THE IMPACT OF HV FUSE DESIGN AND APPLICATION ON THE DEVELOPMENT OF INTERNATIONAL STANDARDS

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Abstract: All fuse types that presently exist were once used in a new application for the first time. The process whereby such a new fuse and application becomes sufficiently recognized that its special requirements are covered in standards, both national and international, is both complex and somewhat arbitrary. The objective of this paper is to discuss this process as it relates to certain fuse designs and to explain why differences often exist between national and international (IEC) standards.

Keywords: (high voltage fuse, electric fuse, fuse standards, IEC)

1. Introduction

For a particular fuse application, there are three main requirement areas that should be considered, and so warrant inclusion in a standard. The first area involves the ability of the fuse to function under normal conditions. When there are no fault or overload conditions present, it must be able to carry current without any deterioration that might impair its ability to later perform an interrupting function. In addition, as a device that produces heat, it must not cause thermal damage to other equipment, and when the whole fuse includes insulating supporting means, it must meet appropriate dielectric requirements. Physical requirements (size, suitability for liquid immersion, etc.) also fall into this area. The second area relates to the ability of the fuse to be able to successfully interrupt all fault current conditions that it is required to interrupt (that is for the fuse to perform its primary intended function). The third area relates to the ability of a fuse to coordinate correctly with other protective devices in the system. Standards address these areas with testing requirements and application advice. The ability of a fuse to meet requirements in all of these areas must be considered when determining the suitability of a particular fuse design for an application.

The sets of circumstances that lead to fuses being developed to meet a particular market need are quite varied. At one extreme is the situation where an existing design is used for a new application that requires no testing and perhaps only a minor mechanical change to the fuse. An example of this may be a fuse requiring different mounting hardware. If this does not affect the fuse operation, and the conditions of the application do not demand more capability from the fuse, no additional tests are necessary. At the other extreme is the situation where a new fuse design is needed because no existing design is suitable. The new requirements may be physical (e.g. smaller in length or diameter), electrical (e.g. fault currents having higher TRV values, X/R, or circuit voltage), or environmental (e.g. higher ambient temperature, use in an enclosure, or immersion in fluid). Circumstances such as these would obviously require extensive testing to demonstrate the capability of the new design.

Between these two extremes are conditions that may require only limited additional testing, perhaps where an existing design is used in a new application. Additional tests could be very simple, for example thermal tests to establish a new fuse current rating, or complex, for example the need for capacitive current interrupting tests on a fuse to be used for capacitor protection that has previously only been tested with inductive currents.

If one has a completely new application, it is easy to see why not all of the tests needed to ensure a fuse will be suitable are in an established fuse standard. However, when a new fuse is developed for an existing, established, application, it would be easy to suppose that that all of the necessary testing to qualify the design does appear in the relevant fuse standards. Unfortunately, this is not necessarily true, and to understand why requires a knowledge of what standards are, and how they are developed. In most cases, tests have been added to standards based on field problems, or problems discovered in the development of a basic fuse type. As a result, one can say that, in general, existing standards were written for specific designs of fuses, and for specific applications. However, this normally requires several manufacturers to suggest changes. Suppose a manufacturer discovers that their fuse design needs a particular test to ensure its suitability for an application. This may not be reflected in the standard, either because they do not propose such a test for inclusion (perhaps thinking it unique to their design) or because a proposal from them was not accepted by the standards making body.

Presently, there tends to be two major "schools" of thought concerning the writing and maintaining of standards. The first holds that only the simplest tests, that everyone can agree applies to all fuses, should be included in standards. The premise for this approach is that, since testing just “to the standard” does not and can never relieve a designer of the responsibilities of thoroughly understanding his or her product, and hence carrying out the appropriate testing, an elaborate standard is unnecessary. This could be considered the "old school" approach, and, since the premise is undoubtedly correct, is valid in a situation where all manufacturers and users are very knowledgeable. Members of the second "school" acknowledge that standards can never contain all of the testing necessary for a manufacturer to know that their design is good. However, they hold that, since users tend to be less knowledgeable today (and in many parts of the world enrolment in electrical power degrees has declined significantly in recent years), it is appropriate that standards contain more application information and more comprehensive testing requirements, to cover known areas of concern. The content of any particular national or international standard tends to lie between these two extremes, reflecting the view of the majority of those involved with its development. Generally, users tend to fall more into the second "school", and manufacturers are somewhat split between them.

