TIME-CURRENT CHARACTERISTICS OF MINIATURE FUSES

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ABSTRACT

Miniature fuses are made in a very large variety of designs and types, and for diversity of applications, resulting in a large number of different requirements with respect to dimensions, electrical characteristics, a.s.o. Several different standards exist for miniature fuses as e.g. IEC and UL standards for fuses for use in electronic and household appliances, ISO for automotive applications a.s.o. This great variety of types and designs as well as the existance of different standards create some specific problems with respect to the design and manufacturing of miniature fuses. On the other hand, a comparison of requirements and standards results in some interesting conclusions, as will be shown in the paper. Special attention will be given on the time-current characteristics of miniature fuses, not only from a viewpoint of standards, but also influencing parameters will be discussed. A method of computing the It-characteristic from the minimum fusing current up till the higher overcurrents will be presented briefly as well as comparison with experimental results.

1. INTRODUCTION

Due to the large number of different requirements with respect to dimensions, electrical characteristics a.s.o., miniature fuses are made in a large variety of designs and types and for a diversity of applications. Several standards exist for miniature fuses, each specifying their own requirements with respect to, amongst others, time-current characteristics. First of all the current IEC-publication 127 [1] should be mentioned. This specifies several kinds of 5 x 20mm and 6.3 x 32mm catridge fuses, whereas the draft IEC-publication 127 part 3 specifies requirements for sub-miniature fuses. UL-document 198G [2] gives also requirements for miniature fuses but they differ remarkably from IEC-requirements. Moreover, for automotive applications USA-standards exist as well as the DIN 72581 and at this moment a draft ISO standard.

This large variety in standards and applications poses an interesting challenge to the fuse designer to meet all these different electrical requirements in fuses with different shaping and dimensions. (see fig. 1) It is of course not pratical to make all these designs for all the current ratings required purely on the basis of experience, trial and error. This paper will show some basic design tools in a simplified way. (in order to keep this paper within reasonable length) Not all characteristics will be discussed, we confine ourselve to the time-current (It)characteristics.

2. A FIGURE OF MERIT FOR THE It-CHARACTERISTIC

Many miniature fuses are of a simple design, allowing for a not too complicated description of the pre-arcing behaviour by means of the well-known energy balance equation [3] :

$$\lambda \cdot \frac{\partial^2 T}{\partial x^2} + J^2 \rho_o (1+\beta T) - GT = c_v \gamma \frac{\partial T}{\partial t} \qquad (2.1)$$

Where :

λ : heat conductivity of the fuse element material. $[Wm^{-1} K^{-1}]$

T : temperature of the fuse element [K]
$T = T(x)$

J : current density $[Am^{-2}]$

ρ_o: specific resistance at ambient temperature. $[\Omega m]$

β : temperature coefficient of the specific resistance . $[K^{-1}]$

G : total heat flux per deg C in radial direction to the surrounding of the conductor. $[Wm^{-3}K^{-1}]$

