SURGE PERFORMANCE OF MINIATURE FUSES
A Study of the Influencing Factors

R. Brown, B.Eng., M.Phil.
Dubilier-Beswick, Frome, Somerset, England, BA11 1PP.

ABSTRACT

This paper identifies the parameters which have an influence on the surge performance of miniature fuses, so that fuses with superior time-lag properties to those presently available can be developed. A measure of surge performance is described called the thermal time constant of the fuse, τ, with the dimension of time. After developing an equation for τ, it is shown how each term of the equation may be maximised theoretically and practically to give high surge performance. An indirect method of measuring τ is explained and the correlation between measured and calculated values for two types of fuses given.

LIST OF SYMBOLS

α = Temperature coeff. of resistivity, k^{-1}
c = Specific heat capacity, $J\ kg^{-1}k^{-1}$
d = Diameter, m
d.f. = Delay factor
h = Radial heat loss coefficient, $W\ m^{-2}k^{-1}$
I = Current, A
I_a= Adiabatic melting current, A
I_m= Minimum fusing current, A
K = Thermal conductivity, $W\ m^{-1}k^{-1}$
m = Density, $kg\ m^{-3}$
P = Perimeter, m
ϱ_o = Specific resistivity, Ω m
S = Cross-sectional area, m^2
t = Time, s
t_a= Adiabatic melting time, s
τ = Thermal time constant, s
T = Temperature, k
T_M= Adiabatic melting point, k
T_m= Steady-state melting point, k
x = Axial displacement, m

1. INTRODUCTION

Throughout the history of the miniature fuse the performance demanded from its diminutive package has always been increasing. The fuse designer has had to meet this demand by careful engineering and not a little ingenuity as energy sensitive semiconductors and circuits with high inrush currents have proliferated, all requiring reliable and cheap protection. This is unlikely to alter in the future as the telecommunications industry joins the foray with requirements, at the subscriber line interfaces of its exchanges, for miniature fuses which blow at continuous overload currents of as little as 200mA and yet can carry 60A for 1ms.

It is the behaviour of a miniature fuse when subjected to these high overload, short duration surges which is of great importance when choosing overcurrent protection for a given application. In fact, fuses are broadly classified according to their response to such stimuli, for example quick-acting, time-lag etc.[1]. This paper is concerned with the factors which influence this particular fuse characteristic. These may be divided into three types:-

(1) the thermophysical properties of the fuse element material,
(2) geometrical factors and
(3) techniques which alter the fuse element's inherent properties e.g. Metcalf-effect.

By studying the fundamental equation which governs the heating of a fuse wire it is possible to determine, in detail, how each of these may be optimised to give a fuse with a required surge performance.

The emphasis will be on those aspects of the fuse which give it the ability to withstand such surges i.e. its time-lag properties. This is because a simple straight fuse wire is inherently quick-acting and so a large amount of design effort is expended on developing time-lag types. Figure 1 shows typical operating curves for time-lag and quick-acting miniature fuses. The time-lag fuse takes longer to operate at high overload currents.

In order to optimise the time-lag properties of a miniature fuse it is first necessary to develop some measure of this particular attribute. One way of doing this is to define a 'delay factor', d.f. as the ratio between a high overload current and the minimum fusing current:-

$$d.f.=I_a/I_m \qquad (1)$$

The problem with equation 1 is that the adiabatic melting current, I_a must be associated with a certain adiabatic blowing time e.g. 1ms or 10ms. This means that a single fuse can have a multitude of delay factors dependent on the blowing time chosen for fixing I_a.

Alternatively, it is possible to obtain a 'thermal time constant', τ, for the fuse which has a direct relationship to d.f. but is independent of the adiabatic blowing time and so has a unique value for a particular type and rating of fuse.[2] This is the approach which will be taken here.

