THE ROLE OF FUSE FILLER IN CIRCUIT PROTECTION

H.W.Turner and C.Turner

INTRODUCTION The operation of a fuselink, as is represented by its time/current characteristic for the pre-arcing period, and its total operating characteristic (or 'let-through' characteristic) for the total period of pre-arcing time and arcing time, is markedly influenced by the filler used in the fuselink, as well as by the element material and configuration.

Years of experience have resulted in the continued use of silica sand as a filler, and apart from some specially treated types of sand which find application today, there has been relatively much less effort spent on the study of this aspect of fuse construction since the initial experiments, in which the limitations of the techniques then available for study made the subject a difficult one in which firm conclusions could not be reached. With the improved techniques of investigation and testing now available, and newer methods of digital analysis, these phenomena can now be studied in more detail.

The voltage per constriction in a fuselink for general purpose performance is limited and cannot be significantly increased without introducing ranges of current where the fuse fails, and thus changing it into a back-up fuse. However, if the number of constrictions could be reduced (i.e. more volts per constriction) then there could be a corresponding reduction of both the power loss and the physical size of the fuselink.

These and many advantages would accrue, if a better alternative to sand could be found.

ACTION OF FILLER IN CONTROLLING FUSE PERFORMANCE The effectiveness of circuit protection provided by fuses is controlled by the filler in two main ways. Firstly the prearcing performance of the fuse and its freedom from damage or ageing during this period sets the time/current characteristic limits at which the protection comes into action, and secondly the efficiency and repeatably controlled current decay during the extinction of the arc in the filler determines the effectiveness with which the fault is disconnected after the start of operation of the fuse.

These main aspects and the effect of filler in determining them may be subdivided in the following ways:-

1. Effect on time/current characteristic by conduction of heat from the element and raising its current rating.
2. Reducing its prearcing and let-through I^2t corresponding to a given current rating.
3. Withdrawal of energy from the arc by fusion, resulting in rapid decay of current and ensuring current limiting action.

Dr.C.Turner and Mr.H.W.Turner are with the Electrical Research Association Ltd., Power Engineering Division.

4. Damping of recovery voltage transient by increased electrical conductivity when hot.
5. Formation of molten shields containing arc within solid filler, preventing merging of arcs and flashover between elements or between nearby turns on the helically wound element (e.g. in H.V. fuses).
6. Assistance of extinction by pressure build-up in the molten shields, which also contain some of the mechanical and thermal shock on the barrel.
7. Further protection against thermal and mechanical shock on the barrel by the remaining unmelted quartz. Thermal shock which might otherwise crack the barrel is delayed by the high ratio of thermal resistance to capacitance of the filler, and arrives at the barrel after the arc at the centre of the cartridge is extinguished.

The filler also provides the following useful functions:-

1. It supports elements and protects them from damage (except in pulsing operation).
2. It reduces atmospheric attack.
3. It retains the heat and flame of the arc within the barrel and helps to prevent any injury to nearby persons whilst performing its task of protecting the circuit against overcurrent.

Some element materials can be affected by the choice of filler, e.g. Aluminium reacts with sand to give a 'thermite' type of reaction, which can affect the arc extinction deletoriously, or can be exploited in special designs, as described by Lerstrup(1).

Effect on Prearcing Performance Conduction from the element to the filler is an intractable problem because of the difficulty of defining the process of heat transfer between individual filler grains and the air and vapour entrained between them and the surface of the element.

One method by which an estimate of the heat conduction may be made, is to consider the element contained within a cylinder of filler and element support (if any) of radius r_1, at a given distance d along the length of the barrel and bounded by an isothermal surface of temperature ϑ_1. At the steady state, in the region of the centre of the fuse, where r_1 is constant, we have the following expression for the temperature difference between this isothermal surface and the external surface of the fuse, in so far as it can be considered as a cylinder of external radius r_2 and external temperature ϑ_2 :-

$$\vartheta_1 - \vartheta_2 = \frac{Q}{2\pi k} \ln \frac{r_1}{r_2} \qquad (1)$$

in which k is the filler conductivity, which is approximately equal to the conductivity of the barrel material, and Q is the watts dissipated radially per unit length.