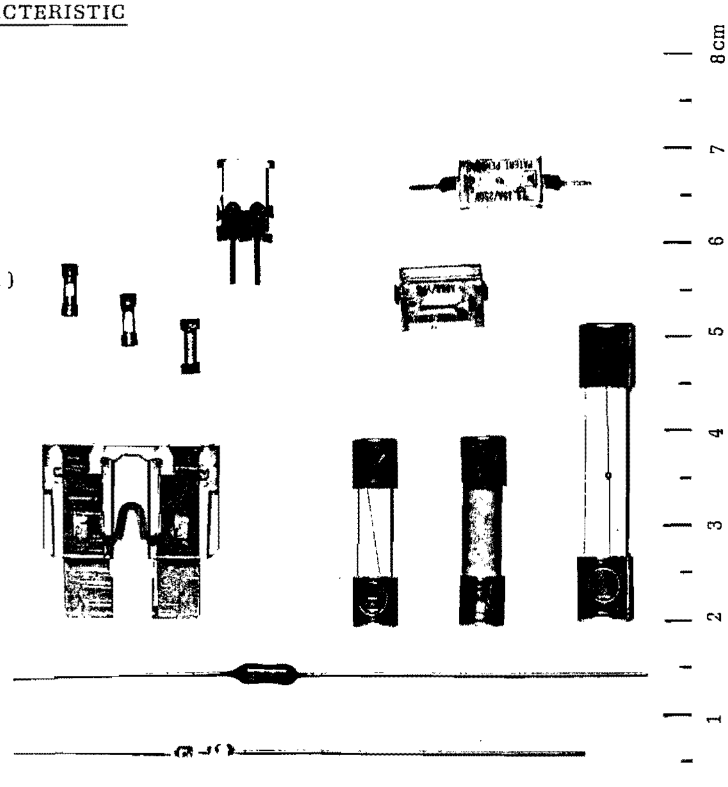


Fig. 1 :Some examples of miniature fuse designs.

c_v : specific heat of the fuse element material. $[\mathrm{Jkg^{-1}K^{-1}}]$

λ : specific mass of the fuse element material. $[\mathrm{kg\ m^{-1}}]$

t : time

x : coordinate as shown in fig. 2.

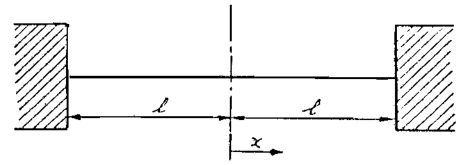


Fig. 2

Equation (2.1) is valid for a stretched and solid fuse element, see fig. 2. Solving this equation will lead to the It-characteristic for this particular case. The heat transfer factor G, which depends mainly on the geometry of the fuse element, its environment and on fuse dimensions, can be determined via experiments. We will return to this later in this text. Although it is in principle possible to compute the It-characteristics, it is not so easy to do this. However, it is less difficult to arrive at some insights with respect to influencing parameters and to define a kind of "Figure of Merit" for the It-characteristic, starting from equation (2.1). For that purpose, we will discuss some special cases.

* For a long wire (that means the temperature in the middle of the wire, thus at x = 0 is not influenced by axial heat transfer) and under steady state conditions, so $\frac{\partial T}{\partial t} = 0$, it follows from e.g. (2.1) :

$$J^2 = \frac{GT}{\rho_o(1+\beta T_m)} \qquad (2.2a)$$

* Introducing the melting temperature T_m we find a simple expression for the minimum fusing current $I_s = J_s A$, where A is the cross-section of the fuse element :

$$I_s^{\,2} = A^2 \frac{GT_m}{\rho_o(1+\beta T_m)} \qquad (2.2)$$

* The case of adiabatic heating, thus neglecting heat transfer to the surroundings of the fuse element, leads to the well-known Meyer's equation :

$$M = \int i^2\,dt = \frac{A^2 \gamma c_v}{\beta \rho_o}\,\ell n(1+\beta T_m) \qquad (2.3)$$

This equation is valid for the larger overcurrents.

Equation (2.2) is represented by vertical lines in the It-graph, examples are given in fig. 3 and indicated as I_{s_1} and I_{s_2}.

Under IEC 127 testing conditions, equation (2.3) is represented by straight lines on a log-log-scale, as shown in fig. 3. (lines M_1 and M_2)

The quotient $\frac{M}{I_s^{\,2}}$ is a measure how the two lines for I_s and M are situated with respect to each other. The value of G is in a certain fuse design and fuse geometry pratically a constant. So determining the quotient :

$$K = \frac{M \cdot G}{I_s^{\,2}} = \frac{\gamma c_v}{\beta T_m}(1+\beta T_m)\,\ell n(1+\beta T_m) \qquad (2.4)$$

gives a value K which is independant of the cross-section A and is only determined by physical parameters of the fuse element material. So K can be computed easily.

The parameter K has the character of a Figure of Merit for the It-characteristic: the smaller K is, the more fast-acting the fuse will be.

Table 1 shows the computed values of some fuse element materials. From this table the conclusion can be drawn that Ag gives a more fast-acting fuse than a Ni wire, complying with the experience.

