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THOUGHTS ON FUSE OPERATION

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INTRODUCTION Nominally simple, the concept of series conductor piece desintegration under overcurrent influence in order to circuit interruption actually involves complex electrical, thermal and mechanical processes.

At present among different kinds of fuses one may distinquish the following operating principles:

i onefold fuses (OF),

ii permanent fuses (PE).

OF today are mainly: expulsion fuses (EF) and quartz-sand filler fuses, which commonly are called h.r.c. fuses.

PF, primary developed abt ten years ago in Japan(1), now are intensively improved in some other countries too. The explanation of fuse operation principles in case of PF therefore is now to early and because of that will be out of consideration in this paper. However, all the interested with PF may take aquaintance with papers(2,3) well introducing into actual state of the problem. There are some other papers and especially patents in the field of PF too.

Also EF will be omitted because normally they are not short--circuit current-limiting devices. The mode of EF operation shown in paper(4) is like many other a.c. current interrupting devices: they finally interrupt at some succesive naturally current zero passing. The arc-quenching process is here in large scale independent from thermal pre-arcing phenomena(5).

In contrary to EF h.r.c. fuses normally are current-limiting devices with arc-quenching process predicted by thermal pre-

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-arcing phenomena. That is the reason, why this paper gives some thoughts on h.r.c. fuse operation principles only.

During the decades prior to the second world war experimental and theoretical physics had gathered some basic knowledge on the interrupting process of h.r.c. fuses. However, there was a wide gap between the fundamental science and the possibility to apply the results of development in physics to the problem of interruption of high and low currunts under the conditions fuse have to operate.

25 year ago Baxter(6) published his well known book with more systematic fundamental laboratory tests results of h.r.c. fuses operation physics.

The last period gives many further fundamental results mainly for h.r.c. fuses with stripe fuse-elements, synthesized in book(7). Another polish book(8) and a recently edited one in U.K.(9) have the h.r.c. fuses applications for safety in electrical systems as their main subject.

Finally, the Läpple´s book(10) gives a critical review of published informations up to abt 1950 in the field of electric fuses, which are supplemented e.g. up to 1965 by ERA Report(11) and others.

Therefore the answer on the question 'how does a h.r.c. fuse really operates' now is much more easy than formerly.

In spite of that we are still far away to complete the knowledge concerning especially the fuse-element disrupting and arc-quenching processes. In close connection with these there are the thermal states of the fuse-element reached just prior its disrupting. These thermal states have not a fully explanation yet, especially in the case of deep notched fuse--elements.

In addition, this matter hase become more complicated due to new h.r.c. fuse design inventions*), which introduced in practice permanently modify the fuse-element disrupting and arc-quinching process.

That´s why in the following there only will be given some explanations for more or less simple and common cases.

SOME REMARKS ON H.R.C. FUSE OPERATION The temperature distribution along the fuse-element just prior its disintegration is the main predicting factor of the arc-ignition and arc-quenching processes.

Today the dimensions and material properties of fuse-link contacts and of fuse-link insulating tube are nearly these same for the same h.r.c. fuse size manufactured by several firms. Therefore for a given preloading state and for a given overcurrent the temperature distribution along the fuse-element greatly depends on longitudinal mode of its cross-section variation (Fig.1).

The h.r.c. fuse-elements may be divided as follows:

i Long or short, depending upon ratio L/D, where D-the outer diameter and L-the length of the fuse-link with given fuse element. It is called long with L/D> apprx.5 or short with L/D < apprx.5.

ii Uniform or notched cross-section.

iii With one stripe or one wire, with multi-stripe or multi-wire fuse-elements.

Because of the great thermal coupling between neck and shoulders of notched elements, by the steady state or by long time overloads the temperature differences along the fuse element are not significant (Fig.1 temperature distributions1). But for short-circuits the differences are very distinct (Fig.1 distributions2).

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*) e.g. during 1974 the number of established h.r.c. fuse patents in USA only is abt 50

The correct and faulty operation of a fuse by overloads and short-circuits may be investigated in idealized oscillograms (Fig.2, 3, 4, 5).

Overload Current Interruption Independently from correct or faulty operation (Fig. 2 and 3) there goes during period A a heating process of the whole fuse as a consequence of Joule's heat-emitting in fuse-element. These heat conditions may be calculated using corresponding equations or methods given e.g. by papers[12, 13, 14, 15].

The arc-ignition and arc-buring process depends from:
i shape of fuse-element,
ii value of overload current ratio to the rated current of the fuse-link.

There are possible the following arc mechanisms:
i one-arc,
ii multi-arc.

One-arc ignition will occur, if:
i Short fuse-link has uniform-section or multi-notched fuse-element, which all notches have this same cross-section (Fig.1a,b) or central notch has the minimum cross-section.
ii Long fuse-link has a central notch with minimum cross-section.

For a uniform-section short fuse-element there must be additionally a low-enough overcurrent value. E.g. in the case of 500 V fuses with 0,35 mm dia silver wire fuse-elements the one-arc ignition will occur with overcurrents up to 5 I_n and up to 8 I_n if the wire is Soft[16], where I_n - the rated current of the fuse. In all mentioned cases the arc ignites at the beginning in or near the centre of fuse-element.

For d.c. one-arc there exist a calculation method of overcurrent interruprion process parameters[17]. This method should be succesfully adopted for a.c. one-arc interruption.

For short or long multi-notched elements the next arcs may ignite later with time-lag dependent from the cross-section differences of said notches.

Figures 2 and 3 are typical for one-arc ignition and one-arc burning process. The notations u_a and u_i used in figures correspond to the arc-voltages and to arc-ignition or arc--extinction voltages appearing near each current-zero.

The arc-burning time-interval B ends in moment t_2 with final interruption (Fig.2) or in moment t_e with complete evaporation of fuse-element and the arc-flames ejection appearing through holes melted in fuse-link-contacts (Fig.3). Temperature T measured in the section, where the first arc-burning will occur and further in the cathode and anode spot of an arc.

It is interesting to note, that during period B there may occur an aperiodical component of current (the moment t_{ap}) introduced by sudden change of discharge resistance[18].

In long fuse-links with uniform-section fuse-element and in short fuse-links with overcurrents greater than mentioned before values 5 I_n or 8 I_n there occurs a multi-arc ignition and multi-arc burning process with unduloids formation.

A recently published paper makes clear, that unduloid formations on the wire is independent from the current[20]. Upon my opinion, the current mainly accelerates the whole process and keeps the more strict periodical disintegration module only.

During the period C for correctly operating fuse the remainded fulgurite becomes cool, but, if fuse operation is faulty, the fulgurite is growing till to current interruption by another device in that circuit.

<u>Short-Circuit Current Interruption</u> As said before, in-

dependently from correct or faulty operation (Fig.4 and 5), during period A there goes a heating process mainly of the fuse-element. The heat conditions are more close to an adiabatic one now and are very simple, if there are pure adiabatic. They are complicated enough, if a heat transfer from norched parts to shoulders may appear.

The short-circuit disintegration process of the fuse-element depends from their shape. In case of uniform-section there appears a striated mechanism, more subtly described by Nasiłowski [21] and by Hibner [22] for stripes.

In case of a notched fuse-element there are two disintegration possibilities: striated mechanism or an one-arc mechanism. If the notches are long enough, they disintegrate with striation. For very short and deep notches an one-arc mechanism appears. Normally in the last case most fuse--elements have many short notches with these same cross-sections periodically distributed along the stripe. Therefore the arcs will appear in all the notches simultaneously. Than the arcs will elongate till to the current interruption or till to arc-flames ejection through holes melted in fuse--link-contacts. Such faulty arc-quenching mechanism is not showed in the Fig.5.

Fig.5 correspondes to the fuse-link expl-osion during arc--burning period (moment t_e), as a result of pressure shock wave.

During the period C in a correctly operating fuse the fulgurite becomes cool. Its property are described in the paper [22]

All mentioned mechanisms are not yet fully investigated. In spite of that, we may calculate the peak arc-voltage U_a [22], the let-through current i_o [23] and reacently we got a method of voltage and current calculation during period B [24], if notches are deep and short.

We are at the beginning of exploration of problems concerning the pressure shock wave p. The pressure shock wave withstand of a fuse-link body is an important parameter deciding the successful short-circuit interruption.

Moreover, the post-arc conductivity of a fulgurite is a problem, which needs a better investigation. This problem was discussed before last war in Germany(25), and in spite of existing a new paper(26), there is an essential lack in fundamental scientific work.

FINAL REMARKS However in previous paragraph the more detailed explanations are given how does a h.r.c. fuse operate, the text valume now is large enough. So it is time to get some short final remarks.

Many aspects of h.r.c. fuse operation are omitted in the paper. E.g. there are not any remarks concerning: long and short-time ageing phenomena of fuse-elements(27, 28) voltage--current fuse-arc characteristics(29), arc-burning and arc--quinching phenomena for multi-wire and multi-stripe fuse-elements(30, 31), phenomena in arc-quinching medium(32, 33), behaviour of fuse-elements in LC circuit(34, 35) and so on.

All these and other questions should be involved during Conference discussion to get more precise answers how does really h.r.c. and other kinds of fuses operate.

REFERENCES

1 'Stombegrenzungsvorrichtung'. Bundesrepublik Deutschland. Deutsches Patentamt. Anmeldetag 30.10.69 (1954736.5-32). Mitsubishi Denki K.K. Tokio. Japan

2 Jones N.D.: 'Self-healing fuse development'. IEEE Power Process a. Elec. Specialists Conf. Rec. Atlantic City. N.J. 1972 New York: 1972. p.140-145

3 Franck E.U.: 'Polar and ionic fluids at high pressures and temperatures'. Pure a. Appl. Chem. 1974. No.4.p.449--468

4 Lipski T.: 'Theoretical principles of h.r.c. electric fuses design'. Second Int.Symp.: Switching Arc Phenomena. 25-27 Sept.1973.Łódź. Poland. Part I. p.229-240
5 Kacprzak B.: 'High-voltage gas-expulsion fuses for overhead lines and for reclosing'. (in polish) Ph. D. Dissertation. T.U. Gdańsk. 1974
6 Baxter H.W.: 'Electric fuses'. London 1950. E.Arnold a.Co. Edition
7 Lipski T.: 'Low-voltage electric fuses' (in polish). Warszawa 1968. WNT Edition
8 Piasecki J.:'Low-voltage electric fuses' (in polish). Warszawa. 1958. PWT Edition
9 Jacks E.: 'H.r.c. fuses.Design and application for safety in electrical systems'. London. 1975. E.a.F.N. Spon Ltd Edition
10 Läpple H.: 'Electric fuses: A critical reviev of published information'. Butterworth's Scientific Publications. 1952
11 Turner H.W., Turner C.: 'Advances in electric fuses. Asummary of published information 1950-1965'. ERA Report No.5228. 1967
12 Guile A.E.: 'The calculation of complete time current characteristics of certain cartridge fuses with strip elements'.El. Energy. 1956. Nr. 4. p.114
13 Sabaneeva G.I.: 'On the transient heating calculation of fuse-elements' (in russian). Elektrotechnika. 1965.Nr.7 p.37
14 Barbu I.: 'Contributions of an electrothermic phenomenon appearing in electric fuses and digital calculation of this phenomenon'(in rumanian). Ph.D.Dissertation. T.U.Timişoara.1971
15 Wilkins R., Mc Ewan P.M.: 'A.c. short-circuit performance of notched fuse elements'. Proc.IEE.No.3. March 1975. p.289-292
16 Ossowicki J.: 'Attempt at systematic arrangement of mechanisms of wire fuse elements disintegration at overload'. First Int.Symp.: Switching Arc Phenomena. 9-12 Dec. 1970. Łódź. Poland. p.204-209
17 Ossowicki J.: 'An analysis of d.c. overload current inter-

ruption by l.v. fuses with wire fuse-elements' (in polish). Ph.D.Dissertation. Electrotechnical Institute. Warszawa. 1974

18 Lipski T., Ossowicki J.: 'Preliminary conclusions from investigation of overload current-interruption by l.v. fuses' (in polish). Przegląd Elektrotechniczny. 1968. No.1. p.32-36.

19 Lipski T., Furdal A.: 'New observations on the formation of unduloids on wires'. Proc.IEE. No.12. December 1970

20 Meyer E., Rinderer L.: 'Use of capillary and pinch instability for dendritic crystal growing'. Journal of Crystal Growth. 1975. p.199-208

21 Nasiłowski J.: 'Investigation of fuse-wire disintegration module' (in polish). Ph. D. Dissertation. Electrotechnical Institute. Warszawa. 1965

22 Hibner J.: 'A resistance gradient method for calculation of arc overvoltage peak values generated by current limiting fuses' (in polish). Ph. D. Dissertation. T.U. Gdańsk 1973

23 Rauch W.: 'Strombegrenzung bei der Abschaltung von Wechselstrom-Kurzschlüssen durch Sicherung'. ETZ-A. 1958. H.16. S.543-547

24 Dołęgowski M.: 'Geschwindigkeit der Verlängerung des Lichtbogens bei den Streifensicherungen mit Sandlösch-Mittel'. Second Int.Symp.: Switching Arc Phenomena. 25-27 Sept. 1973. Łódź. Poland. Part I. p.275-282

25 Läpple H.: 'Die Vorgänge bei der Kurzschluss-Unterbrechung durch schellschaltende Hochspannungs-Sicherungen'. VDE Fachb. Vol.6. s.72

26 Lipski T.: 'Post-arc currents in sand-filled fuses' (in polish). Przegląd Elektrotechniczny. 1964. No.1. p.17-21.

27 Lipski T., Hibner J., Burczyk : 'Ageing phenomena in time-lag fuses' (in polish). Acta Technica Gedanensia. 1965. No.3. p.123-138

28 Sletterink A., Vlutters H., v.d.Zwaag H.: 'The influence of diffusion phenomena on time-current characteristics of fuse links'. Holectechniek. 1972. No.3. p.118-123

29 Huhn P.: 'Über das Verhalten eines durch Drahtexplosion

Eigeleiteten Lichtbogens in Kornigem Medium' Ph. D. Dissertation, T.U.Hannover. 1971

30 Lipski T.: 'Some problems of l.v. fuses with stripe fuse--elements' (in polish). Przegląd Elektrotechniczny. 1961. No.10. p.404-407

31 Rosen P.: 'Comments and introduction to film illustrating arcing phenomena in h.v. fuse-links'. Second Int.Symp.: Switching Arc Phenomena. 25-27 Sept. 1973. Łódź. Poland. Part II. Postconference Materials. p.164-166

32 Hibner J.: 'Influence of granularity of quartz sand filler on peak voltage occuring during the disintegration of stripe-fuse elements of fuses'. First Int. Symp.: Switching Arc Phenomena. 9 - 12 Dec.1970. Łódź. Poland. p. 232-236

33 Turner H.W., Turner C.: 'Phenomena occuring during the extinction of arcs in fuses'. Second Int. Symp.: Switching Arc Phenomena. 25-27 Sept . 1973, Łódź. Poland. Part I. p. 253-257

34 Vermij L.: 'Fuse-elements as part of an LC circuit'. Holectechniek. 1972. No.1. p.30-35

35 Abdel-Asis A.M., Lindmayer M.: 'Untersuchungen an Sicherungen zum Kurzschlussschutz von Kondensatoranlagen'. Biull. SEV. 1974. No.2. S.77-84

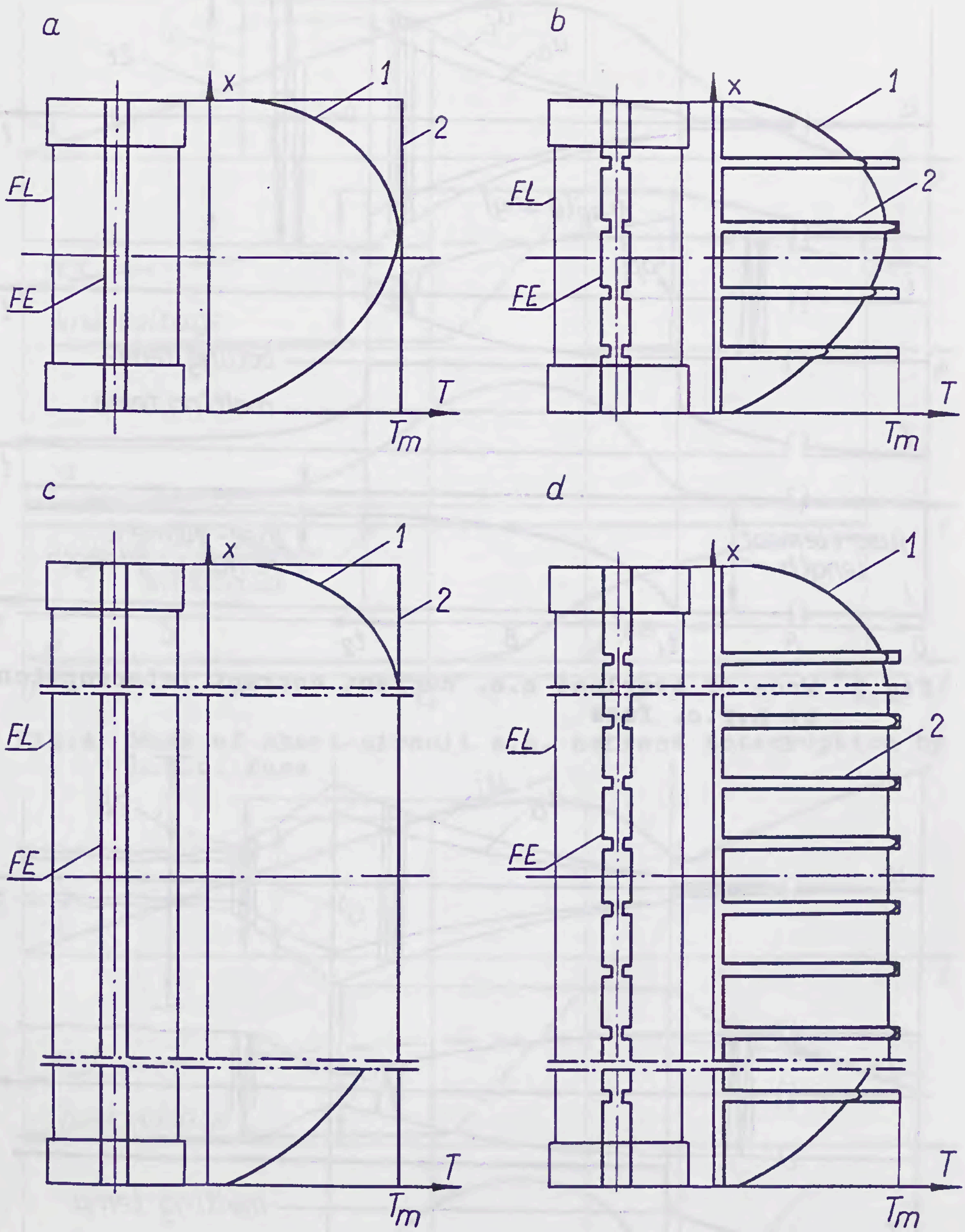

Fig.1 Idealized temperatur distributions from cool state just prior fuse-elements FE disintegrations along uniform section figures a and c and notched figures b and d fuse elements streached in the h.r.c. fuse links FL
1 - steaty state or long time overload heating,
2 - adiabatic short-circuit heating