The object of this paper is to give illustrations of how fuse developments and applications have produced changes in International Electrotechnical Commission (IEC) standards, based on input from certain national standards. However, it will also illustrate why some proposed changes have not been reflected in IEC and so why national and international standards are not always in agreement.

2. The standard development process

The basic process whereby standards are developed may be illustrated by an entertaining (and possibly apocryphal) story from the earliest days of current-limiting fuses. It is said that as maximum fault currents rose, CL fuses were unable to successfully interrupt the higher currents. A standard was therefore developed to require fuses to be tested to determine their maximum interrupting (breaking) current (now also called I_1 or Test Duty 1). At high currents, failure generally tends to be of a bursting nature. This is because the higher the prospective current, the higher is the current at melting. This produces greater shockwaves from material vaporization, and energy absorption by the fuse occurs over a shorter time. It was therefore easy to see why a fuse might experience problems at higher currents, and solutions included making the fuse body and end caps stronger. When failures continued to be experienced, even though the maximum interrupting rating of the fuse had not been exceeded, it was discovered that current-limiting fuses were also sensitive at a lower value of current where absorbed (arc) energy was actually higher. This was the now well-known (although perhaps not well understood) I_2, or TD2, test condition. For some designs, this condition was more severe than the I_1 condition. At the time, this was not intuitively obvious, despite the fact that it is relatively simple to calculate that the system stored energy at fuse melting (most of which must be absorbed by the fuse) actually increases as fault currents decrease, at least until just before the fuse no longer current limits. However, since for many designs the stored arc energy represents less than half of the actual arc energy, the point on the voltage waveform when a fuse begins to arc makes a big difference to the additional energy supplied from the source during arcing. This increases the current that produces maximum arc energy to a value higher than that producing maximum stored energy. Higher arc energy produces larger diameter fulgurites (the fulgurite is the insulating glassy material produced when an element arcs and melts quartz sand filler material). Again speaking generally, failures in the maximum arc energy region tend to be of a thermal nature, or for spirally wound elements, of a turn-to-turn bridging nature. The point here is that while, in retrospect, it is relatively easy to predict what should be realized about the behaviour of a new fuse design, at the time it is much less obvious. This has proven the case in many other fuse developments; it has required service experience (and sometimes service failures) to understand the complexities of what, to too many people, is considered a relatively simple device, the fuse.

The above illustration of the standards making process points to the main reason why national and international standards differ. When a group gathers to produce or update a standard, the primary driving force is their own experience with the fuse designs with which they are familiar. The worldwide production of High-Voltage fuses, while representing a substantial industry in terms of units and economic value, is never the less quite small when compared to many other parts of the electrical industry. As a result, not many countries have indigenous fuse design and manufacturing operations. It is therefore not unusual for only a few countries to send experts to participate in the development of IEC fuse standards, even though much wider fuse usage exists in countries that are not represented. Furthermore, participation has been declining. For example, in the last ten years, there have been four meetings of the IEC High-voltage Fuse subcommittee SC32A with two of them in the last five years. Although 21 countries sent representatives to one or more of these meetings, only six were represented at both of the last two meetings! Most of the actual work is done in the influential working group/maintenance team meetings (those responsible for actually writing the text submitted for national committee voting). In the last five years, there have been six of these meetings, but only seven countries have been represented. With a small number of experts, it is often difficult for consensus positions to be established when new ideas are introduced, because practices are indeed different in different parts of the world. As a result, IEC standards tend to represent the minimum requirements for the majority of fuse types. However, this “lowest common denominator” approach may not represent an adequate test requirement for all fuse types and applications. With increasing “globalisation”, there comes a desire to use a common standard everywhere, but even IEC itself, with its recent rulings on “Global Relevance”, recognizes that a “one size fits all” approach does not necessarily represent the best possible solution everywhere. In fact, although the use of a single common standard has many obvious advantages, in a significant number of applications it can be at best, unhelpful, while at worst, it may lead to fuses being used in applications for which they are unsuited and potentially hazardous.

