BEHAVIOUR AND OPERATION OF THE FUSE

1. INTRODUCTION

Fuses can protect all kinds of electrical products: cables, motor circuits, transformers, batteries etc. and even semi-conductors.
It is well established that a power semiconductor, owing to its small thermal capacity has to be associated to a very fast protective device.
The H.R.C. fuse is this best protective device because it is based on the same thermal phenomena as the semiconductor.
This paper will deal only with the most widely used type of fuse for this kind of protection: the sand-filled fuse with a completely enclosed operation. There are therefore not any external phenomena while this kind of fuse is operating.

2. DESCRIPTION

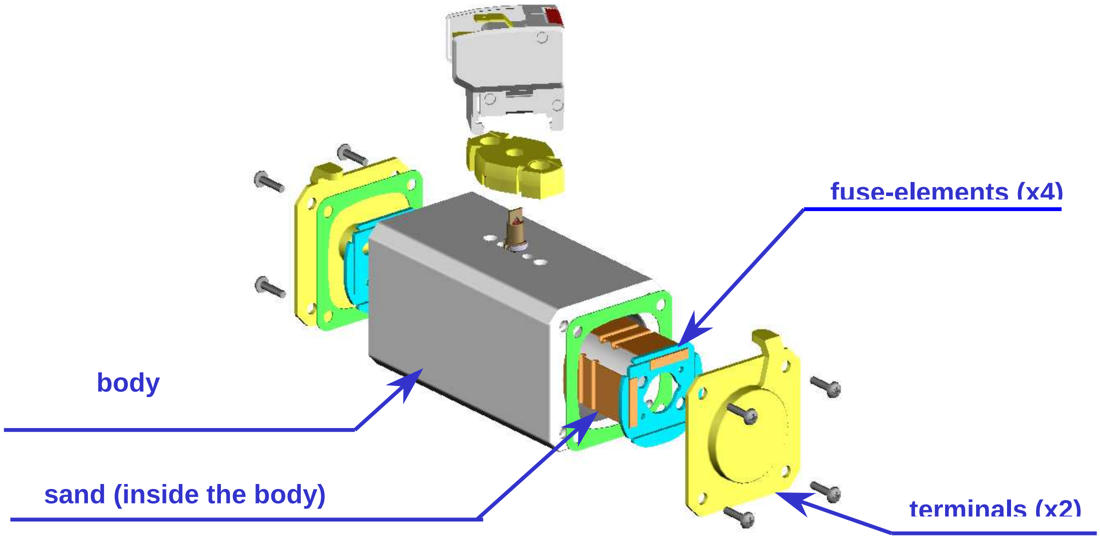


Figure 1

The main components (see figure 1) of such a fuse are:

The body: made of insulating material (ceramic or fibber glass for example). The material used has to provide a good mechanical strength and a good behaviour under high temperatures.

The terminals: made of good electrical conductor material.

- **The fuse element**: one or several fuse elements are linked to the connecting parts. The shapes and the dimensions of the fuse elements depend upon the desired characteristics and are made with a highly conductible material. Pure silver is the most often used material because of its very low resistivity, its good malleability and easy machining properly and also a good stability at the different temperatures under which it works when submitted to its current rating, or overloads to withstand. Along the fuse element there are rows of necks (reduced sections) are accurately cut (figure 2). When a short circuit occurs all necks melt quickly and simultaneously. The shape of the necks change the fuse characteristics.

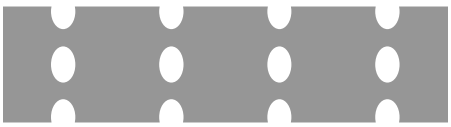


Figure 2 : fuse element

The filler: it is an inert and anhydrous material. Silica sand is generally used. The size of the grains is chosen according to the desired arcing performance, and the packing inside the body has to be very hard in order to provide a constant porosity. The purpose of the filler is to absorb the arc energy and to ensure a good insulation after arc extinction.

3. FUSE OPERATION UNDER OVERCURRENT FAULTS

3.1. Introduction to prearc, arc and the two types of overcurrent

When an overcurrent fault is higher than the minimum fusing current, the operation of the fuse is composed of two distinct periods: the prearcing period and the arcing period (figures 3 and 4)

The prearcing period: it starts at the time 0 when the overcurrent fault is applied to the fuse, and it stops at the time t_p when the melting temperature of the fuse elements is reached just prior the very beginning of the arc ignition. Between time 0 and t_p the circuit characteristics are not modified by the fuse. During this period one can therefore easily express the fault current versus the source voltage and the circuit parameters.
The arcing period: it starts exactly when a one-arc ignition or multi-arcs ignitions occurs. This period will end only at he time t_t when the arc complete extinction occurs. The arc extinction (or arc-quenching) depends upon the source voltage and the circuit parameters together with the fuse characteristics. Obviously, the fuse modifies the circuit characteristics during this period.

