THERMAL CONSTANTS OF FILLER AND THEIR INFLUENCE ON THE METALLURGICAL EFFECTS IN FUSE ELEMENTS DURING PULSE DUTY

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1. Introduction

Pulse duty is a form of preloading of a fuselink, which can have an influence on subsequent performance. The importance of pulse duty for miniature fuses has been recognised internationally, as can be seen from the new edition of the IEC miniature fuse specification: IEC 127, now being prepared, which includes tests to ascertain pulse withstand of miniature time-lag fuselinks. These tests consist of 1000 cycles at 10 I_n with a duration corresponding to 40% of the pre-arcing I^2t and a repetition rate of 1 pulse per 30 s, followed by one hour at 1.25 I_n. (I_n = rated current.)

After this test the pre-arcing time at 1.7 I_n should be less than 300s. These tests apply to both unfilled and sandfilled miniature fuselinks, and the interval between pulses is normally sufficiently long to make sure that the pulsing has no cumulative effect.

Effects of preloading were considered in an earlier paper (Ref.1), in which it was shown that it was possible to discriminate between temporary and permanent effects.

Pulse duty at a given mean current normally acceptable by the fuselink can result in operation of the fuselink if the I^2t in a short period at the commencement of the pulse exceeds the short-time pre-arcing I^2t of the fuselink (Ref.2).

This paper deals with pulse duty which is very close to the latter situation, but which is insufficient to cause operation of the fuselink on a single pulse.

It has been established (Ref.3), that fuselinks which are sand-filled are far less susceptible to pulse effects than unfilled fuselinks, and the reasons for this are connected with the thermal conditions which are prevalent in the two cases. These thermal conditions are considered in detail below.

2. Experimental Details and Results

Commercial fuselinks of two different types, both sand-filled, with ceramic barrels, were subjected to a series of pulses of dc current. Both types had wire elements, with melting point addition ('M effect'), which was placed near the ends of the elements for type A and in the centre of the element for type B. Two ratings of fuse were used, 3A and 13A. Calculated adiabatic pre-arcing I^2t was considerably different for the different types.

The source of energy for testing with 'square' current pulses was a constant current pulse unit, capable of producing trains of pulses of duration from 0.1 ms to 99.9s, at a fully adjustable duty cycle. The maximum current which could be sustained for 10 ms without deterioration by these fuses was determined by setting a level at the pre-arcing I^2t and subjecting the fuses to trains of pulses of various values below this level, starting with 50% of the level. The pulses were applied at 10 to 20 ms intervals, so that an estimate of the rate of change of temperature during cooling could be obtained. In general the period 'on' was equal to, or approximately twice the period 'off'. Fig.1 shows typical curves of the change of temperature produced during each pulse and the cooling period for the first ten pulses for equal pulse and cooling periods.

Current and voltage were monitored on a digital oscilloscope, and data stored on floppy disc for further analysis by a dedicated on-line computer. The temperatures were calculated from the resistance ratio of the fuse elements. This is a good means of predicting the proximity to the blowing time of a fuse, and has been used in testing HV fuses at small overcurrent (Ref.4).

X-rays of some of the fuses were taken to determine changes in structure. Structural changes were also investigated by opening up the fuses after test and using an optical microscope. Sections were examined using a scanning electron microscope. The composition of diffused areas was determined by the X-ray emission producing an explanation of the unchanged blowing characteristic even though the metallurgical state was changed after severe pulsing. More details of this aspect of the work are given in Ref.3.

The effects of the thermal constants of the sand filler are such that the fuselinks were capable of accepting single pulses of up to 95% of their 'blowing' current, and rapidly repeated pulses exceeding 70% of their blowing current, without changing their characteristics, and were thus more resistant to the effects of pulsing than the low breaking capacity (unfilled) types previously described in Ref.1.

In the following section a simplified theoretical analysis is presented, which isolates the physical property of the sand which has the biggest effect at different stages of the pulsing process.

