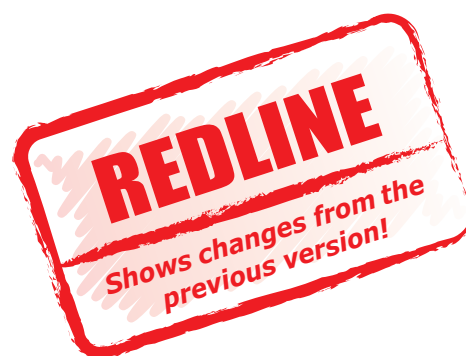


IEEE Guide for the Application, Operation, and Coordination of High- Voltage (> 1000 V) Current-Limiting Fuses

IEEE Power & Energy Society

Sponsored by the
Switchgear Committee



IEEE
3 Park Avenue
New York, NY 10016-5997
USA

3 April 2012

IEEE Std C37.48.1™-2011
(Revision of
IEEE Std C37.48.1-2002)

This is a Redline Document produced by Techstreet, a business of Thomson Reuters.

This document is intended to provide users with an indication of changes from one edition to the next. It includes a full-text version of the new document, plus an indication of changes from the previous version.

Redlines are designed to save time and improve efficiencies by using the latest software technology to find and highlight document changes. More professionals are using valuable new technologies like redlines, to help improve outcomes in a fastpaced global business world.

Because it may not be technically possible to capture all changes accurately, it is recommended that users consult previous editions as appropriate. In all cases, only the current base version of this publication is to be considered the official document.

Redline Processing Notes:

1. ~~Red Text~~ - Red strikethrough text denotes deletions.
2. Blue Text - Blue underlined text denotes modifications and additions.

Abstract: A tutorial style document that provides additional guidelines, beyond those in IEEE C37.48™, for the application and coordination of high-voltage power- and distribution-class current-limiting fuses.

Keywords: coordination, current-limiting fuses, disconnecting switches, fuse application, high voltage, high-voltage fuses, IEEE C37.48.1, rated maximum voltage, single pole air switches, time-current-characteristics, TCC

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2012 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 3 April 2012. Printed in the United States of America.

IEEE is a registered trademark in the U.S. Patent & Trademark Office, owned by The Institute of Electrical and Electronics Engineers, Incorporated.

National Electrical Code and NEC are registered trademarks in the U.S. Patent & Trademark Office, owned by The National Fire Protection Association.

PDF: ISBN 978-0-7381-7164-7 STD97196
Print: ISBN 978-0-7381-7189-0 STDPD97196

IEEE prohibits discrimination, harassment, and bullying. For more information, visit <http://www.ieee.org/web/aboutus/whatis/policies/p9-26.html>.
No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

Abstract: A tutorial style document that provides additional guidelines, beyond those in IEEE C37.48™, for the application and coordination of high-voltage power- and distribution-class current-limiting fuses.

Keywords: coordination, current-limiting fuses, disconnecting switches, fuse application, high voltage, high-voltage fuses, IEEE C37.48.1, rated maximum voltage, single pole air switches, time-current-characteristics, TCC

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2012 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 30 March 2012. Printed in the United States of America.

IEEE is a registered trademark in the U.S. Patent & Trademark Office, owned by The Institute of Electrical and Electronics Engineers, Incorporated.

National Electrical Code and NEC are registered trademarks in the U.S. Patent & Trademark Office, owned by The National Fire Protection Association.

PDF: ISBN 978-0-7381-7164-7 STD97196
Print: ISBN 978-0-7381-7189-0 STDPD97196

IEEE prohibits discrimination, harassment, and bullying. For more information, visit <http://www.ieee.org/web/aboutus/whatis/policies/p9-26.html>.
No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

Notice and Disclaimer of Liability Concerning the Use of IEEE Documents: IEEE Standards documents are developed within the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (IEEE-SA) Standards Board. IEEE develops its standards through a consensus development process, approved by the American National Standards Institute, which brings together volunteers representing varied viewpoints and interests to achieve the final product. Volunteers are not necessarily members of the Institute and serve without compensation. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information or the soundness of any judgments contained in its standards.

Use of an IEEE Standard is wholly voluntary. IEEE disclaims liability for any personal injury, property or other damage, of any nature whatsoever, whether special, indirect, consequential, or compensatory, directly or indirectly resulting from the publication, use of, or reliance upon any IEEE Standard document.

IEEE does not warrant or represent the accuracy or content of the material contained in its standards, and expressly disclaims any express or implied warranty, including any implied warranty of merchantability or fitness for a specific purpose, or that the use of the material contained in its standards is free from patent infringement. IEEE Standards documents are supplied "AS IS."

The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE standard is subjected to review at least every ten years. When a document is more than ten years old and has not undergone a revision process, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE standard.

In publishing and making its standards available, IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity. Nor is IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing any IEEE Standards document, should rely upon his or her own independent judgment in the exercise of reasonable care in any given circumstances or, as appropriate, seek the advice of a competent professional in determining the appropriateness of a given IEEE standard.

Translations: The IEEE consensus development process involves the review of documents in English only. In the event that an IEEE standard is translated, only the English version published by IEEE should be considered the approved IEEE standard.

Official Statements: A statement, written or oral, that is not processed in accordance with the IEEE-SA Standards Board Operations Manual shall not be considered the official position of IEEE or any of its committees and shall not be considered to be, nor be relied upon as, a formal position of IEEE. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that his or her views should be considered the personal views of that individual rather than the formal position of IEEE.

Comments on Standards: Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE. However, IEEE does not provide consulting information or advice pertaining to IEEE Standards documents. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Since IEEE standards represent a consensus of concerned interests, it is important to ensure that any responses to comments and questions also receive the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to comments or questions except in those cases where the matter has previously been addressed. Any person who would like to participate in evaluating comments or revisions to an IEEE standard is welcome to join the relevant IEEE working group at <http://standards.ieee.org/develop/wg/>.

Comments on standards should be submitted to the following address:

Secretary, IEEE-SA Standards Board
445 Hoes Lane
Piscataway, NJ 08854
USA

Photocopies: Authorization to photocopy portions of any individual standard for internal or personal use is granted by The Institute of Electrical and Electronics Engineers, Inc., provided that the appropriate fee is paid to Copyright Clearance Center. To arrange for payment of licensing fee, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Notice to users

Laws and regulations

Users of these documents should consult all applicable laws and regulations. Compliance with the provisions of this standard does not imply compliance to any applicable regulatory requirements. Implementers of the standard are responsible for observing or referring to the applicable regulatory requirements. IEEE does not, by the publication of its standards, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

Copyrights

This document is copyrighted by the IEEE. It is made available for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making this document available for use and adoption by public authorities and private users, the IEEE does not waive any rights in copyright to this document.

Updating of IEEE documents

Users of IEEE Standards documents should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of amendments, corrigenda, or errata. An official IEEE document at any point in time consists of the current edition of the document together with any amendments, corrigenda, or errata then in effect. In order to determine whether a given document is the current edition and whether it has been amended through the issuance of amendments, corrigenda, or errata, visit the IEEE-SA Website at <http://standards.ieee.org/index.html> or contact the IEEE at the address listed previously. For more information about the IEEE Standards Association or the IEEE standards development process, visit IEEE-SA Website at <http://standards.ieee.org/index.html>.

Errata

Errata, if any, for this and all other standards can be accessed at the following URL: <http://standards.ieee.org/findstds/errata/index.html>. Users are encouraged to check this URL for errata periodically.

Patents

Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. If a patent holder or patent applicant has filed a statement of assurance via an Accepted Letter of Assurance, then the statement is listed on the IEEE-SA Website at <http://standards.ieee.org/about/sasb/patcom/patents.html>. Letters of Assurance may indicate whether the Submitter is willing or unwilling to grant licenses under patent rights without compensation or under reasonable rates, with reasonable terms and conditions that are demonstrably free of any unfair discrimination to applicants desiring to obtain such licenses.

Essential Patent Claims may exist for which a Letter of Assurance has not been received. The IEEE is not responsible for identifying Essential Patent Claims for which a license may be required, for conducting inquiries into the legal validity or scope of Patents Claims, or determining whether any licensing terms or conditions provided in connection with submission of a Letter of Assurance, if any, or in any licensing agreements are reasonable or non-discriminatory. Users of this standard are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. Further information may be obtained from the IEEE Standards Association.

Participants

At the time this IEEE guide was completed, the Revision of Fuse Standards Working Group had the following membership:

John G. Leach, *Chair*
Glenn R. Borchardt, *Secretary*

Chris Ambrose
Nicholas Brusky
Samuel Chang
Dan Gardner
Stephen P. Hassler
Gary Haynes

Frank G. Ladonne
Frank C. Lambert
Chris Lettow
James R. Marek
Sean Moody
Frank J. Muench
Donald M. Parker

R. Neville Parry
Timothy Royster
Mark W. Stavnes
Bill Walter
Alan Yerges
Janusz Zawadzki

The High-Voltage Fuses Subcommittee that authorized the formation of the balloting group had the following membership:

John G. Leach, *Chair*
Frank J. Muench, *Secretary*

John G. Angelis
Glenn R. Borchardt
Dan Gardner
Stephen P. Hassler
Gary Haynes

Frank G. Ladonne
Chris Lettow
James R. Marek
Donald M. Parker
R. Neville Parry
R. Kris Ranjan

Timothy Royster
John S. Schaffer
Mark W. Stavnes
Alan Yerges
Janusz Zawadzki

This document was sponsored by the Switchgear Committee of the IEEE Power and Energy Society. When this document was approved, the members of the Switchgear Committee had the following membership:

Ken Edwards, *Chair*
Ted Olsen, *Vice Chair*
Paul B. Sullivan, *Secretary*
Michael Wactor, *Standards Coordinator*

Roy Alexander
Chris Ambrose
Michael Anderson
John G. Angelis
Mauricio Aristizabal
Charles J. Ball
Paul D. Barnhart
L. Ronald Beard
Robert Behl
W. J. (Bill) Bergman
Stan Billings
Antone Bonner
Anne Bosma
John Brunke
Ted Burse
Eldridge Byron
Ray Capra
Chih Chow
Frank DeCesaro
Patrick DiLillo
Alexander Dixon
Randall Dotson
Denis Dufournet
Peter W. Dwyer
Douglas Edwards
Leslie Falkingham
Lawrence Farr

Keith Flowers
Marcel Fortin
David Galicia
Mietek Glinkowski
S. S. (Dave) Gohil
Keith I. Gray
Helmut Heiermeier
Luther Holloman
Danny Hoss
James Houston
Richard Jackson
Cory Johnson
Harry Josten
Dan Konkle
Stephen Lambert
John G. Leach
Dave Lemmerman
George Lester
Hua Ying Liu
R. Long
James R. Marek
Frank Mayle
Deepak Mazumdar
Nigel P. McQuin
Steven Meiners
Jeffery Mizener

Georges Montillet
Anne F. Morgan
Charles Morse
Frank J. Muench
Yasin Musa
Jeffrey Nelson
Paul Notarian
Michael Orosz
Donald M. Parker
Robert J. Puckett
Carl Reigart
Timothy Royster
Roderick Sauls
Devki Sharma
Michael D. Sigmon
R. Kirkland Smith
H. M. Smith
James Smith
David Stone
Alan D. Storms
James Swank
Thomas Tobin
Charles Wagner
John Webb
John Wood
Rich York
Janusz Zawadzki

The following members of the individual balloting committee voted on this guide. Balloters may have voted for approval, disapproval, or abstention.