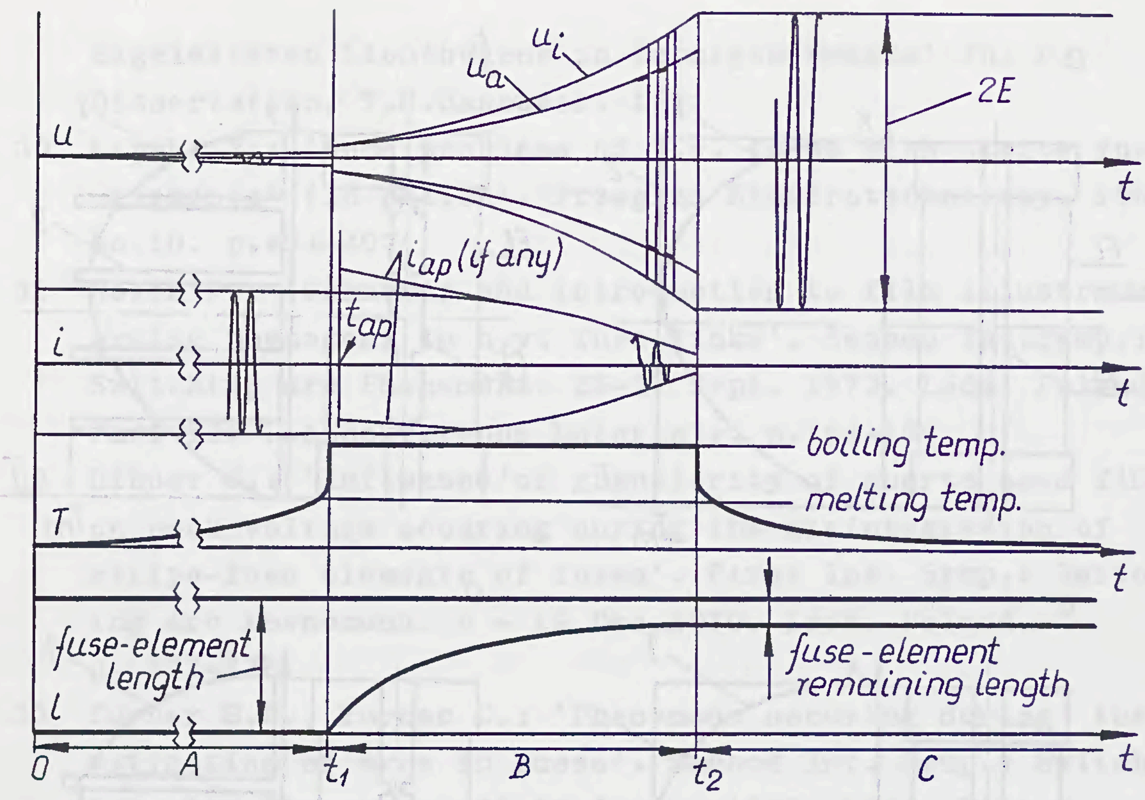

Fig.2 Mode of overload a.c. current correct interruption by h.r.c. fuse

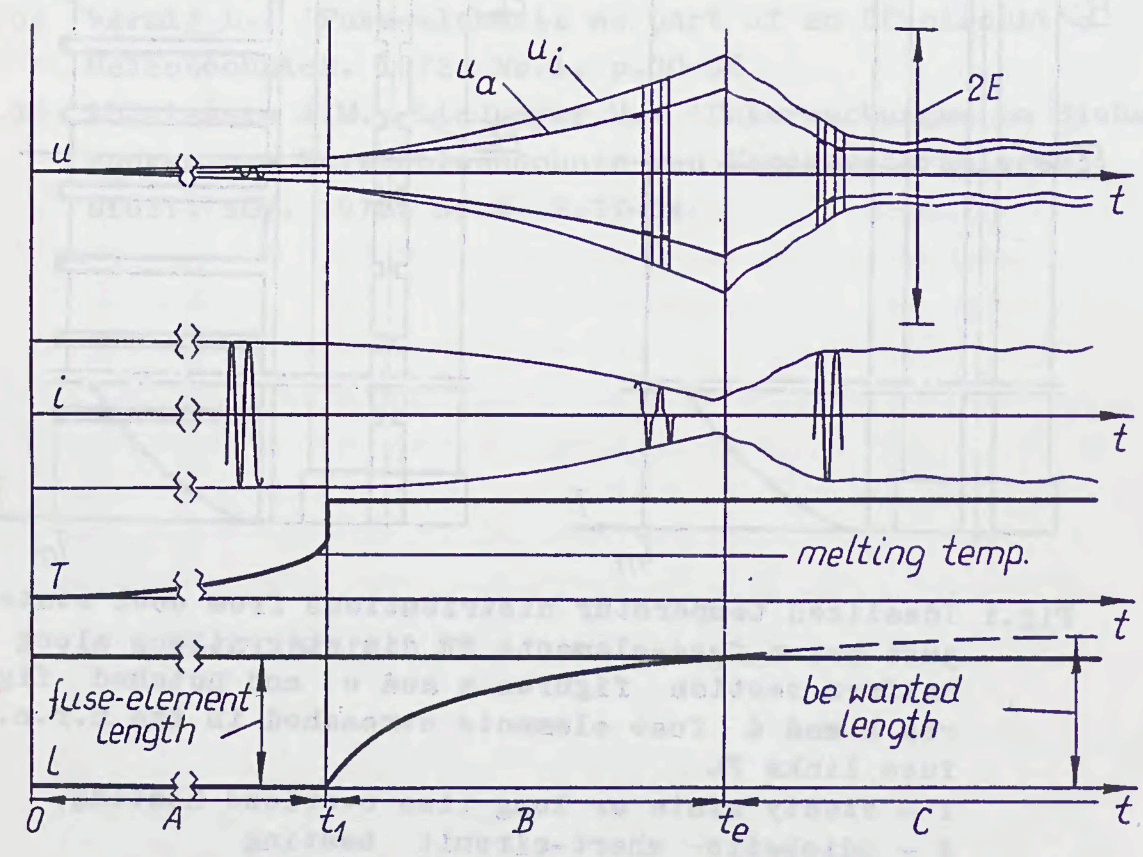

Fig.3 Mode of overload a.c. interruption by h.r.c. fuse with arc expulsion in moment t_e

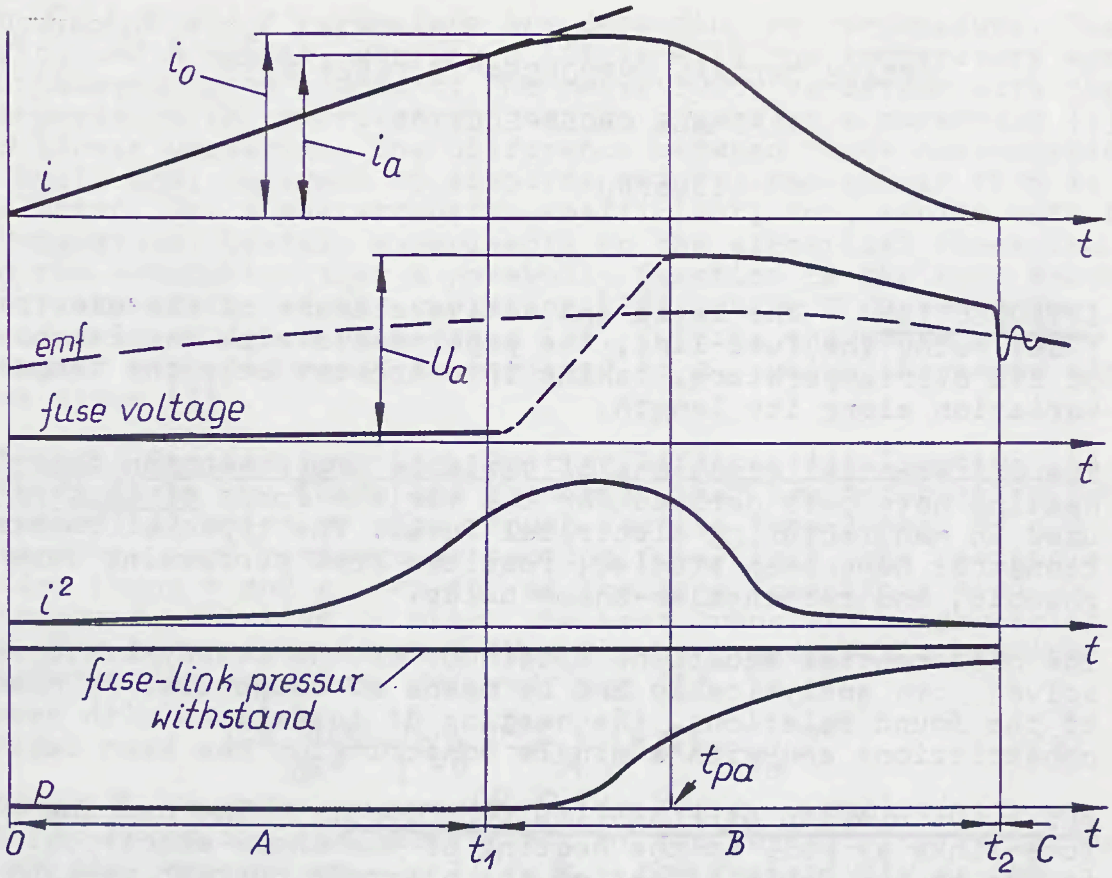

Fig.4 Mode of short-circuit a.c. correct interruption by h.r.c. fuse

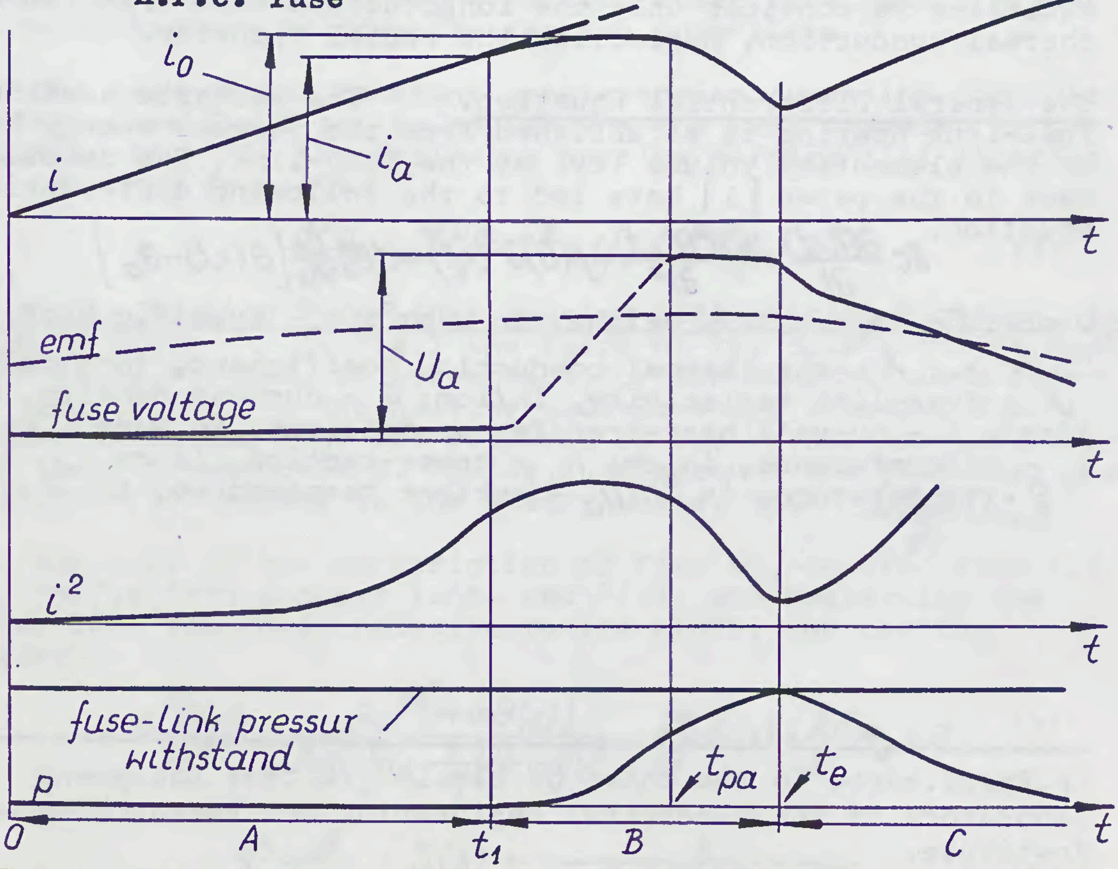

Fig.5 Mode of short-circuit a.c. interruption by h.r.c. fuse with the fuse-link explosion in moment t_e

STEADY THERMAL PHENOMENA IN FUSES WITH VARIABLE CROSS-SECTION

I.Barbu

INTRODUCTION The basic and active element of the electrical fuses being the fuse-link, the paper deals with the calculation of its overtemperature, taking into account only the temperature variation along its length.

The differential equations of variable cross-section fuse-links heating have been derived for the various forms of constrictions used in manufacturing electrical fuses. The types of constrictions that have been studied, resulted from performing some round, rhombic, and rectangular-shape holes.

The differential equations obtained for the steady-state were solved both analytically and by means of computers. By means of the found relations, the heating of fuse-links with several constrictions and with a single constriction has been calculated.

FUSE-LINK HEATING DIFFERENTIAL EQUATIONS. The heating of the fuse-links as well as the heating of the whole electrical fuse is due to the Joule effect of the electric current passing through the fuse-link. When establishing the differential equations we consider only the longitudinal heat transfer by thermal conduction, neglecting the radial transfer.

The General Differential Equation. The variable section fuse-link heating is established from the thermal energy balance of the elementary volume (dv) of the fuse-link. The calculations made in the paper [1] have led to the following differential equation.

$$\gamma c \frac{\partial \theta(x,t)}{\partial t} = \lambda \frac{\partial^2 \theta(x,t)}{\partial x^2} + \rho(\theta) J^2(x,t) - K(\theta) \frac{l_x}{A_x} \left[\theta(x,t) - \theta_a \right] \qquad (1)$$

where: γ - is the bulk weight, in g/cm^3; c - specific heat, in ws/^{o}C;g.; λ - the thermal conduction coefficient, in W/cm^{o}C; ρ - fuse-link resistivity, in Ωcm; J - current density, in A/cm^2; K - overall heat-transfer coefficient, in W/cm^2 ^{o}C; l_x - circumference, in cm; A_x - cross-section, in cm^2; θ - temperature, in ^{o}C; θ_a - ambient temperature, in ^{o}C.

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The γ, c, λ, K and ρ parameters are depending on temperature. The γ, c, and λ values, varying a little with the temperature are considered to be constant. The resistivity variation with the temperature is important and can be viewed as a parabolic [2] or linear variation. The difference between these curves being a small one, in order to simplify things, the linear form is selected. The K heat-transfer coefficient, too, varies with the temperature. Certain experiments on the electrical fuses led to the conclusion that a parabolic function is the most accurate expression of its variation [3] , while K does not increase to a higher value than 1.5, (within the range of the studied temperatures), as compared to ρ , which increases about 3-4 times [2] .

<u>Constant Section Fuse-Link Heating Differential Equation, in Steady State</u> There are two cases that are interesting from a practical point of view. Round section fuse-links, of a d diameter, and rectangular section fuse-links, the rectangle sides being b and g . As far as the long fuse-links are concerned, relative to which the heat transfer by convection is also taken into account ($K \neq 0$), the steady state heating differential equation, derived from (1), is:

$$\lambda \frac{d^2\tau(x)}{dx^2} + \left[\alpha \rho_0 J^2 - K \frac{l}{A}\right] \tau(x) = -\rho_a J^2 \qquad (2)$$

where: τ - overtemperature$(\theta - \theta_a)$ in °C; ρ_0 - resistivity at °C, in Ω cm; α - the coefficient of the resistivity variation with the temperature, in 1/°C; ρ_a - the resistivity at the ambient temperature, in Ω cm; l/A - a constant equal to 4/d when considering the round section fuse-links, and 2/g when considering the rectangular section fuse-links

In the case of the constant cross-section fuse-link constrictions, (see Fig 1 a), by neglecting the heat transfer by convection (K = 0); the following heating differential equation is obtained from (2).

$$\frac{d^2\tau}{dx^2} + \frac{\alpha \rho_0}{\lambda} J^2 \tau(x) = -\frac{\rho_a}{\lambda} J^2 \qquad (3)$$

<u>Variable Section Fuse-Links Heating Differential Equation, in Steady State</u> In Fig.1 the shape of the constrictions that are being studied, is presented. For the constrictions given in Fig.1b and 1c, the heating equations are obtained from (1) where lx/Ax and J(x) are replaced by the values corresponding to these constrictions. Taking into account the fact that the equation (1) refers to the steady-state, then $\frac{\partial \theta(x,t)}{\partial t} = 0$

In the case of the constriction of Fig. 1b, derived from (1), by taking into account lx/Ax and J(x), and neglecting the fuse-link thickness relative to its width, the heating equation is.

$$\lambda \frac{d^2\theta(x)}{dx^2} + \frac{\rho_0 I^2 [1 + \alpha\theta(x)]}{4g^2 \left[a + \frac{x}{x_1}\left(\frac{b}{2} - a\right)\right]^2} - \frac{2K}{g}\theta(x) + \frac{2K}{g}\theta_a = 0 \qquad (4)$$

where:

$$\frac{lx}{Ax} = \frac{2}{g} \; ; \; J(x) = \frac{I}{2g\left[a + \frac{x}{x_1}\left(\frac{b}{2} - a\right)\right]} \qquad (5)$$

Similarly, for the constriction of Fig. 1c, one obtaines:

$$\lambda \frac{d^2\theta(x)}{dx^2} + \frac{\rho_0 I^2[1+\alpha\theta(x)]}{4g^2[a+r-\sqrt{r^2-x^2}]} - \frac{2K}{g}\theta(x) + \frac{2K}{g}\theta_a = 0 \tag{6}$$

where:

$$\frac{lx}{Ax} = \frac{2}{g} \; ; \; J(x) = \frac{I}{2g[r+a-\sqrt{r^2-x^2}]} \tag{7}$$

FUSE-LINK HEATING EQUATIONS. In order to determine the solutions of the above given differential equations, a particular limiting-condition has been introduced, having the form:

$$-\lambda \frac{\partial \tau(x)}{\partial x}\Big|_{x=0} = \eta\, \tau(x)\Big|_{x=0} \tag{8}$$

Where η is the heat-transfer coefficient, at the fuse-links ends. The fact has been accepted that the relation (8) is also valid for the coordinate corresponding to the end of the fuse-link constriction (x_1 coordinate, in Fig.1).