In section 3, this paper seeks to illustrate how certain fuse design and application developments have led to changes in some national standards. Sometimes these changes have resulted in changes to IEC standards, while in other cases they have yet to be accepted internationally. For applications having requirements not presently covered by IEC standards, particular care must be taken if fuses are selected that have only been tested to IEC. Because the author is most familiar with IEEE and IEC standards, the comparisons made in this paper will be between these documents. Obviously, many other national standards reflect regional concerns, and may have relevance outside their immediate area of influence.

3. Differences in standards

3.1 Introduction

IEEE high-voltage fuse standards are developed, primarily, by representatives from the USA and Canada. However, the IEEE, as an international body, welcomes participation from any member. The IEEE fuse standards therefore tend to represent, not only practice in the USA, but also practice throughout the world where North American-style electrical distribution systems are used. After development, however, recognition as an American National Standard is obtained from ANSI (American National Standards Institute Inc.). The IEC and IEEE standards to be compared are listed in “References”.

3.2 Publishing format

The most obvious difference between IEC and IEEE standards is the form in which they are published. While of no technical consequence, a brief explanation of the format differences is in order. IEC has two main fuse test standards, IEC 60282-1 [1] for current-limiting fuses and IEC60282-2 [2] for expulsion fuses. IEEE incorporates both fuse types into one testing standard, C37.41 [3]. However, this one standard is used in conjunction with other standards. C37.40 [4] covers Standard Service Conditions and Definitions, while C37.48 [5] and C37.48.1 [6] contain application information. Individual types of fuses have their own specification documents that contain information such as preferred values of current, voltage, and interrupting rating, arc voltage limits, etc. In addition, fuses are classed as either power or distribution class, depending upon the typical location where they are to be used. Power class tends to be used closer to a substation and is characterized by higher values of X/R for example. Specification documents are C37.42 [7] for expulsion type distribution class fuses and cutouts, C37.46 [8] for power class fuses (expulsion and current-limiting) and C37.47 [9] for distribution class current-limiting fuses.

3.3 Voltage rating

After format, possibly the most obvious difference between IEEE and IEC standards is in the voltage used to test fuses. In both IEEE and IEC standards, actual fuse interrupting tests are performed in single-phase circuits. However, for current-limiting fuses, IEC tests assume that all current-limiting fuses are intended for use in grounded wye three-phase circuits, while IEEE standards assume that many fuse types are intended for single-phase operation. This difference in approach can be traced to the fact that, at least at one time, most European fuses were used in three-phase circuits while many North American type fuses were used in single-phase circuits. IEC standard 60282-1 therefore requires that the high current tests (I_1 and I_2) be performed at only 87% of the rated voltage of the fuses. As specified in the application section of the standard, if a fuse is to be used in a single-phase circuit, or in a delta system, the rated voltage of the fuse should be at least 115% of the maximum applied voltage. In the case of IEEE standards, all distribution class fuses are tested with a voltage equal to the rated voltage of the fuse. For power class fuses, only the I_1 test is performed at 87 percent of the rated voltage of the fuse (at the full rated maximum interrupting current) and then the test is repeated at 87 percent of the rated maximum interrupting current, but at the full rated maximum voltage. A power fuse is therefore suitable for single-phase use providing the available fault current does not exceed 87% of its rated interrupting current. Many current-limiting fuse designs combine these two tests, using 100 percent of both rated maximum voltage and rated interrupting current as is done for distribution class fuses. Expulsion fuses tested to IEC are allowed the same option (two sets of I_1 tests) if the fuse is only to be used in three-phase circuits, otherwise they are tested at full voltage.

Although these testing differences are quite confusing, in the past this has not been a problem. IEC standards have two columns of preferred standard voltages, series I and series II. The first is noted as being based on practice in Europe, and the second on practice in the U.S.A and Canada. Because most fuses tested to IEC have used the European voltages, which are generally higher than the North American values, the nearest higher voltage rating European fuse will normally have been tested to as high or higher voltage than a North American fuse. For example, compare preferred series II voltages of 8.3kV and 15.5kV with series I voltages of 12kV and 17.5kV. Even though I_1 and I_2 tests for current-limiting fuses would be performed at 10.44kV and 15.2kV for the European fuses, these values exceed, or are very close, to standard North American voltages.