William J. Ackerman
Satish Aggarwal
Chris Ambrose
Michael Baldwin
Steven Bezner
Glenn R. Borchardt
Harvey Bowles
Jeffrey Bragg
Steven Brockschink
Chris Brooks
William Byrd
Eldridge Byron
Thomas Callsen
Jerry Corkran
Glenn Davis
Gary Donner
Edgar Dullni
Gary Engmann
C. Erven
Dan Evans
Marcel Fortin
Fredric Friend
Daniel Gardner
Mietek Glinkowski
Edwin Goodwin

Randall Groves
John Harder
Timothy Hayden
Gary Haynes
Gary Heuston
David Horvath
Richard Jackson
Edward Jankowich
Andrew Jones
John Kay
Jim Kulchisky
Saumen Kundu
Chung-Yiu Lam
Stephen Lambert
Benjamin Lanz
John G. Leach
R. Long
Greg Luri
William McBride
Georges Montillet
Sean Moody
Daniel Mulkey
Jerry Murphy
Dennis Neitzel
Arthur Neubauer
Michael S. Newman

Joe Nims
Ted Olsen
Lorraine Padden
Mirko Palazzo
Donald M. Parker
R. Neville Parry
Christopher Petrola
Iulian Profir
Michael Roberts
Timothy Robirds
Charles Rogers
Timothy Royster
Thomas Rozek
Bartien Sayogo
James Smith
Jerry Smith
Gary Stoedter
David Tepen
John Vergis
William H. Walter
John Wang
Kenneth White
Charles Worthington
Jian Yu
Janusz Zawadzki

When the IEEE-SA Standards Board approved this guide on 7 December 2011, it had the following membership:

Richard H. Hulett, *Chair*
John Kulick, *Vice Chair*
Robert M. Grow, *Past Chair*
Judith Gorman, *Secretary*

Masayuki Ariyoshi
William Bartley
Ted Burse
Clint Chaplin
Wael Diab
Jean-Philippe Faure
Alexander Gelman
Paul Houzé

Jim Hughes
Joseph L. Koepfinger*
David J. Law
Thomas Lee
Hung Ling
Oleg Logvinov
Ted Olsen

Gary Robinson
Jon Walter Rosdahl
Sam Sciacca
Mike Seavey
Curtis Siller
Phil Winston
Howard Wolfman
Don Wright

*Member Emeritus

Also included are the following nonvoting IEEE-SA Standards Board liaisons:

Satish Aggarwal, *NRC Representative*
Richard DeBlasio, *DOE Representative*
Michael Janezic, *NIST Representative*

Michelle Turner
IEEE Standards Program Manager, Document Development

Erin Spiewak
IEEE Standards Program Manager, Technical Program Development

Introduction

This introduction is not part of IEEE Std C37.48.1-2011, IEEE Guide for the Application, Operation, and Coordination of High-Voltage (>1000 V) Current-Limiting Fuses.

During the process of determining the need for revising IEEE standards to include the category of “full-range” current-limiting fuses, users and specifiers, both at utilities and at manufacturers, were surveyed. This survey revealed that additional information to that then available from fuse standards needed to be made available to the specifiers and users of all types of high-voltage current-limiting fuses to avoid confusion between the different types, and their capabilities.

As a result, the High-Voltage Fuses Subcommittee of the IEEE Power & Energy Society’s Switchgear Committee established a task force to develop additional standards information that would summarize pertinent information regarding current-limiting fuses in general and full-range fuses in particular. This task force became the working group on full-range fuses. With cooperation from the National Electrical Manufacturers Association (NEMA), it created a seminar, which formed the basis of the original (2002) edition of IEEE Std C37.48.1, an IEEE guide. This document contained additional application information, to that presented in IEEE Std C37.48, to detail the application and coordination of full-range and other current-limiting fuses. This revision updates the 2002 edition.

The present revision was prepared by the Revision of Fuse Standards Working Group of the High-Voltage Fuses Subcommittee.

This guide is one of a series of complementary standards covering various types of high-voltage fuses and switches, so arranged that two of the standards apply to all devices while each of the other standards provides additional specifications for a particular device. For each device, IEEE Std C37.40™, IEEE Std C37.41™, plus the standard covering that particular device constitute a complete set of standards for each device. In addition, IEEE Std C37.48 is an application, operation, and maintenance guide for all of the devices, and this guide provides additional guidelines, more specifically for current-limiting fuses.

The following standards comprise this series:

IEEE Std C37.40™, IEEE Standard Service Conditions and Definitions for High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories.

IEEE Std C37.41™, IEEE Standard Design Tests for High-Voltage (>1000 V) Fuses, Fuse and Disconnecting Cutouts, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Fuse Links and Accessories Used with These Devices.

IEEE Std C37.42™, IEEE Standard Specifications for High-Voltage (>1000 V) Expulsion-Type Distribution-Class Fuses, Fuse and Disconnecting Cutouts, Fuse Disconnecting Switches, and Fuse Links and Accessories Used with These Devices.

IEEE Std C37.43™, IEEE Standard Specifications for High-Voltage Expulsion, Current-Limiting, and Combination-Type Distribution and Power Class External Fuses, with Rated Voltages from 1 kV through 38 kV, Used for the Protection of Shunt Capacitors.

IEEE Std C37.45™, IEEE Standard Specifications for High-Voltage Distribution Class Enclosed Single-Pole Air Switches with Rated Voltages from 1 kV through 8.3 kV.

IEEE Std C37.46™, IEEE Standard Specifications for High Voltage (>1000 V) Expulsion and Current-limiting Power Class Fuses and Fuse Disconnecting Switches.

IEEE Std C37.47™, IEEE Standard for Specifications for Distribution Fuse Disconnecting Switches, Fuse Supports, and Current-Limiting Fuses.

IEEE Std C37.48™, IEEE Guide for Application Operation, and Maintenance of High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories.

IEEE Std C37.48.1™, IEEE Guide for the Application, Operation, and Coordination of High-Voltage (>1000 V) Current-Limiting Fuses.

Contents

1. Overview	1
1.1 Scope	1
1.2 Purpose	2
1.3 Background.....	2
1.4 Description of fuse enclosure packages (FEPs) using current-limiting type indoor distribution-class and power-class fuses	2
2. Normative references.....	3
3. Acronyms and abbreviations	4
4. Fuse operation	4
4.1 Introduction	4
4.2 Thermal characteristics	4
4.3 Interrupting characteristics	6
4.4 Comparison of power fuses versus distribution fuses.....	7
4.5 Comparison of current-limiting versus expulsion and other types of non-current-limiting fuses.....	7
4.6 Fuse construction and operation	9
4.6.1 General.....	9
4.6.2 Current-limiting fuses	10
4.6.3 Expulsion and other types of non-current-limiting fuses	15
5. Current-limiting fuse types, class, and definitions	18
5.1 Introduction	18
5.2 Fuse class.....	19
5.2.1 Introduction.....	19
5.2.2 Power-class current-limiting fuses.....	19
5.2.3 Distribution-class current-limiting fuses.....	20
5.3 Types of current-limiting fuse	20
5.3.1 General.....	20
5.3.2 Backup fuses	21
5.3.3 General-purpose fuses.....	22
5.3.4 Full-range fuses.....	22
5.4 Current rating conventions	23
6. Application considerations and cautions	26
6.1 Electrical aspects	26
6.1.1 Response of current-limiting fuse to steady-state conditions—overview	26
6.1.2 Response of current-limiting fuse to overcurrent conditions—overview.....	26
6.1.3 Transformer applications	26
6.1.4 Feeder and sectionalizing applications.....	28
6.1.5 Shunt Capacitor applications	29
6.1.6 Potential [voltage] transformer applications	32
6.1.7 Motor circuit protection and coordination	33
6.1.8 System voltage considerations	37
6.1.9 Fuse replacement	37
6.1.10 Current-limiting fuses and power quality issues	37
6.2 Physical application considerations for current-limiting fuses	38
6.2.1 General.....	38
6.2.2 Fuse types/mounting for current-limiting fuses	38
6.2.3 Mechanical impact considerations for current-limiting fuses	39
6.2.4 Environmental effects on ratings of current-limiting fuses	40

7. Current-limiting fuse coordination	41
7.1 General	41
7.2 Tap-line coordination.....	42
7.2.1 General.....	42
7.2.2 Determining the zone of protection for current-limiting fuses (reach)	43
7.2.3 Selecting minimum fuse current ratings.....	45
7.2.4 Coordinating current-limiting fuses with other protective devices	46
7.3 Coordination of motor-starter current-limiting fuses and other protective devices	55
7.4 Backup current-limiting fuse coordination	56
7.4.1 General.....	56
7.4.2 Devices protecting each other	57
7.4.3 Prevention of damage to the backup current-limiting fuse	60
7.4.4 Overload protection for the backup current-limiting fuse.....	62
7.5 Coordinating current-limiting fuses with arresters	63
Annex A (informative) Theoretical treatment of current interruption by a fuse.....	64
A.1 Introduction	64
A.2 Interruption without circuit modification.....	66
A.3 Interruption with circuit modification.....	68
Annex B (informative) Bibliography.....	70

IEEE Guide for the Application, Operation, ~~Classification~~, and Coordination of High- Voltage (>1000 V) Current-Limiting Fuses ~~with Rated Voltages 1–38 kV~~

IMPORTANT NOTICE: IEEE Standards documents are not intended to ensure safety, health, or environmental protection, or ensure against interference with from other devices or networks. Implementers of IEEE Standards documents are responsible for determining and complying with all appropriate safety, security, environmental, health, and interference protection practices and all applicable laws and regulations.