There are two main kind of overcurrents: the short circuit current (large values) and the overload. All fuses operate well on short circuit currents. Most semiconductor fuses are not designed to provide protection against long-duration overloads. Electronic or other means must be used to switch the circuit off when overloads occur. However new style gR semiconductor fuses (as it is defined by the IEC 60269) can provide overload protection as low as 160% of fuse rated current as a gG fuse does when protecting cables.
There are two large family of fuses as it is shown on §3.3.

3.1.1. The short circuit current (figure 3) :

All fuses operate the same way when they interrupt a short circuit current.
At the end of the prearc the melting temperature of the fuse elements is reached in each neck (960°C for silver).
Then after a very short time the silver is changed into vapour and arcs start simultaneously at all necks. The current is limited down to the Ic value and starts to decay toward the zero value.

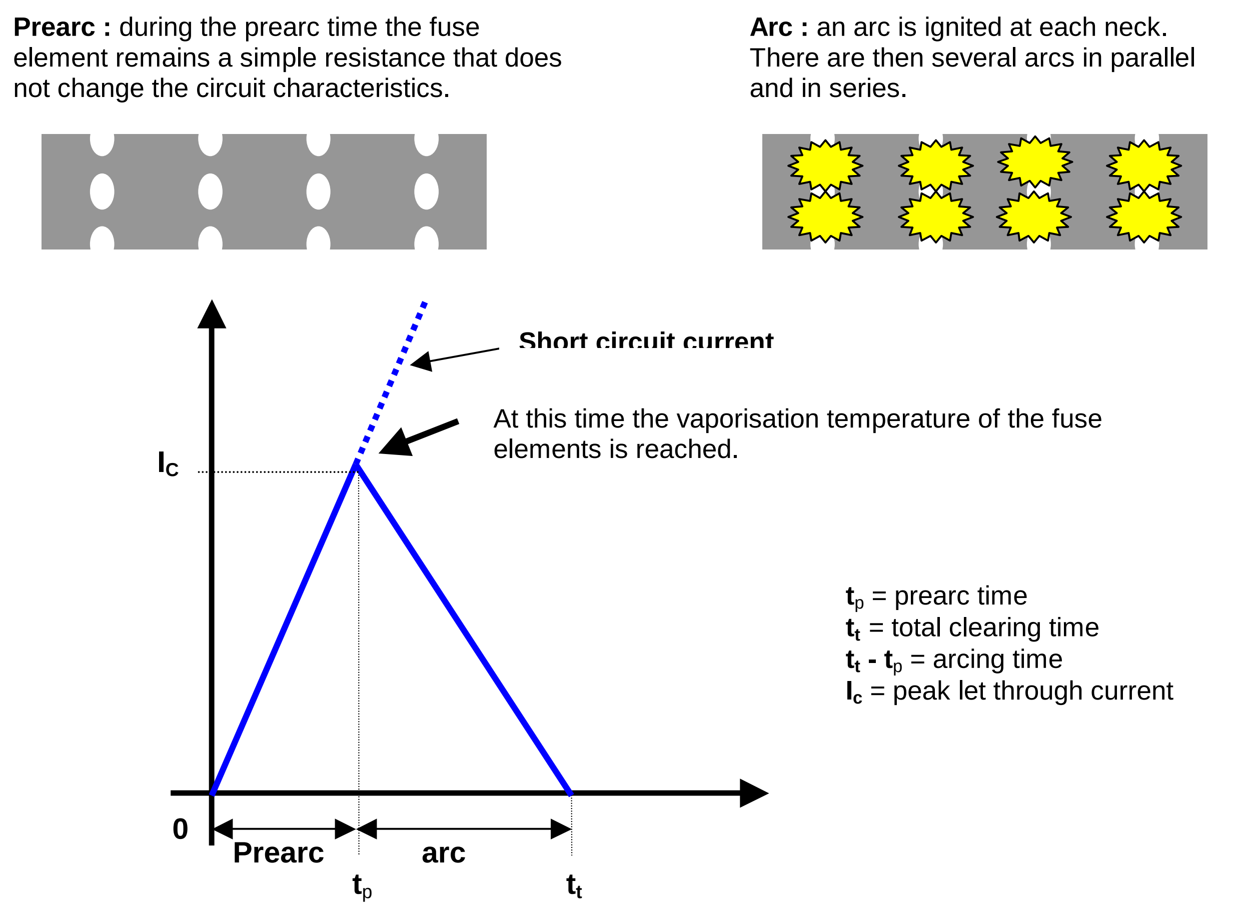


Figure 3: short circuit current

3.1.2. Fuse operation on overloads

When the fault current is low there are 2 kinds of problems:

- **The fuse body is damaged**:

  When the prearc time is longer than 1 second there is an excessive heating of the fuse elements (several hundred degrees) resulting in damages in the body like:

  cracks of the bodies made of ceramic

  carbonisation of the bodies made of fibre glass impregnated with other materials (melamine, silicone, epoxy…).