A serious problem could arise, however, if a manufacturer were to test a fuse using the IEC standard, but picking a North American preferred voltage (series II) and using 87% of this voltage as the I_1 and I_2 test voltages. In this case, a misunderstanding on the part of the user could lead to service failures. For example, it is common to use an 8.3kV North American fuse (tested to IEEE) on a single-phase circuit based on 12.47kV or 13.2kV grounded wye three-phase circuits. The maximum permitted line-to-neutral voltages on these two circuits equals 7.62kV and 8.07kV respectively. If an 8.3kV fuse were tested to IEC, a single fuse would only have been shown to be capable of interrupting 7.2kV, and so may experience difficulty with a 6% or 12% over-voltage in the two circuits, respectively. A similar situation exists with many other standard North American system voltages. This is because the standard North American fuse voltages were chosen to correspond to standard system voltages assuming that the fuses would be tested using North American testing practices. This is not an unreasonable assumption! Here is a case where, in an attempt to make a European standard into an International standard, the melding together of two different philosophies may lead to incorrect application if the user does not fully understand the subtleties of the IEC standard, and does not read the “fine print”!

3.4 Extended recovery (maintained) voltage

3.4.1 Introduction

During fuse interrupting performance tests, recovery voltage is maintained across the fuse for a minimum specified period after current interruption. This is to show that current flow will not be re-established, and that the fuse will be able to withstand system voltage for an extended period. Obviously, this duration must be sufficient to achieve its aim without being any longer than necessary (due to the high cost of test time). All fuse standards have a specified duration that depends on the type of fuse and the type of test. For example, IEEE standards for current-limiting fuses have durations of one minute for the I_1 test and 10 minutes for the I_2 and I_3 tests (I_3 being essentially the lowest current at which a fuse must demonstrate interruption capability). In IEC standards, current-limiting fuses have durations of only 15 seconds for the I_1 test and one minute for the I_2 and I_3 tests. For non-dropout expulsion type fuses (fuses that remain connected in the circuit after operation) both IEC and IEEE require 10 minutes for test currents higher than 20% of the rated interrupting current and one minute for the two required lower current tests. Dropout fuses require only 0.5 seconds or the dropout time, whichever is greater. The IEC expulsion fuse standard has the same values as the IEEE standard because it was revised in the mid 1990s to essentially lineup with IEEE C37.41. However there is clearly a substantial difference between the IEC and IEEE standards for current-limiting fuses. It could be argued that, if the longer duration is necessary for a valid test, the testing of some fuse designs to IEC standards would seem to be inadequate, or alternatively, manufacturers testing to IEEE are wasting a lot of money! To understand why this difference exists, and what steps have recently been taken to narrow the gap, requires first a study as to why, over 30 years ago, the IEEE standard was changed from the values still used by IEC.

3.4.2 Changes to the IEEE fuse standards

Specified recovery voltage durations were first established in an era when virtually all current-limiting fuses used ceramic or glass bodies, ceramic cores, silver elements, quartz sand, and copper or brass end caps. Generally, these fuses were what would now be classed as backup fuses. With this type of design, electrical breakdown tends to occur immediately after interruption, or not at all. Therefore, providing the fuse body did not burst due to thermal stress (usually within about one minute), a brief recovery voltage period was enough to show that a fuse would not then fail by dielectric breakdown. This was valid even if the fuse body temperature continued to rise for some time after current interruption as heat was gradually transferred from the fulgurite through the filler material. Most early fuse designs contained virtually no components that could thermally deteriorate over time.