3. Importance of the Thermal Constants

3.1 Conductivity

In the above experiments it was seen that the rate of cooling of the fuse element was approximately proportional to the difference in temperature between the wire and the ambient air at the surface of the cartridge (equal to the temperature of the cartridge surface in these experiments).

Although the full equilibrium condition was not reached in these tests, it is interesting to see that the changes in temperature during the pulsing were predictable from the thermal constants of the filler, together with knowledge of the corresponding constants for the element material. The constants involved were the thermal conductivity and diffusivity of the materials.

We first consider the effects of pulse duty upon the fuse element, its temperature rise during pulsing and the equation representing the equilibrium temperature/time relation reached by the element. Assuming no loss of heat, the temperature rise of the element from θ_1 to θ_2 will be given (Ref.1) by the solution of the equation (1):

$$\int_{t_1}^{t_2} i^2\,dt = A^2 \frac{dc}{\rho_o \alpha} \quad \ln \frac{(\theta_2 + \frac{1}{\alpha})}{(\theta_1 + \frac{1}{\alpha})} \qquad (1)$$

where

$$\int_{t_1}^{t_2} i^2\,dt = \text{the } I^2t \text{ delivered between times } t_1 \text{ and } t_2$$

θ_1 = temperature of a segment of element cross-section A at time t_1

θ_2 = temperature of a segment of element cross-section A at time t_2

d = density of element material

c = specific heat of element material

ρ_o = resistivity of element material at 0^oC

α = temperature coefficient of resistance of element material averaged over θ_1 to θ_2.

Thus the I^2t required to raise the temperature from θ_1 to θ_2 may be calculated. The I^2t needed is greater than this amount by the extra I^2t required to make up the losses during the heating process. In the interval between pulses, cooling takes place, and although equilibrium may not yet be reached, it was found possible to calculate the approximate rate of cooling from consideration of steady state conduction, assuming the heat to be conducted out radially. The thermal conductivity K of the sand is approximately equal to that of the barrel in this case, and of the order of 5×10^{-4} $Wmm^{-1} K^{-1}$. Conduction rate is controlled by the equation:

$$\frac{dQ}{dt} = \frac{2\,K\pi}{\ln(d_2/d_1)} \,(\theta_m - 20) \qquad (2)$$

Taking the outer temperature of the barrel to be 20^oC

where

dQ/dt = rate of loss of heat

d_1 = diameter of the wire (in mm)

d_2 = outer diameter of the barrel (in mm)

θ_m = mean temperature of the wire

But $dQ/dt = \pi/4 \times d_1^2 \; c_v \, d\theta/dt$ for each unit length of wire, where

c_v = specific heat per unit volume of the wire

$d\theta/dt$ = rate of cooling

For SI units, equation (2) reduces to

$$\frac{d\theta}{dt} = \frac{1.4}{d_1^2 \ln(d_2/d_1)} (\theta_m - 20)$$

$$= K' (\theta_m - 20). \qquad \text{(dimensions in mm)}$$

Results are shown in Fig.2 for fuselinks of types A and B.

Comparison of experimental and calculated results are given in Table 1.

Table 1

Comparison of calculated cooling constants with experimental results.

External diameter of all fuse barrels = 5.75 mm

Fuselink type and rating	Wire dia mm	K' Calculated	K' Experimental
A (3A)	0.094	38.5	39.5
B (3A)	0.122	24.4	26
B (13A)	0.33	4.5	6

The thickest wire shows evidence of significant conduction of heat to the end caps. It thus appears that the cooling between pulses is controlled by the conductivity of the filler, particularly for the thinner wires.