  These damages occur before the fuse elements melt.

  The CC' curve (see § 3.3.) plotted on the time current curve of some fuses shows the instant when the fuse body is damaged.

  All fuses with the CC' curve are "a" type fuses in the IEC 60269 standard.

- **The arc goes out of the fuse through the terminals:**

  When the prearc time is long all rows of necks may not melt simultaneously. One arc only is initiated increasing quickly its length as it gets the whole voltage of the circuit. Then the arc extinction must be achieved before the arc reaches the ends of the fuse.

  Fuses not able to interrupt overloads high enough to melt the fuse elements are as well "a" type fuses in the IEC 60269 standard.

For both above reasons another protecting device must be associated to the "a" type fuses. Such fuses have a minimum interrupting capacity around two to more than six times the fuse current rating.

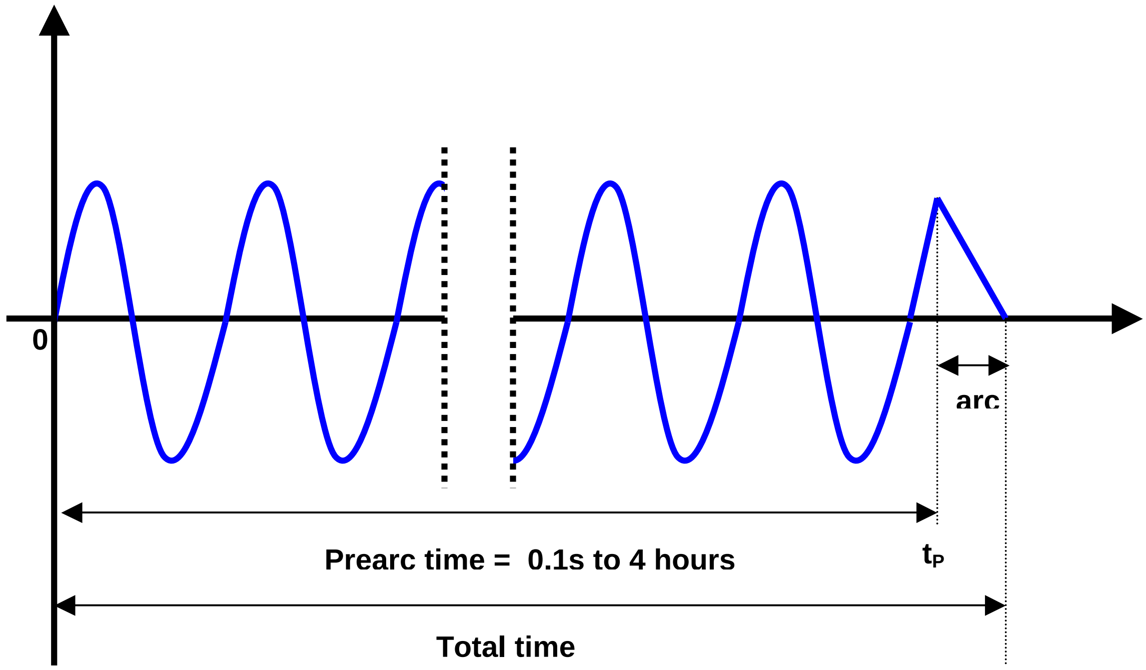


Figure 4: overload

The IEC mentions: for times longer than 0.1 s, for practical purposes the difference between pre-arcing and operating time is negligible.

3.2. The prearcing period

During this period, there is a heating process of the fuse elements (and even of the whole fuse if the prearc time tp is long enough) as a consequence of the Joules effect due to the current flowing through the fuse elements.

Therefore, the fuse elements temperature rises up to the melting point (960℃ for silver), then there is a conversion of the solid phase into a liquid phase, then another temperature rises up to the vaporisation point and finally the conversion into the vapour phase.

During the solid phase, a part of the thermal energy is stored to the fuse element itself, the other part is transmitted to the surroundings of the fuse element.