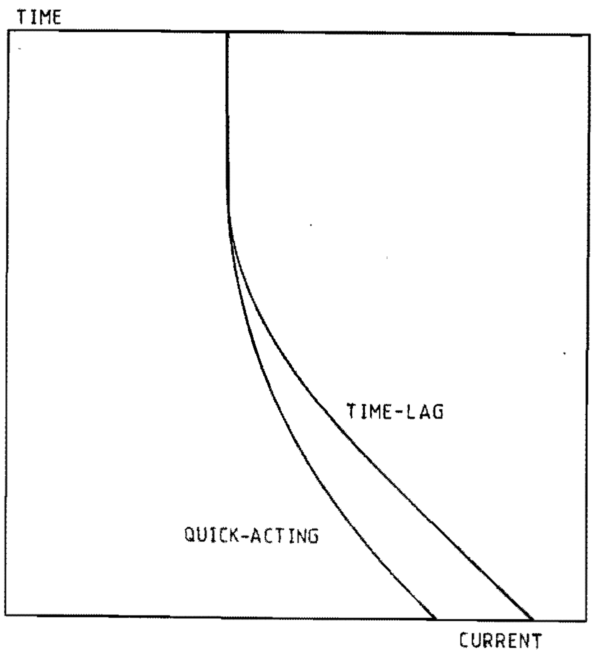

Figure 1

Typical time/current curves

2. THE THERMAL TIME CONSTANT

The operation of a fuse is governed by the delicate balance between Joule heating of the element and heat loss to the environment by the mechanisms of conduction, convection and radiation. This may be represented by an energy-balance equation, first developed by Verdet in 1872:-

$$mcS.\frac{\partial T}{\partial t} = \frac{I^2 \rho_0 (1+\alpha T)}{S} + KS.\frac{\partial^2 T}{\partial x^2} - PhT \qquad (2)$$

In this equation, the term on the left is the rate of increase of internal energy, the first term on the right is the Joule heating, the second is the axial conduction loss and the third is the radial loss which is due to convection and radiation combined. This last term is represented as a simple function of the wire perimeter and its temperature although in reality it has a complicated dependence due to the 3-dimensional convective fields existing within the fuse body. However, empirical results have shown that this simplification is reasonable when applying the equation to miniature fuses.[3] All the quantities in (2) are calculated per unit length of the element.

2.1 Adiabatic Condition.
When a fuse is subjected to very high overload currents it heats and melts before any appreciable heat loss can occur. The process is thus adiabatic and (2) can be simplified as follows:-

$$\frac{dT}{dt} = \frac{I^2 \rho_0 (1+\alpha T)}{mcS^2} \qquad (3)$$

By separation of variables and then integrating we obtain:-

$$I_a^2 t_a = \frac{mcS^2}{\rho_0 \alpha}.\ \ln(1+\alpha T_M) \qquad (4)$$

which shows that for high currents the pre-arcing I^2t is constant, as we would expect.

2.2 Steady-state Condition.
If a current is applied to the fuse which is just less than I_m the element temperature will increase until heat loss exactly balances the heat input. In this instance equation (2) reduces to:-

$$\frac{I^2 \rho_0 (1+\alpha T)}{S} + KS.\frac{d^2 T}{dx^2} = PhT \qquad (5)$$

since dT/dt=0. This is difficult to evaluate for I but can be made considerably easier if axial heat loss is small compared to the radial loss. This is reasonable when considering wires which have a large length/perimeter ratio as is usually the case with miniature fuses. In this instance (5) becomes:-

$$\frac{I^2 \rho_0 (1+\alpha T)}{S} = PhT \qquad (6)$$

Putting $T=T_m$ we can equate $I=I_m$ giving:-

$$I_m^2 = \frac{PhT_m S}{\rho_0 (1+\alpha T_m)} \qquad (7)$$

2.3 Equation for τ
Having formulated equations involving I_a and I_m it is now possible to define τ. Dividing (4) by (7):-

$$\frac{I_a^2 t}{I_m^2} = \frac{mcS.[(1+\alpha T_M).\ln(1+\alpha T_m)]}{Ph\alpha T_m} = \tau \qquad (8)$$

The factor τ has the dimension of time and can be thought of as the thermal time constant of the fuse. It can be seen to be directly related to d.f. as follows:-

$$\tau = (d.f.)^2.t_a \qquad (9)$$

where t_a is the adiabatic blowing time. We can now separate (8) into a number of factors which can be studied individually to see how τ can be maximised:-

$$\tau = \left[\frac{(1+\alpha T_m).\ln(1+\alpha T_M)}{\alpha T_m}\right] \times \frac{1}{h} \times \frac{S}{P} \times mc \qquad (10)$$