Such steady state conditions exist up to the minimum fusing current, where ϑ_1 is near the operating temperature of the element. At the centre of a very long element in a long cartridge (e.g. a high voltage fuselink), Q is approximately equal to the total watts per unit length dissipated in the cartridge, due to the small amount of longitudinal loss in that region. Equation (1) shows that for such fuses the minimum fusing current is very dependent upon the effective value of the conductivity k. Allowance for different conductivity of the barrel material can be simply made by considering the thermal conductor as a series of concentric cylindrical tubes.

The whole body can be treated as divided into infinitely thin shells by a system of isothermal surfaces. The lines of flow of heat consist of a system orthogonally cutting these shells, and, of course, no two lines of flow nor two isothermal surfaces can intersect, and heat flow can only be in one direction at a given point. By limiting the number of lines and shells considered, the system lends itself to computational analysis. Attempts to solve the problem from first principles give considerable difficulty, largely because of the approximations necessary to get the simple solution of equation (1).

Defining r_1 is difficult in any case, and the value of k is not a well defined parameter, being affected markedly by traces of moisture, and water vapour diffusion in interfaces make up to an order of magnitude difference in the effective value of k in cylindrical elements of different radii. This can be treated by the same method as for the barrel/filler change in conductivity. Even without water vapour present, k is a quantity, dependent on the crystal structure of the quartz, so that grain shape and packing also influence its value. The effective value of k also changed with different times of operation, since there is reversible transport of residual moisture in the fuse, and surface coating of filler can produce additional problems of degradation and vapour transport, which can affect the time/current characteristics non-reversibly. However, it is clear from (1) that radial loss of heat is controlled by the filler to a very large extent.

At very short times, the effect of the filler is less, since the conditions are not in equilibrium and pulsed heat transfer occurs according to equations of the form:-

$$K\left(\frac{\partial^2\vartheta}{\partial x^2}+\frac{\partial^2\vartheta}{\partial y^2}+\frac{\partial^2\vartheta}{\partial z^2}\right)=c\,\frac{\partial\vartheta}{\partial t} \qquad (2)$$

The heat transfer between the element and the bulk of the filler is difficult to determine exactly, for the reasons stated, but is of vital importance. The subsequent heat transfer in the pulsed condition is seen from (2) to be highly dependent on the ratios of thermal conductivity k to thermal capacity per unit volume (c), and this controls the rate of rise of the heat pulse and its velocity of transmission through the material.

This rate of rise is clearly important in determining the local conditions for the element, and has the effect of delaying the melting of the element at all times longer than the very short melting times for which the heating can be considered as adiabatic. The exact region of this short time operation is dependent upon design of the fuse element and its contact with the filler, but for necked elements of high aspect ratio it is above the boundary of the adiabatic I^2t region because of significant heat flow between the neck and other regions of the element at pre-arcing times of 0.01 seconds or less (Leach, Newbery, 2 McEwan). It is clear therefore, that the filler has a large effect on all parts of the prearcing time characteristic except the very short time end, and thus the largest range of operating times of the circuit protection in practice are effectively set by the filler in the fuselink.

<u>Effect on Arcing Performance</u> Arc extinction in a sand filled fuse depends to a greater extent upon the thermal and electrical characteristics of the filler than on the characteristics of the element, whose function is to initiate the breaking process at preferred locations within

the filler at a reproducible virtual pre-arcing time, and subsequently not to break up excessively along its length, producing excessive overvoltages, or otherwise to interrupt the process of controlled current extinction.

The arc energy, much of which is derived from the stored inductive energy in the circuit, must be absorbed in this period. This is done by melting the filler, heating it from its initial temperature to the melting point and fusing it by providing the required latent heat. As analysed by the authors (4), 2.1 kilojoules is required for every gramme of sand melted. In the same reference, the authors analysed the influence of grain size, and showed that this aspect of filler properties has a pronounced influence on arc extinction, especially in the region of small overcurrent performance. However, when the arc is initiated in a controlled manner in fuselinks of a range of designs, the subsequent clearance of the arc appears to depend more on point on wave and stored inductive energy available than on other factors, as illustrated in Fig. 2.