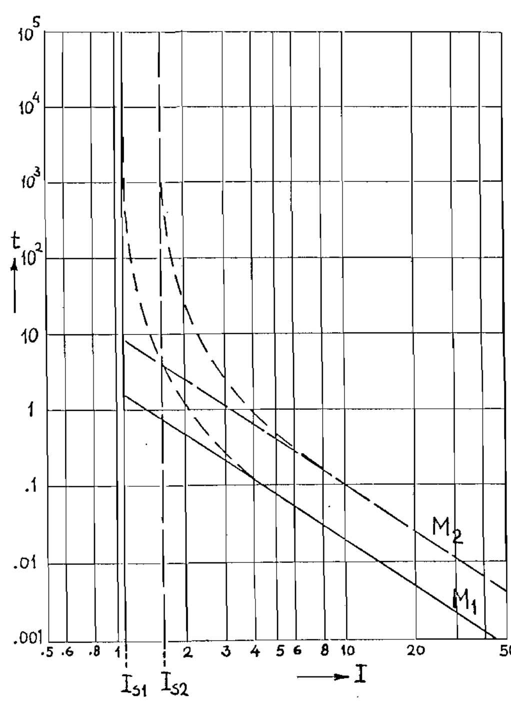


Fig. 3. Asympthotes of the It-characteristic being the minimum fusing current I_s and the line representing Meyer's integral M. The dotted line shows examples of actual It-characteristics with different value of I_s and M (the current I is given in arbitrary values)

Table 1

	T_m(°C)	β(K^{-1})	J(kg m^{-3}) 10^3	c_v(J $kg^{-1}K^{-1}$)10^3	K
Ag	960	4,3	10,49	0,234	5,0
Zn	420	4,2	7,13	0,35	4,0
Ni	1453	6,8	8,9	0,439	10,3

It should be kept in mind that conclusions like this are only valid for pure, solid, stretched and long metal conductors in a given configuration (G constant), so the effects of plating, M-effect, etc, are not taken into consideration. The K-value, as mentioned above, has only a value for the comparison of the effect on the It-characteristic of different fuse element materials. However, other parameters can be taken into account as well.
As an example, the length of a fuse element may have an influence on the minimum fusing current I_S of a fuse, which can also be computed from equation (2.1) For short fuse elements, the radial heat transfer (the factor G) is negligible, compared with the axial heat transfer via the ends of the fuse element. Then, under steady state conditions it follows from (2.1) :

$$\lambda\frac{d^2T}{dx^2} + J^2\rho_o(1 + \beta T) = 0$$

with the solution for T at x = 0, viz T_o :

$$\cos \ell J \frac{\beta\rho_o}{\lambda} = \frac{1}{1 + \beta T_o} \qquad (2.5)$$

Introducing $T_o = T_m$ and consequently $J = J_S$, we have an expression for the minimum fusing current density J_S as an function of the length $l = \frac{1}{2}L$ of the fuse element and for a given metal conductor.

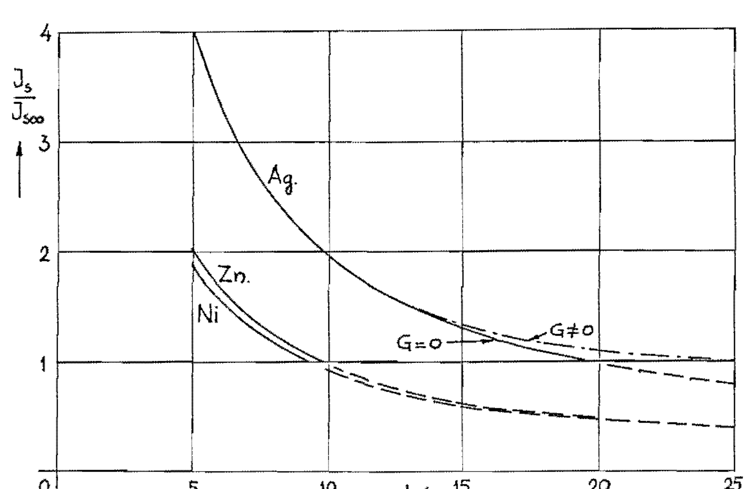
For a specific case (a non-filled, 5x20mm glass-fuse) the value of G is in the order of $G \approx 10^7$ Wm^{-3} K^{-1}. With this value the minimum fusing current density for a long wire, neglecting the axial heat transfer, (denoted by $J_{S\infty}$) can be computed from equation (2.2A) So, from equations (2.2a) and (2.5), the relation between J_S (for short fuse elements) and $J_{S\infty}$ can be computed. The result of such computations is shown in fig. 4 for the metals Ag, Ni and Zn.