The prearc I^2t may be reduced by making constrictions along the fuse elements while the electrical resistance keeps a low value (see figure 5). This provides different time current curve shapes.

different kind of constrictions = different shapes of the time / current curve

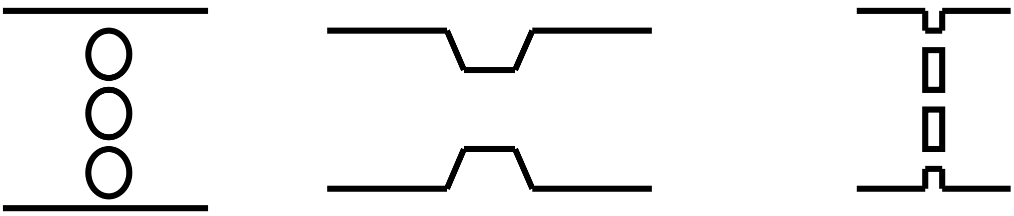


Figure 5: different kind of constrictions

3.3. The arcing period

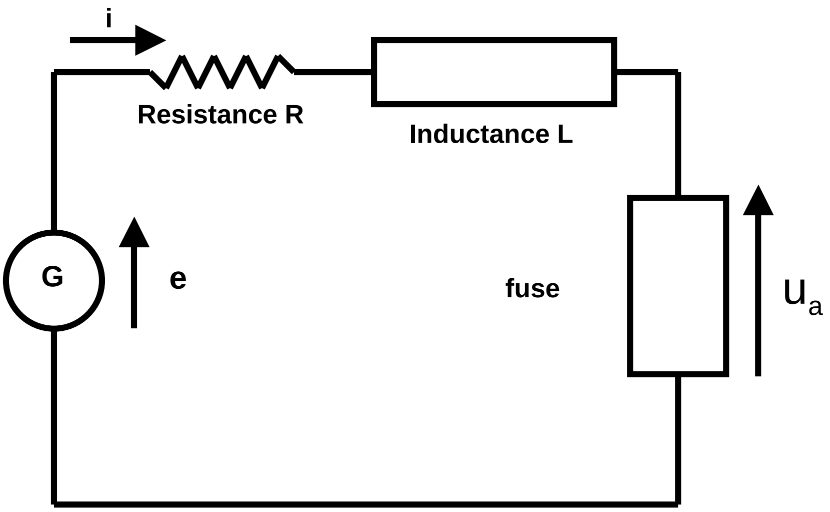


figure 6

During the arcing period, the use of differential equations resulting from Kirchoff's law for a given circuit (figure 6) leads to the following equation:

$$\mathbf{e = Ri + L\frac{di}{dt} + u_a}$$

With:

e = voltage supplied by the generator
$\mathbf{u_a}$ = arc voltage of the fuse
R = resistance of the circuit
L = inductance of the circuit

at the moment of the arc ignition, the peak value **Ic** of the current passing through the fuse is determined by both the circuit parameters during the prearcing period and by the prearcing I^2 t of the fuse

Starting from the $\mathbf{I_c}$ value, the current will reach the zero value within a duration depending upon the arc voltage (figure 7)

Therefore the $\frac{\mathbf{di}}{\mathbf{dt}}$ is negative during the arc extinction process

Since the Ri value is very small we get:

$$\frac{di}{dt} = \frac{1}{L}(e - u_a)$$

This shows clearly the $\frac{\mathbf{di}}{\mathbf{dt}}$ is negative only when $\mathbf{u_a} > e$