Some other aspects will now be considered, namely:-
(1) Variation of filler conductivity with temperature
(2) Variation of overvoltage with filler

and the consequences of filler behaviour on the permissible dimensions for fuselinks will be discussed.

(1) Variation of filler conductivity with temperature.
The electrical resistivity of quartz is steeply dependent on temperature, as is illustrated in Fig. 3. The difference of a few hundred degrees causes changes of several orders of magnitude in the resistance of a previously melted arc channel. As stated above, this has a useful damping effect on transients, by effectively making fuse operation a form of resistance switching. The disadvantage, however, is the slow recovery of insulation subsequent on short circuit operation of fuselinks of high current rating.

As discussed above, the mass of filler melted is proportional to the arc energy, and consequently a fuse operation at high inductive energy results in a considerable volume of melted sand and correspondingly low resistance. Furthermore, the whole of this arc energy is stored in the molten mass, which cools slowly because of the good thermal insulation of the sand and of the fuse barrel. Even fuselinks of relatively modest current rating take a measurable time to recover isolation, particularly if they have short constrictions in their element design, resulting in short 'fat' fulgurite lengths joined by lengths of unblown silver tape at the completion of the operation. An example is given in Fig. 4. This oscillogram was obtained using the technique shown in Fig. 5. This method of studying fulgurite resistance is operated in the following manner:- The small contact gap B is initially bridged by a fine wire and an arc is initiated as soon as the making switch A is closed. This arc continues to burn until the fuselink clears the circuit and then rapidly extinguishes, and the Galvanometer G, with total resistance R_G records a time dependent voltage V_G (dependent upon its voltage calibration). The fulgurite resistance $R_F = \dfrac{V_S - V_G}{V_G} \times R_G$

Typical results are shown in Fig. 6. illustrating the resistance behaviour for experimental wire fuses and commercial fuses of the same rating (30A). The difference is explained by study of the fulgurite by X-ray or optically after demounting the fuse after test. The wire fuses broke into globules along the whole length, producing one long thin molten channel of high initial resistance and rapid cooling, resulting in a rapid rise in resistance after blowing. The single neck type fuse produced a short fat molten mass of correspondingly lower resistance and much slower cooling.

Other things being equal, the bigger the current rating of the fuselink, the slower the recovery of resistance. This can give problems in fuse testing, depending on how quickly the resistance is measured within the three minutes allowed in some standards. It could be argued that for shock risk protection this resistance should be measured quickly, but for present designs of large rating fuselink this is an academic argument, which could mitigate against some of the better designs using existing filler. Specifications would be improved if this insulation measurement were required to be made at a specified time, e.g. exactly 3 minutes after operation.

Fig. 7 shows how this recovery varies with sand supplied from different sources, being a function of grain size and trace impurities. However, if a significant improvement in this factor is required, a new type of filler material would be needed, which might perhaps be inferior to sand in other respects.

(2) Variation of overvoltage with filler.
Experiments carried out on a range of sands reveal significant changes in overvoltage. The spacing of the bands in the fulgurite after fuse operation, which can be revealed by X-rays, is influenced by grain size, resulting in larger numbers of bands per unit length with a finer filler, other things being equal. This is accompanied by higher values of peak voltage.

The conclusion from these experiments is that the filler size incluences the break-up of the element. Fuse elements with long reduced sections tend to behave like the wire elements, but very short necked elements behave differently, although they are also affected by filler properties.

<u>Effect of Filler Behaviour on Fuselink Dimensions</u> The barrel containing the element in its filler has also to contain the molten mass produced by the arcing, and the boundary of that mass should be clear of the inner surface of the barrel to prevent cracking of the barrel and failure. In particular, the short fat lengths of fulgurite formed with short necked elements should be contained in the barrel. Constrictions nearest the end caps should be suitably spaced to prevent end cap piercing, and the fuse must be completely filled to avoid failure in this region.