2.4 Maximising τ
Taking the square bracket first, this may be considered as the 'trigger effect' bracket since it shows how τ is affected by using a mechanism which triggers the element to melt at a lower temperature under steady-state conditions than under adiabatic conditions. This is essentially the process behind M-effect and spring type anti-surge fuses. Figure 2 shows how the value of this bracket varies with T_m and T_M (keeping α constant). It can be seen that it is slightly advantageous to use a high melting point material if no trigger effect is employed, but the real gains are obtained when a large separation between T_m and T_M can be achieved.

The first of the geometrical factors is the term 1/h, the radial heat loss term, and is obviously maximised when the surface heat loss coefficient, h is a minimum. In practical terms this means that the element should be thermally insulated.

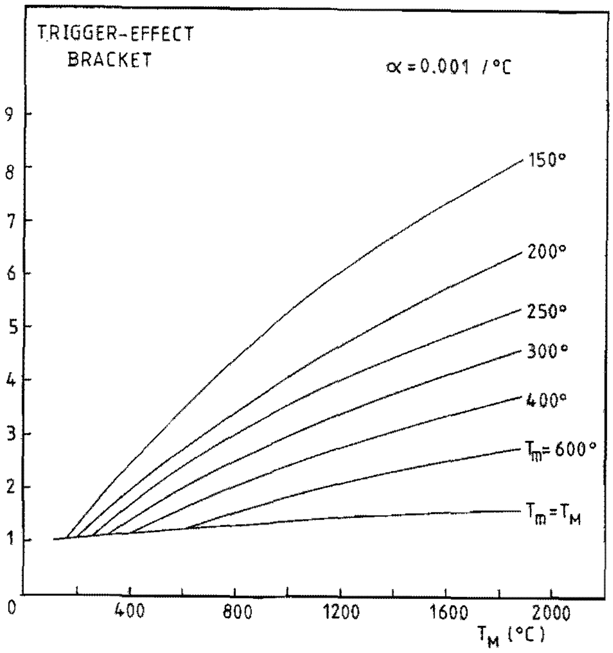

Figure 2

Value of trigger effect bracket

The second geometrical term is S/P, the ratio of cross-sectional area to perimeter. This is a maximum when the element is a solid, circular wire and in this case has the value d/4. Therefore, it should be of the largest possible diameter, which is why, for a given element material, surge withstand performance increases with I_n (the rated current). The corollary of this idea is that, for a given I_n, the resistivity of the element material should be maximised. This is to be achieved within the constraints of the internal dimensions of the fuse body and the breaking capacity required.

The final term (mc) is the product of the density and specific heat capacity of the element material, sometimes called the thermal mass. For a given volume, substances with a high thermal mass require a large amount of heat energy to raise their temperature appreciably. This term should be maximised.

3. PRACTICAL METHODS OF INCREASING τ

Now we know how τ, and hence surge performance is affected by each of terms in equation (10) it should be possible to determine practical ways of incorporating those features which increase τ in the design of a time-lag fuse.

The most obvious practical example of increasing the value of the trigger effect bracket is by using an M-effect blob on the fuse wire. With a tin/lead solder blob on a silver wire the value of the bracket increases from 1.99 to 3.73 (making T_m equal the eutectic temperature of 60/40 tin/lead solder). Alternatively, the wire may be tin-plated causing the M-effect to take place along the entire length of the element.

Another way the value of this term is increased is by using a copper or copper-containing wire. At low overloads, the elevated temperature causes the copper to slowly oxidise, increasing the element resistance and effectively causing it to blow at a much reduced temperature.

A more versatile way of implementing the trigger effect would be to employ a pyrotechnic compound in place of the solder. With a well defined ignition temperature and sufficient heat output, such a compound could be used in conjunction with <u>any</u> metal, causing it to melt at a temperature well below T_M.