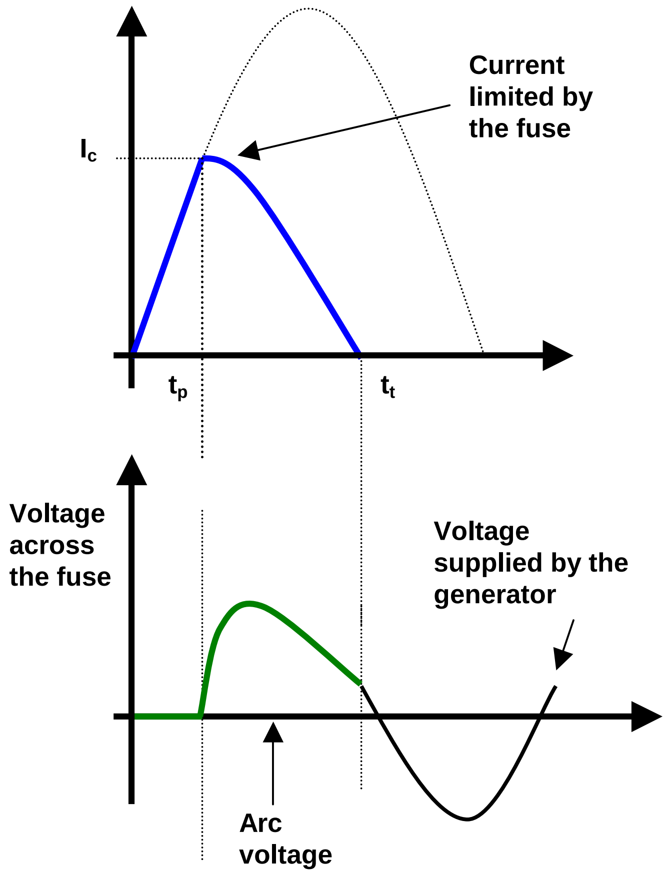


Figure 7: oscillogram

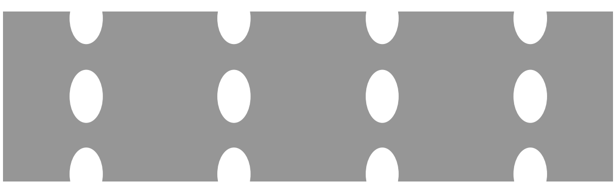
Conclusion: it is absolutely necessary to generate an arc voltage higher than the voltage of the power supply in order to stop the current and to open the circuit.

3.4. Two large families of fuses

Another technique found by Mr METCALF is to use a low melting point alloy or tin (see figure 8) to force the opening in the middle of the fuse element when there is a low overload in the fault circuit. This concept allowed to create two large families of fuses.

“ a “ type fuse: aM, URD, A70QS etc.)
Generally very fast acting fuse

“ g “ type fuse (gRB, gG, etc.) with M-effect fuse element



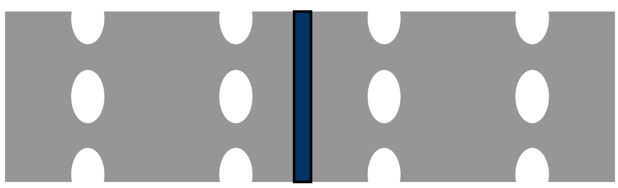
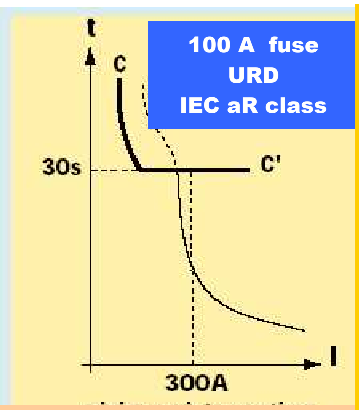
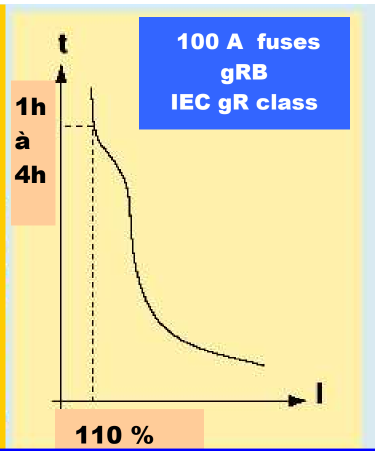


Figure 8: two main kind of fuse elements for two large families of fuses



Above the CC' curve it is forbidden to use the fuse (association with another protective device is absolutely necessary)

As soon as the overcurrent can cause the melting of the fuse (even in 4 hours), « g » fuses can break all currents.



IEC 60269 « a » type fuses:
aM (motor)
aR (semi conductor)

UL 248 part 13 fuses: protection of semi conductors (component « UL Recognized »)

IEC 60269 « g » type fuses :
general purpose: gG, gM, gN, gD
semiconductor: gS & gR

UL 248 fuses: classes J, L, RK5, RK1, T, K5, K,H…..(component « UL Listed »)

FERRAZ SHAWMUT examples:
PSC 690 V URD (semiconductors)
aM fuses (motors)
Form 101 fuses (A50P, A70P, A70QS, …)

FERRAZ SHAWMUT examples:
PSC 690 V gRB (semi conductors)
gG (general)
AJT fuses (classe J Time Delay)