In the USA, there was a quicker adoption of different fuse construction materials than in Europe. This was caused by factors that included the high cost of ceramics, the desire for more compact fuses, and a requirement to be able to interrupt lower currents (general-purpose and full-range fuses). Application differences encouraged the development of different fuse types. For example, a lower domestic utilization voltage (110V rather than the 240V in Europe) and greater distances between customers led to the widespread use of small transformers containing current-limiting fuses. Typical materials used for current-limiting fuses in the USA have included glass-reinforced epoxy fuse bodies, mica-based materials, gas evolving materials, and plastics for cores, and, to assist in current interruption, silicone rubber and various filler additives. While many of the newer designs performed very well, during the 1960's a series of service problems were experienced in North America with several common types of current-limiting fuses from a variety of manufacturers. Most of these fuses were characterized as having components made from materials that included organic matter (that is materials incorporating the element carbon in their chemical structure) and/or gas evolving materials in which one of the gasses included water vapor. After extensive testing it was determined that a possible failure mode of this type of fuse was re-establishment of current flow some period of time after an apparently successful current interruption. That is to say, failure was occurring after the end of the brief specified duration of recovery voltage that had been used to certify the designs. Although several different failure modes were discovered (see 3.4.3), in all cases the obvious solution was to increase the specified duration. This allowed time for fuse components to begin to cool, and for any component deterioration caused by heat flow to occur, before voltage was removed from the fuse. The recovery voltage duration had to be a compromise between assuring that appropriate "deterioration" had occurred while minimizing the testing cost and inconvenience. For the reasons outlined in 3.4.3, durations of 10 minutes were chosen for Test Duties 2 and 3. In the current-limiting region, failure phenomena were linked primarily to high component temperatures. Because I_2 generally produces more heat than I_1, a value of only 1 minute was chosen for Test Duty 1. These changes to the IEEE recovery voltage duration were adopted in 1969. Experience has confirmed that fuses tested this way do not then breakdown after an operation in normal service.

3.4.3 Choice of recovery voltage duration

Several potential failure mechanisms were identified. One appears to be the production of carbon from organic materials in the fuse body (with no other organic material in the fuse). This carbon is not produced until a particular body temperature is reached, and the time for this to occur depends on the fuse design. The most critical factors would appear to include the heat generated in the fulgurite (arc energy), the distance between the fulgurite and the fuse body, the thermal conductivity of the filler material, and of course the breakdown temperature of the organic material. Tests have shown that peak body temperatures typically occur between about 1 and 4 minutes after current interruption. Testing experience has shown that the majority of breakdown failures from this mechanism occur during the first 5 minutes of recovery voltage, although a small number of failures have been reported between 5 and 10 minutes [10]. A recovery voltage duration of 10 minutes therefore appears to be appropriate, incorporating some safety margin. IEEE and IEC standards for expulsion fuses permit the 10 minute recovery voltage period to be terminated if the leakage current through the fuse is monitored, and has been below 1mA for at least two minutes. However, this technique is not suitable for current-limiting fuses (and is therefore not permitted). For the type of failure mechanism described above, leakage current is typically very low for most of the period before breakdown. This is because the decomposition process is not initiated by heat from any leakage current, but rather from thermal conduction within the fuse. When failure does occur, the leakage current usually increases for less than a few seconds before complete breakdown occurs. This failure phenomenon is most common with I_2 tests, but could occur for I_3 tests where extensive arcing occurs, and/or where fuse melting time is very long, particularly if element temperatures are not limited by the use of low melting point materials (e.g. "M" effect).

The physics of this failure mechanism appears not to have been investigated and explained. Observation suggests that although the carbon must come from the fuse body, the final conductive path is not usually along the body, but rather along the fulgurite surface. One mechanism that has been postulated by the author is that breakdown of the body material, at temperatures between about 250ºC and 400ºC, produces a gas containing carbon atoms. Since the temperature of the fulgurite is much hotter, (quartz sand melts at approximately 1700ºC) a gas could further breakdown depositing carbon atoms on the fulgurite or the sand immediately adjacent to the fulgurite, ultimately producing a conductive path. This would appear to be an interesting phenomenon, worthy of study by a laboratory possessing the appropriate equipment.

Another failure mode that has been observed involves fuses that generate water vapor to assist current interruption. The water (often contaminated by decomposition products of the binders used to construct the gas-evolving materials) is deposited on the inside surface of the body. "Treeing" has been observed on this surface, ultimately leading to a steady increase in leakage current until failure. This has normally occurred within 10 minutes of fuse current interruption. The phenomenon has been observed for both I_2 and I_3 tests on fuses. Fuses using gas-evolving materials are usually classed as general-purpose or full-range.