This IEEE document is made available for use subject to important notices and legal disclaimers. These notices and disclaimers appear in all publications containing this document and may be found under the heading "Important Notice" or "Important Notices and Disclaimers Concerning IEEE Documents." They can also be obtained on request from IEEE or viewed at <http://standards.ieee.org/IPR/disclaimers.html>.

1. Overview

1.1 Scope

This guide provides information ~~that supplements that presented in IEEE Std C37.48TM-1997¹~~ on the application, operation, and ~~maintenance~~ coordination of high-voltage ~~(1–38 kV)~~ (>1000 V) fuses, ~~fuse disconnection switches,~~ and ~~accessories for use on alternating current distribution systems,~~ associated equipment. The information supplements that presented in IEEE Std C37.48TM.¹ These guidelines apply to the following specific types of equipment, intended for use on alternating current distribution and power class systems:

- a) Distribution and power class current-limiting type fuses.
- b) Distribution and power class current-limiting fuse disconnecting switches. c) Items a) and b) used in fuse enclosure packages ~~(see types listed in 1.1).~~
- d) ~~Removable switch blades~~ Fuse supports of the type ~~used exclusively~~ intended for use with distribution and power class fuses, and fuse disconnecting switches.
- e) Disconnecting devices created by the use of a removable switch blade in a distribution or power class fuse support.
- f) Distribution class and power class current-limiting, and combination ~~expulsion types of~~ external capacitor fuses used with a capacitor unit, groups of units, or capacitor banks.
- g) Backup current-limiting fuses ("motor-starter fuses") used in conjunction with high-voltage Class E2 motor starters (see ANSI/UL 347 [B1]²).

~~NOTE—Some of the power and distribution class current limiting fuses listed above are the same as those listed in IEC 60282-1 (2002-01).~~

¹ Information on references can be found in Clause 2.

² The numbers in brackets correspond to those of the bibliography Annex B.

~~1.1 Description of fuse enclosure packages using current limiting type indoor distribution and power class fuses~~

- a) ~~Type 1C—A fuse mounted in an enclosure with relatively free air circulation within the enclosure. (Example: A fuse mounted in a live front pad mounted transformer or in a vault.)~~
- b) ~~Type 2C—A fuse mounted in a container with restricted air flow surrounding the fuse, but with relatively free air circulation within the enclosure on the outside surfaces of the enclosure. (Example: A fuse inside a canister in a vault.)~~

~~e) Type 3C—A fuse mounted in a container with restricted air flow surrounding the fuse but relatively free liquid circulating within the enclosure on the outside surfaces of the container. (Example: A fuse inside a canister immersed in transformer oil.)~~

~~d) Type 4C—A combination of types 2C and 3C, where the container is partially in air and partially in liquid. (Example: A fuse inside a canister immersed in transformer oil.)~~

~~e) Type 5C—A fuse mounted in an enclosure, directly immersed in liquid, with relatively free liquid circulation around the fuse. (Example: An oil immersed fuse in a transformer or switchgear enclosure.)~~

1.2 Purpose ~~of the document~~

The purpose of this guide is to expand on aspects of the general fuse application guide, IEEE Std C37.48, in areas associated with the application and coordination of high-voltage (>1000 V) current-limiting fuses. This guide is more “tutorial” in nature than IEEE Std C37.48, and includes descriptions as to how different types of fuses work. It was developed to create a better understanding of how most fuse types operate, but with an emphasis on current-limiting fuses after the category “full-range” was added to the existing categories of “backup” and “general-purpose” current-limiting fuses.

~~During the process of determining the need for revising the standards to include full range fuses, users and specifiers, both at utilities and at manufacturers, were surveyed. This survey revealed that additional information needs to be made available to the specifiers and users of all types of high-voltage current-limiting fuses. There were widespread and deep misunderstandings as to what types of current-limiting fuses were available, how to differentiate between types of current-limiting fuses, how to properly apply each type of current-limiting fuse, and how to properly handle and store fuses.~~

~~As a result, the High Voltage Fuse Subcommittee of the IEEE Power Engineering Society's Switchgear Committee established a task force to develop additional standards information that would summarize pertinent information regarding current-limiting fuses in general and full range fuses in particular. This task force became a working group on full range fuses. It has created this additional application information to guide the application and coordination of full range fuses.~~

1.3 Background

In order to fully understand the behavior of current-limiting fuses and the application relationship between them and other types of fuses which do not significantly limit the first peak of current (hereafter referred to as expulsion and other types of non-current-limiting fuses), a number of references to these “other” types of fuses will be made. It is not the intent of the authors of this guide to claim that any type of fuse is inherently “better” or “worse” than any other. The intent is to present design and operating characteristics of, as well as application guidelines for, current-limiting fuses. However, since such fuses are used on the same system as, and are coordinated with, expulsion and other types of non-current-limiting fuses, some discussion of their design and operating characteristics is also appropriate.

In all cases, it is of particular importance to follow the specific application guidelines published by the manufacturer of any particular device to be used. The manufacturer's guidelines should always take precedence over the opinions expressed in this guide, which are, of necessity, something of a generalization.

Some of the current-limiting type fuses listed in 1.1 are similar to those now covered in IEC 60282-1. However, differences exist in the testing requirements of IEC, IEEE, and ANSI. IEEE fuse standards primarily reflect applications common in North America and in countries that use electrical systems designed using similar principles. IEC standards tend to rely heavily on practices common in Europe. Since IEC testing differences include testing at different voltages for the same fuse rated

voltage, and different or no testing for fuses intended for use in a surrounding temperature above 40 °C, the user is advised to exercise caution if devices specified and tested per IEC standards are compared with those specified and tested per IEEE and ANSI standards. The differences in test requirements may result in devices tested to IEC not being suitable for applications where devices tested to IEEE and ANSI standards are required, or vice versa.

In the headings and the text of this document, there are some areas where information is included in brackets []. The information in the brackets is a term used in IEC standards that may be similar to the term used in this document, a term that is common in some parts of the world, or a term that has been used previously in IEEE or ANSI standards. Caution is again advised when making comparisons.

1.4 Description of fuse enclosure packages (FEPs) using current-limiting type indoor distribution-class and power-class fuses

— Type 1CL: A fuse mounted in a large enclosure with relatively free air circulation within the enclosure (e.g., a fuse mounted in a live-front pad mounted transformer or in a vault). The relevant fuse rated maximum application temperature (RMAT) is based on that of the air that is cooling the fuse. It may be noted that, if a fuse were mounted outdoors but in an ambient temperature above 40 °C, conditions on the fuse would be the same.

— Type 2CL: A fuse mounted in a fuse container. This is a relatively small enclosure, defined as one supporting the fuse and restricting the air, gas or liquid flow surrounding the fuse (e.g., a fuse inside a canister in a transformer or a vault). However, the fluid flow (gas, liquid, or a combination of the two) that cools the outside surface of the container has relatively free circulation. The relevant fuse RMAT is based on that of the fluid that is cooling the container. Fuses tested in accordance with IEEE C37.41 for use in air no hotter than 40 °C that are encapsulated with solid insulation (e.g., rubber or epoxy) can be considered to be this type of FEP when so encapsulated. In this case the relevant fuse RMAT is based on that of the fluid that is cooling the encapsulated fuse.

= Type 3CL: A fuse directly immersed in liquid and mounted in an enclosure with relatively free liquid circulation around the fuse (e.g., an oil-immersed fuse in a transformer or switchgear enclosure). The relevant RMAT is based on that of the liquid that is cooling the fuse.

NOTE— In the versions of IEEE/ANSI fuse standards approved before 2008, FEPs using current-limiting fuses were designated as being of types 1C through 5C. In order to simplify FEP types, include additional types, and align with IEC practice, these types have been rationalized into three categories. Type 2CL includes the former types 2C, 3C and 4C, while type 3CL is the same as type 5C.²

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.

~~This guide shall be used in conjunction with the following publications. If the following publications are superseded by an approved revision, the revision shall apply.~~

IEC 60282-1 ~~(2002-01)~~, High-voltage fuses—Part 1: Current-limiting fuses.³

IEEE Std C37.40TM ~~1993~~, TM, IEEE Standard Service Conditions and Definitions for High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories.^{4, 5}

IEEE Std C37.41~~1994~~TM, IEEE Standard Design Tests for High-Voltage ~~Fuses (>1000 V)~~ Fuses, [Fuse and Disconnecting Cutouts](#), Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and [Fuse Links and Accessories Used with These Devices](#).

~~ANSI-IEEE Std C37.42TM 1996, IEEE American National~~ Standard Specifications for High-Voltage (>1000 V) Expulsion-Type Distribution-Class Fuses, [Fuse and Disconnecting](#) Cutouts, Fuse Disconnecting Switches, and Fuse Links [and Accessories Used with These Devices](#)

~~ANSI-IEEE Std C37.46TM 1981, IEEE American National~~ Standard Specifications for [High Voltage \(>1000 V\) Expulsion and Current-limiting](#) Power [Class](#) Fuses and Fuse Disconnecting Switches.

~~ANSI IEEE Std C37.47 TM 1981 (R1996), IEEE American National~~ Standard Specifications for Distribution Fuse Disconnecting Switches, Fuse Supports, and Current-Limiting Fuses.

IEEE Std C37.48~~1997~~, TM, IEEE Guide for Application, Operation, and Maintenance of High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories.

IEEE Std C57.91TM-1995, IEEE Guide for Loading Mineral-Oil-Immersed Transformers.

~~ANSI C37.44 1981 (R1992), American National Standard Specifications for Distribution Oil Cutouts and Fuse Links.~~

~~ANSI C37.45 1981 (R1992), American National Standard Specifications for Distribution Enclosed Single-Pole Air Switches.~~

~~ANSI C37.53.1-1989, American National Standard for Switchgear—High Voltage Current Limiting Motor Starter Fuses—Conformance Test Procedures.~~

~~IEC 60282-2 (1997-12), High voltage fuses—Part 2: Expulsion fuses.~~

~~IEC 60291 (1969-01), Fuse definitions.~~

~~IEC 60549 (1976-01), High voltage fuses for the external protection of shunt power capacitors.~~

~~IEC 60644 (1979-01), Specification of high voltage fuse links for motor circuit applications.~~

~~IEEE Std C37.100TM-1992, IEEE Standard Definitions for Power Switchgear.~~

~~NOTE—The IEEE standards referred to in this clause are trademarks owned by the Institute of Electrical and Electronics Engineers, Incorporated.~~

² Notes in text, tables, and figures of a standard are given for information only, and do not contain requirements needed to implement the standard.

³ IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembe, CH-1211, Genève 20, Switzerland/Suisse (<http://www.iec.ch/>). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

⁴ IEEE publications are available from The Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

⁵ The IEEE standards or products referred to in this clause are trademarks owned by The Institute of Electrical and Electronics Engineers, Incorporated.

IEEE Std C57.93™-~~1995~~²⁰⁰⁷, IEEE Guide for Installation [and Maintenance of Liquid-Immersed](#) Power Transformers.

IEEE Std C57.109™-1993, IEEE Guide for [Liquid-Immersed](#) Transformers Through-Fault-Current Duration.

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

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

3. Acronyms and abbreviations

[A²s](#) ampere-squared-seconds (unit of I^2t)

[FEP](#) fuse enclosure package

[RMAT](#) rated maximum application temperature

[TCC](#) time-current-characteristic

4. Fuse operation ~~and theory~~

4.1 Introduction

An enormous variety of fuses are available today. They are used as a reliable means of protecting and/or limiting damage to apparatus from overcurrents in both low- and high-voltage systems. This guide is limited to high-voltage (>1000 V) current-limiting fuses intended for use in alternating current circuits.

Before different types of high-voltage fuses are examined in detail, a summary of the essential characteristics common to all fuses will be presented. These are the thermal characteristics (current rating and melting characteristics) and interrupting characteristics (voltage rating and interrupting ratings).

Discussion will then proceed to introduce a fundamental comparison of power-class versus distribution-class fuses and current-limiting versus expulsion and other types of non-current-limiting fuses.

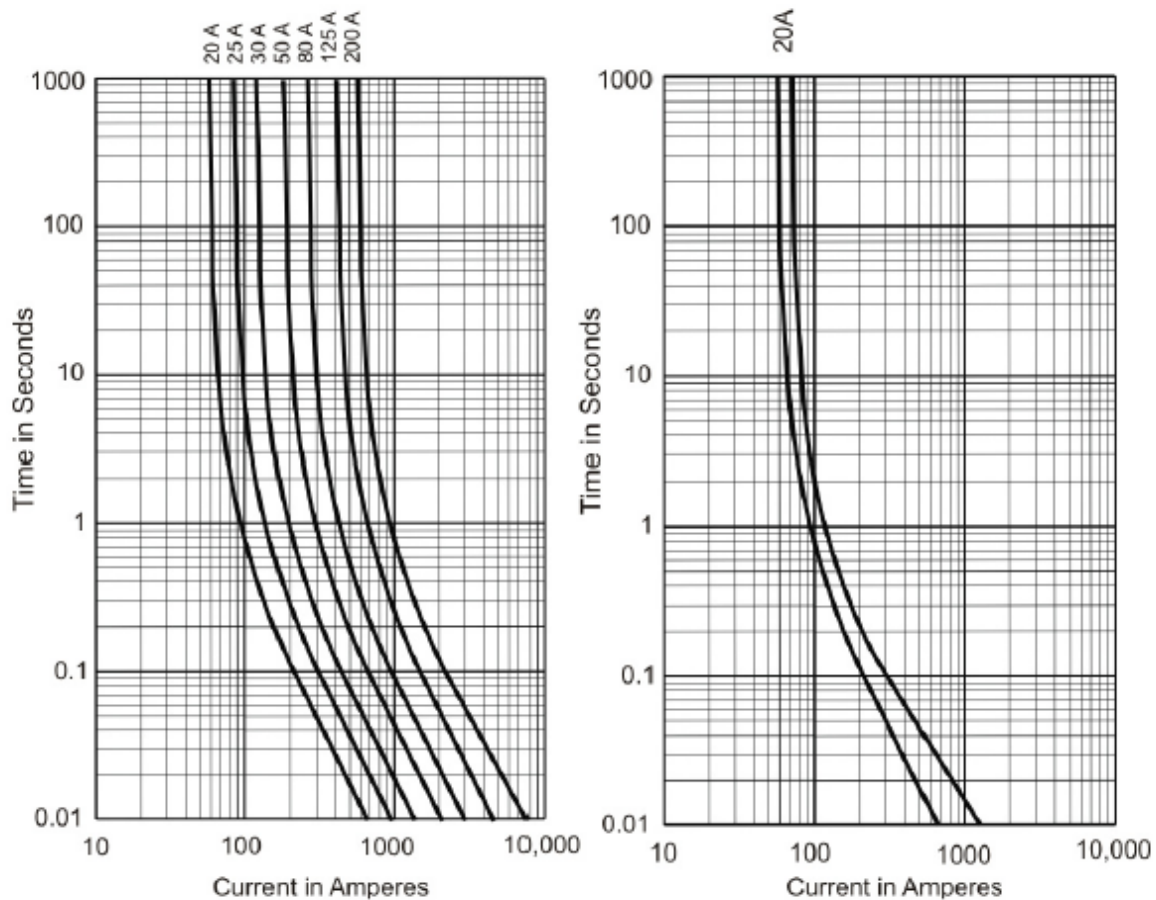
4.2 Thermal characteristics

Despite the variety of types, all true fuses, by definition, are devices that open a circuit with a fusible part, which is heated and severed by current flowing through it. This fusible part is called the "element." When current flows through a fuse, heat is generated and its element temperature rises. For a current less than or equal to its rated continuous current (the "name-plate" current rating), temperatures rise until a steady-state condition is reached in which the heat generated equals the heat dissipated. At rated continuous current, fuses conforming to the IEEE/ANSI C37 series of standards will have temperature rises within the limits specified in IEEE Std C37.40-~~1993~~.

When a current (higher than rated continuous current) flows through the fuse, the temperature of the element will rise. For some higher currents, steady-state conditions may again be achieved, but at a higher temperature. This temperature may exceed the values specified for a fuse carrying its rated continuous current. Whether such a situation is acceptable, or must be avoided, will depend on the fuse type and the application. A discussion of fuse types and typical applications is presented in Clause 5 and Clause 6. At some point in time, if the current has sufficient magnitude, the higher current will cause the fuse element to melt before steady-state temperature conditions are achieved. After melting, the fuse must interrupt the current, ~~but that also will be~~ discussed in 4.3.

For a given fuse, the relationship between the magnitude of the current that causes melting and the time needed for it to melt is given by the fuse's melting time-current-characteristic (TCC), usually shown as a TCC curve plotted on log-log graph paper. The curve is produced from time-current tests, which are specified in IEEE Std C37.41-1994. They are performed with constant current applied to the fuse, in an ambient temperature between 20 °C and 30 °C, with the fuse carrying no initial current. IEEE Std C37.41-1994 specifies that a melting TCC is to be drawn showing the minimum-melting time of a fuse (including an allowance for the manufacturer's minus variations—for manufacturing tolerances etc.) when carrying symmetrical current.

The typical shape of a fuse's melting TCC is shown in Figure 1A. The severing of a fuse element is caused by predominantly thermal, rather than mechanical means, so there is virtually no limit on how short the melting time can be. This very fast operation (melting) of a fuse at very high currents tends to be a distinguishing characteristic of fuses compared to most other protective devices.



1A: Typical minimum melting time-current-characteristic curves (for 25 °C). Any variation should be positive (above and to the right of the curves). Any variation for the total clearing TCC should be negative (below and to the left of the curve).

1B: Typical minimum melting and total clearing time-current-characteristic curves for a 20 A fuse. Any variation for the total clearing TCC should be negative (below and to the left of the curve).

[Figure 1 – Typical minimum melting and total clearing time-current-characteristic curves](#)

A fuse has a long melting time at a low current because the low rate of heat input into the element is only slightly greater than the rate of heat loss from the element. As a result, the temperature of the element will increase slowly. As current increases, the melting time becomes shorter, not only because of the higher rate of heat input but also because the heat being produced in the areas with reduced cross section, and/or in the center of the elements, cannot be removed as fast as it is being produced. This gives fuses very inverse melting characteristics. At very short melting times, no heat is lost from the smallest cross section of the element. The melting I^2t is, therefore, constant within this range. I^2t , or actually $\int i^2 dt$, is a value proportional to the heating effect of a current of a particular rms value and duration. When I^2t is multiplied by a resistance value through which it “flows,” the energy (heat) generated in that resistance is obtained. I^2t , [expressed in units of ampere-squared seconds \(A²s\)](#), is a useful concept for fuse-to-fuse and fuse-to-equipment protection and coordination, and will be discussed in ~~more depth in 3.6.~~ [various subclauses \(e.g., see 7.2.4.2\).](#)

4.3 Interrupting characteristics

After the fuse element melts, the fuse must interrupt the current (which continues to flow through an arc). After interruption, the fuse must withstand any immediate [transient recovery voltage \(TRV\)](#) condition and the subsequent steady-state recovery voltage. When a fuse melts, there will always be some period of arcing before the current is interrupted. The melting time (adjusted by an allowance for the manufacturer’s plus variations for manufacturing tolerances, etc.) is added to this arcing period to obtain the total-clearing time. Total-clearing TCC curves are drawn to present this information. Normally, at long melting times, arcing as a portion of total clearing time is negligible, while at short melting times it can be significant. Thus, for a given fuse, the minimum-melting TCC [curve](#) and the total-clearing TCC [curve](#) tend to diverge at shorter times (higher currents), as illustrated in Figure 1B, [which shows the minimum-melting and total-clearing time-current-characteristic curves plotted for the same fuse.](#)

The two TCC characteristics described ~~above~~ are used to coordinate with comparable characteristics of other fuses or protective devices to selectively isolate faulted circuits and to protect equipment. This is a very important consideration in the operation of electric systems.

In addition to TCC curves, a CL fuse manufacturer is required to present maximum and minimum I^2t information for their fuses, likely to be experienced in service. In addition to "minimum melting [pre- arcing] I^2t " discussed in 4.2, which represents the smallest I^2t to melt the fuse (at the maximum rated interrupting current, and with minimum manufacturing tolerances), the highest I^2t let through by the fuse at any current that causes a current-limiting action is called the "maximum clearing I^2t ". It is the sum of the melting I^2t and arcing I^2t (arcing I^2t being that which "flows" during the time when the fuse is arcing), and can occur at any current up to the rated maximum interrupting current of the fuse, depending on fuse design. Other terms that have been commonly used for maximum clearing I^2t include "maximum operating I^2t ", "maximum let-through I^2t ", "total I^2t value", maximum total I^2t , and "total clearing I^2t ". The presentation of I^2t values may be in simple tabular or diagrammatic form (for example, histograms) or may employ graphical presentation with prospective current as abscissa and I^2t as ordinate, both scales being logarithmic.