Constant Section Fuse-Link Heating Equations. Considering the thermal regime to be symmetrical relative to the half of the fuse-link, the heating is determined by solving the equation (2). With the limiting conditions:

$$\frac{d\tau(x)}{dx}\Big|_{x=0} = 0 \; ; \; \tau(x)\Big|_{x=x_1} = \tau_1 \tag{9}$$

the following solution is obtained:

$$\tau(x) = \tau_1 \frac{chax}{chax_1} + \frac{\rho_a AJ^2}{Kl - \alpha\rho_0 AJ^2}\left[1 - \frac{chax}{chax_1}\right] \tag{10}$$

while with limiting conditions:

$$\frac{d\tau(x)}{dx}\Big|_{x=0} = 0 \; ; \; -\lambda\frac{\partial \tau(x)}{\partial x}\Big|_{x=x_1} = \eta\,\tau(x)\Big|_{x=x_1} \tag{11}$$

The following solution is obtained:

$$\tau(x) = \frac{\rho_a AJ^2}{Kl - \rho_0 \alpha AJ^2}\left[1 - \frac{gchax}{ashax_1 + gchax_1}\right] \tag{12}$$

where:

$$g = \frac{\eta}{\lambda} \; ; \; a = \sqrt{\frac{Kl}{\lambda A} - \frac{\rho_0}{\lambda}\alpha J^2} \tag{13}$$

The relations (10) and (12) are valid in the case of the constant section constrictions as well as for example in Fig. 1.a. However, because of the heat transfer by means of convection, as compared to conduction, in the case of constrictions, might be neglected (k=0), the heatings are obtained by solving equation (3). In the case of limiting conditions of the type (9) the expression of heating is:

$$\tau(x) = \tau_1 \frac{\cos a'x}{\cos a'x_1} + \frac{\rho_0}{\alpha\rho_a}\left[\frac{\cos a'x}{\cos a'x_1} - 1\right] \; ; \; a' = J\sqrt{\frac{\alpha\rho_a}{\lambda}} \tag{14}$$

and in the case of the limiting conditions (11) the following result is obtained:

$$\tau(x) = \frac{\rho_a}{\alpha\rho_0}\left[\frac{g\cos a'x}{g\cos a'x_1 - a'\sin a'x_1} - 1\right] \qquad (15)$$

The Heating of Variable Section Constrictions Equations. The differential equation of heating the constriction Fig.1.b, presented in (4), neglecting the heat transfer by means of conduction (k=0), might be also written as follows:

$$(1+xc)^2 \frac{d^2\tau}{dx^2} + d\,\tau(x) = -e \qquad (16)$$

where:

$$c = \left(\frac{b}{2} - a\right)\frac{1}{ax_1}\ ;\ d = \frac{\alpha\rho_0 I^2}{4\lambda g^2 a^2}\ ;\ e = \frac{\rho_a I^2}{4\lambda g^2 a^2} \qquad (17)$$

The solution of equation (16) with the limiting conditions of the type (9) is:

$$\tau(x) = \left(\tau_1 + \frac{\rho_a}{\alpha\rho_0}\right)\frac{r_2 e^{r_1 \ln(1+xc)} + r_1 e^{r_2 \ln(1+xc)}}{r_2 e^{r_1 \ln(1+x_1 c)} + r_1 e^{r_2 \ln(1+x_1 c)}} - \frac{\rho_a}{\alpha\rho_0} \qquad (18)$$

$$r_{1,2} = 0{,}5 \pm \sqrt{0{,}25 - \frac{\alpha\rho_0 x_1^2 I^2}{4\lambda g^2\left[\frac{b}{2} - a\right]^2}}$$

THE FUSE-LINKS HEATING CALCULATION. On calculating the heat under the forms established in the previous chapter, it is very important to know the values of the heat transfer coefficients, k and η, for the studied types of fuses. These coefficients being, besides their physical significance when we refer to the manner in which they have been introduced, also operands, we consider it to be necessary that their values should be determined for each type of fuses. In work [3] the values of the heat transfer coefficients, for some types of fuses are presented. Other values are determined from later research-works and calculations.

Constant Section Constrictions Heating Calculation. The one constriction fuse with a constant section has been designed for the case of a ultrarapid 30V, 160A fuse used for the protection of the installation from the top of the railway carriages. The form of the fuse-link is the one shown in Fig. 1 a having the following dimensions: b=1,2 cm; x_1=0.025 cm; b'=0.004 cm; g=0.015 cm. The overtemperature τ_1 of the constriction has been determined by the relation (15) for the abscissa $x=x_1$ (the end of the constriction) and $\tau_{max.}$ respectively x=0 for the centre of the constriction. The value of a' has been calculated according to the relation (14) and is 5,16 cm, and η as determined from experiments and calculations has been 4,6w/cm^2 $^\circ$C. With the values indicated above it has been obtained from the calculations τ_1 =430°C and τ_{max}= 436°C. As can be seen, between the centre of the constriction and its edge, there is a small temperature difference ($6^{o}C$).

<u>Variable Section Constrictions Heating Calculation.</u> Because of the fact that the differential equations (4) and (6) are difficult to solve analitically, even approximately, it has been resorted to the electronic computer. The computing program has been conceived for the following sizes of the fuses: $\lambda = 3.93 W/cm^{o}C$; $\alpha = 4.39\ 10^{-3}\ 1/^{o}C$; $\rho_o = 1.6\ 10^{-6}\ \Omega\ cm$; $\theta_a = 20^{o}C$; $I = 50A$; $a = 0.75$ cm; ($a' = 0.145$ cm); $x_1 = 0.175$ cm ($x_1 = 0.105$ cm); $\theta_{a1} = 80^{o}C$ ($\theta'_{a1} = 200^{o}C$); $\gamma = 0.175$ cm ($\gamma' = 0.105$ cm); $K = 0.025 W/^{o}C\ cm^2$ and $K = 0.025\ 10^{-2} W/^{o}C\ cm^2$. As can be observed, some sizes have two values, values which correspond to two constrictions made along the fuse.

The result of the calculation for the two constructional variants and for two forms of constrictions (Fig.1b and c), are presented in Fig.2. It is observed that the value of the heat transfer coefficient K, has practically no influence upon the heating value. These results justify the hypothesis of neglecting the convection heat transfer (K=0). It is also observed that in such cases the difference of temperatures between the centre and the edge of the constrictions is small, of some degrees order.

<u>Constrictions Fuse-Link Heating Calculation.</u> The majority of the electric fuses fuse-links are made of strips along which are made constrictions, in order to obtain a limiting effect of the current and a specific type of time-current fuse characteristic. Exact calculation expressions for this type of fuse-link have not been deduced yet. The independent constrictions have been considered, in order to calculate the overtemperatures, by determining the heating for each constriction, separately. The heating of the fuse-link, considered without constrictions has also been determined. The parameters of the 20A ultrarapid fuse-link are the following
$J = 2.42\ 10^{4} A/cm^2$; $x_1 = 2,4$ cm; $\eta = 18 W/^{o}C\ cm^2$; $K = 0.014 W/^{o}C\ cm^2$;
$J_{n1} = 7.27\ 10^{4} A/cm^2$; $\eta_{n1} = 1.15 W/^{o}C\ cm^2$; $l_{n1} = 0.061$ cm; $A_{n1} =$ $1.375\ 10^{-4}\ cm^2$; $x_{n1} = 0,025$ cm $J_{n2} = 6.06\ 10^{4} A/cm^2$;
$A_{n2} = 1.65\ 10^{-4}\ cm^2$; $l_{n2} = 0.071$ cm; $\eta_{n2} = 1 w/^{o}C\ cm^2$; $x_{n2} = 0,025$ cm
$J_{n3} = 5.19\ 10^{4} A/cm^2$; $\eta_{n3} = 0.9 W/^{o}C\ cm^2$; $l_{n3} = 0.081$ cm; $A_{n3} =$ $1.925\ 10^{-4}\ cm^2$; $x_{n3} = 0,025$ cm The heating of the fuse-link considered homogenous, has been determined by the formula (12) and it is represented in Fig.3, while the constrictions heating has been determined by the formula (15). The results of the calculation for the extremity and the centre of the constriction are the following: $\tau_{11} = 556^{o}C$; $\tau_{max\cdot 1} = 564^{o}C$; $\tau_{21} = 345^{o}C$; $\tau_{max\cdot 2} = 350^{o}C$; $\tau_{31} = 225^{o}C$; $\tau_{max\cdot 3} = 228^{o}C$. The graph of the fuse-link heating, taking into account the overtemperature of each constriction is represented in Fig.3. It is possible to observe in this case too, that the difference of the temperature between the extremity and the centre of the constriction is of the order of degrees. It is worthwhile to mention that such curves for constrictions fuse-links are presented in specialized literature [5] [6] with no details concerning

their calculation.

CONCLUSIONS. In order to determine the heating of the electric fuses, fuse-links precise analytic computation relations may be obtained, which are more or less complicated. The main problem is to know the heat transfer coefficients, for the differential equations might be solved by means of the electronic computers (if it is not possible to use the analytical method).

From the calculation of the constrictions heating, results that the temperature difference between the centre and the edge of the constrictions is of the Celsius degrees order. It is also observed that in steady state the overtemperature of the ultrarapid fuses fuse-links is great in the centre of the fuse-link (ex:564 ^{o}C), that is, of the order of some hundreds of degrees. These heatings correspond to some current densities of the order of some thousands of amperes pro mm^2.

Although the difference of temperature along the constrictions is small, its existence determines a very intensive thermal regime of the fuse. For example the maximum supratemperature of the fuse-link at the same current, without constrictions, is under 300^{o}C, and with constrictions it is of 564^{o}C.

BIBLIOGRAPHY

[1] Barbu, I.: Contributii privind unele fenomene electrotermice din segmente nefuzibile si modelarea lor. Rezumatul tezei de doctorat. I.P.Timisoara, Timisoara 1971.

[2] Avramescu, A.: Incalzirea adiabatica a conductorilor din cupru, aluminiu si argint. In: Studii si Cercetari de Energetica, tomul V, 1955, nr.3-4.

[3] Barbu, I.: Consideration sur la transmission de la chaleur dans les coup-circuits unipolaires à filet. In: Lucrarile ICPE nr 21, 1969, p.83-91.

[4] Barbu, I.: Consideratiuni asupra fenomenelor stationare electrice si termice la functionarea sigurantelor fuzibile. In: Electrotehnica 17, nr 4, aprilie 1969, p.137=143.

[5] Lipski, T.: Bezpieczniki niskonapieciowe. Wydawnictwa Naukowo-Technicze Warszawa.

[6] Henselmeyer, G. si Walter, R.; Neue Diazed - Sicherungen. In: Siemensz 33 nr 6, iunie 1959, p.417-424.

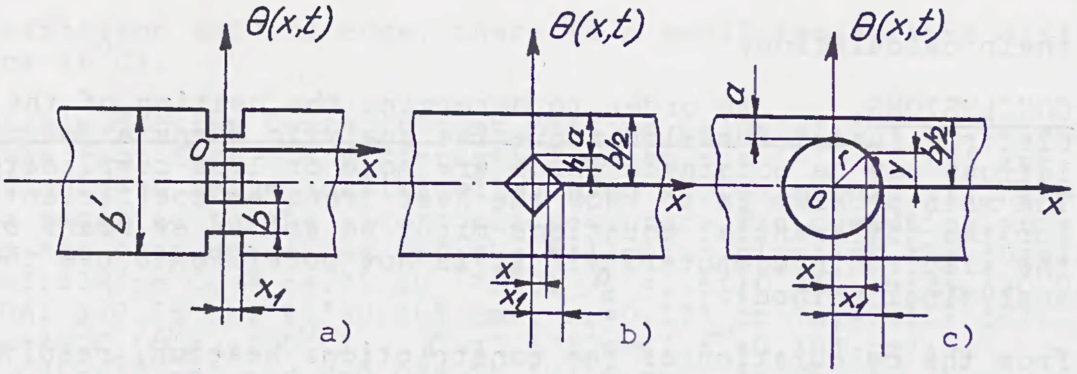

Fig.1 Constrictions types made along the fuse-links

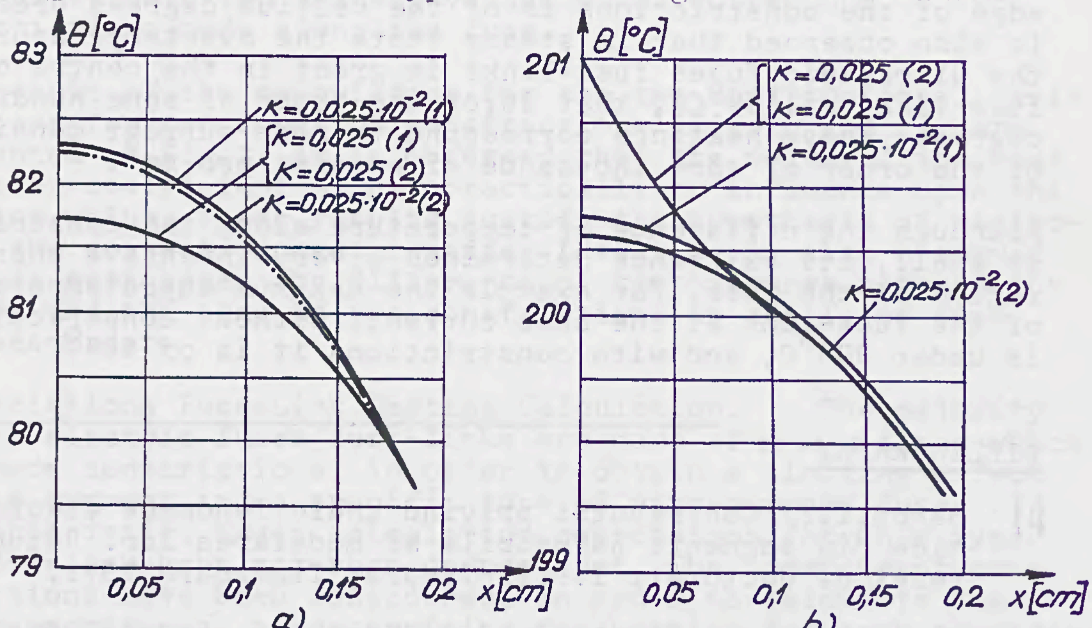

Fig.2 Variable section constrictions heating
a) temperature $\theta_{al} = 80^{o}C$; b) temperature $\theta_{al} = 200^{o}C$
1: rhombic-shape holes
2: annular-shape holes

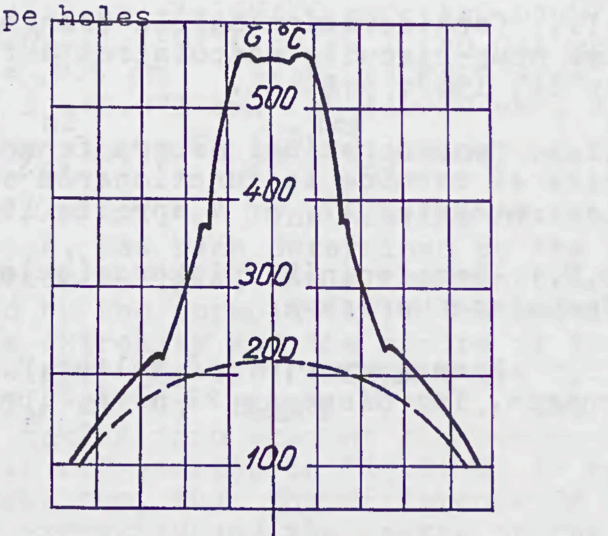

Fig.3 Constrictions fuse-links heating

SURVEY OF NUMERICAL METHODS FOR SOLVING TIME-VARYING FUSE EQUATIONS

P.M. McEwan and L. Warren

Principal Nomenclature

c	Specific heat
ρ	Density
T_A	Ambient temperature
T	Fuse element temperature
T_m	Fuse element melting temperature
σ	Electrical conductivity
σ_A	Ambient value of electrical conductivity
k	Thermal conductivity
K	Thermal difusivity (k/cρ)
Δt	Time step length
t	Time
Δx	Step length
I	Prospective current
a	Cross-sectional area
J	Current density
α	Temperature coefficient of Resistance
i, n	Generalised space and time identifiers (T_i^n corresponds to temperature at point $i\,\Delta x$ along element at time $n\,\Delta t$ seconds)

1. INTRODUCTION Computer prediction of fuse characteristics have obvious labour saving benefits and advantages in computing fuse performances which are difficult or impossible to determine from tests.

Prior to digital computers equations of the form of (1) for simulating prearcing performances of fuses were impossible to solve accurately for all but the very simplest of fuse geometries unless gross reductions were made in fuse representations. The advent of high speed digital computers and powerful numerical methods has greatly enhanced equation solving capability enabling improved predictions of fuse performance.

The ideal pre-requisites of numerical methods for solving equations by computer are:

- High Accuracy
- Guaranteed Numerical Stability
- Low Computer Running Times
- Minimum Complexity
- Low Computer Storage

This paper presents results of a study of numerical methods for solving

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parabolic equations to enable selection of the most suitable numerical methods for solving the pre-arcing performance of fuses subject to the stated idealised numerical constraints.

$$c\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\frac{(k\partial T)}{\partial x} + \frac{\partial}{\partial y}\frac{(k\partial T)}{\partial y} + \frac{\partial}{\partial z}\frac{(k\partial T)}{\partial z} + \frac{J^2}{\sigma} \qquad \ldots (1)$$

2. NUMERICAL METHODS STUDIED Fuse numerical solutions involve dividing fuse elements into small sections and determining the temperature of each section over discrete time intervals. By this technique the partial differential equations governing joulean heat flow in fuse elements may be approximated by difference equations using surrounding temperature values and temperature rise calculated in terms of space and time ordinates for all fuse geometries. This treatment reduces (1) to sets of simultaneous algebraic equations which may be solved at successive time intervals using a numerical method.

Three broad classes of numerical method exist for solving the type of algebraic equations resulting from fuse modelling. These methods are:

Matrix methods
Finite Element methods
Finite Difference methods

Upon examination Matrix and Finite Element methods were found to require much greater storage than the Finite Difference variety as numerical coefficients in the latter method's algorithms are implicit and thus do not need storing. In addition Finite Difference methods were found to be more flexible for generalised solutions and simpler to apply.

The Finite Difference methods were consequently preferred for solving fuse equations. These methods were applied to time-varying fuse equations and critically examined against the criteria established in Section 1 by comparing computed results with analytical solutions of equation (1).

A simple example of electro-thermal heat flow was used for comparison purposes. The example was that of a thermally insulated uniform section current carrying conductor with ends held at zero temperature. Time-varying solutions are feasible for this problem providing that heat is generated at a constant rate[1]. The heat flow for this case is one dimensional and therefore governed by (2).

$$c\rho \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} + \frac{J^2}{\sigma} \qquad \ldots (2)$$

The analytical solution for temperature along the conductor is given by (3). The general form of temperature variation with time and position along the conductor is shown in figure 1 for general values of time equal to (n-1) Δt, n Δt and (n+1) Δt.

$$T = \frac{J^2 \ell^2}{2k\sigma}\left\{1 - \left(\frac{x}{\ell}\right)^2 - \frac{32}{\pi^3}\sum_{n=0}^{\infty}\frac{(-1)^n}{(2n+1)^3}\cos\frac{(2n+1)\pi x}{2\ell}\, e^{-\frac{\pi k t (2n+1)}{4c\rho \ell}}\right\} \qquad \ldots (3)$$

Temperature may be monitored along the conductor at discrete points Δx at time intervals Δt, 2 Δt ... (n-1)Δt, nΔt, etc., as indicated.Numerical solution of the same problem requires replacement of derivatives $\partial T/\partial t$ and $\partial^2 T/\partial x^2$ in (2) by difference approximations. For instance $\partial^2 T/\partial x^2$ may be deduced at all points along the conductor at time $n\Delta t$ in terms of temperature at generalised points $(i-1)\Delta x$, $i\Delta x$ and $(i+1)\Delta x$ giving

$$\left(\frac{\partial^2 Ti}{\partial x^2}\right)^n = \frac{(T^n_{i+1} + T^n_{i-1} - 2T^n_i)}{\Delta x^2} \qquad \ldots (4)$$

The time derivative at all points $i\Delta x$ at time $n\,\Delta t$ consequently becomes

$$\left(\frac{\partial Ti}{\partial t}\right)^n = \frac{K}{cp}\,(T^n_{i+1} + T^n_{i-1} - 2T^n_i) + \frac{J^2}{cp\sigma} \qquad \ldots (5)$$

This approximation is made at all points along the conductor and leads to $(\ell/\Delta x - 1)$ simultaneous equations for specifying temperature along the conductor.

The time derivative may be approximated also by differences, the simplest of which is

$$\left(\frac{\partial Ti}{\partial t}\right)^n = \frac{(T^{n+1}_i - T^n_i)}{\Delta t}$$

and leads to the Euler formulation and Explicit numerical prediction method for T_i at $t = (n+1)\,\Delta t$

i.e.
$$T^{n+1}_i = T^n_i + \left(\frac{\partial T_i}{\partial t}\right)^n \Delta t \quad \ldots \text{Euler Method}$$

from which

$$T^{n+1}_i = T^n_i + M(T^n_{i+1} + T^n_{i-1} - 2T^n_i) + \frac{J^2\,\Delta t}{cp\sigma}$$

$M = \frac{k\,\Delta t}{cp\,\Delta x^2}$ and is termed the modal parameter.

The Explicit method predicts T' for T^{n+1} in figure 2.