A third observed failure mode occurs within fuse cores, even when the material from which they are made is inorganic. Inorganically bonded mica makes a very effective core material, since it can be punched very precisely. However, mica contains molecular water that is released at quite high temperatures. Some forms of mica product therefore have a temperature limit above which the release of water molecules causes the core to "puff up" (analogous to "popping" pop corn). It was discovered that the creation of what was, in effect, a hollow core could result in electrical breakdown in high stress areas of the core in certain designs. Since the failures occurred in the 1 to 10 minute time frame, they were discovered by development testing using the IEEE fuse standard and appropriate remedial action was possible. Obviously, if a core includes organic material, this could lead to problems if carbon was produced in a location and quantity that could lead to a breakdown. Such problems have been discovered by the extended recovery voltage test.

Based on the long and successful experience with the extended recovery voltage duration testing of IEEE standards, in the year 2000 the USA requested that such testing be included in IEC 60282-1 (it was already included in IEC60282-2). At the same time, elevated temperature testing for fuses in enclosures (discussed in 3.5) was also proposed. The USA felt that it was important for International Standards to reflect the concerns of the North American market, not just because we are members of the world community, but also because the same basic types of fuses and applications common in North America are in use in other countries around the world. It is certainly possible to postulate that "North American" type fuses, produced outside North America but intended for the same applications as fuses tested to IEEE standards, might only be tested to IEC standards. This could lead to equipment failures if the IEC recovery voltage duration was insufficient to show up a deficiency in the design. The USA's proposals to IEC became very controversial. A small number of European countries vigorously opposed them, although other countries, both inside and outside Europe were more favorably disposed to the suggestions. The positions taken by IEC participants tended to reflect their experience with designs that were most common in their country (or that they themselves manufactured). One basic argument against the proposals was that if certain existing designs were not experiencing field problems, it is an unreasonable burden to increase testing on all fuses because other designs and applications exist that do need more rigorous testing. Of course, this is a powerful argument against <u>ever</u> making changes to standards, and is only valid if certification requirements are such that all existing designs must be re-tested to a new standard. This issue points to a fundamental difference in philosophy between European and North American practices, and partially explains why, in the past few decades, the USA has embraced changes to standards so much more readily than Europe. It also explains why IEEE and IEC standards that were once so similar are now so different. This is discussed in 3.4.5.

3.4.5 Certification procedures

In the USA, two types of certification are common for high-voltage fuses. The first, limited primarily to industrial applications, and mostly to motor starter fuses, is UL recognition. Underwriters Laboratories Inc. conduct a thorough evaluation of a product, including observing all short-circuit testing and production testing before recognizing the product. UL examination is ongoing during the product's life. This is a long, rigorous, and expensive process. Electric Utilities do not use UL recognition (which applies mostly to higher volume low-voltage products). The other type of certification, used for all other HV fuses and applications, is "self-certification". In this, the fuse manufacturer performs testing, either at an independent laboratory or in their own facilities, and issues their own certificate of compliance. In Europe, the most common form of certification is to employ a "third party", usually a test laboratory such as KEMA. This tends to be more expensive than self-certification, although less costly than UL recognition. In addition, European customers are more likely to require re-certification to the latest standard. This is not the practice in the USA, where established designs are not re-certified unless required by a customer (which is uncommon unless problems have been experienced). Re-certification can obviously be an expensive proposition.

3.4.6 IEC proposal for extended recovery voltage

After many years of IEC debate in the maintenance team (MT3) and sub-committee (SC32A) responsible for IEC 60282-1, a compromise position has been reached. At the time of writing, a Committee Draft Vote (CDV) is in preparation for submission to the National Committees in mid-2003. The proposal is to change the recovery voltage duration **only** for fuses that contain critical amounts of organic material, and are therefore classed as "organic". The duration is increased to 10 minutes for backup, general-purpose, and full-range type fuses at TD2, and for general-purpose and full-range type fuses at TD3. To address the concern regarding re-certification, the <u>fuse manufacturer</u> is allowed to decide whether their product should be classed as "organic". Therefore, if a fuse contains organic or other material that could lead to breakdown after current interruption, the design is classed as organic and it would receive the more rigorous tests. However, if the fuse contains no organic material, or if it contains organic material but in such quantity or location that the manufacturer feels that the fuse is not likely to be subject to deterioration and breakdown, then it would not be classed as organic, and would receive only the usual testing. It is anticipated that a manufacturer would conduct sufficient testing during the development phase of a new design to determine whether the longer duration tests are necessary for the certification testing.

