clearing I^2t of an expulsion fuse therefor rises with rising fault current, so is not normally used for any purpose). As a result, the clearing curve of a non-current-limiting fuse will always cross the minimum melting curve of any larger fuse when these devices are compared for coordination purposes. Coordination is thus only possible if the available fault current is less than the value at which they cross.

5.4 A coordination example: Current-limiting fuse to current-limiting fuse

The down-stream fuse must clear the maximum fault current at its location before the upstream fuse is damaged. To prevent damage to the up-stream fuse, the clearing time of the down-stream fuse should be less than 75 % of the minimum melting time of the upstream fuse for all current up to the maximum prospective current where the downstream fuse is located. In the case of I^2t coordination, the maximum clearing I^2t of the down-stream fuse should be less than 75% of the minimum melting I^2t of the upstream fuse.

Looking at a practical example shown in Figure 20 where a 125A full-range current-limiting fuse is to coordinate with a 65A general-purpose fuse at location A.

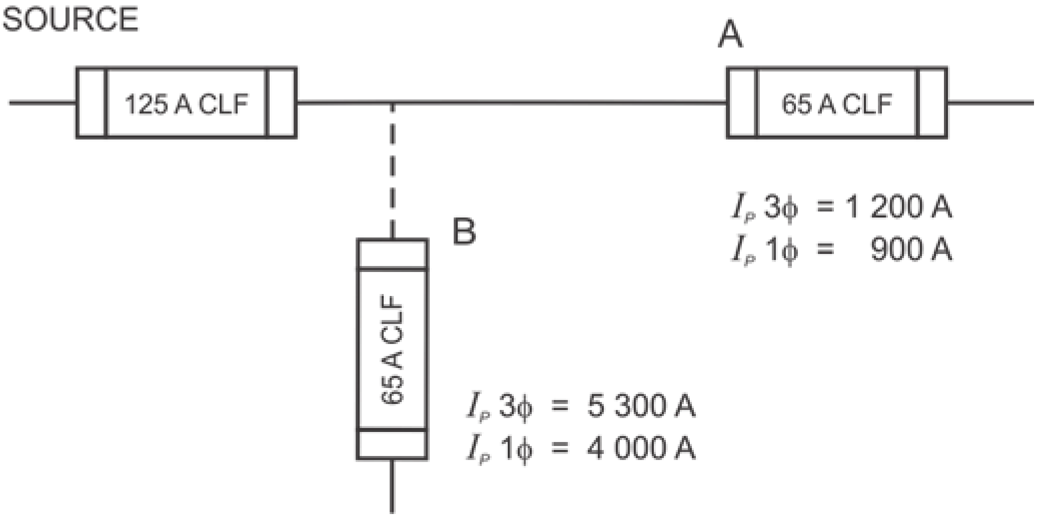


Figure 20 – Current-limiting fuse/Current-limiting fuse coordination example

The TCC curves for this combination are illustrated in Figure 21. However, before comparing the fuse TCC curves, we need to verify that the 125 A CLF has adequate reach, that is it can operate with a fault at the 65A fuse. At this fuse the phase to ground prospective current I_P is 900 A, assuming a bolted fault (a bolted fault being one in which the fault impedance is essentially zero). A full-range current-limiting fuse, can interrupt any current that causes it to melt, so it will operate with a current corresponding to the top of its published minimum melting TCC curve. However, a fault persisting for hours would not be desirable so a utility will likely pick a shorter time for which they would like fuse operation. If a time of 300 s is chosen as a desirable maximum, the 300 s current for the 125 A fuse is 300 A. Since the phase-to-ground fault current at the 65 A fuse is 900 A, the fuse will melt in less than 300 s. However, another consideration is the fact that actual fault currents will be somewhat less than the calculated value, as a result of fault impedance. In this example, the current could be one third less (a "reach margin" of 3) and still operate the fuse in less than 300 s.