An alternative formulation uses forward difference formula and results in the Implicit (Laasonen) method.

$$T^{n+1}_i = T^n_i + \left(\frac{\partial T_i}{\partial t}\right)^{n+1} \Delta t$$

$$T^{n+1}_1 = T^n_i + M(T^{n+1}_{i-1} + T^{n-1}_{i-1} - 2T^n_i) + \frac{J^2\,\Delta t}{cp\,\sigma} \quad \ldots \text{Implicit Method}$$

In this case T^{n+1}_i is solved iteratively at each time step at all points along the conductor. The Implicit method predicts T" for T^{n+1}_i in figure 2.

Clearly from inspection of T^{n+1}_i predictions with the Explicit and Implicit methods a more accurate formulation would be the average of both predictions. This formulation leads to the 2nd order Runge Kutta formula and Crank Nicholson method.

$$T_i^{n+1} = T_i^n + \frac{1}{2}\left\{\left(\frac{\partial T}{\partial t}\, i\right)^{n+1} + \left(\frac{\partial T}{\partial t}\, i\right)^n\right\}\Delta t$$

giving

$$T_i^{n+1} = T_i^n + \frac{M}{2}\left\{T_{i+1}^{n+1} + T_{i-1}^{n+1} + T_{i+1}^{n} + T_{i-1}^{n} - 2(T_i^{n+1} + T_i^n)\right\} + \frac{J^2\,\Delta t}{cp\,\sigma}$$

The Crank Nicholson algorithm is implicit in T_i^{n+1} and T_{i+1}^{n+1} and must also be solved iteratively. The Crank Nicholson method predicts T''' for T_i^{n+1} in figure 2.

A variation in the Implicit method was used by Leach, Newbery and Wright[2].

Here $T_i^{n+\frac{1}{2}}$ is computed at $t = (n+\frac{1}{2})\,\Delta t$ using the Standard Implicit method and T_i^{n+1} obtained by linear extrapolation using $T_i^{n+\frac{1}{2}} = \frac{1}{2}(T_i^{n+1} + T_i^n)$.

Another method used for solving parabolic equations is the "Du Fort Frankel" method. This method uses central difference formulae over the interval 2 Δt viz:

$$\left(\frac{\partial T_i}{\partial t}\right)^n = \frac{(T_i^{n+1} - T_i^{n-1})}{2\,\Delta t} \quad \text{and} \quad T_i^n = \frac{(T_i^{n+1} + T_i^{n-1})}{2}$$

whereupon

$$T_i^{n+1} = T_i^{n-1} + 2M(T_{i+1}^{n+1} + T_{i-1}^{n+1} - T_i^{n+1} - T_i^{n-1}) + \frac{2J^2\,\Delta t}{cp\,\sigma}$$

3. <u>BASIS FOR COMPARISON</u> The above methods were compared with analytical solutions for temperature along uniform current carrying conductors as specified in section 2. The solution for time-varying temperature distribution is given by (3) and shown in figure 3. Numerical solutions were obtained for each of the methods discussed and the Crank Nicholson and Leach et al. methods were found to be identical and the most accurate for this problem. Errors increased as prediction time lengthened and as the step length Δx increased for all methods, figure 4.

Prediction of prospective current versus melting time was more accurate, figure 5, which is to be expected from inspection of respective expressions for maximum temperature along the conductor and melting current.

$$\hat{T} = \frac{I^2 \ell^2}{2a^2 K\sigma}\left\{1 - \frac{32}{\pi^3}\sum_{j=0}^{\infty}\frac{(-1)^j}{(2j+1)^3}\, e^{-\frac{k(2j+1)^2\pi^2 t}{4cp\ell^2}}\right\}$$

$$\frac{I_{MFC}}{I} = \left\{1 - \frac{32}{\pi^3}\sum_{j=0}^{\infty}\frac{(-1)^j}{(2j+1)^3}\, e^{-\frac{k(2n+1)^2\pi^2 t}{4cp\ell^2}}\right\}^{\frac{1}{2}}$$

where $I_{MFC} = \left(\frac{2KT_m a^2\sigma}{\ell^2}\right)^{\frac{1}{2}}$

4. ACCURACY OF METHODS Errors in numerical solutions occur due to 'round-off' and 'truncation' errors. Round-off errors are produced upon rounding off computed values to fixed decimal places and are not normally problematical with modern computers. Greatest error is introduced by approximating derivatives by simple forward and backward difference formulae and is termed truncation error. The error occurs at each computation step and may propagate to excessive proportions unless controlled.

Truncation error is assessible upon expanding T_i^{n+1} in Taylors series in both time and space ordinates. For example in the one dimensional Explicit formulation considered in section 2 the truncation error is

$$= \left\{ \frac{\partial T}{\partial t} - \frac{K}{cp}\frac{\partial^2 T}{\partial x^2} - \frac{J^2}{cp\sigma} \right\} - \left\{ \frac{(T_i^{n+1} - T_i^n)}{\Delta t} - \frac{K}{cp}(T_{i+1}^n + T_{i-1}^n - 2T_i^n) + \frac{J^2}{cp\sigma} \right\}$$

$$= \tfrac{1}{2}\Delta t \left(\frac{\partial^2 T_i}{\partial t^2}\right)^n + \frac{K}{cp}\frac{\Delta x^2}{12}\left(\frac{\partial^4 T_i}{\partial x^4}\right)^n$$

The coefficients of Δt and Δx^2 in the error term are bounded because of the continuity of the partial derivatives and will take values depending upon the problem under investigation. The truncation error $= K_1\Delta t + K_2(\Delta x)^2$ for all sufficiently small Δt and Δx. Usual practise expresses the truncation error and implied conditions symbolically as

$$O[\Delta t] + O[(\Delta x)^2]$$

The truncation errors for the other numerical methods are determined in similar manner and are as summerised.

	Truncation error
Implicit Method	$O[\Delta t] + O[(\Delta x)^2]$
Crank Nicholson Method	$O[(\Delta t)^2] + O[(\Delta x)^2]$
Du Fort Frankel Method	$O[(\Delta t)^2] + O[(\Delta x)^2] + O[(\frac{\Delta t}{\Delta x})^2]$

Clearly for good accuracy Δx and Δt should be arranged to be much less than unity and for the Du Fort-Frankel method $\Delta t << \Delta x$.

The errors were found consistent with computed results where the Crank Nicholson method was the most accurate and the Du Fort Frankel the least. The poor accuracy of the Du Fort Frankel method was expected as the method requires a starting method to obtain T_i^{n-1} at the first time step and $(\Delta t/\Delta x)$ was finite.

5. BEHAVIOUR OF NUMERICAL METHODS In solving solutions over long times it is desirable to use the largest possible time step to minimise computer running time. Increase of Δt for a given fuse model however increases the modal parameter M and affects the accuracy and behaviour of solution. Moreover if M is increased indiscriminately solutions may oscillate giving false convergence and in some cases become instable.

The numerical behaviour of all the methods were studied using Richtmeyers[4] generalised stability analysis and test runs with each method. Richtmeyers stability analysis covers numerical formulations of the form

$$T_i^{n+1} = T_i^n + \left\{ \theta \left(\frac{\partial T_i}{\partial t} \right)^{n+1} + (1-\theta) \left(\frac{\partial T_i}{\partial t} \right)^n \right\} \Delta t$$

The formulation is suitable for investigating the behaviour of the Explicit, Implicit and Crank Nicholson methods as $\theta = 0, 1, \frac{1}{2}$ corresponds to each method respectively.

Richtmeyers Analysis though general is valid only for equations of the form

$$\frac{\partial T}{\partial t} = \frac{K}{cp} \frac{\partial^2 T}{\partial x^2} \quad \ldots (6)$$

The equation though simpler than (2) for one dimensional joulean heat flow in conductors is useful in providing guidance on stability performance of the methods considered, however for practical fuse modelling numerical behaviour should also be assessed from test runs with various time steps.

Analytical solution of (6) is

$$T_i^n = \sum_{m=-\infty}^{\infty} A_{(m)} \, e^{jmi\,\Delta x} \left(\xi_{(m)} \right)^n \quad \ldots (7)$$

where
$$A_{(m)} = \frac{1}{2\pi} \int_{-\pi}^{\pi} \psi(x) \, e^{-jmx} \, dx$$

and $\xi_{(m)}$ is termed the growth factor and is given as

$$\xi_{(m)} = \left\{ \frac{1 - 2M(1-\theta)\left[1 - \cos(m\,\Delta x)\right]}{1 + 2M\theta\left[1 - \cos(m\,\Delta x)\right]} \right\}$$

From inspection of (7) T_i^n is convergent providing $\xi_{(m)} < \pm 1$. $\xi_{(m)}$ however varies with θ and therefore with numerical method.

Behaviour of $\xi_{(m)}$ is shown for the Explicit, Implicit and Crank Nicholson methods, figure 6 and the following important constraints apply.

Numerical Method	Limiting Value of M	
	Smooth Convergence	Stable Oscillation
Explicit	.25	0.5
Implicit	∞	-
Crank Nicholson	1	∞
Du Fort Frankel	-	∞

Clearly all methods except the Explicit method are unconditionally stable.

The methods were examined by increasing Δt until oscillations occurred using a practical fuse model. In the case of the Crank Nicholson method small oscillations were observed in solutions when Δt was increased to excessive step lengths of the order of 10s. All the other methods behaved as predicted by Richtmeyers analysis.

Rate of convergence is important in minimising computer running times. Again according to Richtmeryer[4] convergence rate is related to solution trunction error and generally the lower the error the faster the convergence. From figure 6 it is clear that the Implicit method though always smoothly convergent has larger errors than the Crank Nicholson method and is therefore relatively slowly convergent.

6. DISCUSSION Several numerical methods have been presented for solving fuse electro-thermal equations and were assessed against analytical solutions for comparison purposes. Although the chosen analytical solutions bear little resemblance to actual fuses, they do permit establishment of some general guide lines on the numerical behaviour of solutions of fuse equations.

Other numerical methods termed 'Multi Time Step' methods[4] were also considered. These methods were theoretically slightly more accurate than the methods presented in this paper but storage was at least twice the maximum storage for the presented methods and more complex to program, as 'Multi Time Step' varieties involve storing and computing with temperature values at three or more times steps at each time interval.

The method found most suitable from these and subsequent studies was the Crank Nicholson method even though the Explicit method was superior in accuracy, convergence and storage. The Explicit method was rejected for calculating conductor temperature as the method became unstable at low values of M which limited applications to exceptionally small values of Δt.

The methods were checked for the more practical fuse case where electrical conductivity varied with temperature. The problem investigated was identical to that specified in section 2 except that

$$\sigma(T) = \frac{\sigma_A}{(1+\alpha(T_i^n-T_A))}$$

The results using the presented methods were again compared and two interesting findings made.

(a) The method used by Leach et al[3], which gave identical results with the Crank Nicholson method when joulean heat generated was constant, gave lower temperature predictions than the Explicit, Implicit, Crank Nicholson and Du Fort Frankel methods. This result may be expected as the method used by Leach et al. assumes temperature rises identically over both halves of the time interval. The Du Fort Frankel method was again the least accurate.

(b) Predictions of times to reach melting temperature using σ_{AV} established at $(T_m+T_A)/2$ and $\sigma(T)$ were in reasonable agreement for short melting times but differed increasingly as melting times increased. This finding is of interest as it demonstrates that for the conditions stated the 'mean electrical conductivity' value may be used in some short-circuit calculations without great error, (figure 7).

7. CONCLUSIONS Numerical methods for predicting fuse characteristics have been assessed against the desirable criteria of high accuracy, stability, low computer storage and running times with minimum complexity. The method of Finite Differences was found superior to other methods and the Crank Nicholson formulation the most suitable for solving fuse equations.

8. REFERENCES

1. Carslaw, H.S., Jeager, J.C. : "Conduction of Heat in Solids', Pub. Clarendon Press, Oxford, 1959.

2. Leach, J.G., Newbery, P.G., Wright, A. ; "Analysis of HRC Fuselink Prearcing Performance by a Finite Difference Method", Proc. IEE, Vol. 120, No.9, September 1973.

3. Richtmeyer, R., Morgan, K.W. : "Difference Methods for Initial Value Problems", Pub. Interscience, 2nd Edition.

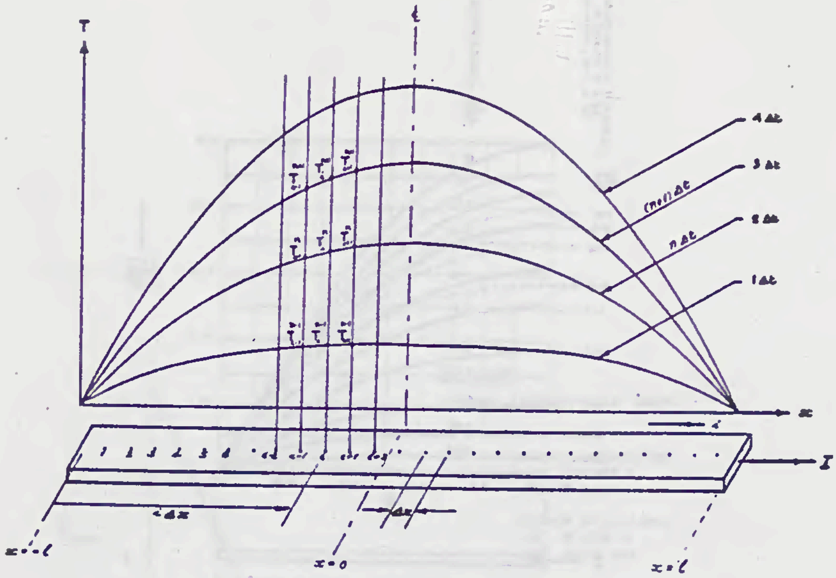

FIGURE 1 TEMPERATURE : TIME DISTRIBUTION ALONG THERMALLY INSULATED CURRENT CARRYING CONDUCTOR

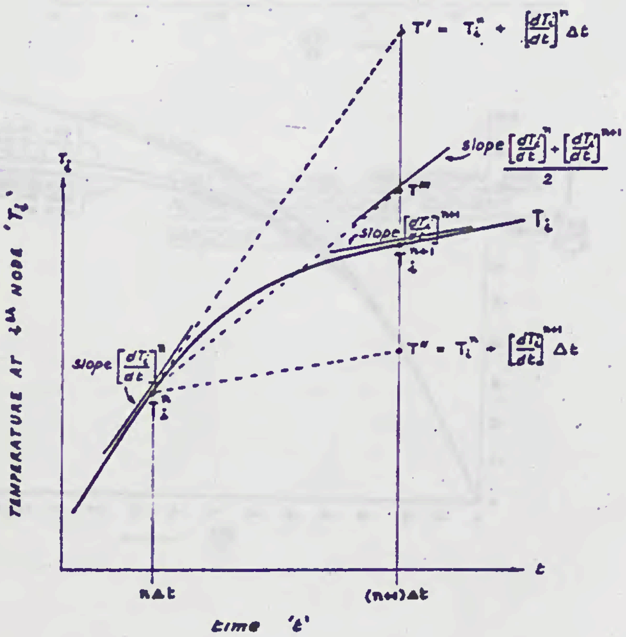

FIGURE 2 GRAPHICAL DEMONSTRATION OF NUMERICAL PREDICTION METHODS

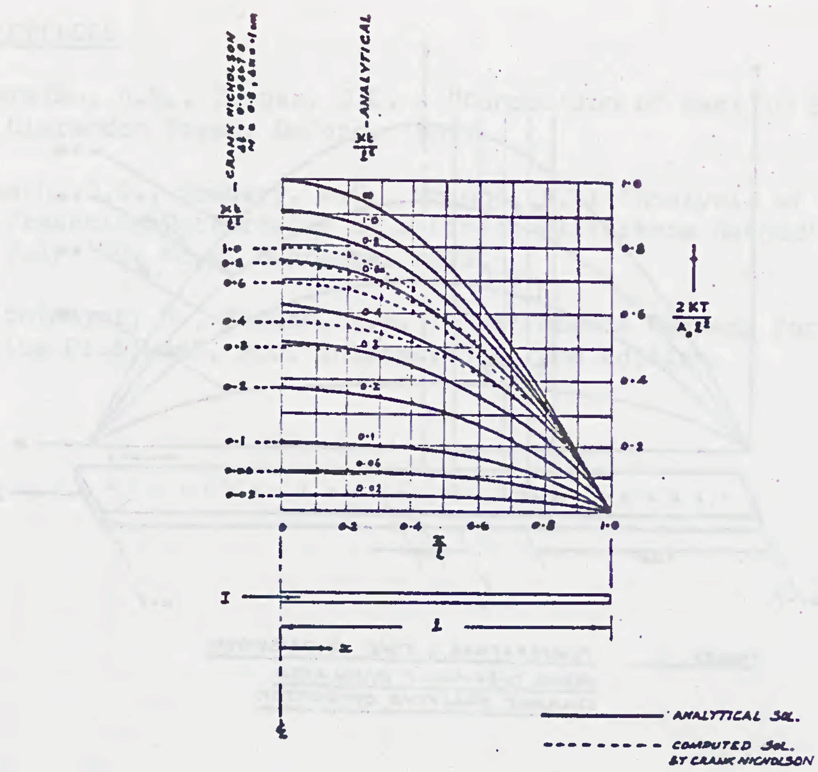

FIGURE 3 COMPUTED AND ANALYTICAL SOLUTIONS FOR THERMALLY INSULATED CONDUCTORS

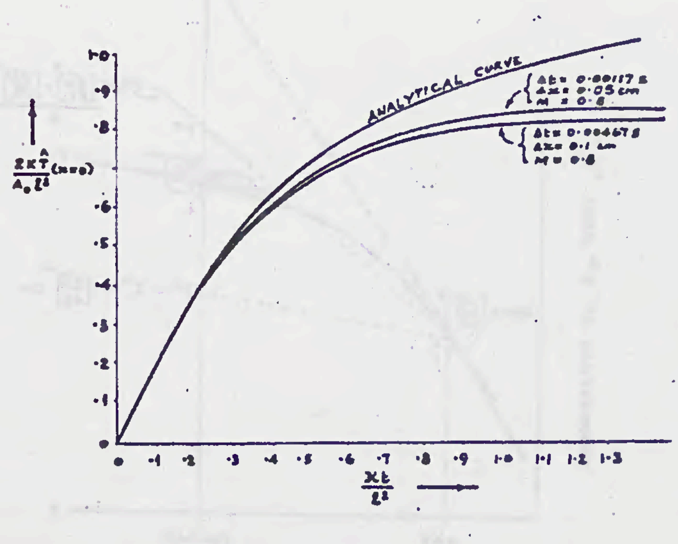

FIGURE 4 COMPARISON OF ANALYTICAL AND CRANK NICHOLSON SOLUTIONS FOR THERMALLY INSULATED CURRENT CARRYING CONDUCTOR PROBLEM