3.2 Diffusivity

When the fuse element in sand is subjected to pulses of current at regular intervals, the temperature rises during the current-carrying period, and falls between pulses. Initially, the rise of temperature is considerably higher than the fall, but for currents below the 'run-away' condition, an equilibrium is eventually reached, where the temperature rise during the pulse equals the fall during the off period. This condition is due to the loss of heat into the surrounding sand. The distribution of temperature in the sand can be approximately represented, taking a simplified case of a temperature variation $\Delta\theta$ at the surface of the element of the form $\Delta\theta = \theta_x \cos A$, with the number of cycles per second f, $A = 2\pi ft$, and $dA/dt = 2\pi f$ radians per second. The rate of flow into the sand is dependent on the diffusivity of the sand, κ, which is related to the thermal conductivity, K, the density, ρ and the specific heat c, by:

$$\kappa = \frac{K}{\rho c}$$

the rate of flow can be expressed by the well-known equations:

$$\kappa \frac{d^2\theta}{dx^2} - \frac{d\theta}{dt} = 0 \qquad (3)$$

or $$\kappa \frac{d^2\theta}{dx^2} - \frac{d\theta}{dA}\frac{dA}{dt} = \kappa \frac{d^2\theta}{dx^2} - 2\pi f \frac{d\theta}{dA} = 0 \qquad (4)$$

This equation can be solved by taking the constant $\mu = \sqrt{\frac{\pi f}{\kappa}}$ to give

$$\Delta\theta = \theta_x e^{-\mu x} \cos (A - \mu x)$$

For any distance x away from the element in the sand, the temperature variation is from $\theta_x e^{-\mu x}$ to $-\theta_x e^{-\mu x}$, with a lag in temperature of phase angle μx.

Assuming a fluctuation of temperature in the sand of 10% of the fluctuation in the element to be sufficiently low to be able to neglect further effects of the sand, the thickness of sand layer affecting the element surface temperature can be calculated from this formula. For maximum fluctuation at any depth $\cos (A - \mu x) = 1$ and $\Delta\theta = \theta_x e^{-\mu x}$.

if $\Delta\theta = 0.1\theta_x$, then $e^{-\mu x} = 0.1$

and $\mu x = 2.3$

that is: $x = 2.3 \sqrt{\kappa/\pi f}$ (mm)

The actual diffusivity of the sand surrounding the element is very dependent on the packing factor, the grain size and any impurities or moisture present, so that figures given in the literature may vary by a factor 10 or more.

Taking the following properties for a well-known fuselink:

$K = 5.10^{-4}$ W mm^{-1} K^{-1}

$C = 1.2$ J g^{-1} K^{-1}

$\rho = 1.8 \times 10^{-3}$ g mm^{-3}

then the diffusivity for closely packed sand is $\kappa = 0.23$ mm^{2}s^{-1}

For f = 50 Hz this gives a "depth of penetration": 0.088 mm

This is a measure of the cooling effect of the sand, which cools the surface of the wire during the passage of the pulse and thus can delay the onset of M-effect operation during pulsing. The greater the "depth of penetration", the greater the effect. This local cooling increases with diffusivity of the sand used, "penetration" being approximately proportional to the square root of the diffusivity. The grains in contact with the wire may have a diffusivity which is an order of magnitude greater than the bulk of the filler, the bulk diffusivity being reduced due to the air in the interstices.

The above provides an explanation of the superior performance on pulsing of fuselinks with M-effect in sand compared with similar ratings in unfilled miniature fuselinks (low breaking capacity types).

4. Conclusions

The following conclusions are drawn from the results:

1. The improved resistance to pulsing of sand-filled wire element fuses of low current rating is dependent upon the thermal constants of the filler.
2. The cooling between pulses appears to be determined largely by the thermal conductivity of the filler.
3. The local protective cooling which delays the operation of M-effect, during passage of the pulse, appears to be determined by the diffusivity of the filler.

References

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4. Turner, H W and Turner C : 'Improvements relating to the testing of electric fuses', British Patent No. 117, 817, 1968.