With high voltage fuses a compromise may be necessary between the use of a star core big enough to space the fused masses efficiently throughout the filler but small enough to leave adequate sand clearance between the element and the barrel.

<u>MEANS OF STUDY OF THE BEHAVIOUR DURING ARCING</u> Special techniques must be used to investigate this region, because in general the process takes place in an opaque cartridge with the element completely surrounded by filler. Much can be learned by studying a cross section with a transparent plate in front of the element, but this does not give a true picture of the behaviour in a porcelain barrel. This can only be obtained by indirect methods or pulsed X-ray observation, as described below.

<u>The Crowbar Method</u> This is a quite effective way of studying the effects of arcing and consists of placing a solid state 'crowbar' circuit across the fuselink during operation. The crowbar is triggered at a range of delays during the arcing period, the delay pulse being initiated by the peak arc voltage on operation just after the conclusion of the prearcing period.

If the delay is set at zero, a quantity of fulgurite can be found which represents the degree of arcing energy before voltage peak, which varies with the design of the fuselink. Initiating at an earlier stage in the process offers a means of studying this region, which could be critical in (for example) semiconductor protection types, with very short necks and a (comparatively) long duration at short arc, low arcing voltage conditions. The crowbar must have a sufficiently low back-emf to bypass this condition adequately. The disadvantage of this method is, of course, the delay between the event and the subsequent study of the fulgurite after dismantling the fuse or X-ray investigation. During this period the molten mass can move whilst cooling and solidify into different forms to those existing at the time of the incident. But as solidification is in general quite rapid, this method is very instructive.

<u>The Pulsed X-Ray Technique</u> This is a powerful method of study involving the use of special X-ray equipment yielding high power pulses of X-rays of durations measured in nanoseconds. This effectively freezes the situation at the point in the arcing at which the X-ray is triggered, which can be directly related to the oscillograms of current and voltage at that instant.

The particular instant can be identified by a Z-modulated pulse on the oscilloscope, from the triggering pulse of, the X-ray equipment or from a pulse derived from an X-ray detector in the fuse circuitry. It is also possible to produce a mark on the oscillogram by direct action of the X-rays when using a rotating camera technique of recording, but the authors have found this to be difficult.

The use of repeated pulses from such an equipment is very valuable for studying the behaviour of the arc developing in fuselinks of a commercial type under conditions of failure whilst operating in the region of small overcurrents. The photographic material, in a cover excluding light, is rotated on the large disc, at such a rate that the repetition rate of the X-ray pulses produces a series of discreet images. The delay between pulses required to study this slow growth of development of the arc is of the order of 50 milliseconds, whereas the duration of the X-ray pulse is of the order of nanoseconds, so that the image is not blurred due to the rotation of the plate.

The initiation of the arcing within the fuselink can be clearly observed, and the growth of the arc can be traced, together with the spread of the molten region and arc channel within the filler. The known rotation speed and the spacing of the images gives a time calibration to identify the condition relative to a simultaneous oscillogram of current and voltage.

<u>The High Speed Photography Method</u> This technique employs a high speed camera to investigate a model in which the element is pressed against a quartz glass plate and the filler pressed behind it.

Many of the early stages of arcing of the element can be observed in this way, but unfortunately its use is limited in the study of filler by the fact that the filler action only takes place on one side of the element and the plate is usually destroyed before the true filler action takes place.

The virtue of the method lies in the very large number of high speed photographs which are possible with modern cameras, to study the initial break up of element in filler on arc initiation, and also the processes leading to element break up immediately prior to this instant.

The effect of ordinary filler is slight in this region due to the adiabatic nature of the fuse element fusion, although very fine filler can produce a marked effect on arc voltage, and this method is a possible means of studying this effect.

<u>New Possible Techniques</u> Digital methods of investigation are providing powerful tools for the analysis of large amounts of data, and giving 'instant analysis' by on-line mini computers.

Such application to this field is not as yet known, although there are clear possibilities of using the types of technique of scanned X-ray study such as are now common in medical diagnosis. This type of equipment offers interesting possibilities for further study.