The thermal insulation of the fuse element is difficult to improve unless evacuating the fuse body is considered, since air itself is such a good insulator. Experiments have shown that introducing ordinary thermal insulators into the fuse body, such as fibre glass, has the effect of increasing the heat loss from the element because the internal dimensions are so small. However, there is thermal insulation available which can be used to some advantage and this is based on the microporous principle where the material consists of small cells with a diameter less than the mean free path of an air molecule. Using this technique it has been possible to increase τ by approximately 1.5 times.

The S/d term can be increased by using a high resistivity material, thereby increasing the element diameter. An indirect method of doing this is presently used in the helical type fuse where a wire is wound on an insulating core. This effectively increases the resistivity provided the turns do not touch. Obviously, the core diameter should be as small as possible in relation to the outside diameter of the helix so that S/d is maximised.

Data relating to the thermal mass of various metals is shown in figure 3. It shows that the traditional fuse element material, silver has a fairly low value of 2.47×10^6 J kg^{-1} K^{-1} while some of the high resistivity alloys are around 4×10^6 J kg^{-1} K^{-1}. Bearing in mind the comments concerning resistivity in the previous paragraph, for time-lag applications it would appear that such alloys are ideal.

The emphasis in this section has been on metallic fuse elements but the theory does not exclude non-metals which make available a much wider range of thermophysical properties, provided that they can be realised in a form suitable for inclusion in a miniature fuse.[2,4]

4. THEORETICAL AND EXPERIMENTAL VALUES FOR τ

It is possible to show that τ is the time taken for the centre of the fuse element, when carrying I_m, to reach 63% of T_m.[3] So, to evaluate τ directly is almost impossible because of the difficulty in measuring the element temperature inside the fuse body. However, it is possible to obtain a value for τ <u>indirectly</u> from I^2t data as follows. Using equation (9):-

$$\tau = (d.f.)^2.t_a$$

$$\tau = (I_a/I_m)^2 \, .t_a \qquad (11)$$

METAL	$mc \times 10^{6}$ $(Jm^{-3}k^{-1})$
NICKEL	4.09
STAINLESS STEEL	4.04
INVAR	4.02
WROUGHT IRON	3.77
COBALT	3.74
CONSTANTAN	3.73
PURE IRON	3.59
NICKEL SILVER	3.48
COPPER	3.44
MANGANIN	3.40
MILD STEEL	3.30
BRONZE	3.17
BRASS	3.15
PLATINUM	2.92
ZINC	2.75
GOLD	2.55
SILVER	2.47
ALUMINIUM	2.47
TITANIUM	2.37
TIN	1.65
SOFT SOLDER	1.58
LEAD	1.43
ANTIMONY	1.37
BISMUTH	1.23
SODIUM	1.20
MAGNESIUM	0.43

Figure 3

Thermal mass of various metals

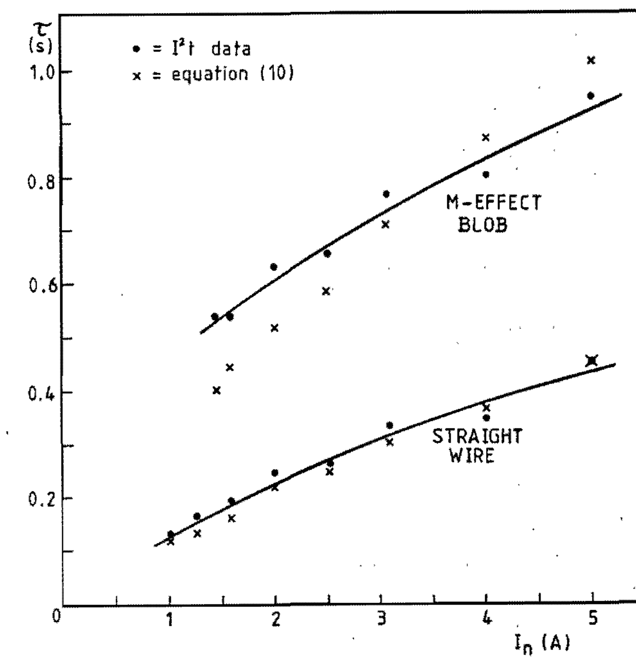

Figure 4

Values of τ for two types of fuses

Since I^2t is constant for high overloads we can chose t_a and therefore find I_a. Estimating I_m from known non-blowing and blowing conditions, τ can be found from (11). Figure 4 shows the results obtained in this way for two types of 20mm x 5mm glass bodied fuses, one a straight silver wire and the other a silver wire with an M-effect solder blob. It can be seen that the M-effect fuse has a considerably higher value of τ than the simple straight wire type. This is confirmed by the former being classed as time-lag according to IEC 127:1974, while the latter is quick-acting.