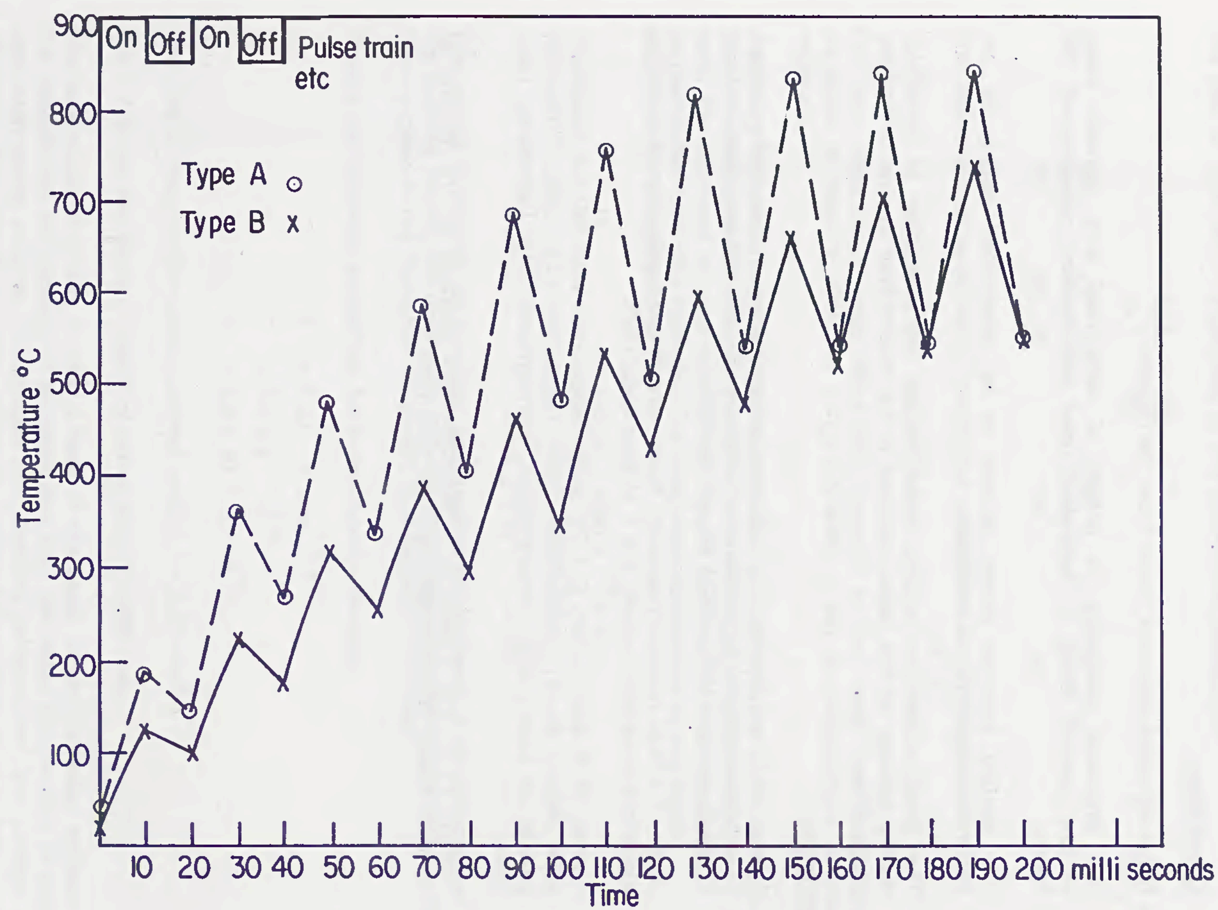

Fig. 1 : Temperature Changes for 3 A Fuselinks, Types A and B. Current Pulse: Type A : 10 A, Type B : 16.7 A