Figure 9 : two large family of fuses

- **Comparison of the time current curve of 4 IEC 60269 fuse types**

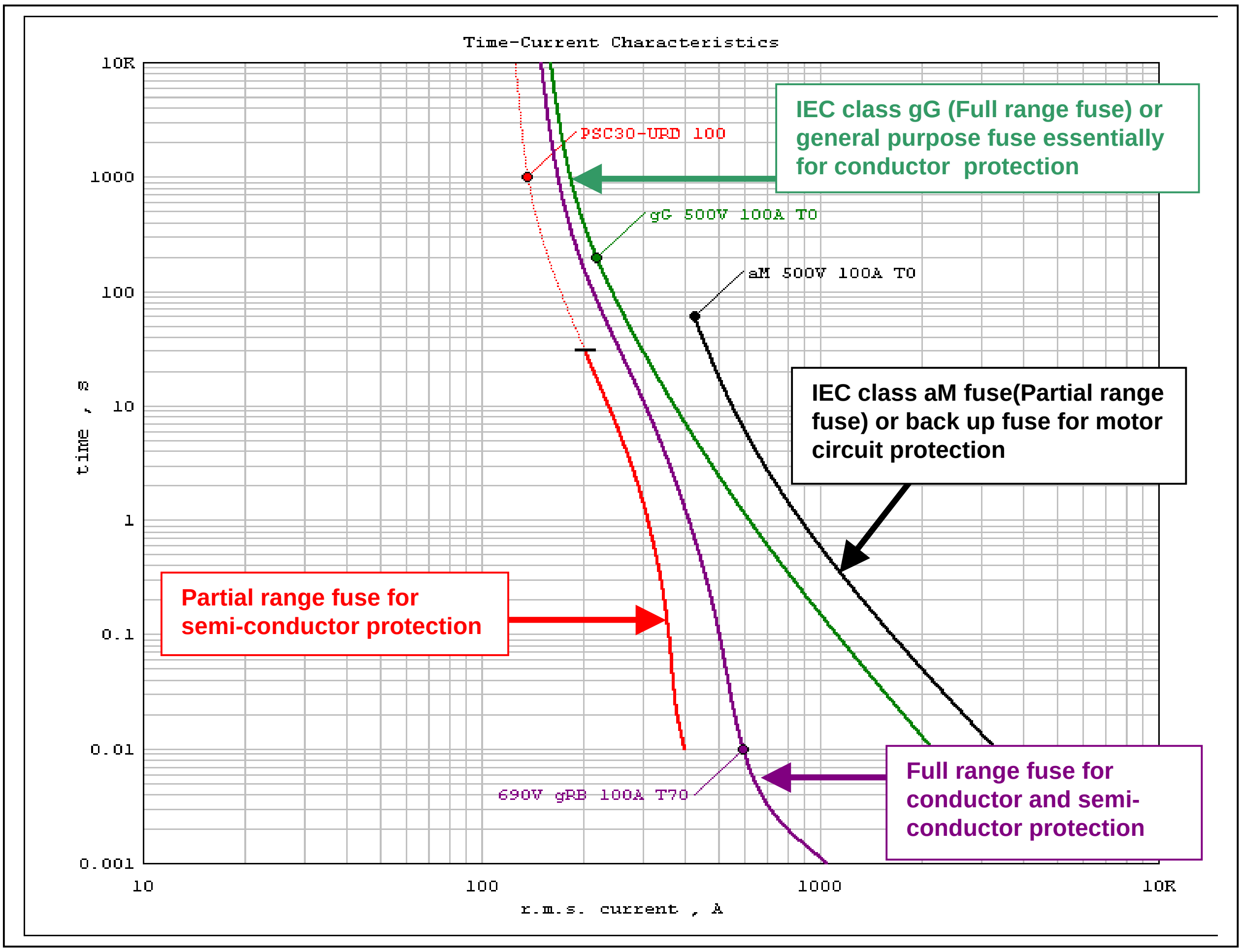


Figure 10: comparison of the time current curve of 4 different IEC fuses

3.5. Interrupting energy, the key part played by the filler

The interrupting energy dissipated inside the fuse is the energy produced during the arcing period:

$$\mathbf{W_a = W_L + W_S - W_R}$$

With

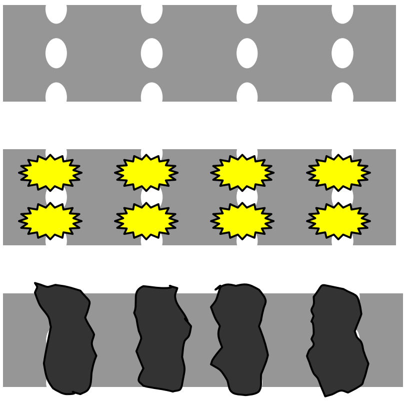
$$W_a = \int_{t_p}^{t_t} u_a \, i \, dt = \text{arc energy}$$

$$W_L = \frac{1}{2} L I_c^2 = \text{energy stored in the inductance at the end of the prearcing period}$$

$$W_S = \int_{t_p}^{t_t} e \, i \, dt = \text{energy provided by the source power during the arc quenching process}$$

$$W_R = \int_{t_p}^{t_t} R \, i^2 \, dt = \text{energy lost in the circuit resistance}$$

Fuse element during high current interruption



Prearc: all notches of the fuse element melt simultaneously for high magnitude currents. The energy is negligible because the voltage drop across the fuse is very small.