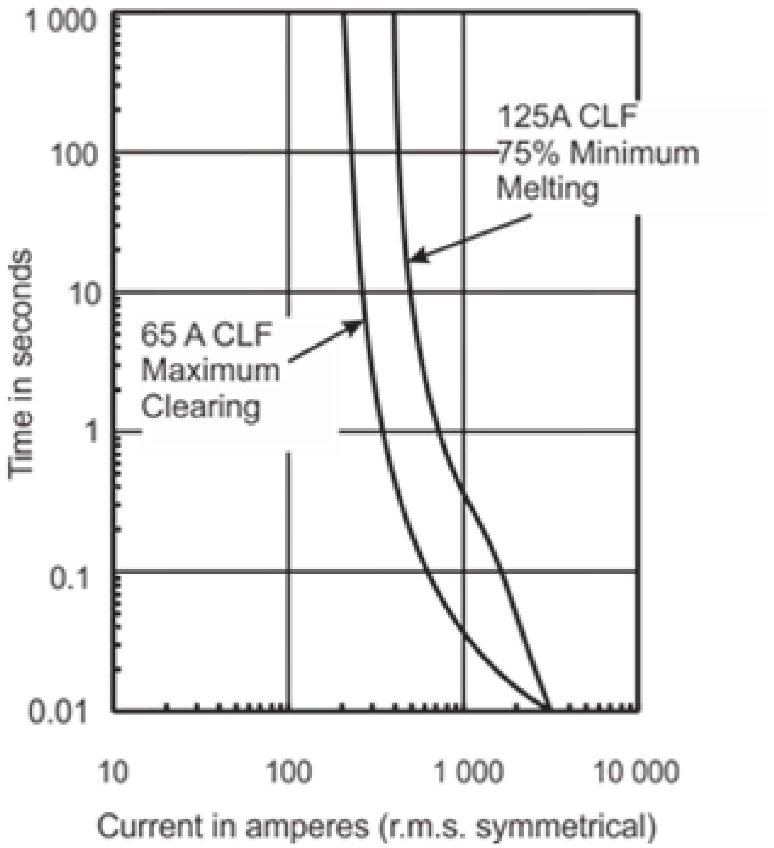


Figure 21 – Time current curves for example

To check TCC curve coordination between the 125 A and 65 A fuse, draw the minimum melting curve at 75 % of the melting time, to prevent damage to the up-stream fuse, for the 125 A CLF and the maximum clearing curve for the 63 A CLF. Note that the curves intersect at approximately 3 100 A, and at a time below 0.01 s. Therefore, since the maximum prospective current at the 65 A CLF does not exceed 3 100 A, time coordination exists. Because the prospective current is less than the point at which the 125 A TCC curve crosses the 0.01 s line, I^2t coordination does not need to be checked.

Had the prospective fault current at the 65 A fuse been higher, 4 000 A for example (position B in Figure 20), then I^2t coordination would have to be checked because the current is higher than the 0.01 s point on the TCC. The maximum clearing I^2t for the 65 A fuse is 100 000 A^2s, while the minimum melting I^2t for the 125 A fuse is 100 800 A^2s. In this case, I^2t coordination at 4 000 A would not be achieved (100 000 A^2s > 0.75 × 100 800 A^2s = 75 600 A^2s). If a 150 A fuse could be used instead of the 125 A fuse (with a melting I^2t of 136 000 A^2s) then this would be acceptable (100 000 A^2s < 0.75 × 136 000 A^2s = 102 000 A^2s). Reach would still be acceptable because although the 300 s current would be higher for the 150 A fuse (at 350 A) the prospective fault current is also higher. Coordination of the larger 150 A fuse with up-stream protection would also need to be checked.

5.5 Current-rating and interrupting capacity for fuses in parallel

Fuse manufacturers supply both current-limiting and expulsion type multi-barrel fuses that are mounted in a parallel arrangement. Such "factory" paralleled arrangements are not the subject of this section.

Configurations of two or more fuses have been successfully used in parallel for many years when authorized by the manufacturer. This may be done by a user, a third-party assembler, or by a manufacturer supplying a device that holds two or more fuses in a single fuse support. This provides for increased current ratings but the continuous current carrying capability of the combination will usually be somewhat less than the sum of the current ratings of the individual parallel fuses due to variations in path resistances and proximity heating effects. The fuse manufacturer should be consulted to determine the appropriate de-rating factor. Only fuses from the same manufacturer and having the same type reference and rating should be connected in parallel, and care should be taken to keep the connections symmetrical so that each parallel fuse and conductor path have the same resistance and inductance.

5.6 Considerations for connecting fuses in series

The voltage rating of a combination of two or more fuses in series cannot be guaranteed to be higher than the individual voltage rating of each of the separate fuses. If a situation arises where two or more fuses connected in series are needed to achieve a higher voltage than either fuse alone, the combination in question should be subject to separate tests to verify the application. In some cases, a manufacturer will supply such fuses either as matched pairs, or permanently joined together in series.

In some cases, in three phase applications, it is assumed that series connected current-limiting fuses will share voltage and be able to interrupt fault current at a voltage higher than the voltage with which they were tested. Traditionally this has only been considered to occur when fuses are in their current-limiting mode. Care should be exercised when selecting and replacing fuses for applications in multi-phase circuits if the assumption has been made that, under fault conditions, two fuses will be effectively in series and will share the line-to-line voltage. For two fuses to share the voltage, they must be of the same fuse rating, the same model and/or type of fuse, and be from the same manufacturer; consult the manufacturer for more information.

5.7 Partial discharge

One concern with certain types and applications of fuses is the possibility of partial discharge occurring on the fuse elements, in this case commonly termed "corona". Partial discharge occurs from the sharp edges of energized apparatus parts. There is a particular concern with potential transformer fuses. Because of the delicate nature of the elements used in some low current rating fuses, any appreciable partial discharge will lead to the element being damaged (the element material is removed, ion by ion, and deposited on the fuse filler and body). Such damage could lead to nuisance (or even incorrect) operation of the fuse. Suitable fuse mounting, to avoid the onset of partial discharge, is therefore important; primarily of concern is the location of ground-connected components near to the fuse. Problems have arisen with, for example, liquid submerged CL fuses where there is often a relatively close ground plane. If this occurs, in addition to increasing the partial discharge measurements of, for example, a transformer, fuse element deterioration is possible. In general, the outside surface of a CL fuse should be considered as a conductor for clearance purposes, rather than an insulator, because an element can be quite close to the inside surface of the body and the space between them is partially air. Even if there is insulating liquid outside the fuse, the sand/air mixture granular filler can result in a high surface voltage gradient at the element.

6. Conclusion

When completed, the “twin” standards IEEE Std C37.48-2020(?) and IEC TR 60282 will represent a, possibly unique, example of cooperation (including copyright) between IEEE and IEC. We have produced equivalent, but different, standards containing essentially identical application information, but with each designed to maximize the convenience to their respective audiences or “stakeholders”. In this particular case a “dual-logo” document or “joint development” would not have produced a document that would have been best attuned to the needs of those anticipated to use it, largely because of historical differences in terminology and references to other standards. I hope that both organizations will be able to take inspiration from the procedures followed by the HV Fuses Subcommittees of both groups and use this model for similar situations in order to allow the “customer to come first”, the hallmark of all successful undertakings.

7. Bibliography

[1] Jakubiuk K.: Secondary striation during fuse-element disintegration. Int. Conference on Electric Fuses and their Applications, Torino (Italy), p 95, September 1999.