In addition to rated current, a fuse has a rated maximum voltage. This is the highest voltage at which the fuse is designed to operate, and it is important that a fuse not be called upon to interrupt current at a higher voltage.

A fuse manufacturer assigns a rated maximum interrupting current to a fuse, based on the highest current ~~that a fuse at which testing (per relevant standard requirements) has been tested to, thereby providing a demonstration of successful interruption.~~ performed. In addition, some fuses also have a rated minimum interrupting ~~cur- rent, which-~~ current. This is the lowest current that the fuse ~~has been tested to, thereby providing a demonstration of~~ manufacturer assigns for successful

interruption, based on testing, (while this is not necessarily the lowest current that it can actually interrupt, its application should not assume any lower current interrupting capability). A fuse may not function as intended, with potentially serious results, when attempting to interrupt outside its maximum and minimum interrupting rating.

4.4 Comparison of power fuses versus distribution fuses

Both current-limiting and expulsion fuses are classified by ~~ANSI~~ [IEEE](#) C37 standards as either power-class or distribution-class fuses. The differentiation between the two classes reflects the different system conditions that exist where fuses are normally applied on a power system based on specific requirements for generating sources, substations, and distribution lines. ~~Each class has its own unique set of voltage, current, and construction requirements (see ANSI C37.42, .44, .46, and .47 for examples of typical fuse requirements).~~ Testing of each fuse type and class must follow particular requirements detailed in IEEE Std C37.41 together with individual specification requirements listed in IEEE Std C37.~~41-1994~~.42, IEEE Std C37.43, IEEE Std C37.45, IEEE Std C37.46, and IEEE Std C37.47. Such specifications include, for example, maximum peak overvoltages for current-limiting fuses and dielectric test voltages for fuse supports. A comparison of some of these specifications is given in Table 1. Power-class fuses are tested to TRVs and X/R ratio values more likely to be encountered in or near the generating source or substation and on three-phase circuits. Distribution fuses have specifications more closely matched with requirements of the distribution system, further away from the source or substation on single or three-phase circuits.

Table 1.— Comparison of IEEE fuse specifications

Requirement	IEEE ANSI C37.42 distribution ~~cutouts and~~ <u>class</u> <u>expulsion</u> fuse <u>links</u>	~~ANSI C37.44 oil cutouts and fuse links~~	IEEE ANSI C37.46 power <u>class</u> <u>expulsion and</u> <u>current-limiting</u> fuses	IEEE ANSI C37.47 distribution current-limiting fuses
Rated <u>maximum</u> kV	~~2.6~~ <u>5.5</u> to 38	~~2.6 to 15~~	2.8 to 16	2.8 to ~~27~~ <u>38</u>
Rated continuous current—Amps	to 200	~~to 200~~	to 700	to 200
Rated <u>maximum</u> interrupting current—kA Sym.	2.6 to 16	~~2.2 to 7.1~~	1.25 to 80	12.5 to <u>125</u> ~~50~~
X/R ratio at <u>rated</u> maximum interrupting current	~~1.33~~ <u>0.75</u> to 15	~~2.3 to 12~~	≥ 15	≥ 10

Because current-limiting fuses are relatively insensitive to high X/R ratios, the performance difference between power-class and distribution-class current-limiting fuses is generally not significant. The basis for current-limiting fuse function, at high currents, involves inserting a high resistance into the faulted circuit, which forces the power factor of the circuit as a whole toward unity. Thus, a distribution current-limiting fuse can often be applied at or near generating sources and substations; [consult the manufacturer for more information](#).

4.5 Comparison of current-limiting versus expulsion and other types of non-current-limiting fuses

All fuse types have the following characteristics, namely:

- a) They can carry continuous current.

b) They are intended to interrupt abnormal overcurrents and isolate circuits. Their melting and interrupting time characteristics can be coordinated with those of other circuit overcurrent protective devices.

c) They all interrupt the circuit at a modified or normal current zero, by having a dielectric recovery that is greater than the TRV imposed by the power distribution system, [thus limiting the duration of a fault or overload current.](#)

d) They all dissipate the arc energy released in the fuse to reduce the likelihood of thermal breakdown after current zero.

However, there are other interrupting characteristics that divide fuses into separate types. [The differences are primarily seen when the current is such that fuse melting occurs before the first major peak of a fault current.](#) Expulsion and other types of non-current-limiting fuses ~~limit the fault duration, while~~ essentially allow the full peak of the available fault current to pass until [the current](#) is interrupted at a normal current zero of the circuit. [Figure 2a shows an expulsion fuse melting under these conditions. There is no significant arc resistance and so no significant arc voltage. As a result the current that flows is almost the same as if the fuse had not melted. At the first natural current zero, the arc is extinguished \(as at every current zero\). If the dielectric strength of the gap in the fuse, produced by the arcing, is sufficient to withstand the circuit recovery voltage \(including any transient caused by parallel circuit capacitance\) the current is not re-established \(as seen in Figure 2a\). In practice, whether additional loops of current flow depends on factors such as the fault-current magnitude, the fault initiation timing, and the fuse size and design.](#) Because the circuit's normal current zero is typically not close to the voltage zero, a high TRV may occur. Common examples of fuses that exhibit this behavior are expulsion, vacuum, SF₆, boric acid, liquid, and some electronically-actuated fuses.

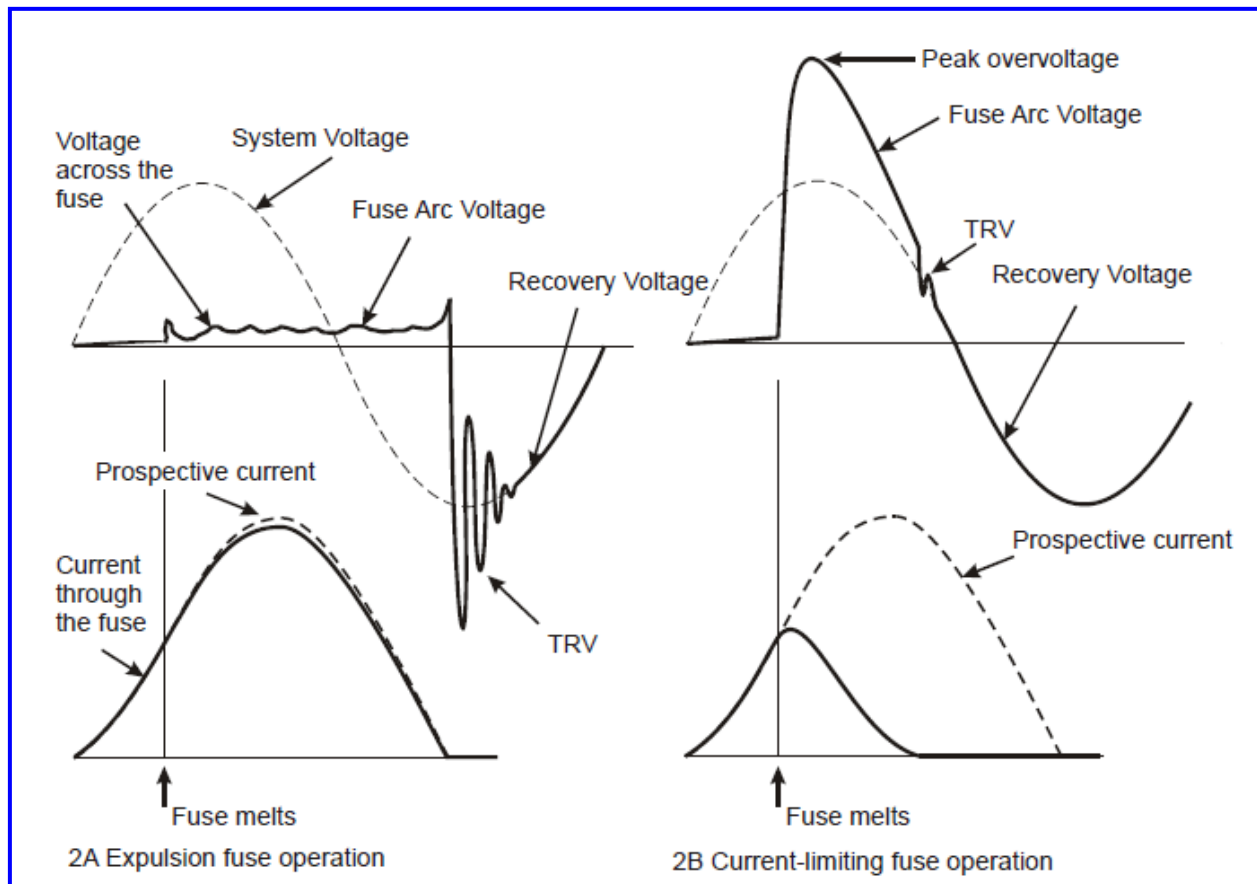


Figure 2 – Expulsion fuse and current-limiting fuse operation

Current-limiting fuses, by contrast, can limit faults in magnitude and duration when they melt before the first major peak of the fault current. A current-limiting or “current zero forcing” fuse begins limiting the rising fault current as soon as its element melts and thus prevents the current from reaching its prospective peak value. The current-limiting action results from melting of a rather long fuse element that interacts with the constraining and cooling medium (typically sand), to introduce a quickly rising equivalent resistance into the fault circuit. ~~Thus, the fuse melting and arcing results in a high arc voltage appearing across the fuse, and the fuse changes a high-~~ Figure 2b shows a current-limiting fuse carrying a fault current that causes it to melt before the first peak. As soon as the fuse arc voltage equals the system instantaneous voltage, the current peak occurs. After this the current falls and the fuse arc voltage exceeds the system voltage because circuit inductive voltage opposes the falling current and adds to the system voltage. The fuse changes a high-

current, low power factor fault circuit into a lower current, higher power factor circuit. As a result, the current is forced to near zero well before the normal current zero of the circuit and close to the voltage zero. This typically occurs within less than 1/2 cycle of the fault initiation. Because the current zero is moved close to the voltage zero, [low](#) TRVs result. The operation of current-limiting fuses will be expanded upon in 4.6.2. The various types of current-limiting fuses include commutating, as well as non-commutating, electronically actuated fuses.