3.5 Elevated temperature testing

3.5.1 Introduction

Traditionally, standard service conditions for IEEE and IEC standards included an ambient temperature no higher than 40 ºC. In North America, the use of fuses in enclosures that subjected them to elevated surrounding temperatures or restricted cooling became common in the 1960's. Fuses are often used in transformers, where they are subjected to very significantly elevated surrounding temperatures. This practice was later followed in many other countries that used similar types of distribution systems. Other fuses, in both Europe and elsewhere, are used in switchgear subjected to solar radiation and high outdoor temperatures, or contained in "pods" or canisters that severely restrict heat loss from the fuse. Although thermal conditions for these applications are less severe than the transformer applications, service problems were experienced with fuses in many types of enclosures all over the world, usually due to misapplication. Clearly, changes in fuse standards to recognize these expanded service conditions became necessary.

3.5.2 IEC Response

In the early 1990's IEC responded to just the application aspects of current-limiting fuses in enclosures in what is now informative Annex F of IEC 60282-1 ("Determination of derating when the temperature surrounding the fuse exceeds 40 ºC"). The object was to determine the correct rated current for a fuse in an enclosure, so that it would not overheat, and so generate excessively high surrounding temperatures. It was felt that in this way no problems would occur (e.g. causing a backup fuse to melt at a current it could not interrupt). However, while this approach may be adequate for an inorganic backup fuse, in the USA it was felt that general-purpose and full-range fuses are often intended to be able to interrupt fault/overload currents. These currents may cause the fuse's surrounding temperatures to be higher than 40ºC before the fuse is required to interrupt. Even with a backup fuse, while it may not be intended to interrupt an overload current, overloading that produces high surrounding temperatures may also lead to insulation breakdown and a high fault current that the fuse has to clear. In IEEE standards it was felt that addressing only fuse derating was inadequate for their typical applications.

3.5.3 IEEE response

In response to problems in the USA and Canada, IEEE standards developed new application information <u>and testing</u> for "fuses in enclosures". This was first published for current-limiting fuses in 1980 and for expulsion fuses in 1991. Concerns over the effect of enclosure and/or elevated temperature on fuse performance were addressed in four main areas. The first area was that of the effect of changes in heat loss on the melting characteristics and current rating of the fuse, and was addressed with application information. The second area was that of elevated fuse component temperatures after current interruption, where the concerns were similar to those discussed in section 3.4. The third area involved the effect on general-purpose and full-range fuses, where long time melting currents could be reduced, possibly to values less than a fuse could successfully interrupt. These two areas were addressed with additional current interrupting tests. The fourth area involved sealing liquid submersible fuses to prevent leaks at elevated temperatures. This was addressed by thermo-cycling tests.

The concept of "rated maximum application temperature" (RMAT) was introduced. This is the highest surrounding fluid temperature, specified by the fuse manufacturer, for which a fuse is rated as suitable for use. It is the temperature at which additional interrupting tests are performed, and in the case of a sealed fuse, the maximum thermo-cycle temperature. Fuse tests at I_2 and I_3 are therefore specified at this elevated temperature, in addition to the usual tests at room temperature. In the case of a general-purpose fuse, a new (lower) I_3 current has to be used, one that causes melting in not less than one hour under the high temperature and/or restrictive cooling conditions. In the case of a full-range fuse, the I_3 current test is done only at the RMAT, but with the current to be interrupted determined as being lower than the lowest current that could melt the fuse at its RMAT. Testing is normally performed in an oven but if a particular enclosure subjects the fuse to more severe conditions, then the tests should be in that enclosure. The combination of fuse and enclosure is defined as a "fuse enclosure package" (FEP) and it is the responsibility of the FEP manufacturer to test the fuse in their enclosure, or to ensure appropriate tests have been performed.

It was found that, for most fuse designs, breakdown failures caused by elevated body temperatures at I_2 tended to be more common during this testing. The reason is that the final temperatures of the body and other components tend to be higher when the fuse starts off hot. This occurs despite the arc energy being slightly lower due to a reduction in melt I^2t. Because failures were found to be temperature driven, elevated temperature I_1 testing was considered unnecessary. It was found that the 10 minute recovery voltage duration was effective at catching these thermally induced breakdowns, although when the fuse is in a close fitting enclosure, the greater thermal mass of the fuse and container tended to push the fuse breakdown time closer to ten minutes than those occurring in open air.