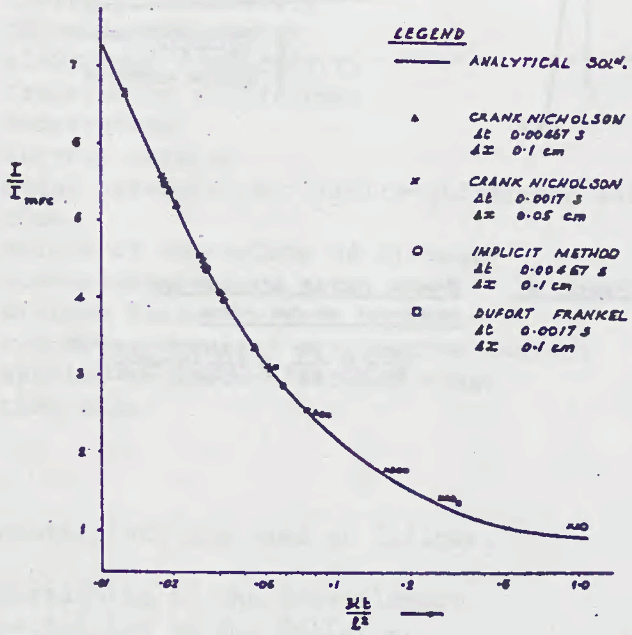

FIGURE 5 CURRENT : TIME PREDICTION FOR THERMALLY INSULATED CURRENT CARRYING CONDUCTORS

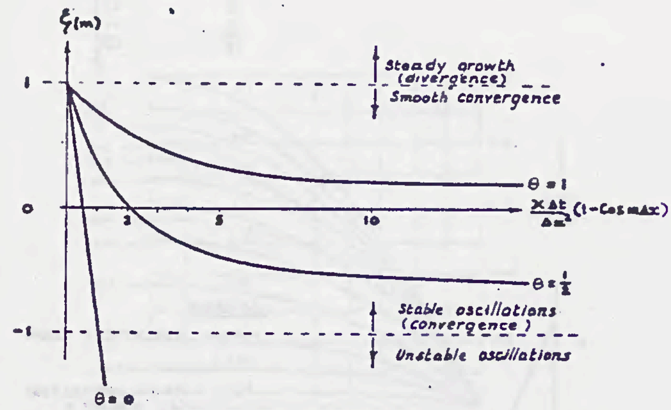

FIGURE 6 GROWTH FACTOR BEHAVIOR FOR EQUATIONS OF THE FORM

$$\frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial x^2} \doteq \theta\left[\frac{\partial T}{\partial t}\right]^{n+1} + (1-\theta)\left[\frac{\partial T}{\partial t}\right]^{n-1}$$

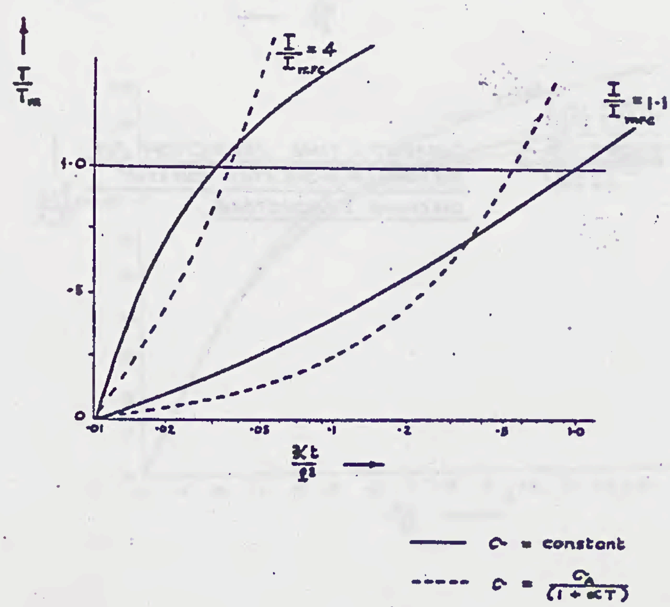

FIGURE 7 TEMPERATURE PREDICTION PROFILES FOR CONSTANT AND TEMPERATURE VARYING ELECTRICAL CONDUCTIVITY

A DECOUPLED METHOD FOR PREDICTING TIME-CURRENT CHARACTERISTICS OF HRC FUSES

P.M.McEwan and R.Wilkins

PRINCIPAL SYMBOLS

C	specific heat
ρ	density
K	thermal conductivity
κ	thermal diffusivity
σ	electrical conductivity
α	temperature coefficient
T	temperature
J	current density
M	modal parameter for finite-difference solutions
t	time
v	volume of sub-volume of element
A_s	sub-volume surface area
M.F.C.	minimum fusing current
I	r.m.s. symmetrical prospective current
Δx, Δy, Δz	spatial separation between nodes
Δt	time step

Suffixes and superscripts are used as follows:

e	pertaining to the fuse-element
f	pertaining to the filler
A	at ambient temperature
m	at melting temperature
i, j, k	spatial identifiers
n	time identifier. Thus $T_{i,j,k}^{n}$ is the temperature at a point whose coordinates are $i\Delta x$, $j\Delta y$, and $k\Delta z$ at a time $n\Delta t$

INTRODUCTION Calculation of the complete time-current characteristics of practical fuses must be done using numerical methods (1), (2). These fuses usually contain elements with multiple constrictions in the form of notches. Finite difference methods have been found most suitable.

For each value of prospective current the temperature distribution within

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the fuselink is computed as a function of time until melting occurs at some point on the fuse element. In the regime of the time-current characteristic, heat loss from element to filler, and along the element to the end connections is significant in determining the melting time.

However, a full 3-dimensional finite difference model of a practical fuselink requires a vast number of nodes, since the node spacing is fundamentally determined by the need to accurately represent the element thickness and the geometry of the reduced element section. This means that colossal computer running times are necessary to obtain a solution.

Excessive computer storage and running times may be overcome without adverse effect by using a decoupled numerical solution. In this method the transient temperature distribution along the element is computed by conventional methods, but at each step a separate calculation is made of heat lost to the filler from the surface of the element. Axial and lateral heat transfer within the filler, and the effect of the outer cartridge are neglected. These assumptions become invalid for very long melting times (for currents approaching the M.F.C.). In this region a quite different, quasi-steady-state representation is necessary.

The decoupled method has been found to give predictions of time-current characteristics in good agreement with test results for a wide variety of fuselinks.

<u>FUSE REPRESENTATION</u> The decoupled model is shown in Fig.1. The fuse element is divided into subvolumes as shown, thus permitting the solution of the transient (2-dimensional) temperature distribution within the fuse element by finite-difference methods. Nodes are introduced normal to each subvolume to permit calculation of the temperature distribution in the filler adjacent to the element. The following assumptions are made:

(i) the outer cartridge and environmental effects play no part in the processes.

(ii) heat conduction in the filler occurs normal to the subvolume surfaces, i.e. in the y-direction only.

(iii) the current distribution within the element remains unchanged throughout the transient (1), (4).

(iv) K_e and K_f do not vary with temperature.

(v) the fuse end-caps are represented as fixed-temperature boundaries.

(vi) the thermal capacity of each subvolume of the element is lumped at a single node. This is possible because the element thickness is very small compared with Δy.

The conventional time-current characteristic (3) covers the range $0.01s < tm < \infty$. The decoupled model is valid also over this range, except for very long melting times, where assumption (i) becomes invalid. Determination of the M.F.C. must be done using a steady-state representation, in which environmental effects are very important.

<u>SOLUTION METHOD</u> The Joulean heat generated within the element subvolume is determined by computing the current density distribution by numerical solution of the electric field problem[4]. The heat lost to the filler surrounding each subvolume is given by Fourier's Law[5] as:

$$q_f = - K_f \left. \frac{\partial T}{\partial y} \right|_{y=o} . A_s \qquad \text{..... (1)}$$

The <u>net</u> heat generated within the subvolumes may then be taken as the actual heat generation <u>less</u> the heat lost by conduction to the filler. This is

$$q' = \frac{Ji,j^2}{\sigma_e} + K_f \left. \frac{\partial T}{\partial y} \right|_{y=o} \frac{As}{v} \qquad \text{..... (2)}$$

(Watts/unit vol.)

This approach is valid because the element thickness is very small compared with the element width and length.

The 2-dimensional temperature distribution within the element is then governed by (5)

$$K_e \frac{\partial^2 T}{\partial x^2} + K_e \frac{\partial^2 T}{\partial z^2} + q' = \rho_e C_e \frac{\partial T}{\partial t} \qquad \text{..... (3)}$$

Since heat flows in the filler are assumed normal to each subvolume surface, they are governed by the one-dimensional equation

$$K_f \frac{\partial^2 T}{\partial y^2} = \rho_f C_f \frac{\partial T}{\partial t} \qquad \text{..... (4)}$$

The Crank-Nicholson method [1] is used for the iterative numerical solution of (3) for the element temperature distribution. The time step Δt is determined by the element diffusivity and dimensions. This permits the use of the much faster explicit (non-iterative) method for the solution of (4), since the thermal response of the filler is much slower than that of the element.

This gives, for the element (k = 1)

$$T^{n+1}_{i,j,1} = \frac{Me}{2(1+2M_e)}\left\{T^{n}_{i,j-1,1} + T^{n}_{i,j+1,1} + T^{n}_{i-1,j,1} + T^{n}_{i+1,j,1} - 4T^{n}_{i,j,1} + T^{n+1}_{i,j-1,1} + T^{n+1}_{i,j+1,1} + T^{n+1}_{i-1,j,1} + T^{n+1}_{i+1,j,1}\right\}$$

$$+ \frac{1}{(1+2M_e)}\left\{T^{n}_{i,j,1} + \frac{J_{ij}^{2}\Delta t}{\sigma_A \rho_e C_e}\left[1 + \alpha_e (T^{n}_{i,j,1} - T_A)\right] + \frac{K_f A s \Delta t}{\rho_e C_e v}\left.\frac{\partial T_{i,j,k}}{\partial y}\right|^{n}_{y=o}\right\} \quad \ldots\ldots (5)$$

and for the filler (k > 1)

$$T^{n+1}_{i,j,k} = T_{i,j,k} + M_f\left\{T^{n}_{i,j,k-1} + T^{n}_{i,j,k+1} - 2T^{n}_{i,j,k}\right\} \quad \ldots\ldots (6)$$

where $M_e = \frac{\mathcal{K}_e \Delta t}{\Delta x^2}$, $M_f = \frac{\mathcal{K}_f \Delta t}{\Delta y^2}$ $(\Delta z = \Delta x)$

The surface gradient is obtained by numerical differentiation, (6) using

$$\left.\frac{\partial T_{i,j,k}}{\partial y}\right|^{n}_{y=o} = -\frac{(11T^{n}_{i,j,1} - 18T^{n}_{i,j,2} + 9T^{n}_{i,j,3} - 2T^{n}_{i,j,4})}{6\Delta y} \quad \ldots\ldots (7)$$

The solution proceeds in successive time-steps as follows. The element temperature distribution is found by iterative solution of (5). This gives the boundary values $T^{n}_{i,j,1}$ which are then used for the solution for the filler temperature distribution using (6). (7) then gives the gradients for use in (5) at the next time step.
The algorithm is illustrated by the flow chart shown in Fig.2.

DISCUSSION The use of the explicit method for the filler minimises storage and running time but certain precautions must be taken to avoid propagation of large errors (1), which may occur when $\frac{K_f \Delta t}{\Delta y^2} > 0.5$. This places a restriction on the lowest value of Δy which can be used. ($\Delta y > \sqrt{2K_f \Delta t}$ for stability). However, too large a value of Δy cannot be used as the truncation error increases in proportion to Δy^2.

For quartz filler the thermal diffusivity is very small (typically 3×10^{-3} cm^2 S^{-1}) and this permits very small values of filler nodal spacing (Δy min $\simeq 0.07$ Δt). Instability is avoided in practice by using M = 0.166 to determine Δy. This value gives minimum truncation error for simple problems (7).

The time step Δt must be determined by successive test runs of the program using progressively smaller values of Δt. The computer program is general in that fuses are simply specified by the input data. The melting time is calculated as a function of several prospective currents which are multiples of the M.F.C. Where the M.F.C. is unknown, suitable prospective currents are determined by scaling short-circuit values obtained from the action integral (8). Individual I: tm solutions are terminated when any element subvolume exceeds melting temperature. The prearcing time is then accurately determined by linear interpolation between the latest and the previous maximum temperature values.

RESULTS A range of single notched silver strip elements centrally positioned in quartz-filled ceramic cartridges was used, and the time-current characteristics were determined experimentally and also by using the program. The elements varied in width, length, thickness, shoulder:neck ratio, and body size, but the same filler was used throughout.

The dimensions of each fuse are given in Fig.3, and the time-current characteristics are shown in Fig.4.

Fig.4 shows that the decoupled method gives very good agreement with the experimental curves, up to 2s for notched elements with large shoulder:neck ratios (typically 10:1) and up to 10s for elements with smaller shoulder:neck ratios (of the order of 5:1).

Typical computer running times and storage requirements are shown below.

The data shown refers to the prediction of the complete characteristic of each fuse using a moderately slow business machine (ICL 1901 A).

Fuse type	Running time (Δt = 0.04s)	Storage (words)
1	5h	< 10k
2	8h	< 10k
3	26h	< 8k

For a modern fast computer the running times will be reduced by a factor of about 200.

PHYSICAL DATA

The electrothermal data which was used is given below.

K_e	4.2	$Wcm^{-1}{}^oC^{-1}$
K_f	5.86×10^{-3}	$Wcm^{-1}{}^oC^{-1}$
αe	0.00445	${}^oC^{-1}$
C_e	0.232	$W\text{-}s\text{-}g^{-1}{}^oC^{-1}$
ρ_e	10.49	$g\text{-}cm^{-3}$
C_f	1.176	$W\text{-}s\text{-}g^{-1}{}^oC^{-1}$
ρ_f	1.8	$g\text{-}cm^{-3}$
σ_A	6.11×10^6	$S\text{-}cm^{-1}$
T_m	960.8	${}^oC$
T_A	22.0	${}^oC$

CONCLUSIONS The decoupled method gives accurate predictions of time-current characteristics without excessive computer time and storage.

The accuracy of predictions was found to be highly dependent upon the choice of time step used. Experience is necessary to determine the maximum economical value, which does not affect the accuracy of the results.

The accuracy of the computed filler heat losses was difficult to assess, but since axial and lateral heat flow in the filler, the influence of the cartridge, and environmental effects are neglected, it must be expected that the computed losses are only approximate for long melting times. The decoupled model will not give accurate results beyond 10s unless an alternative method of computing the losses to the filler is used, based upon quasi-steady state solutions.

ACKNOWLEDGEMENTS Thanks are due to the Computing Services of Preston and Liverpool Polytechnics.

REFERENCES

1. McEWAN, P.M. and WARREN, L. : "Survey of numerical methods for solving time-varying fuse equations". Int.Conf. on Electric Fuses and their Appl^n. Liverpool Polytechnic April 1976.

2. LEACH, J.G., NEWBERY, P.G., and WRIGHT, A.: "Analysis of high-rupturing capacity prearcing phenomena by a finite-difference method".
Proc.IEE, 1973, vol 120, pp 987-993.

3. B.S.88: 1967.

4. WILKINS, R., and McEWAN, P.M. : "A.C. short-circuit performance of notched fuse-elements".
Proc. IEE, 1975, vol 122, pp 289-292.

5. CARSLAW, H.S., and JAEGER, J.C. : "Conduction of heat in solids" (Clarendon Press, 1959).

6. BICKLEY, W.G. : "Formulae for numerical differentiation" Mathematical Gazette, Vol 25, 1941, pp 19-27.

7. RICHTMEYER, R., and MORTON, K.W. : "Difference methods for initial-value problems" (Interscience).

8. BAXTER, H.W. : "Electric fuses" (Arnold 1950).

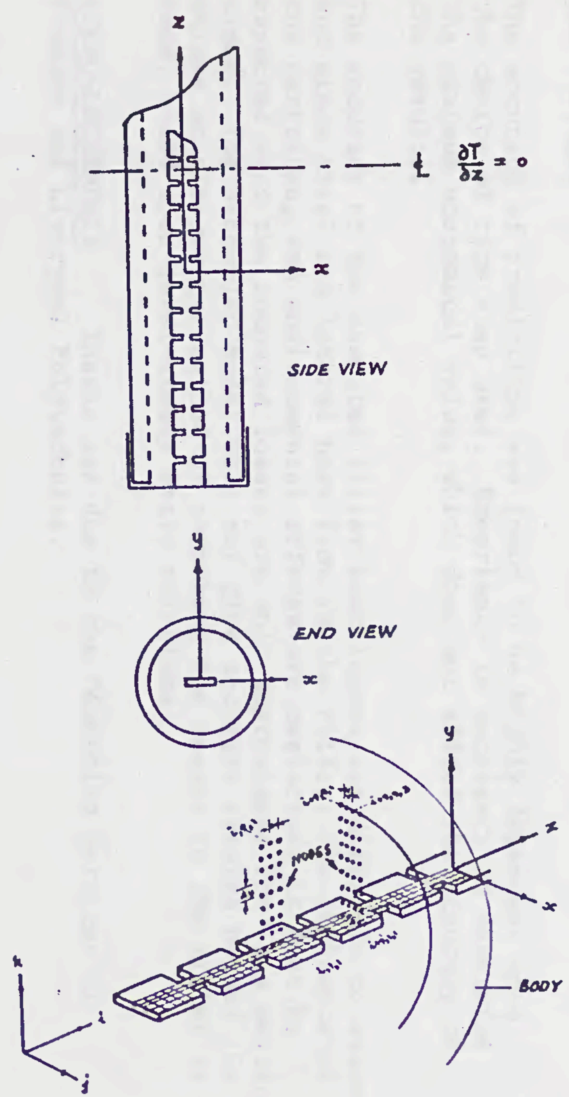
z
$\frac{\partial T}{\partial z} = 0$
x
SIDE VIEW
y
END VIEW
x
y
z
x
NODES
BODY

FIG. 1

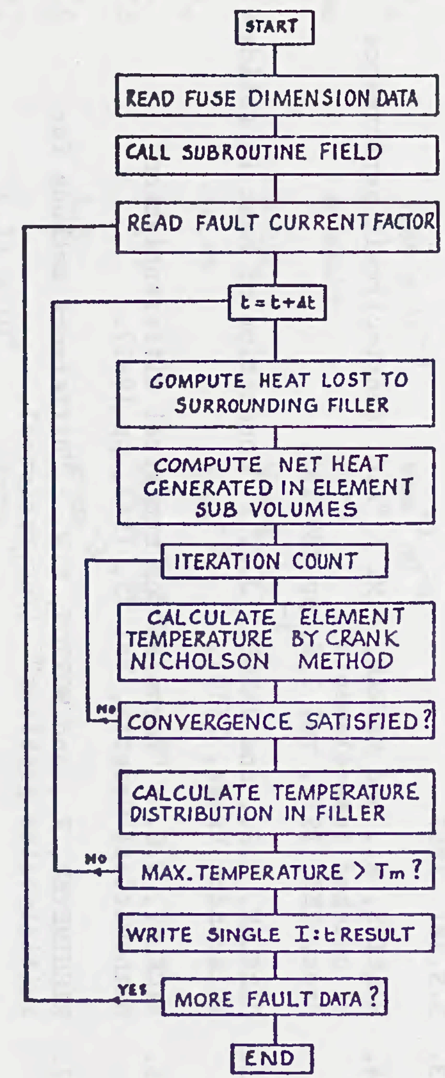
START
READ FUSE DIMENSION DATA
CALL SUBROUTINE FIELD
READ FAULT CURRENT FACTOR
t = t + Δt
COMPUTE HEAT LOST TO SURROUNDING FILLER
COMPUTE NET HEAT GENERATED IN ELEMENT SUB VOLUMES
ITERATION COUNT
CALCULATE ELEMENT TEMPERATURE BY CRANK NICHOLSON METHOD
NO
CONVERGENCE SATISFIED?
CALCULATE TEMPERATURE DISTRIBUTION IN FILLER
NO
MAX. TEMPERATURE > Tm ?
WRITE SINGLE I:t RESULT
YES
MORE FAULT DATA ?
END

FIG. 2

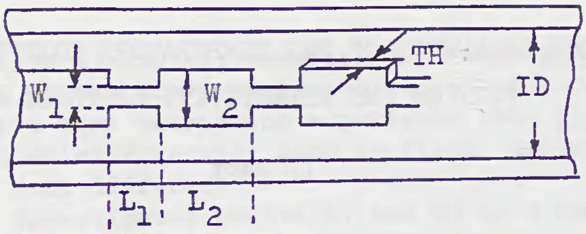

FIG.3

Element type	Number of notches per element	Fuse dimensions (cm)					
		ID	L_1	W_1	L_2	W_2	TH
1	23	1.27	0.161	.07455	0.485	0.1527	.00508
2a	23	1.27	0.066	.0724	0.578	0.3175	.00762
2b	23	1.27	0.066	.0724	0.578	0.3175	.01016
3a	5	0.94	0.0786	.0766	0.714	0.812	.00508
3b	5	0.94	0.0786	.0766	0.714	0.812	.01524
3c	5	0.94	0.0786	.0766	0.714	0.812	.02286