From this graph it can be seen that a silver element of certain cross-section in a 5 x 20mm fuse, having in many cases a fuse element with a length of 17 - 18mm in it (due to solder joints), will result in an increase of the minimum fusing current by 10-20% compared with a fuse with a much longer fuse element in it. This is the case with Ag, but not with Ni and Zn. (Cu behaves pratically in the same way as Ag in this respect) The value of M (eq. 2.3) does, however, not change. So it follows that the Figure of Merit K will decrease by10-20% using silver fuse elements in a 5 x 20mm fuse.

This example shows that the conclusion which could be drawn from table 1, viz, that a Zn-element would give a more fast-acting fuse compared with a Ag-element, may not be justified.: Nevertheless, a Figure of Merit $K = MG/I^2_S$ can be defined also in the case of short fuse wires. The graphs of fig. 4 indicate also that a certain spread in the value of K (and consequently in the It-characteristic) may easily occur using high-conductivity metals like Ag and Cu. This is due to variations in the length of the fuse element which may result from small variations in production process parameters. This is the more so when producing in large quantities the smaller-sized fuses like miniature fuses.

Fig. 4

The minimum fusing current density J_S of short fuse element, related to the minimun fusing current density $J_{S\infty}$ of very long fuse elements, as a function of the total length L of a streched fuse element of constant cross-section.



3. THE DETERMINATION OF THE It-CHARACTERISTIC

In the previous chapter a characterisation of the It-characteristic is presented, based on two parameters:

- the minimum fusing current I_s.
- the figure of Merit K

These two parameters determine the two asymptotes of the It-characteristic. This is shown in fig. 3. As a remark, in stead of I_s, also the rated current I_n can be taken as a parameter after introducing the fusing factor $f = I_s/I_n$.

The full computation of the It-characteristic can be done by solving the energy balance equation as given in equation (2.1) for a somewhat simplified situation. The problem in solving this equation is the determination of the value of G in each situation. (fuse design, fuse element shaping, a.s.o.) In principle the value of G can be experimentally determined in the following way :

If a current $I < I_s$ is flowing through a fuse, then under steady state conditions the following must be valid:

$$I^2 r_o (1 + \beta T) = G_t T$$

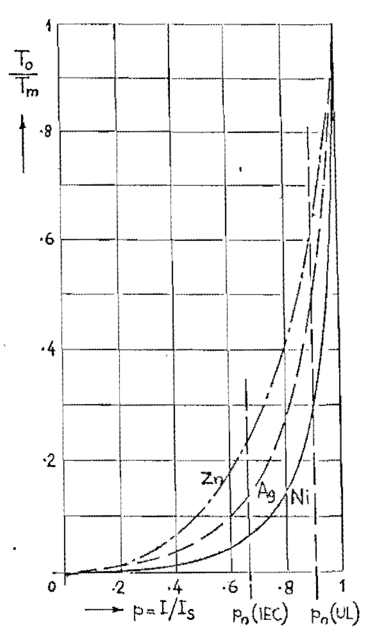
Where r_o is the fuse resistance at ambient temperature. The temperature T now has the meaning of an average across the fuse-length, whereas $G_t[WK^{-1}]$ is the total heat transfer from the fuse element to its surroundings. Introducing $r_T = r_o(1 + \beta T)$ (the resistance at temperature T at current I), then

$$G_T = \frac{I^2 r_T}{T} = \frac{I u_v}{T} \qquad (3.1)$$

where u_V is the voltage drop at current I, which can be measured easily. For long and short fuse elements a relation can be derived from the energy balance equation (2.1) between J/J_s and T_o/T_m, where T_o is the temperature at x = 0 [3].
This relationship for the metals Ag, Zn and Ni is shown in fig. 5.

The temperature distribution under steady state conditions can also be computed, so the average temperature is also computable. This means that from a simple measurement in principle a value of G can be found, taking into account also dimensional aspects. For these calculations a computer program has been designed.

For the computer calculations use was made of voltage drop measurements as shown in fig. 6.