[For a more thorough explanation of fuse theory, see Annex A.](#)

The energy released into the fault is proportional to the duration of the fault and square of the fault current (or I^2t). This energy is primarily responsible for the destructive effects of faults. Current-limiting fuses significantly reduce these effects. Mechanical forces due to magnetic effects of peak currents are also limited. The reduced fault current and duration result in lower stress on all of the equipment that makes up the protected circuit when a fault is cleared by a current-limiting fuse. Other distinguishing characteristics of current-limiting fuses are that they are virtually noiseless and do not usually discharge arc products. For some applications, these factors are an important consideration in fuse selection. Additional features provided by each fuse type are referenced in 4.6.

~~3.6 Circuit interruption and recovery~~

~~During normal circuit conditions, a fuse does not appreciably affect the flow of current in a given circuit. Interruption of current in an electric circuit by a fuse requires the opening of a fusible element, a transition to a nonconducting state, and the ability to withstand the transient and steady-state circuit recovery voltages. Circuits can be inductive, capacitive, or resistive. This discussion is limited to highly inductive fault circuits and to abnormally overloaded circuits with a power factor of less than one.~~

Depending on the current interruption technique employed by a fuse, it may or may not significantly modify the characteristics of the circuit that it protects during the interruption process. In principle, current limiting fuses are energy absorbing, arc constricting devices, which appreciably modify the circuit during the interruption process to force an early current zero when interrupting high magnitude faults. By comparison, expulsion and other types of non-current limiting fuses do not constrict the arc to the same degree and therefore do not significantly modify the circuit during the interruption process. As such, they wait for a normal current zero to occur before interrupting the circuit. Current limiting fuses, when interrupting overload and lower level fault currents, well below their maximum interrupting rating, may also function as non circuit modifying devices.

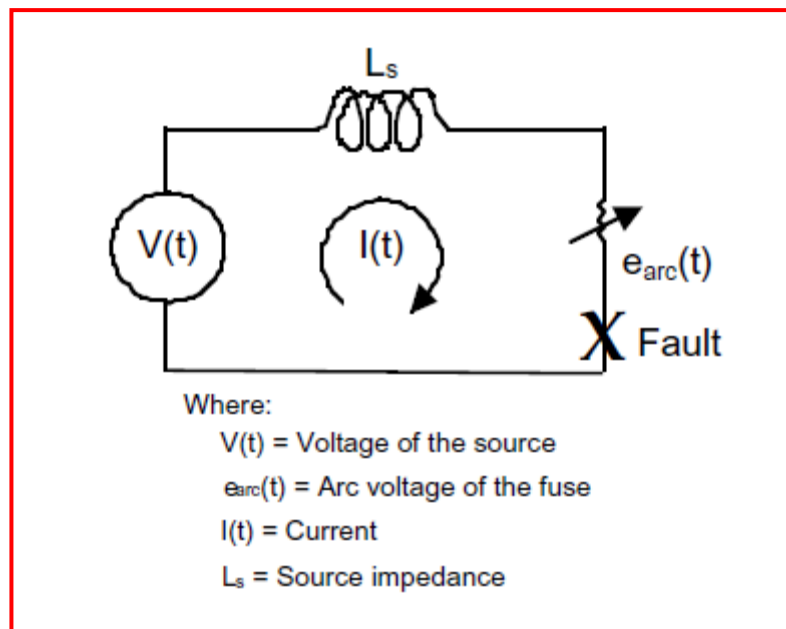


Figure 2—Simplified fault-current circuit

The interruption process begins upon melting of the fuse element and establishing of an arc across the associated gap. The ability to modify the circuit during the interruption process is a function of the arc resistance and associated arc voltage of the fuse once it has melted. The effect may be demonstrated with the aid of the simplified fault circuit in Figure 2. The voltage of the source is designated $v(t)$. Generally, one can assume that the primary impedance of this source is reactive and is based upon its inductance L . The arc of the melted fuse element has some variable magnitude of resistance and associated arc voltage, $e_{\text{arc}}(t)$. Two basic equations can aid in understanding the interactions. The loop equation can be written as Equation (1).

$$v(t) - e_{\text{arc}}(t) = L \, di/dt \quad (1)$$

Accordingly, the introduction of a relatively low arc voltage has little circuit modifying effect. When solved for current we have Equation (2).

$$i(t) = 1/L \int [v(t) - e_{\text{arc}}(t)] \, dt \quad (2)$$

This equation illustrates the following concepts:

- a) The current is proportional to the area under the voltage traces, specifically, their difference. The inductance provides a stored energy and the necessary voltage to sustain the current even though the instantaneous arc voltage of the fuse may momentarily exceed that of the source.
- b) A higher source voltage will yield a higher prospective fault current.
- c) A higher fuse arc voltage sustained over time will result in greater limitation of that fault current.
- d) Current is inversely proportional to the inductance, and therefore, a smaller inductance will produce a higher available prospective fault current.

Figure 3A and Figure 3B depict idealized arc voltages of the two primary fuse types. Figure 3A is that of the non-circuit-modifying (non-current-limiting) fuse with a relatively low arc voltage. This figure indicates that the fuse has not forced a change in current zero. The occurrence of a second loop of fault current is dependent on the fault-current magnitude, the fault-initiation timing, and the fuse size. Figure 3B is that of the circuit-modifying (current-limiting) fuse.

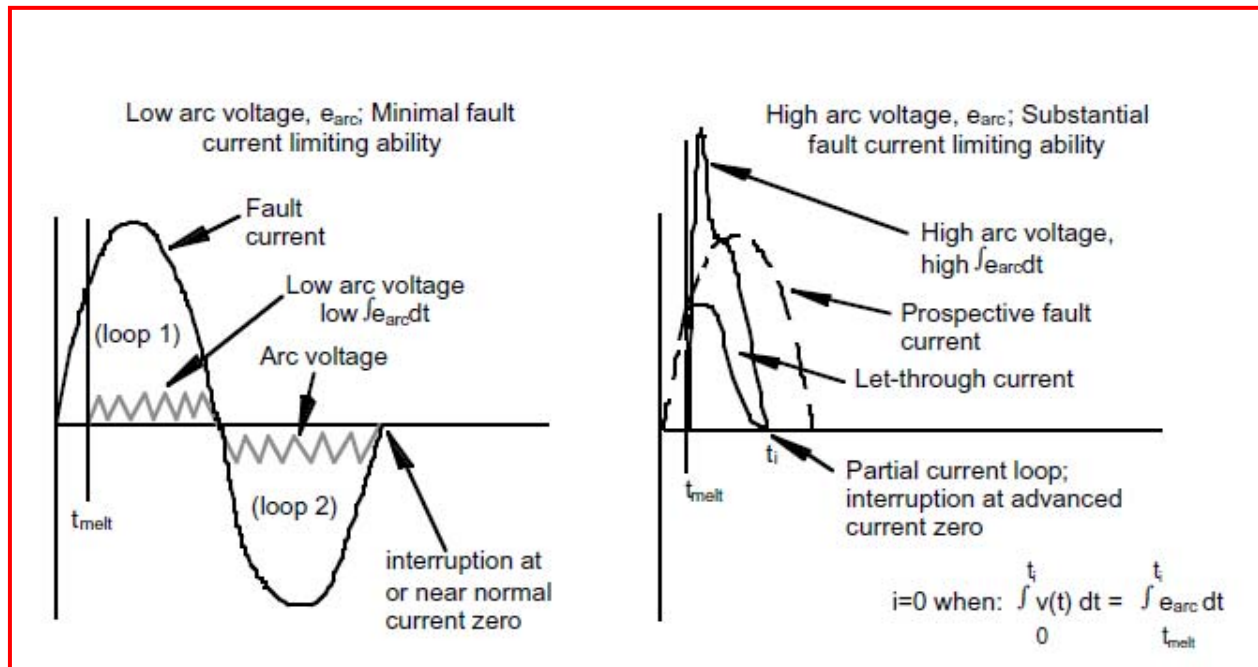


Figure 3A—Low arc voltage and $\int e_{arc} dt$ Figure 3B—High arc voltage and $\int e_{arc} dt$

3.6.1 Interruption without circuit modification

Expulsion and other types of non-current-limiting fuses have been defined as low-arc-voltage devices, which do not appreciably modify the circuit during interruption. By virtue of the low arc voltage, these devices do not significantly limit the magnitude of the fault current. Instead they conduct to a normal current zero for the existing circuit conditions and recover dielectrically at that time to achieve an interruption.

Since the current zero does not coincide with a voltage zero of the source, the fuse must recover against a TRV of that system. In theory, the TRV can reach a level of twice the power frequency recovery voltage. For interruption to occur, sufficient gap length and deionization must be achieved. Depending on the interrupting characteristic of a particular fuse, the interruption may or may not occur at the first current zero.

Figure 4 and Figure 5 depict interruptions at normal current zeros, after which a TRV arises. These circuits are not modified by the interrupting device. This is typical of interruption by expulsion and other types of non-current-limiting fuses; interruption of current-limiting fuses in the non-current-limiting mode (melt times greater than .01 s) also typically interrupt in this manner. The following conditions are met for interruption at normal current zero:

- a) Essentially the full magnitude of fault current has passed (see Figure 3A).
- b) The energy stored in the circuit's inductance has been returned to the source and absorbed by the system (and fault) resistance. It is now virtually zero.
- c) The system voltage at interruption is at some substantial value, typically near the maximum.
- d) As the arc chamber of the fuse recovers dielectrically, it must withstand the TRV of the system, which is now imposed across its terminals.