3.5.2 IEC Proposal

As with the extended recovery voltage duration, the USA felt that the absence of any elevated temperature testing in IEC meant that a large number of worldwide applications were not being adequately covered by an "international" standard. The USA therefore proposed additional "fuses in enclosure" testing for current-limiting fuses, based on the IEEE standards. As discussed earlier, the US proposal met with a lot of opposition from Europe. Since certain European designs used primarily inorganic materials, some felt that any elevated temperature testing was unnecessary, except in the case of full-range fuses. Here, it was recognized that elevated temperatures would reduce the lowest current that a fuse had to interrupt, increasing test severity. However, this had already been addressed in the 1997 edition of IEC 60282-1. The IEEE elevated temperature full-range fuse TD3 testing had been incorporated into IEC for those fuses intended for use in a surrounding temperature over 40 ºC. This was in addition to a more simple room temperature test for full-range fuses intended for use under 40 ºC. Again, after much discussion, a compromise proposal is being introduced into the CDV. At the time of writing, it is proposed that additional testing only apply to "organic" fuses. Again, organic is to be determined by the fuse manufacturer, based on whether they feel such additional testing is necessary. Additional I_2 testing is to be specified at the fuse's RMAT for backup, general-purpose and full-range fuses. However, a further compromise was demanded by some countries. This was that the additional testing only applies to fuses in applications where the fuse itself is not the primary source of heating for the enclosure. Therefore, applications such as fuses in transformers, or switchgear subject to solar radiation, would require the additional testing. However, other applications, such as with the fuse in a "pod", canister, or indoor switchgear, would not be covered, even though such applications affect heat loss from the fuse both before and after current interruption.

TD3 testing of general-purpose fuses is not included, as some felt that users would not expect a general-purpose fuse in an enclosure to still be able to interrupt a (reduced) current that caused melting in one hour. In other words, a general-purpose fuse may not be a general-purpose fuse over 40 ºC. This is to be addressed in an application note. There is an attempt to include I_3 testing of back-up fuses where the melting time is over 100s. The logic here is that extended melting times could result in high body temperatures and elevated surrounding temperatures could lead to even higher body temperatures, but whether this will be included is not yet known.

4. Conclusions

The preceding sections give a few examples of how experiences in new applications, and with new designs of fuses, can result in changes to, and expansions of, national standards, specifically IEEE standards. However, as has been shown, this does not mean that they will automatically be reflected in an international standard. This can happen even if many manufacturers and users require and accept such changes, and the circumstances that have led to such changes exist in more than one country or geographical area. Instead, many factors including differences in philosophy regarding certification testing, the familiarity of a country's representatives with differing fuse types, and even which countries are actively involved in IEC activities, all have an influence on what testing is deemed to be appropriate for inclusion in an international standard. Clearly, it is not possible, or proper, to put everyone's concerns into an IEC standard. However what this means is that users must be very cautious when specifying fuses for a particular application. It may be necessary to consider more than just whether a manufacturer possesses a certificate of compliance with the IEC "lowest common denominator" standard.

5. References

[1] IEC 60282-1 ed5 (2002-01), High Voltage Fuses – Part 1, Current-Limiting Fuses

[2] IEC 60282-2 ED 2.1-1997, High Voltage Fuses – Part 2, Expulsion Fuses

[3] IEEE Std C37.41™-2000, IEEE Standard Design Tests for High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories (ANSI)

[4] IEEE Std C37.40™-1993, IEEE Standard Service Conditions and Definitions for High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories (ANSI)

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[8] ANSI/IEEE Std C37.46™-2000, American National Standard for High Voltage Expulsion and Current-Limiting Type Distribution Class Fuses and Fuse Disconnecting Switches.

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[10] Zawadzki, J., Powertech Labs Inc., Surrey B.C., Canada, "Private communication with USA Technical Advisory Group to IEC SC32A", August 2002

Note that [7], [8], and [9] were developed and published by the National Electrical Manufacturers Association before having ownership and maintenance transferred to IEEE in late 2002.