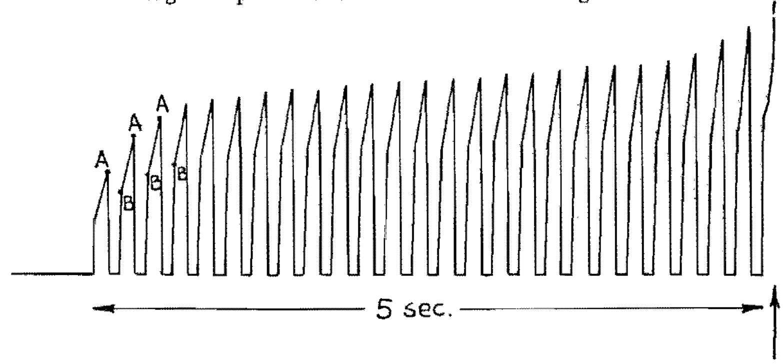


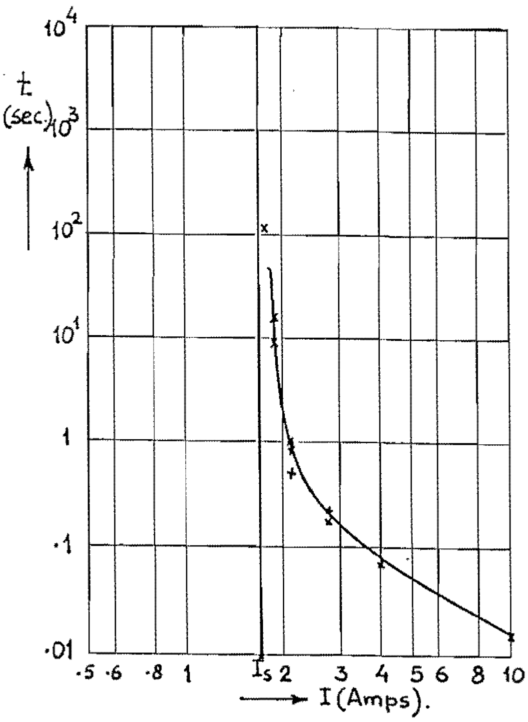
Fig : 6 The voltage across a 5 x 20mm fuse with a rated current of 1 Amp. as a result of a train of rectangular current pulses through the fuse each pulse having a amplitude of 2.5 Amp.

Fig 5 :The temperature T_o at x = 0 related to the melting temperature T_m, as a function of $\rho = I/I_s$ ($I \leq I_s$), for the metals Ag, Ni and Zn for the streched fuse element of constant cross-section.

A train of current pulses was passed through the fuse during which the voltage drops A and B during each pulse were measured and fed into the computer. These voltage drop measurements allowed for the calculation of a value G. With this value it is possible to solve equation (3.1) for that particular case.

Fig. 7 shows one of the results, together with a number of measuring points which are obtained by blowing a number of fuses in normal test equipment, following IEC test rules. Voltage drop measurements were also carried out using the test fuse holder as specified in IEC-publication 127.

As will be seen from fig. 7, the measured points fit very well with the computed curve for this particular fuse.



The preliminary indicates only the principles of the computational methods, it is beyond the scope of this paper to describe the computational process in details. It might, however, demonstrate that a full computation of the total It-characteristic is a possibility, serving the following aims :

* It might reduce development work on miniature fuses considerably because computation gives a quick impression of the It-characteristic of a newly developed fuse, using only a few samples.

* It opens the possibility to study the character of the parameter G as a function of element geometry, dimensioning of the body and other parameters. After gaining such a quantitive knowledge of G, it is even possible to compute the It-characteristic of new designs without having samples available.

We like to point out that the above mentioned gives only a simplified treatment which is to a certain extend only valid for the most simple fuse designs. However, the authors are convinced that the achievements gained so far contributes to a fuse designing process for miniature fuses with better possibilities for optimisation and a better understanding of the influencing parameters on fuse characteristics, departing further from trial and error methods.

Fig. 7 : Calculated It-characteristic of a fast-acting, 1 Amp., 5 x 20mm fuse. The crosses indicate measured values. The line indicating the minimum fusing current I_s is the computed value.

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LITTERATURE

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