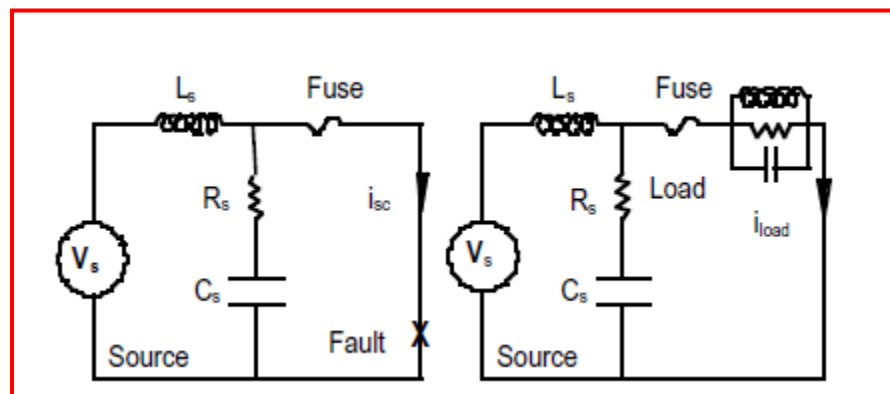


Figure 4A—Fault circuit Figure 5A—Load and overload circuit

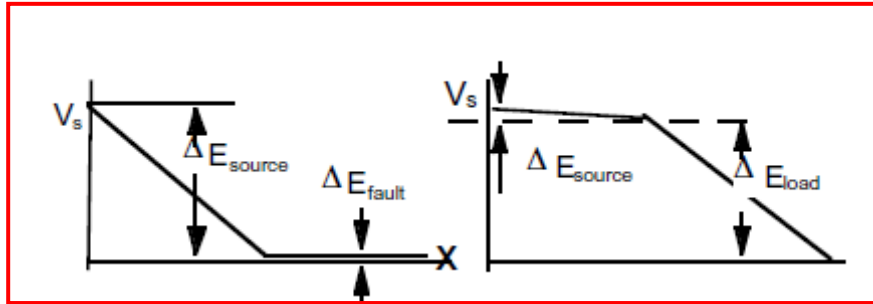


Figure 4B—

Figure 5B—

Voltage drop along circuit when current zero is reached

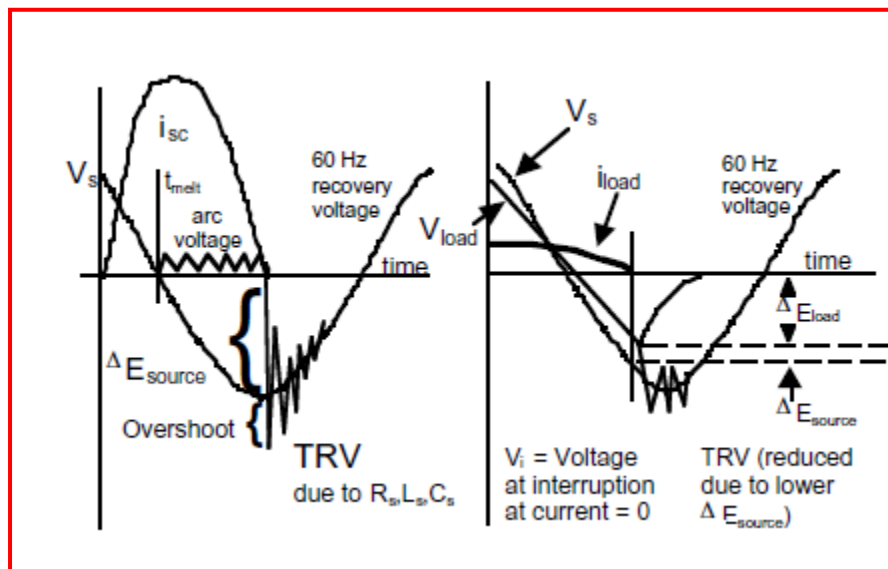


Figure 4C—

Figure 5C—

Current interruption and recovery voltages

(circuit is not being modified)

3.6.2 Interruption with circuit modification

Figure 6 shows how the circuit is interrupted by a current-limiting fuse having a high arc voltage. The arc is highly resistive, though non-linear with respect to current. If the resistive arc impedance is substantially greater than the system inductive impedance, a dynamic condition is established during the interruption process whereby the power factor of the circuit changes from being primarily inductive to primarily resistive. The current is thereby shifted back toward becoming more in phase with system voltage.

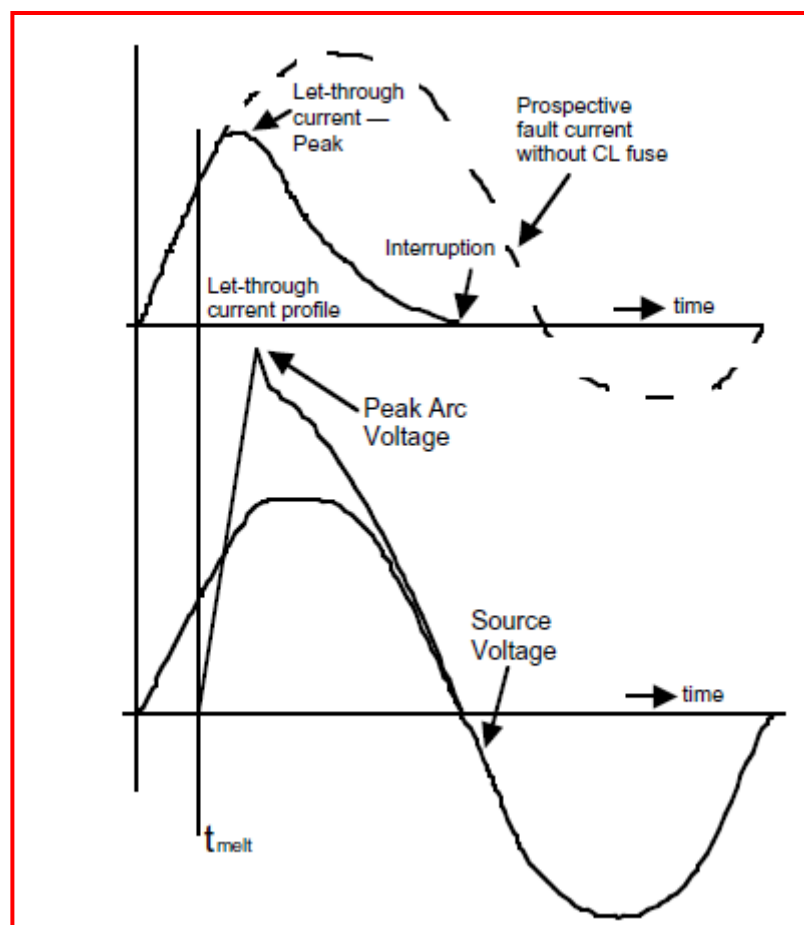


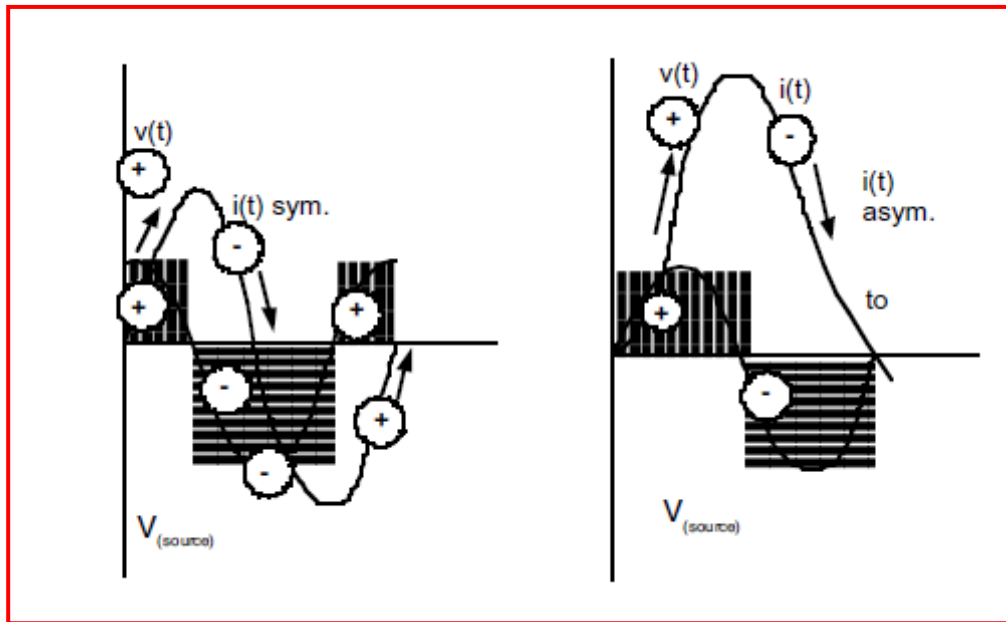
**Figure 6—High current operation of a current-limiting fuse,
with resulting circuit modification**

If we now apply the principles of Equation (2), the large area under the arc voltage curve of Figure 3B when subtracted from the area under the system voltage curve illustrates why there is a limitation of current and subsequent reduction to zero, coinciding generally with the voltage zero. At this newly “created” current zero, the following conditions have been reached:

- a) The system voltage is close to zero.
- b) The stored energy of the inductance has been absorbed, primarily by the fuse, and is now at zero.
- c) The fuse arc voltage is zero.
- d) No significant TRV will develop.
- e) The magnitude of fault current has been limited to a peak value only slightly higher than the instantaneous value at which the fuse begins to arc.

The preceding example indicated an asymmetrical fault, normally the worst case condition for a current limiting fuse, since it has to interrupt against an increasing supply voltage. IEEE Std C37.41-1994 specifies worst case conditions during fuse interruption. A prospective fault current may be symmetrical or asymmetrical depending on the fault initiation point in time on the source voltage wave. This is depicted in Figure 7A and Figure 7B. Note from Equation (2) that the fault current, through a primarily inductive impedance, is related to the integral of the voltage (the area under the voltage trace). The prospective current crest for a fault initiation at a voltage zero (See Figure 7B) may be up to twice that of a fault initiated at a voltage crest (see Figure 7A). The criteria for circuit modification during interruption remain essentially the same in both cases.

We see that the fault current characteristics can be modified by controlling the arc voltage of a fuse. This is a function of the fuse design, which is expanded upon in 3.7.1.1 through 3.7.1.8.



Note: Rise of current corresponds to positive (+) area under $v(t)$;
 Decay of current corresponds to negative (-) area under $v(t)$

**Figure 7A—Symmetrical
 short-circuit current**

**Figure 7B—Asymmetrical
 short-circuit current**

4.6 Fuse construction and operation

4.6.1 General

In the preceding paragraphs, arc voltage has been shown to be ~~a good~~ the primary criterion ~~to~~ compare the two basic fuse that differentiates various types of fuse. Table 2 ~~lists the fuse types and~~ compares other characteristics (under high-current-interrupting conditions) for various types of fuse.

Table 2 — Fuse characteristics and types of fuses

Type of Characteristic	Expulsion, vacuum, oil fuse cutout, SF ₆	Current-limiting, commutating, current-limiters, triggered fuses
Arc voltage	Lower	Higher
Circuit modifying	No	Yes
Current zero shifting	No	Yes
Max. interrupting current	Lower	Higher
Let-through current	Full available current	Current is limited
Fault duration	One loop (1/2 cycle) or more	1/8 to 1/2 cycle
Energy absorbed by fuse	Small amount	Substantial amount
~~Let-through~~ Clearing I^2t	Substantial	Small
Recovery voltage	Transient—up to twice power frequency crest	Equal to power frequency crest
Sub-classifications		Backup, general-purpose, full-range (apply to current-limiting only)
Continuous operating loss	Low	Higher for standard CLF; Lower for commutating current-limiters and triggered fuses
Continuous current rating	Higher	Lower for standard CLF; Higher for commutating current-limiters and triggered fuses

4.6.2 Current-limiting fuses

4.6.2.1 General

The effects of high-magnitude arc resistance and arc voltage and how they act to modify the fault circuit were reviewed in 4.5. Subclause 4.6.2 reviews the means by which this resistance and arc voltage are achieved and controlled in the design of current-limiting fuses. It also reviews various types and classes of these devices.