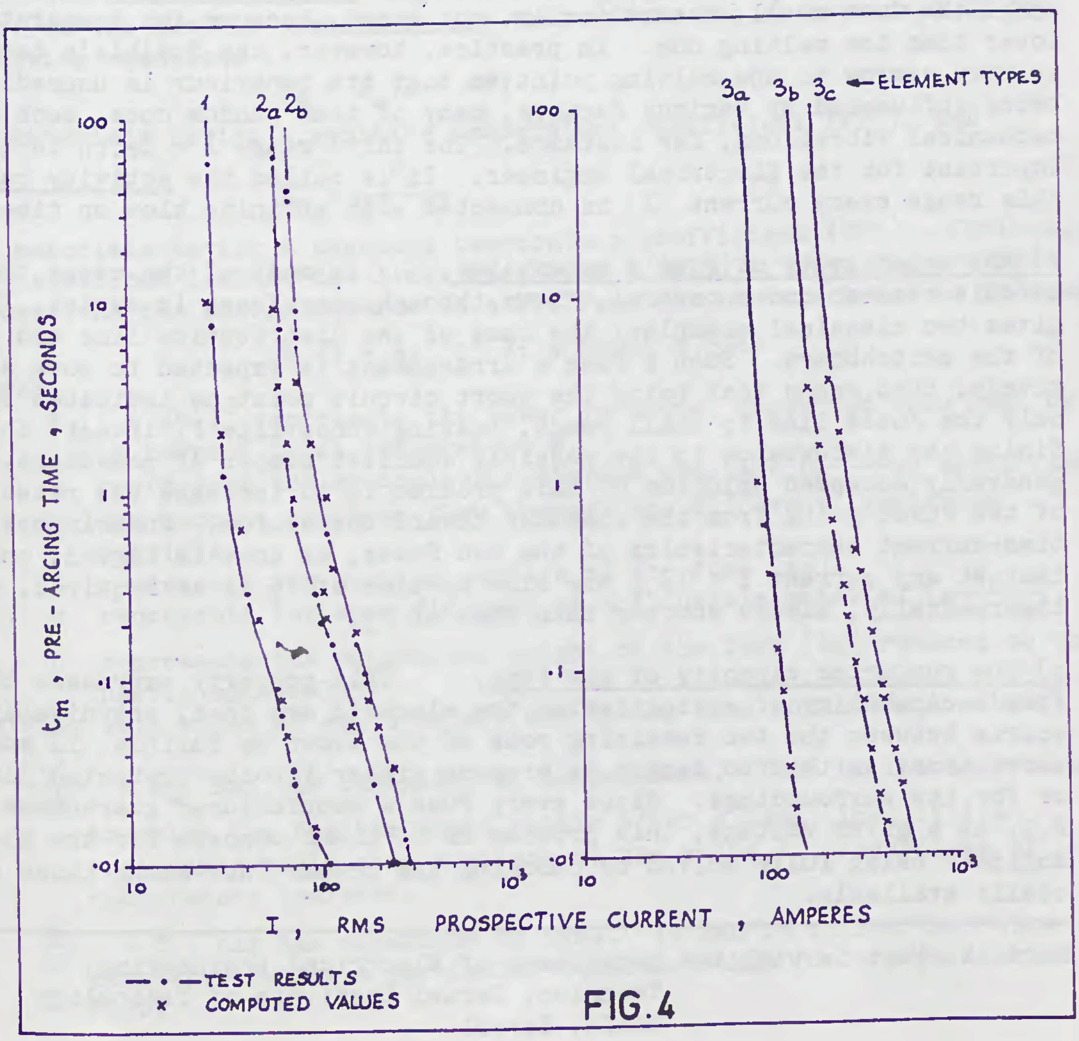

FIG.4

THE INFLUENCE OF THE TEMPERATURE COEFFICIENT (TC) ON THE SELECTIVITY OF FUSES

Y. Naot

INTRODUCTION Every Electrical Engineer, by choosing the proper Fuses for a given electric circuit, bases his considerations upon three well accepted characteristics of the Fuses and their assemblies as follows:

a) The Time-current characteristic. This characteristic gives the time elapsing between the moment in which the current I starts and that in which this current is interrupted by the melting of the fusible element. (blow up time). Fig. 1 shows that this characteristic is asymptotic to a vertical line defining the minimal current that causes the fusible to melt in a real finite time. This current shall be referred to as "the theoretical rated current" $I_{r.th}$. Theoretically speaking, the fusible, when flown exactly by $I_{r.th}$, would reach its melting point without trespassing it. For too obvious reasons, the "technical rated current" I_r must be considerably lower, in order to avoid both an intempestive melting and a too fast aging of the fusible. I_r and $I_{r.th}$ divide the diagram into three separate ranges. The first range $0 < I < I_r$ is called the working range. The current I can flow endlessly without causing any fuse's reaction. The second range $I_r < I < I_{r.th}$ is called the indifference gap. In this range the fuse shall, theoretically, not react, because its temperature is lower than the melting one. In practice, however, the fusible's temperature is very narrow to the melting point so that its behaviour is unpredictable being influenced by various factors, many of them random ones, such as mechanical vibrations, for instance. The third range $I > I_{r.th}$ is the most important for the Electrical Engineer. It is called the activity range. In this range every current I is connected with a finite blow up time.

b) The selectivity of Fuse's assemblies. In most of the cases the short circuit current under control, flows through many Fuses in series. Fig. 2 gives two classical examples: the case of the distribution line and the case of the switchboard. Such a Fuse's arrangement is expected to work selectively, that means that being the short circuit point as indicated in Fig. 2 only the Fuses like F_2 shall react, leaving those like F_1 intact, thus confining the disturbance to the possibly smallest number of consumers. The generally accepted solution of this problem is to increase the rated current of the Fuses going from the consumer toward the source. Superimposing the time-current characteristics of the two Fuses, as done in Fig. 3, one sees that at any current $I > I_{r.2}$ the blow up time of F_2 is as required, at least theoretically, always shorter than that of F_1.

c) The rupturing capacity of the fuse. This property expresses the Fuse's capability of extinguishing the electric arc that, unavoidably, sparks between the two remaining rods of the blown up fusible, in such a short time, so that no danger is present either for the protected circuit or for its surroundings. Since every Fuse's manufacturer guarantees a given R.C. at a given voltage, this problem is of minor concern for the Electrical Engineer being fully solved by choosing the proper Fuse among those commercially available.

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With regard to points a) and b), however, the Fuses almost never react as expected according to the above mentioned rules. Especially speaking about selectivity, it is a very intriguing experience that in most of the cases nobody can predict which Fuse will blow up first, unless their rated currents are very much different.
The present paper investigates points a) and b) in a more sophisticated way in order to explain facts and to suggest how to improve the performance of Fuses and Fuse's assemblies

THE BASIC EQUATIONS. The time-current characteristic can be mathematically derived at various degrees of sophistication.
In order to avoid unnecessary complications, that would be of no help to better understanding, the following simplifying assumptions shall be adopted

a) The surrounding's temperature has been chosen as point of reference. Therefore all the temperatures mentioned in the paper are to be understood as temperature rise above the surroundings.
b) The longitudinal transfer of heat (along the fusible element) has been disregarded. As a consequence the whole fusible element assumes a uniform temperature which is a function of current and time only.
c) The change of resistance of the fusible, due to changes in temperature has been assumed to be linear until the melting temperature θ_m. The temperature coefficient α therefore, has to be understood as a mean value over a wide range of temperature. Under this assumption the resistance of the fusible element at any temperature can be expressed by the following equations :

$$R_\theta = R_o(1 + \alpha\theta) \qquad (1$$

for materials having a positive temperature coefficient (PTC), and

$$R_\theta = \frac{R_o}{1 + \alpha\theta} \qquad (2$$

for materials having a negative temperature coefficient (NTC). Obviously both equations include the limit case $\alpha = 0$ (ZTC). Under the previous assumptions the energy balance of a PTC Fuse can be formulated as follows:

$$R_o(1 + \alpha\theta)\, I^2\, dt = hS\theta dt + cGd\theta \qquad (3$$

where:

. $R_o(1 + \alpha\theta)I^2$ represents the power in Watts, converted into heat by the current I, at temperature θ.

.. h represents the equivalent radiation constant $[\frac{W}{Deg.m^2}]$ which takes into account the heat flow through the different insulating materials.

... S represents the cooling surface of the fuse $[m^2]$.

.... c represents the specific heat of the fusible material $[\frac{Ws}{Deg.Kg}]$

..... G represents the equivalent weight of the fuse [Kg] reduced to the fusible material.

Dividing both sides of eq. 3 by hS, and taking into consideration that:

. $\frac{R_o I^2}{hS} = \theta_\infty$ has the dimension of temperature. This is the temperature to which the fusible would settle after a long time, if its resistance would stay constant at the value R_o, regardless of temperature increase.

.. $\frac{cG}{hS} = T$ has the dimension of time. It can be called the "time constant" having a particular constant value for any particular Fuse.

eq. 3 becomes:

$$\theta_\infty(1+\alpha\theta)dt = \theta dt + Td\theta \qquad (4$$

which is easily solved, being a simple linear differential equation. At the starting moment t=0 the fusible's temperature is assumed to be θ_o depending upon previous load. Accordingly. the solution of eq.4 is :

$$\tau = \frac{t}{T} = \frac{1}{1-\alpha\theta_\infty} \ln \frac{1-(1-\alpha\theta_\infty)\frac{\theta_o}{\theta_\infty}}{1-(1-\alpha\theta_\infty)\frac{\theta_m}{\theta_\infty}} \qquad (5$$

Eq. 5 holds, as previously stated, for the PTC Fuse, including the ZTC fuse as the particular case $\alpha=0$.
The blow up time is given in numerical form, being the ratio $\frac{t}{T}$.
In case of a NTC Fuse, the fundamental equation is :

$$\frac{R_o I^2}{1+\alpha\theta} dt = hS\theta dt + cGd\theta \qquad (6$$

Its solution under the same starting conditions is :

$$\tau = \frac{t}{T} = \frac{\alpha\theta_2}{\sqrt{1+4\alpha\theta_\infty}} \ln \frac{\theta_m-\theta_1}{\theta_o-\theta_1} - \frac{\alpha\theta_1}{\sqrt{1+4\alpha\theta_\infty}} \ln \frac{\theta_m-\theta_2}{\theta_o-\theta_2} \qquad (7$$

where: $\theta_1 = \frac{\sqrt{1+4\alpha\theta_\infty}-1}{2\alpha}$ and $\theta_2 = -\frac{\sqrt{1+4\alpha\theta_\infty}+1}{2\alpha}$ are two factors having the dimension of temperature. The mere inspection of eqs. 5 and 7 show that the blow up time is influenced by three factors: θ_m, θ_o and α. Their influence will be discussed in the next paragraphs.

<u>THE INFLUENCE OF θ_o .</u> θ_o is a function of the current which has flown through the fuse prior to the event of short circuit. Obviously the two limit cases are:

a) $\theta_o=0$. A completely cold fuse. Putting $\theta_o=0$ into eqs. 5 or 7 we obtain one time-current characteristic, which may be called "the cold characteristic".
b) the fuse, prior to the short circuit, was flown by its rated current. In this case its starting temperature was $\theta_o=\theta_m(Ir/Irth)^2$. This value of θ_o gives rise to a second characteristic which may be called "the hot characteristic".

In any other case τ is confined between these two characteristics.
Fig. 4 gives one example for a PTC fuse having $\alpha = 4.10^{-3}$.
The first consequence thereof is that a defined time-current characteristic does not exist. One can only speak about a strip, within it the blow up time is confined. Thus, calling τ_c the longest blow up time, and τ_h the shortest one, it is possible to define the <u>deviation factor</u> as :
$DF = (\tau_c - \tau_h)/(\tau_c + \tau_h)$, that means the maximal expectable deviation from the mean value $(\tau_c + \tau_h)/2$.

Tracing on the same diagram (as done in Fig. 5) two characteristic strips of two fuses having different rated current, one sees immediately the main reason for lack of selectivity. The two strips are partially superimposed. It is, therefore, meaningless to speak of selectivity as if it were an inherent property of the given fuse's assembly. One has rather

to speak about Probability of selective action. (PSA). The PSA can be roughly evaluated, basing on simplifying assumptions. Fig.6 shows a magnified portion of the superimposed strips of Fuses 1 and 2 where I represents the current flowing in Fuse 2 and the blow up time is given in its real value, instead of its numerical form. D_1 represents the width of the strip of Fuse 1 at the given current I and D_2 that of Fuse 2. D represents the width of the common portion of the two strips. As for D_2 one has to take into consideration that if Fuse 1 was "hot" at the event of the short circuit, that means that it was flown by its rated current I_{r1}, therefore the current of Fuse 1 is not I but rather $I+I_{r1}$. The hot characteristic of Fuse 1 shall be accordingly modified.
Assuming now that all the load configurations have equal probability (an assumption which is not always justified) and that any point of D is a potential point of lack of selectivity, one can conclude that the probability of the blow up time of Fuse 1 to be inside of D is D/D_1 and that of Fuse 2 is D/D_2. The total probability of having both the events simultaneously is D^2/D_1D_2. The lower limit of the PSA is therefore given by

$$PSA = 1 - \frac{D^2}{D_1 D_2} \qquad (8$$

Eq.8 shall be considered as a rough evaluation only, because the fact that the cold characteristic of Fuse 1 is influenced by the previous load of Fuse 2 has not been taken into consideration.

THE INFLUENCE OF α AND θ_m. The influence of these two parameters may be better pointed out by a comparative example, instead of developing cumbersome equations.
As such an example, a fuse of 200 A rated current has been chosen, supposing that its theoretical rated current I_{rth} is 15% higher. The melting temperature θ_m has been taken as parameter. The maximally allowed θ_o is that reached by the fuse when flown by its rated current I_r as previously calculated. Letting α change between given limits, both in the PTC and NTC ranges, the cold and hot characteristics have been calculated. The results are given in Fig. 7. Fig. 7 shows the DF as a function of α. It is clear at the first glance that in the PTC range the DF increases with α and with the melting temperature θ_m. The opposite effect appears in the NTC range. An increase in α and in θ_m causes a decrease of the DF, thus improving the fuse as far as its accuracy is concerned. (accuracy = 1-DF).
A further parameter which influences the DF is the ratio $\beta = I_r/I_{rth}$. This ratio influences the indifference gap. The smaller β the larger the indifference gap. Recalling now that the indifference gap defines a range in which the fuse still does not react to a current which actually is exceeding its rated one, one can take β as an index of the promptness of reaction of the fuse.
On the other hand β influences the DF too. Fig. 8 shows its influence taking β as parameter. The smaller β the smaller the DF of the fuse. The consequence is that promptness and accuracy are two properties which do not go together. A good fuse for general purposes shall be based on a fair compromise between them. As Fig. 8 shows such a compromise is much easier achieved using NTC fusibles.

In order to investigate the selectivity behaviour a second fuse having a rated current of 160 A (one stage lower according to European standards), is supposed to be connected in series with the previous one.
The PSA of this arrangement has been calculated using eq. 8 assuming the same TC for the two fuses. Their time constant has also been assumed equal in order to allow the use of the numerical time instead of the real one.

The results are given in Fig. 9 for the following different cases :

Case 1 -F_1 = 200A PTC ; F_2 = 160A PTC.
Case 2 -F_1 = 200A NTC ; F_2 = 160A NTC.
Case 3 -F_1 = 200A PTC ; F_2 = 160A NTC.
Case 4 -F_1 = 200A PTC ; F_2 = 200A NTC.
The inspection of Fig. 9 allows to draw some important consequences.

a) The well accepted opinion that increasing the short circuit current fuses assemblies become less selective is not sound. As far as lack of selectivity is concerned the most dangerous range is by relatively low short circuit currents. By high currents the PSA shows a slight tendency to increase.
b) The use of NTC fuses alone, can substantially improve the PSA. In our case the NTC/NTC arrangement shows an average PSA of 65%, compared with 44% of the PTC/PTC arrangement.
c) The PTC/NTC arrangement shows (at least theoretically) an enormous improvement, reaching an average PSA of > 90%.
d) The PTC/NTC combination allows even the use of two fuses of same rated current, conserving a high degree of PSA. (about 80%).

CONCLUSIONS. The previous considerations lead to some useful conclusions.
a) beside the comonly accepted differentiation of fuses according to their time constant it will be useful to differentiate them also according to their temperature coefficient. Such a differentiation will permit to fit exactly any fuse to its particular purpose.
b) As far as PTC and ZTC fuses are concerned, the author cannot predict serious difficulties. Many alloys are known to have an extremely small TC, while all the pure metals have a definitely positive TC. The realization of the NTC fuse, however, will require the solution of many very difficult problems. Some conductive materials are known to have a negative TC but none of them combines all the required properties. For instance, carbon which is a good conductor and is suitable to be worked out in form of wires, has a too small NTC (.0005 to .0009) and a too high evaporation point (about 3500 Deg.).
All the aqueous solutions of salts have a strong NTC (about .03) combined with a suitable conductivity, but their use as fusible material will require a complete new design of the fuse, because they are liquids. Even assuming to have solved the problems of design, such aqueous solutions can be used only within the limits of the critical temperature of water which is too low for obtaining good fuse's characteristics.
Glass is also among the theoretically possible NTC solutions. It has all the required properties but one. It is solid, can be extruded in form of a wire or a tube, has an extremely high NTC, it becomes as fluid as water beyond a given temperature which is enough high, but does not conduct electric current being cold.
This difficulty can be solved by a new design, so that this kind of solution seems to be promising. Other materials which behave more or less like glass, are molted salts. These materials too can lead to useful solutions after having solved design problems.
Modern chemistry can produce, nowadays, many new artificial materials. The required material really suitable for making fuses should have the strongest NTC as possible. It should be solid, ductile and a good conductor at low temperature. It should destroy itself (not necessarily melt) at a

given temperature, possibly about 1000 Deg.
To develop such a material can be an interesting challenge for people working in Physical Chemistry.

All the previous considerations have been worked out assuming that the short circuit current is constant in time.
Such an assumption can be justified by D.C. By A.C.,when the current is measured by its MSR value, this is true only when the blow up time is relatively long compared with the length of the period.

By very strong short circuit currents eqs. 4 and 6 have to be modified in order to take into consideration the variation of the current in time, thus leading to solutions different from eqs. 5 and 7. Doing so, both the cold and hot characteristics change their form, in the range of very strong currents, but all the previous considerations about accuracy and selectivity remain in force. Such a degree of sophistication seems, therefore, to be beyond the scope of the present paper.