Arc: multiple arcs in series (4 in this example) are created. The energy is very high because at this instant the current has a high peak value and at the same time the voltage across the fuse is higher than the circuit voltage.

The grains of sand in contact with the arc melt and form a glassy body known as **« fulgurite »**

Figure 11

Melted sand = fulgurite

Figure 12

- The sand confines the arc and creates a pressure helping to extinguish the arc but at the same moment the sand porosity prevents the pressure to become too high otherwise the fuse can explode
- The sand porosity allows as well the vapour of silver (when the fuse element is made of silver) to escape from the arc region through the gaps between the grains of sand helping the extinction of the arc.
- After the arc extinction the sand determines the insulating resistance of the fuse.
- The picture (figure 12) shows how looks a fuse element after the breaking of a short circuit current. The significant amount of melted sand indicates the arc energy was large.

4. THE BEHAVIOUR OF THE FUSE UNDER LOAD CURRENTS

If the speed of a fuse (clearing I^2t) is essential to the semiconductor protection, one should not forget the behaviour of the fuse under normal loads it must withstand under real working conditions is very important as well. It has a large effect on the operating temperature of the equipment and moreover on the life duration of the equipment.

The maximum current carrying capability of a fuse depends widely upon two groups of parameters influencing its behaviour:

- Surrounding conditions : (ambient temperature, air cooling, connections etc.). These conditions are most of the time far away from the conditions defined in the IEC or the UL standards.
- Load current variations and overloads.

In opposition to a semiconductor of which the knowledge of the thermal resistance between the junction and the case is sufficient, the heat flow generated by the fuse element goes to the ambient air through several ways (figure 13) such as:

- connections: they are not generally symmetrical. Very often you can even see one connection cooled by a water cooled heat sink and the other connection heated by the flexible of the semiconductor.

- the body of the fuse: is into direct contact with the ambient air temperature (not always uniform).

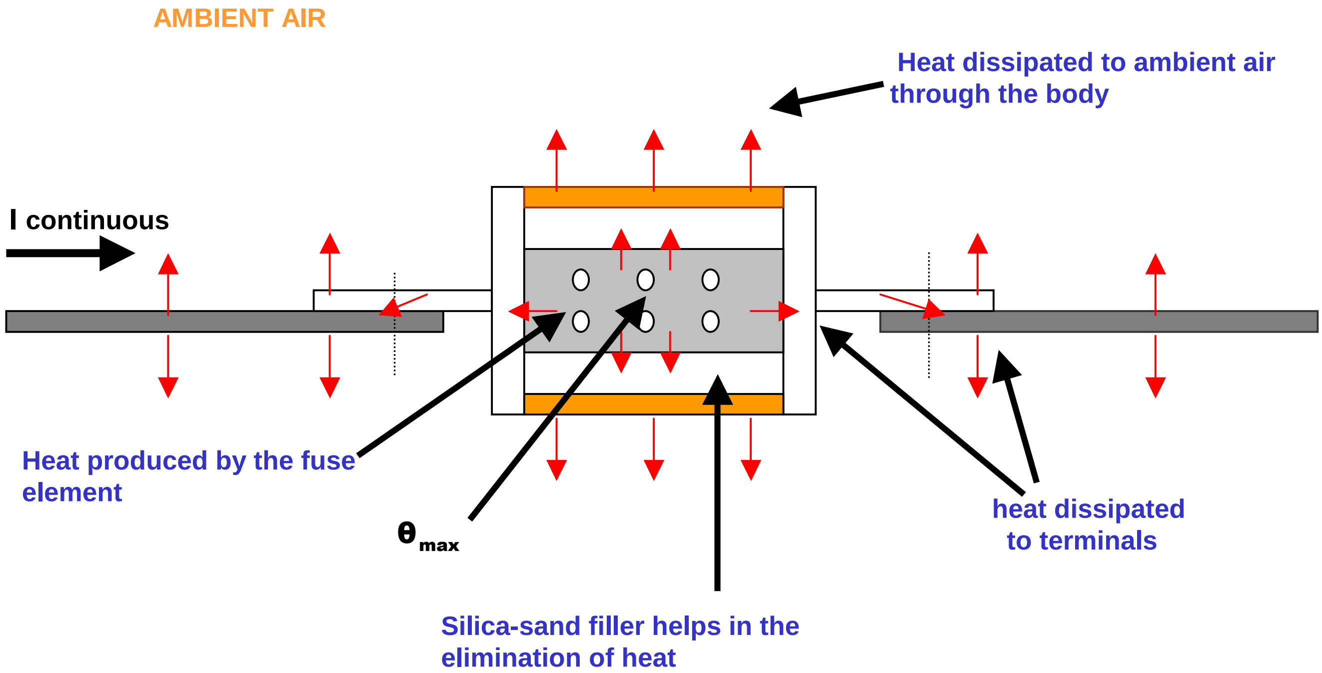


Figure 13

It is therefore impossible to determine a temperature value for the body or the connecting parts in order to have a control on the cooling conditions of the fuse elements.