4.6.2.2 The fusible element and establishment of high arc voltage

The conducting, fusible elements of current-limiting fuses are commonly made of high conductivity materials such as silver or copper, which are supported within the fuse body and surrounded with high-purity quartz sand. [A section of a typical current-limiting fuse element is shown in Figure 3a.](#) When a current-limiting fuse melts at high fault currents the conducting element is segmented into many portions. This segmenting will occur at holes or notches that form restrictions in the current path of the conducting elements. These restrictions are common in higher continuous current designs. Uniform cross section elements (such as wire elements), common in lower continuous current designs, melt and form a multiplicity of bead-like segments. The melted portions of the element are vaporized and diffused into the surrounding sand. At each segment an arc will form. The sum of the voltage drop [components](#) of the arc (anode, cathode, and positive column voltage) are referred to as the arc voltage. The arc voltage of a current-limiting fuse is the sum of the arc voltages of the individual arcs. By comparison, expulsion and other types of non-current-limiting fuses generally employ one arc gap.

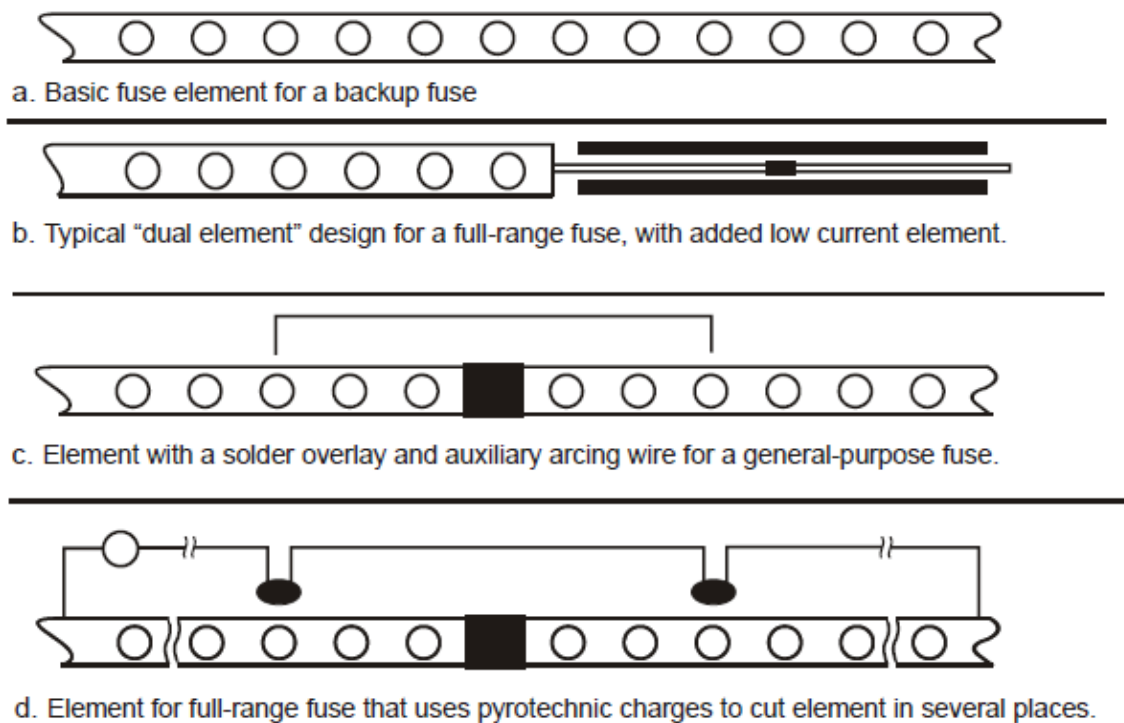


Figure 3—Construction features typical of various types of current-limiting fuse elements

In the case of a current-limiting fuse, the arcs are highly confined, constricted and cooled by the surrounding sand. This constriction and effective cooling leads to a high arc voltage, and a high ratio of arc resistance to arc length, which, together with substantial element lengths leads to a high arc resistance. This greatly impedes the continuing flow of fault current. The surrounding sand is melted by the intense heat of the arc, thus absorbing large amounts of energy. If the arc voltage from one melted point is multiplied by the number of segments formed in the fuse, we find that a very substantial arc voltage can be produced. Immediately after melting, the arc voltage is primarily a function of the number of melted segments and associated arcs. The peak arc voltage occurs shortly thereafter and is also a function of arc length, as well as the number of arcs.

If we refer back to Figure 2B, we can see how the magnitude and the area under the arc voltage curve determines how quickly the total current can be reduced and the current zero moved. The fuse design should maintain the high arc voltage during the interrupting process to maximize the current reduction and limit the fault damage. This is made possible by continued burn back of the element between the segments and continued heat transfer from the molten and vaporized fuse element into the sand. Because of the high resistance imposed by the current-limiting fuse, the current is brought nearly back into phase with the system voltage. In time, the remainder of the fuse element may melt to form a single arc, [reducing arc voltage somewhat. Also](#), increasing arc length only partly compensates for the reduced heat transfer to the now heated surroundings, so that the arc voltage tends to decrease with time until the arc ceases to exist. At this point, resistance increases rapidly, and the fuse must withstand a recovery voltage equal to system voltage.

4.6.2.3 Overvoltages

The insulation requirements of any electrical system and apparatus impose a limitation on the permissible magnitude of an arc voltage. Table 3 gives arc voltage limits specified in ~~ANSI~~ [IEEE Std C37.46 and IEEE Std C37.47-1981](#).

Table 3— Maximum permissible overvoltages for distribution-class and power-class current-limiting fuses

Rated maximum voltage (kV, RMS)	Maximum Peak Overvoltage (kV ~~Crest~~ , <u>peak</u>)			
	From ~~ANSI~~ <u>IEEE Std</u> C37.47-1981		From ~~ANSI~~ <u>IEEE Std</u> C37.46-1981	
	Fuse rated current through 12 A	Fuse rated current over 12 A	Fuse rated current through 12 A	Fuse rated current over 12A
<u>2.54</u> – 2.8	13	<u>9</u>	~~3~~ <u>13</u>	9
<u>5.08</u> – 5.5	25	18	25	18
8.3	38	26	38	26
15.0 – <u>17.2</u>	—	—	68	47
15.5 – <u>17.2</u>	70	49	70	49
<u>23</u> (~~21~~ -22)	~~117~~ <u>105</u>	~~70~~ <u>72</u>	<u>105</u>	<u>72</u>
25.8	—	—	117	81
27	123	84	<u>123</u>	<u>84</u>
38.0	<u>173</u>	<u>119</u>	173	119

Control of the arc voltage is accomplished by limiting the [element length and the number of arc initiating restrictions](#), and subsequent arcing segments, in ribbon element fuses. For a wire element fuse the arc voltage is controlled essentially by its length [and diameter \(multiple series sections of different diameters can be used to control arc voltage\)](#). As seen in Table 3, higher arc voltage limitations are permitted for the lower continuous current fuses where wire designs are prevalent. [However, it should be borne in mind that the permitted high values usually persist for a much shorter duration than do the lower values produced by higher current rating fuses.](#)

Accordingly, the permissible peak arc voltages are approximately three times the system rms voltage for fuses with rated currents over 12 A and approximately five times rated rms voltage for fuses with lower rated currents. Experience has shown this is an acceptable number complying with insulation requirements while resulting in rapid current limitation and relatively low energy let-through during the interruption process.

[Consideration of peak overvoltage can be important when applying current-limiting fuses and lightning arresters on the same circuit \(see 7.5\). The overvoltage produced by a current limiting fuse could cause the arrester to begin to conduct, placing thermal stress on the arrester. The values detailed in Table 3 result in a level of stress low enough for the arrester to withstand. The lower voltage, longer duration voltage peak for higher current rating fuses and the higher voltage, shorter duration voltage peak for small current ratings have demonstrated, through testing and years of field experience that arresters and current-limiting fuses work well together.](#)

4.6.2.4 Heat dissipation

To obtain high arc voltage during interruption, current-limiting fuses use relatively long fuse elements with comparatively high resistance, as contrasted with the shorter element used in expulsion and other types of non-current-limiting fuses. The continuous losses of the former are, therefore, higher. This may limit their use in environments where heat dissipation is a problem. This is covered in greater detail in Clause 6.

4.6.2.5 Fuse [voltage](#) versus system voltage

Successful interruption by a current-limiting fuse requires that the arcing resistance of the fuse be sufficient to modify the fault circuit and create a timely current zero. This means that the fuse element and fuse arc voltage must be configured for a particular circuit voltage. A current-limiting fuse must never be applied such that it is required to interrupt a voltage higher than its rated maximum voltage. If it is applied at a higher voltage, the result is likely to be a failure to interrupt, usually accompanied by physical destruction of the fuse. Conversely, caution should also be used when applying current-limiting fuses at voltages substantially below their rating in order to avoid overvoltage damage to power system components. This is because certain fuse designs (particularly those employing wire type elements) produce arc voltages substantially independent of the applied voltages. Other designs, while producing a lower arc voltage at a reduced applied voltage, may still produce significantly higher arc voltage than fuses designed specifically for the lower voltages. Before applying fuses at voltages substantially below their rating, consult the manufacturer.

4.6.2.6 Energy absorption during interruption

A current-limiting fuse does not normally absorb maximum energy at the rated ~~maximum~~ interrupting current, but often at a substantially lower value of fault current. Under maximum fault conditions, the fuse element melts quickly and produces a sharp reduction of the available fault current, limiting the arc energy. [As the prospective current is reduced \(at the same \$X/R\$ \), circuit inductance is higher and the circuit stored energy at the start of arcing \(\$\frac{1}{2}L i^2\$ \) is higher.](#) Under ~~lower fault~~ [severe circuit](#) conditions, particularly those at voltage zero initiation (high asymmetry), melting and burn back are slower while the system voltage ~~remains high~~ [is near its maximum at the start of the arcing, reducing the rate of decrease of current.](#) Although the [peak](#) ~~available~~ current