Also plotted in the figure are values of τ obtained by evaluating equation (10), substituting the appropriate values for each term (see appendix 1). These are in fairly close agreement, particularly for the quick-acting type.

5. CONCLUSIONS

The paper has indicated how the surge performance of miniature fuses can be improved by designing the fuse to include certain key features. It has shown how a measure of the surge withstand capability can be obtained by defining a thermal time constant, τ which has the dimension of time only. The influences on τ of varying the adiabatic and steady-state melting temperatures, the radial heat loss, the ratio of cross-sectional area to perimeter and the thermal mass of the element have been investigated and practical realisations have been suggested of how each may be maximised. Some of these techniques are being used at present in the development of new types of miniature fuses.

To summarise, for good time-lag properties the fuse element should be of circular section and be solid. It should have a high thermal mass and high resistivity and be thermally insulated from the environment. If a trigger effect can be employed, then the largest possible separation between T_M and T_m should be aimed for. Generally, a high melting point material is preferred.

There are obviously other constraints which must be considered such as power dissipation, volt drop, constructional difficulties etc. which will not allow all these to be fully exploited, but it does indicate the areas which should be given careful consideration when designing time-lag fuses.

APPENDIX 1.

I_n (A)	I^2t (A^2s)	I_a (A)	I_m (A)	τ (s)
Quick-acting				
1.0	0.47	21.7	1.90	0.13
1.25	0.94	30.7	2.38	0.17
1.6	1.79	42.3	3.04	0.19
2.0	3.50	59.2	3.80	0.24
2.5	5.82	76.3	4.75	0.26
3.15	11.9	109	5.99	0.33
4.0	20	141	7.60	0.34
5.0	41	202	9.50	0.45
6.3	75	274	12.0	0.52
Time-lag				
1.4	3.80	61.6	2.66	0.54
1.6	5.00	70.7	3.04	0.54
2.0	9.10	95.4	3.80	0.63
2.5	15.0	122	4.75	0.66
3.15	27.8	166	5.99	0.77
4.0	46.2	215	7.60	0.80
5.0	85.0	292	9.50	0.94
6.3	137	370	12.0	0.95

<u>From I^2t Data</u>

NOTES: 1) t_a = 0.001s
2) I_m based on $1.9I_n$

I_n (A)	d (mm)	1/h (mkW^{-1})	d/4 (m)	τ (s)
Quick-acting				
1.0	0.059	$1.61x10^{-3}$	$1.48x10^{-5}$	0.12
1.25	0.066	1.66	1.65	0.13
1.6	0.076	1.72	1.90	0.16
2.0	0.097	1.82	2.43	0.22
2.5	0.107	1.87	2.68	0.25
3.15	0.127	1.95	3.18	0.30
4.0	0.145	2.02	3.63	0.36
5.0	0.173	2.11	4.33	0.45
6.3	0.198	2.18	4.95	0.53
Time-lag				
1.4	0.095	$1.81x10^{-3}$	$2.38x10^{-5}$	0.40
1.6	0.103	1.85	2.58	0.44
2.0	0.118	1.92	2.95	0.52
2.5	0.129	1.96	3.23	0.58
3.15	0.152	2.04	3.80	0.71
4.0	0.178	2.12	4.45	0.87
5.0	0.200	2.19	5.00	1.01
6.3	0.229	2.26	5.73	1.19

<u>From equation (10)</u>

NOTES:
1) mc = $2.47x10^6$ $Jm^{-3}k^{-1}$ (silver element)
2) Time-lag fuse had a 60/40 Sn/Pb blob
3) Trigger effect bracket
= 1.99 for quick-acting fuse
= 3.72 for time-lag fuse
4) h calculated using $h = 54.4/d^{0.25}$ (ref. 3)

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