Another important difference between a fuse and a semiconductor is the thermal time constant. This parameter has a high enough value in a fuse to allow little sensibility to current variations due to the wave shapes such as sinusoidal ones or rectified ones in converters.

On the other hand, the life duration of the fuse is widely affected by cyclic variable loads the period of which is between a few seconds and a few hours. Despite all the precautions and technology improvements, the contractions and extensions taking place successively in the fuse elements because of successive coolings and heatings cause a metal ageing which may lead to an undesired operation of the fuse.

5. DEFINITION OF CURRENT CARRYING CAPABILITY (C.C.C.) OTHER DEFINITION OF RATED CURRENT.

As shown on figure 13 the maximum admissible temperature $\boldsymbol{\theta}_{\mathbf{max}}$ is in the necks closed to the middle of the fuse element.

For the semi conductor fuses the value of this temperature is determined by the fuse manufacturer depending upon the choice of :

- the materials for the body and terminals
- the design of the fuse element
- the expected life time.

For general purpose fuses the standards specify some temperature rises on terminals and specify as well the power loss.

The current **I** is increased up to the moment θ_{max} (after thermal equilibrium) is reached. When the operating conditions are different from the testing conditions defined in IEC 269 this value of **I** is the C.C.C. of the fuse **(Iccc)**

The rated current (or nominal current) is the C.C.C. obtained under conditions defined by standards such as the IEC 269 and UL 248

6. HOW TO INCREASE THE C.C.C. (Iccc) OF A FUSE IN A GIVEN AMBIENT TEMPERATURE

The fuse can carry more than its rated current In with a good air flow or by mounting the fuse on low temperature connections (liquid cooled)
The advantage of one of the two solutions depends on the fuse length as shown on the table below.

		FUSE		
		So called " short fuses " Un<700v	**So called " long fuses " Un = 1000 V to 2000V**	**Very long fuse Un >3000v**
Evacuation of the heat		**80% connections 20 % body**	**20% connections 80% body**	**1% connections 99% body**
Influence on the Iccc	**Air flow 5m/s**	**Necessary on both body and connections Iccc =1,25 In**	**Necessary on body Iccc = 1.25 In**	**Necessary on body Iccc = 1.25 In**
Current Carrying Capacity	**Less than 60℃ on fuse connections**	**The ambient does not have any longer influence Iccc = 1,25 In to 1,35 In**	**Iccc = 1,05 to 1.25 In**	**Iccc = In**

These ratios are quite interesting for a steady state or small variations current.
When the fuse rating is essentially determined by the withstanding of overloads, the forced cooling does not bring real advantage.
The **"current rating selection"** leaflet shows how to select the fuse rated current when it must withstand overloads or in case of cyclic loads.

7. DEFINITIONS

- **Rated voltage:**
  for IEC 60269 fuses other than 690 V are tested between 110% to 115% of their rated voltage
  Fuses rated 690 V are tested between 105% and 110% of their rated voltage i.e. at least 725 V.
  In North America fuses are tested as per UL standard at 100% to 105% of their rated voltage.

- **Rated current:**
  value of current that the fuse can carry continuously without deterioration under specified conditions.

- **Prospective current of a circuit (Available current in North America):**
  current that would flow in a circuit if a fuse situated therein were replaced by a link of negligible impedance. The value of the prospective current in AC is the R.M.S. value of the AC component.

- **Breaking capacity:**
  value of prospective current (for a.c. the r.m.s. value of the a.c. component) that a fuse link is capable of breaking at a stated voltage under prescribed conditions of use and behaviour.

- **Conventional non fusing current (Inf):**
  value of current specified as that which the fuse is capable of carrying for a specified time (conventional time) without melting.

- **Conventional fusing current (If):**
  value of current specified as that which causes operation of the fuse within a specified time (conventional time)

- **" g " fuse (formerly general purpose fuse):**
  current limiting fuse capable of breaking under specified conditions all currents which cause melting of the fuse element up to its rated breaking capacity.

- **" a " fuse (formerly back-up fuse):**
  current limiting fuse capable of breaking under specified conditions all currents between the lowest current indicated on its operating time-current characteristic and its rated breaking capacity.