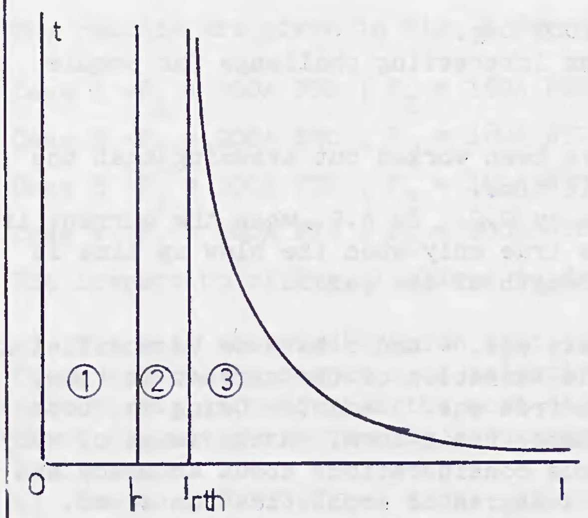

Fig. 1 Time-current characteristic

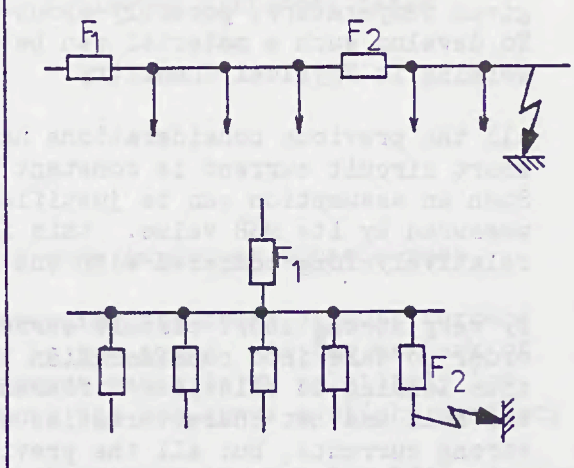

Fig. 2 Assemblies of Fuses

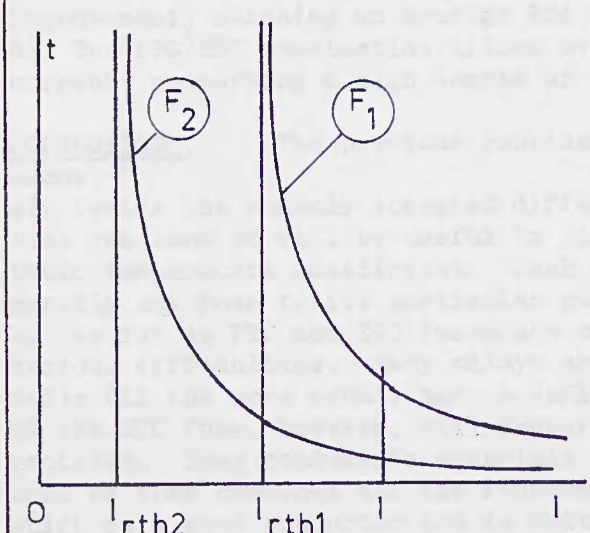

Fig. 3 Definition of selectivity

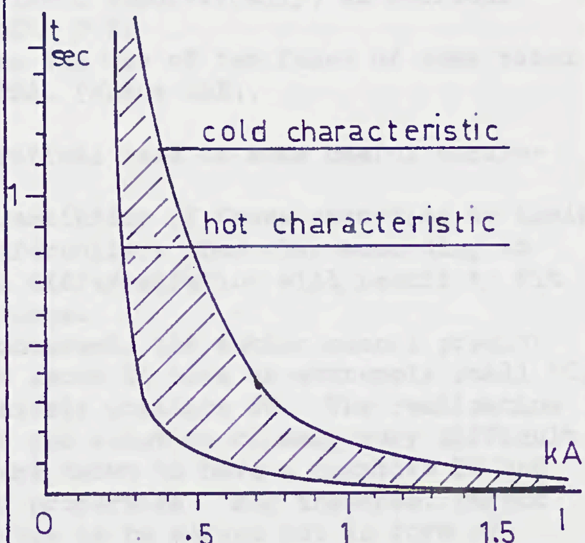

Fig. 4 Time-current strip

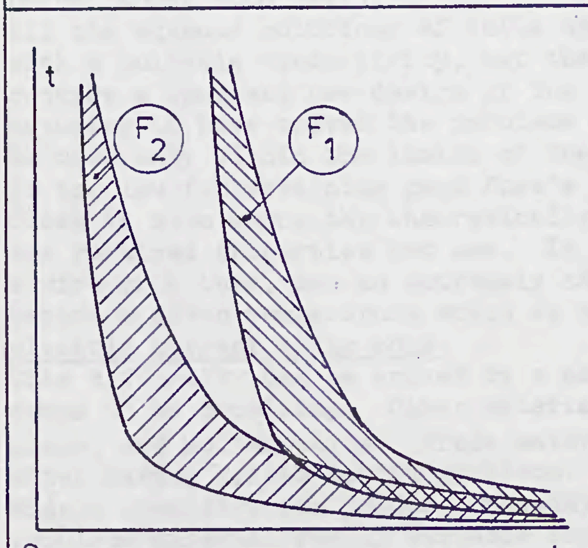

Fig. 5 Superposition of strips

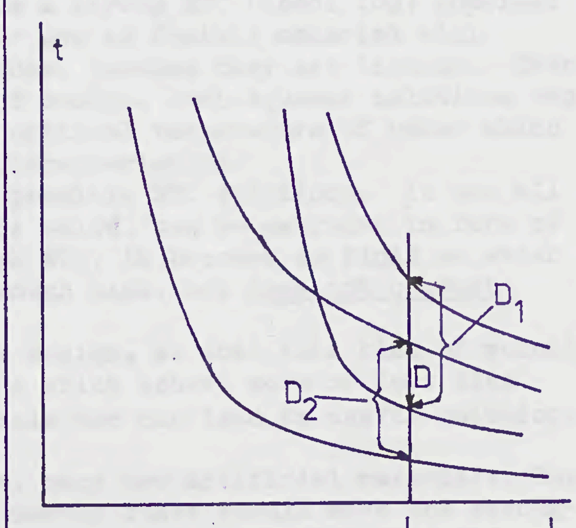

Fig. 6 Evaluation of PSA

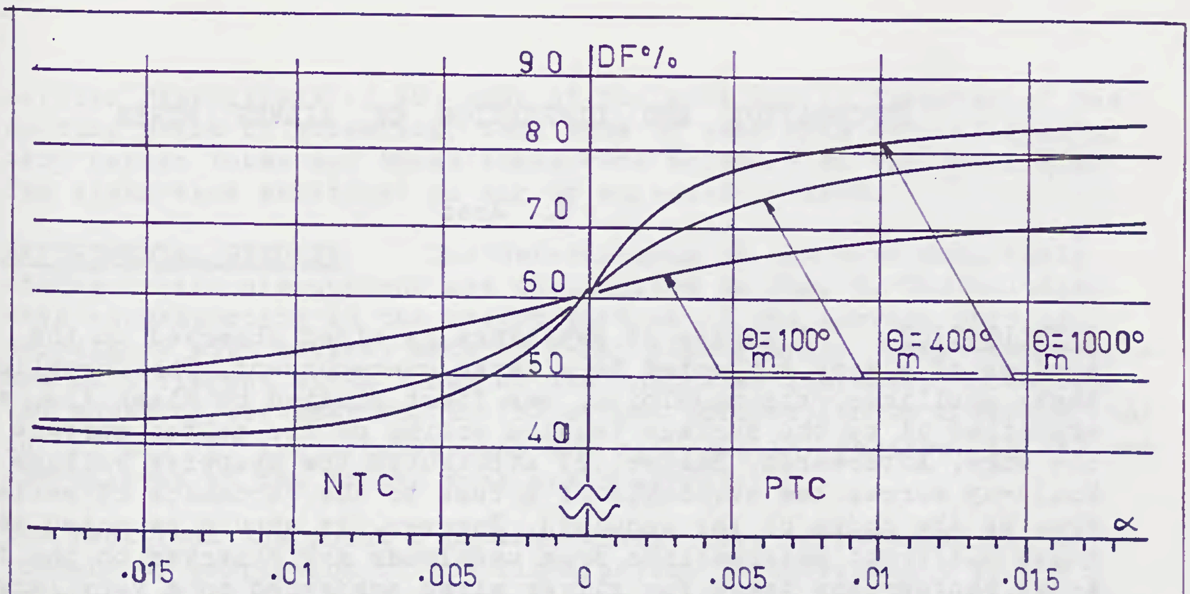

Fig. 7 Influence of α and θ_m on the DF

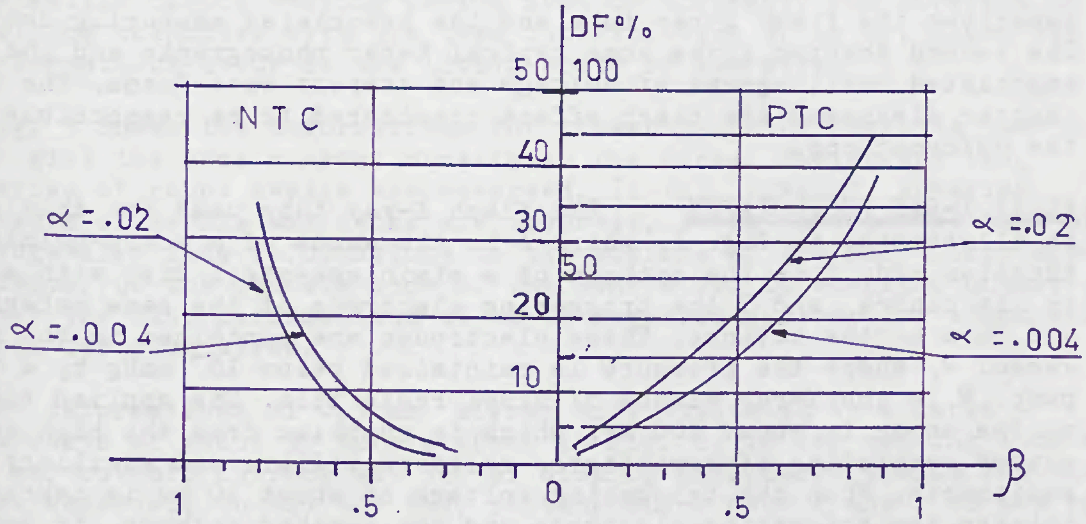

Fig. 8 Influence of β on the DF

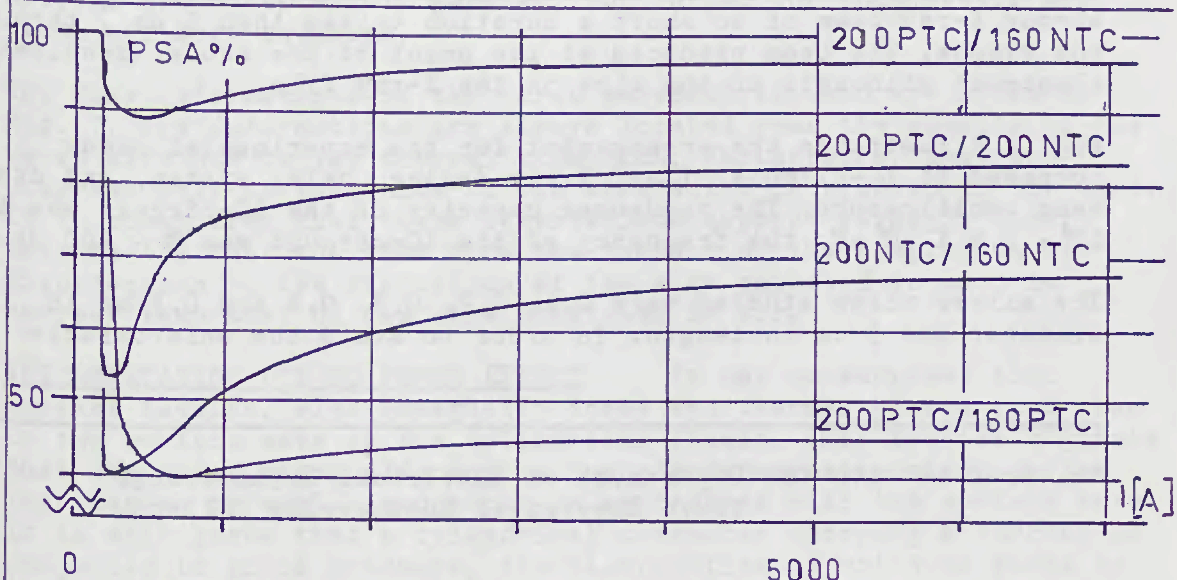

Fig. 9 PSA for different Fuse's combinations

DEFORMATION AND DISRUPTION OF SILVER WIRES

S. Arai

INTRODUCTION A series of swellings is often observed on the surface of a wire subjected to a large over-current. The formation of these swellings, the unduloids, was first studied by Kleen (1), who explained it by the surface tension acting on the molten surface of the wire. Afterwards, Baxter (2) attributed the stepwise voltage build-up across the terminals of a fuse to the formation of series of arcs at the nodes of the unduloid. However, it should be noted that quite different deformations from unduloids are observed on the flash X-ray photographs taken for silver wires subjected to a very large current.

This paper is concerned with such deformations. The first chapter describes the flash X-ray tube and the associated measuring devices. The second chapter gives some typical X-ray photographs and the associated oscillograms of voltage and current wave-forms. The third chapter discusses the pinch effect considered to be responsible for the deformations.

FLASH X-RAY PHOTOGRAPHY The flash X-ray tube used for this study is illustrated in Fig. 1, where A is the anode of a sharp-pointed tungsten rod, C is the cathode of a stainless-steel disc with a hole in its centre, and T the triggering electrode of the same material and form as the cathode. These electrodes are contained in the glass vessel V, where the pressure is maintained below 10^{-4} mmHg by a vacuum pump. W is the X-ray window of vinyl resin film. The applied voltage on the anode is about 100 kv, which is supplied from the high voltage source consisting of capacitors, solid rectifiers and auxiliary equipments. When the triggering voltage of about 10 kv is impressed between the triggering electrode and the earthed cathode, it triggers the spark-over between the cathode and the anode, which radiates a strong X-ray beam of so short a duration (less than 1 μs) through the window. The beam produced at the point of the anode, provides clear-cut silhouett of the wire on the X-ray film.

Fig. 2 illustrates the arrangement for the experimental study composed of LC-circuit, flasf X-ray device, delay system, and dual-beam oscilloscope. The condenser capacity of the LC-circuit was 1 X 10^4 ~ 5.4 X 10^5 μF, the frequency of the LC-circuit was 3 ~ 200 Hz.

The silver wires studied were 0.1, 0.2, 0.3, 0.4 and 0.5 mm in diameter and 5 cm in length. In order to avoid the unfavourable

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earlier disruptions at the ends of the wire due to lowering of the melting point by soldering, both ends of each wire were clamped by thin copper tubes and these tubes were soldered to the terminals. The wires were stretched in air or embedded in sand.

EXPERIMENTAL RESULTS The deformations of the wire from their starts to the disruptions are illustrated in Fig. 3. The voltage wave corresponding to the bright portion of the current wave is correlated with several sets of X-ray photographs. These photographs are of different wires taken at the indicated instants. Photograph (a) shows no deformation. In (b) slight deformation is observed, and in (c) and (d) the deformations are appreciable. Further, in (e) the disruptions of the molten wire are observed.

The fact that the point O on the voltage wave corresponds to the instant of completion of the liquefaction is ascertained by the measurement of the temperature near the melting point with a photomultiplier. Synchronized record of the voltage across the wire and the photomultiplier output is shown in Fig. 4. Since the thermal radiation during melting period must be constant, the duration of melting coincides with the time interval from t_1 to t_2. Thus, the deformations occur in the liquid state of the wire.

Fig. 5 shows the deformations for linearly rising currents such as to give the same current density to the wires. Photograph (a), series of round swells are observed. In (c), however, squarish shapes of swells and necks are observed. It is interesting that the wedge-like fine deformations on the surface of the wire first appear always, on the concave side of the bent wire. It was also observed that the fine deformations of wires appeared earlier for thick wires than for fine wires.

The deformations of 0.5 mm silver wire subjected to a large currents of about 50 Hz are shown in Fig. 6. In (a) melting time was 5 ms, cut-off current was 960 A. Sloping-shouldered swells and necks are observed. In (b) and (c), melting times were 2 and 1 ms and cut-off currents were 2 kA and 2.4 kA respectively. Squarish fine deformations are observed. In general, for larger currents swells and necks are more squarish.

The fine deformations of the wires embedded in sand are shown in Fig. 7. The deformations are always located near the summits of the waved wire due to the thermal expansion. Furthermore, they are observed only on that side of the wire which is pressed to the sand. It is considered that these observations support Vermij's observations (3) that the time from the instant of the completion of liquefaction to the disruption of the wire embedded in sand is shorter than that of the wire stretched in air.

INTERPRETATION DUE TO PINCH EFFECT It may be supposed that surface tension, electromagnetic force and thermal stress give rise to the surface wave on the cylindrical liquid. This section suggests that the wires being affected by the electromagnetic pinch deform into series of swells and necks in accordance with the surface wave. It is well known that a cylindrical conductor carrying a current is subjected to pinch pressure, the distribution of which is given by the following:

$$P = \frac{1}{4}\mu_0 i^2 r_0^2 [\ 1 - (\ \frac{r}{r_0}\ )^2\ ] \qquad (\ N/m^2\ ) \qquad \ldots\ldots(1)$$

where μ_0 is the magnetic permeability of vacuum, i is the current density, r_0 is the wire radius and r is the lateral distance from axis. The maximum pressure occures at the axis and is proportion to the square of the current density. Accordingly the very small irregularities due to the surface wave give rise to a longitudinal force difference acting in the direction from the smaller to the larger cross-section. This longitudinal difference of force gives rise to a flow in the liquid cylinder, making the neck smaller and smaller and the swell larger and larger. A model for the deformation is shown in Fig. 8, where r_1 is the radius of the neck and r_2 the radius of the swell. The flow from the neck to the neighbouring swells is illustrated in Fig. 8. Since the flowing liquid is imcompressible, the following equations are obtained (Appendix)

$$t = T_0 [1.85 - F(\tfrac{1}{2}\ , \theta)] \qquad \ldots\ldots(2)$$

$$\theta = \text{arc sin } k \qquad \ldots\ldots(3)$$

$$T_0 = \frac{4}{\varepsilon\alpha}\ (\ \frac{\sigma}{\mu_0}\ )^{\frac{1}{2}} \frac{\pi r_0^2}{I} \qquad \ldots\ldots(4)$$

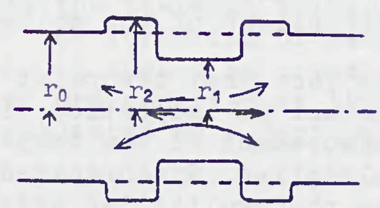
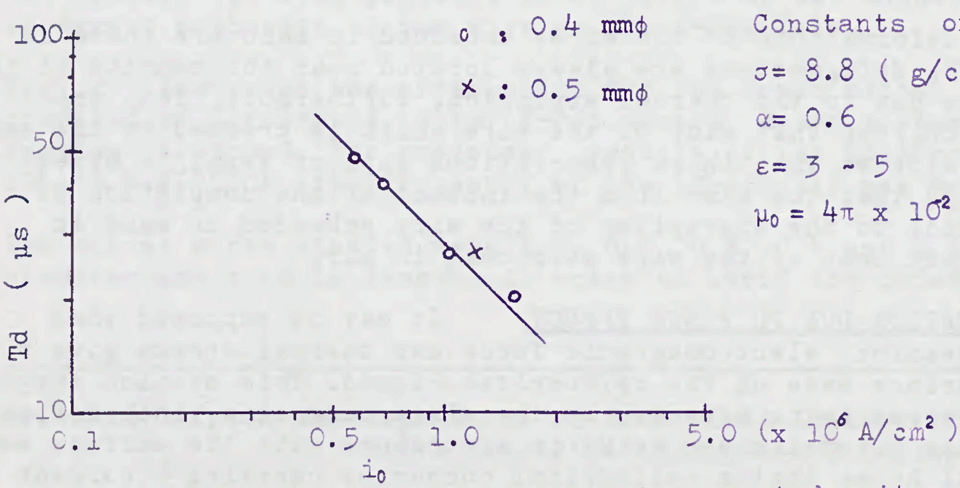


Fig. 8. A model for the deformation

, where t is the time measured from the initiation of deformation, $F(\ \frac{1}{2}\ ,\ \theta\ )$ the elliptic integral of the first kind, α the flow coefficient, ε the ratio of the length of the neck to r_0, σ the density of the wire, I the current flowing through the wire, and k the ratio of r_1 to r_0. The radius of neck reduces with time, until at last the wire disintegrates. The time from the start of deformation to the disintegration Td is given as follows:

$$Td = \frac{7.4}{\varepsilon\alpha}\ (\ \frac{\sigma}{\mu_0}\ )^{\frac{1}{2}} \frac{1}{i_0} \qquad \ldots\ldots(5)$$

where i_0 is the apparent current density which is the current divided by the original cross section of the wire before the current flow.