<u>References</u>:

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3. R. Wilkins, P. M. McEwan Proc. IEE 122, 3, March 1975, 289 - 292.
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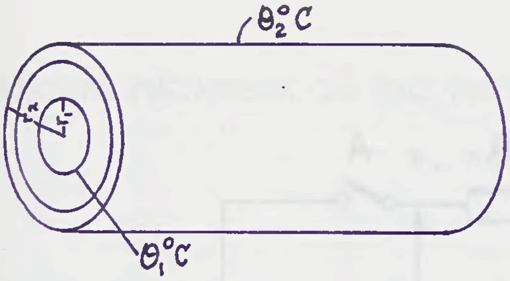

Fig 1. Conduction between Concentric Cylinders.

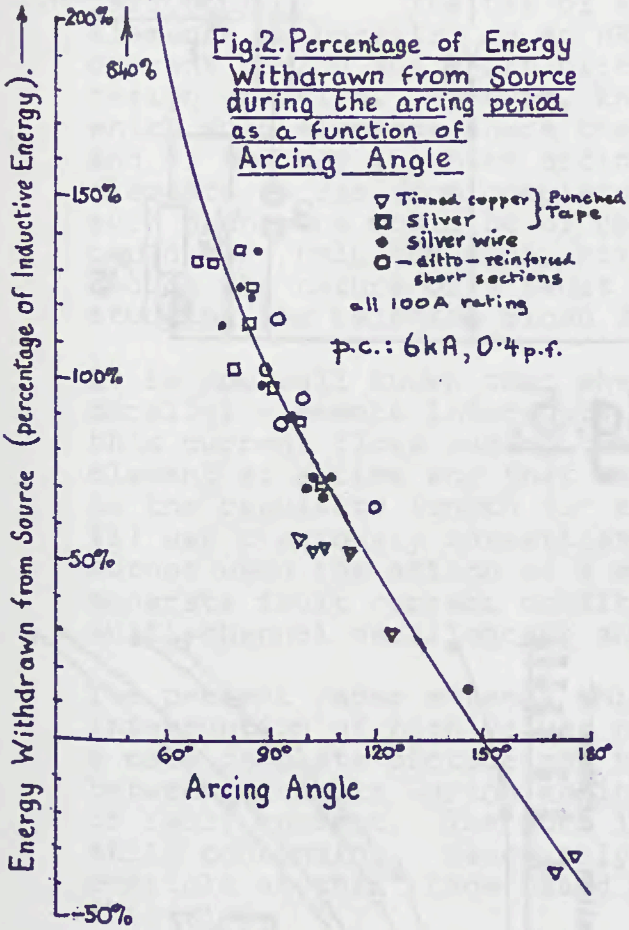

Fig.2. Percentage of Energy Withdrawn from Source during the arcing period as a function of Arcing Angle