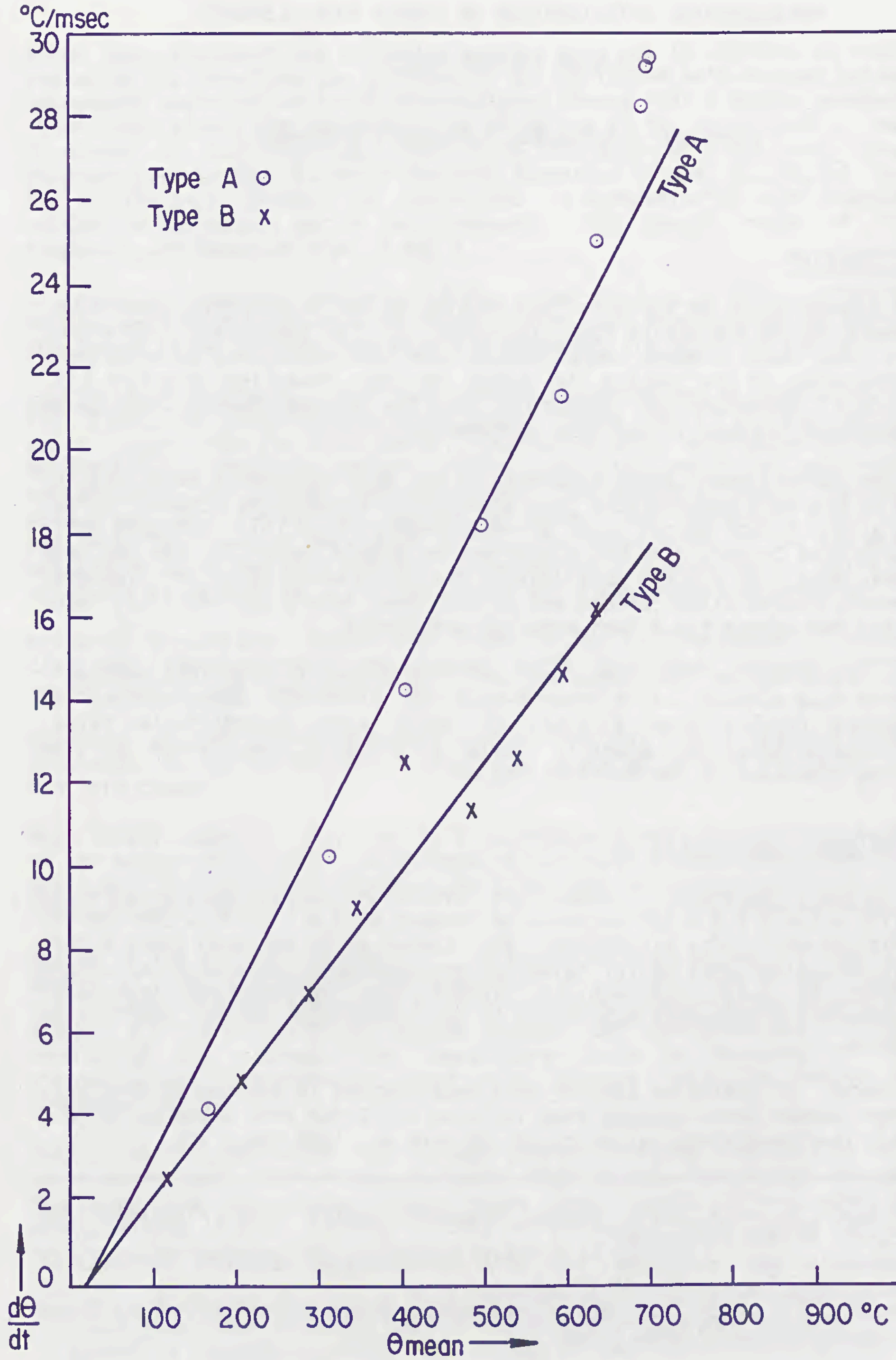

Fig. 2 : Rate of Change of Temperature for 3 A Fuselinks Types A and B