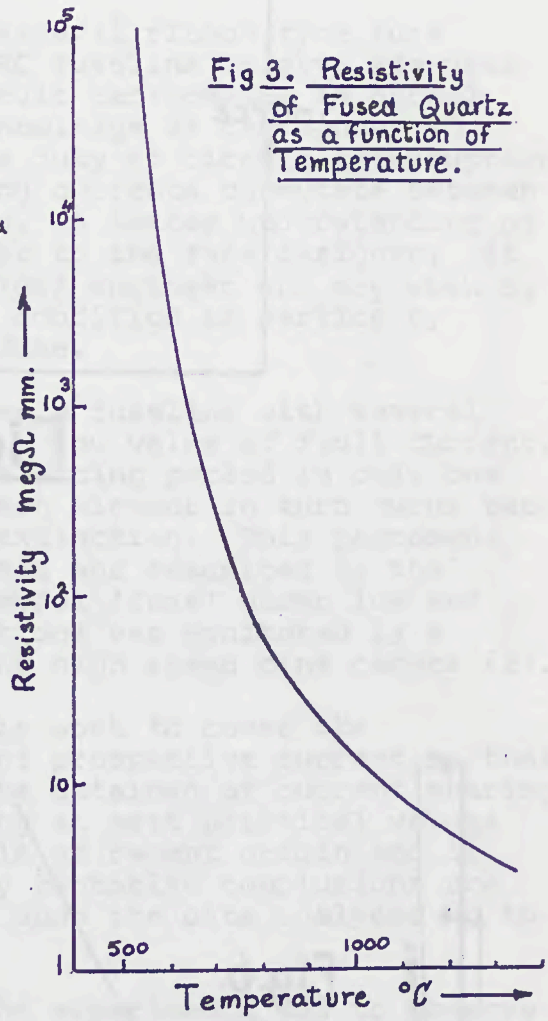

Fig 3. Resistivity of Fused Quartz as a function of Temperature.

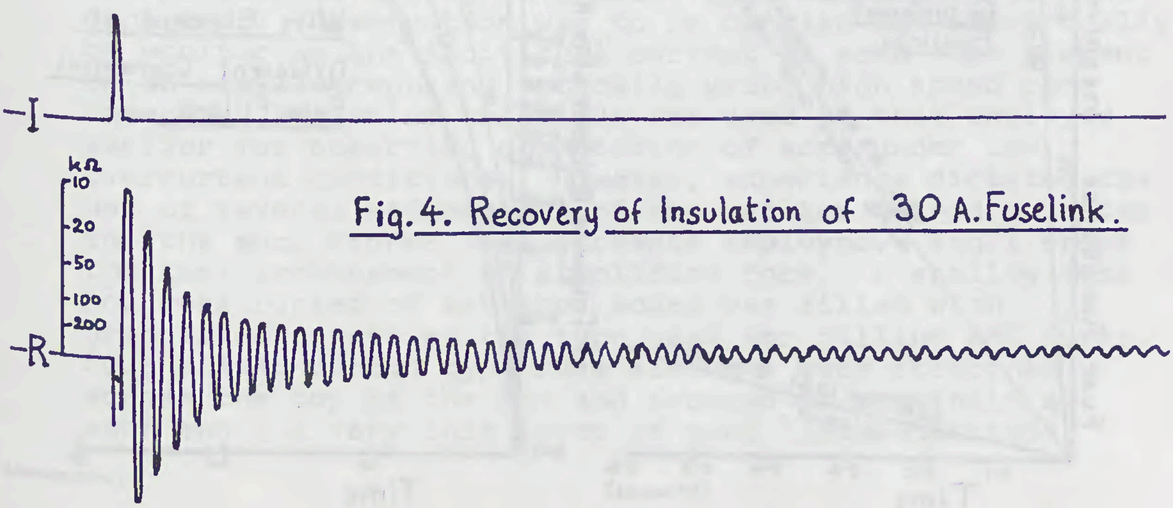

Fig. 4. Recovery of Insulation of 30 A. Fuselink.

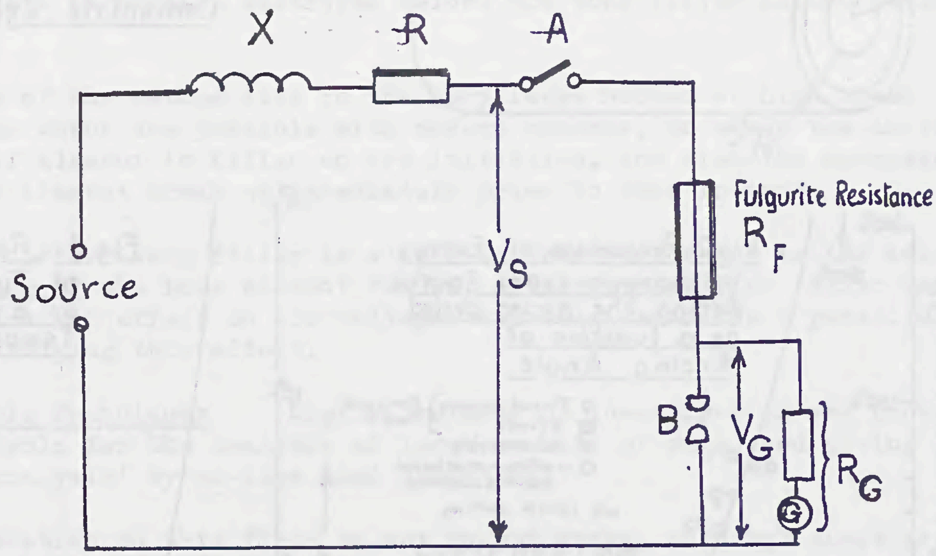

Fig. 5.

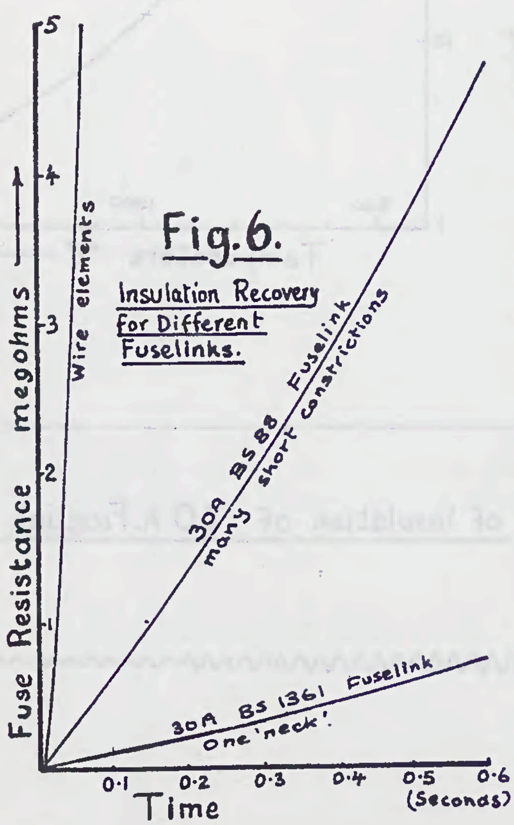

Fig. 6. Insulation Recovery for Different Fuselinks.

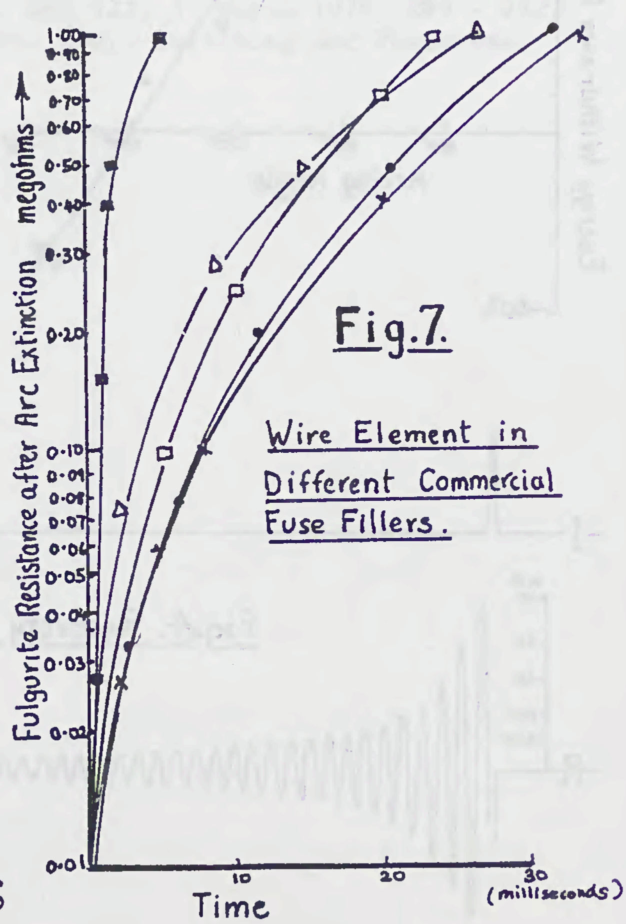

Fig. 7. Wire Element in Different Commercial Fuse Fillers.