Constants on Eq.(5)

$\sigma = 8.8$ (g/cm^3)

$\alpha = 0.6$

$\varepsilon = 3 \sim 5$

$\mu_0 = 4\pi \times 10^{-2}$ (dyn/A^2)

Fig.9. Relations between the apparent current density and the time from the start fo deformations to the disruptions by pinch action.

The relations between Td and the apparent current density i_0 caluculated from Eq. (5) for silver wires with the measured values of ε are shown in Fig.9. And the relations of Td versus i_0 are plotted on the figure. They are given by the time from the instant the photograph was taken to the arcing, ε and r/r_0 of smallest neck at the instant the photograph taken and Eq.(2). A good agreement between the measured results and the analytical results is recognized.

Since the action of pinch effect to the deformations depends upon the current and the diameter of wire, the deformations of the wires of larger diameter due to the very large current are predominantly affected by pinch effect. Accordingly the pattern of the deformation of the wires of large diameters is sharply squarish.

In the case of the wire of smaller diameter or moderately large current flowing through the wire, it may be considered that both the pinch effect and the surface tension would take parts in the deformations and that the pattern of the deformations would be modified as shown in Fig. (5),(6).

SUMMARY For silver wires subjected to very large over-currents, we observed the deformations of the wires just before the initiation of the arcing with a flash X-ray apparatus and a dual beam oscillograph.

It was recognized that the deformations took place after the complete liquefaction of the silver wires. The sharply squarish shapes of necks and swells were observed under conditions of very high current density and the wire of large diameter. The rounded necks and swells were observed on the wire of small diameter or moderate currents.

It is considered that in the case of larger currents flowing through wires of larger diameters, the deformations are caused by pinch effect, and that for moderate current densities or in wires of smaller diameters, the deformations are due both to pinch effect and surface tension.

Since the wires embedded in sand are subjected to the pressed contact with around sand , the fine deformations of the wires occur relatively early after the completion of liquefaction and they are located near the summit of the waved wire.

It is recognized that the stepwise voltage rise corresponds to successive arc initiations at some of the necks.

AKNOWLEDGEMENTS The author is very grateful to Professor A. Hirose for his valuable advice and very detailed discussion. He also wishes to thank the Matsunaga Science Foundation and the Saneyoshi Shogaku Kai for the financial help.

REFERENCES (1) Kleen, W. Ann. Physik 5. 11(1931)579.
(2) Baxter, H.W. Electric Fuses . Arnold London(1950).
(3) Vermij, L. Electrical Behaviour of Fuse Elements(Thesis).

APPENDIX In Fig. 8, flow is divided at the center of the neck.

Since the liquid is incompressible, the following relation is obtained

$$r_1 = k\ r_0 \qquad .....(6)$$

$$r_2 = (\ 2-k^2\ )^{\frac{1}{2}} r_0 \qquad .....(7)$$

The critical radius r_3 , for which the pressure in the neck is equal to the pressure in the swell is given

$$r_3 = k\ (\ 1 - \frac{1}{2}k^2\ )^{\frac{1}{2}} r_0 \qquad ......(8)$$

Within the circle of the radius r_3, flow occurs from the neck to the swell. Let $\bar{P}_1$ and $\bar{P}_2$ be respectively the mean pressure in the neck and in the swell, then the exit velocity is shown as follows:

$$\bar{v} = [\ \frac{2}{\sigma}\ (\ \bar{P}_1 - \bar{P}_2\ )\ ]^{\frac{1}{2}} \qquad ......(9)$$

The volume of fluid that leaves the neck during the infinitesimal time interval dt is

$$dQ = \alpha\pi r_3^2 \bar{v}\ dt = \frac{1}{4}\alpha\ (\frac{2\mu_0}{\sigma})^{\frac{1}{2}} I r_0\ \ k[(1-k^2)(2-k^2)]^{\frac{1}{2}} dt \qquad ......(10)$$

on the other hand, the outflowing volume is

$$dQ' = 2\pi r_1\ dr_1\ \frac{r_0}{2\varepsilon} = \frac{\pi}{\varepsilon}\ r_0^3 k\ dk \qquad ......(11)$$

Since dQ must be equal to dQ', we obtain a function of t and k as follows:

$$dt = \frac{8}{\varepsilon\alpha}\ (\ \frac{\sigma}{2\mu_0}\ )^{\frac{1}{2}}\ \frac{\pi r_0^2}{I}\ \frac{dk}{[(1-k^2)(2-k^2)]^{0.5}} \qquad ......(12)$$

The above differential equation is integrated between t=0 and t with respect to t for the left-hand side and between k=1 and k with respect to k for the right-hand side, Eq.(2) is obtained.

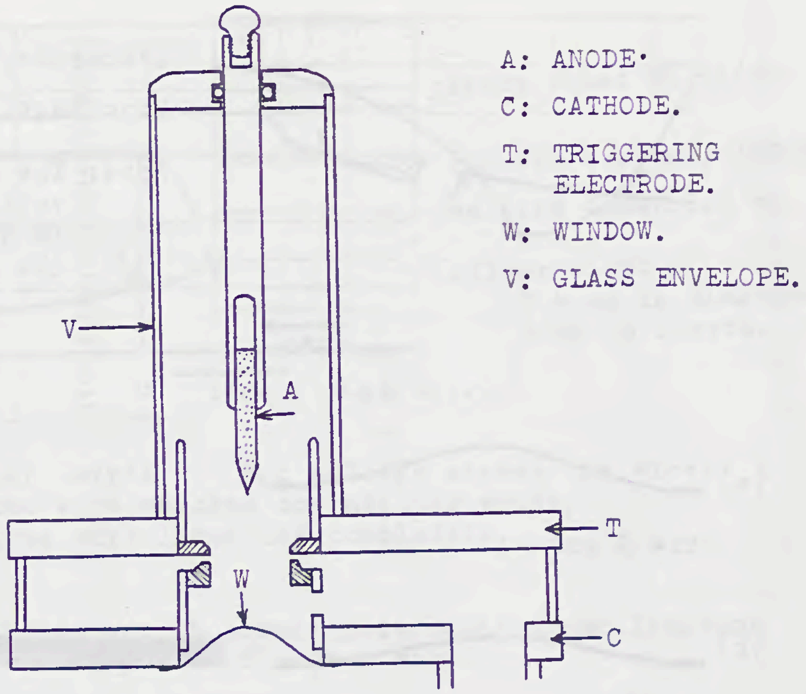
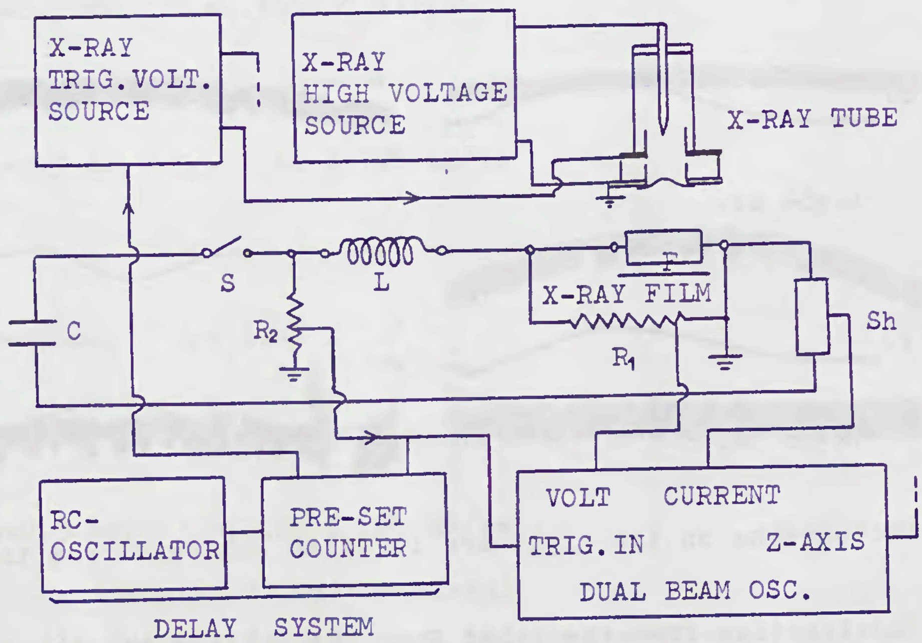
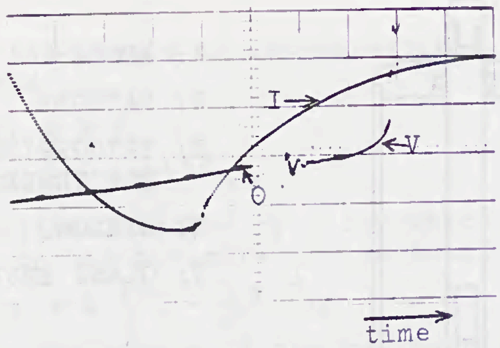


Fig. 1 Flash X-ray Tube.



C: CONDENSER, L: REACTOR, S: SWITCH, F: SAMPLE,
R_1 : VOLTAGE DIVIDER, R_2 : VOLTAGE DIVIDER,
Sh: CO-AXIAL CURRENT SHUNT.

Fig. 2 Block diagram of experimental apparatus.



I: current, sweep time 0.5ms/div.

V: voltage, sweep time 20µs/div.

Note: The overall time of the voltage wave corresponds to the bright portion of the current wave.

(a) 

tx= 3 µs.

(b) 

tx=18 µs.

(c) 

tx=38 µs.

(d) 

tx=54 µs.

(e) 

tx=68 µs.

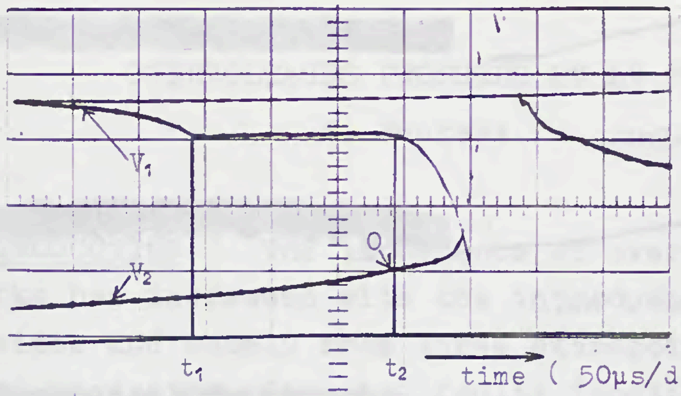
Photographs on the right are 10 times enlarged from the left.

tx: the time from the point O on the voltage wave on the oscillograph to the instant the photograph was taken.

Silver wire: 50 mm in length, 0.5 mm in diameter.

Melting time: 2 ms, cut-off current: 815 A.

Fig. 3 X-ray photographs of deformations and disruptions of silver wires stretched in air and V and I oscillogram.



sweep time: 50 µs/div.

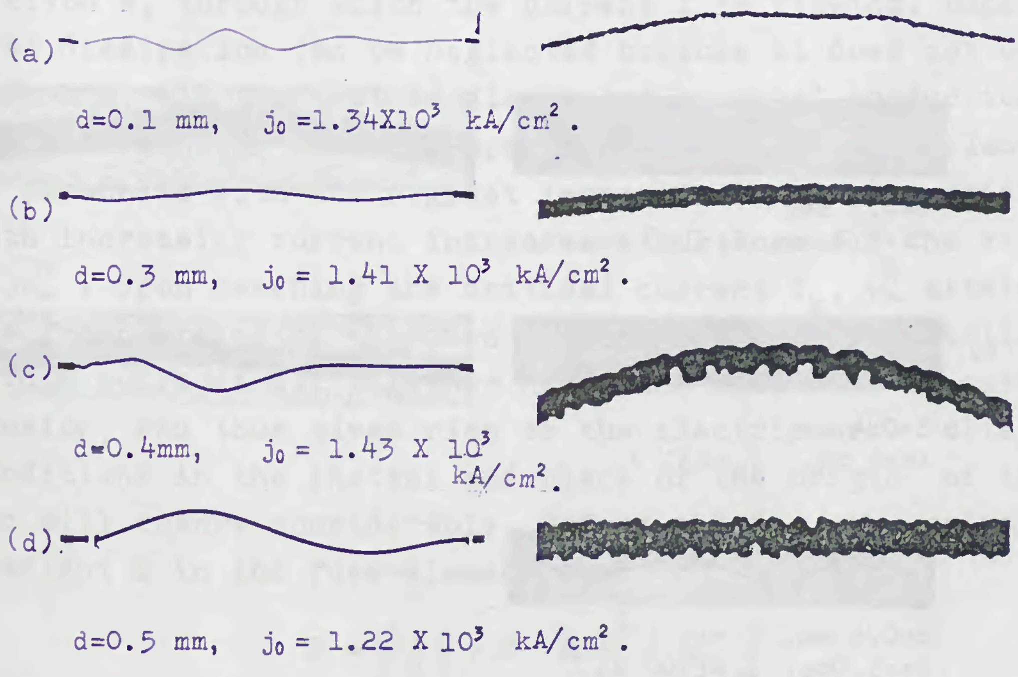
cut-off current: 1070A.

melting time: 2.6 ms.

silver wire:
0.4 mm in diameter,
50mm in length.

V_1 : photomultiplier output, V_2 : voltage across the wire.
t_1 : the instant, the wire reached the melting point,
t_2 : the instant, the wire liquefied completely.

Fig. 4 Typical voltage and photomultiplier-output oscillograms near the melting point of silver wire.



d: the diameter of silver wires.

j_0 : the current density just before the arc-initiation.

Photographs on the right are 10 times enlarged from the left.

Fig.5 X-ray photographs of deformations of the various silver wires for constant current density.

(a)

I_0 =960 A, tm=5ms.

(b)

I_0 =2000 A, tm= 2 ms.

(c)

I_0 =2400 A, tm= 1 ms.

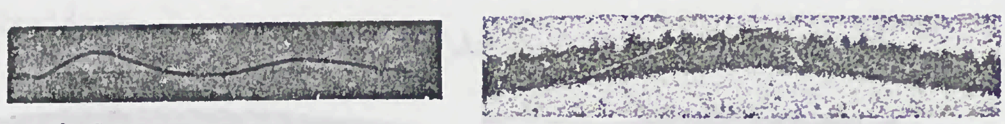
Photographs on the right are 10 times enlarged from the left.

Silver wire: 0.5 mm in diameter, 50 mm in length.

I_0 : cut-off current. tm: melting time.

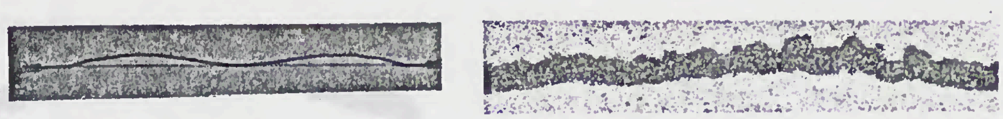
Fig.6 X-ray photographs of deformations of silver wires for various values of current.

(a)



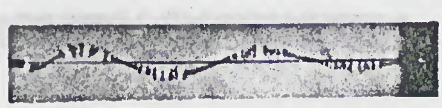
d=0.5 mm,
tm=1.2 ms, I_0 =1.8 kA.

(b)



d=0.4 mm,
tm=4 ms, I_0 =230 A.

(c)



d=0.4 mm,
tm=1.0ms, I_0 =1300 A.

Photographs on the right are 10 times enlarged from the left.

d: the diameter of wires, the length of wires is 50mm.

tm: melting time, I_0: cut-off current.

The mean diameter of grain of sand is 0.42 - 0.32 mm.

Fig.7 X-ray photographs of deformations and disruptions of silver wires embedded in sand.

OVERVOLTAGES PRODUCED BY LV FUSES

J. Paukert

INTRODUCTION The importance of overvoltages in LV networks has increased with the introduction of electronic devices and namely from three standpoints : the damage of semi-conductor elements, faulty functions of electronic devices, interference of communication means both public and private. If we neglect atmospheric overvoltages which, in most cases, do not come into consideration in protected installations according to IEC Publication 71, the LV fuses still remain one of the main sources of the overvoltage .

CASE OF THE FUSE-ELEMENT WITH CONSTANT CROSS-SECTION

We suppose the conductor of the length l and the cross-section s, through which the current I is flowing. Radial heat dissipation can be neglected because it does not overpass 10%. All the heat is dissipated by axial conduction. The distribution of the temperature along the fuse-element is parabolic with the highest temperature ϑ_m being amidst. With increasing current increases simultaneously the value of ϑ_m . Upon reaching the critical current I_k, ϑ_m attains the fusing point of the used material, the fused metallic bridge pulls itself together under the influence of surface tension, and thus gives rise to the electric arc. Voltage conditions in the instant and place of the origin of the arc will change considerably. Before melting, the voltage gradient E in the fuse-element was

$$E = \varrho \, (1 + \alpha \cdot \Delta\vartheta) \cdot \sigma \qquad (1)$$

with α representing temperature coefficient of resistance, $\Delta\vartheta$ temperature rise of fuse-element in the moment of melting, σ current density. For Ag with σ = 100A/mm2 , we have E = 7,8 mV/mm. After the appearance of the arc, there exists

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at the ends of melted element an arc voltage U_0

$$U_0 = U_k + U_a + E_0 \cdot l \qquad (2)$$

As the arc, immediately after its origin, is very short (some tenths of mm), the third member in equation (2) can be neglected, and the arc voltage U_0 will be determined by the sum of cathode U_k and anode U_a drop, which is of the order 50-200V per gap [1] Thus, the overvoltage does not occur if the heating-up of the fuse-element is slow (compare Tab.1).

The second extreme case is the adiabatic heating-up with high overcurrents, where the heat conduction does not make itself felt at all, and all the heat generated in the fuse-element is spent on its heating-up. The axial distribution of the heat has, in this case, a rectangular form. This case occurs if the conductor is heated-up with the current $I \geq 10 \cdot I_k$, where, in the sense of our previous consideration the critical current I_k is the lowest current which can melt the given conductor. The melting temperature is get along the whole length of the fuse-element all at once. The melted metal column behaves as any other column of liquid: its shape does not remain cylindrical, it changes to unduloidic one with contracted and expanded places, due to the influence of surface tension. Fuse-elements in transitory unduloidic phase have been studied especially by Polish authors, particularly by Nasilowski[2], [4] . The contracted places are heated-up more, the unstability of the unduloidic form is growing till the undulois finally disintegrates into n-drops, between which and the ends of the fuse-element, n+1 short arcs will be burning. The arc voltage will be

$$U_0 = (n+1) \cdot (U_k + U_a) + E_0 \cdot \sum_{1}^{n+1} l_i \qquad (3)$$

Compared with the previous case, the arc voltage will be (n+1)times higher and will surpass the source voltage. Between the slow and adiabatic heating-up of the fuse-element, there can exist transitory stages, in which the heat dissipation makes itself only partly felt in areas adjoining the margines of the fuse-element. Theoretically, there can occur cases ranging from the origin of two arcs up to a uniform desintegration along the whole length of fuse-element. Ossowicki [3] distinguished transitory stages in more details, taking as a basis the morphology of disintegration (Tab.1). Empiric formulas for determination of mean distance h, of two particles of a disintegrated fuse-element are given in Tab.2. Analyzing Tab.1, we come to the conclusion that the overvoltage occurs only when the fuse-element disintegrates on the whole length, with overcurrents of about (8 - 15)$\cdot I_n$. With further increase of the overcurrent increases also the overvoltage, because the dependence of the voltage on one elementary arc (i.e. sum of cathode and anode voltage drop) is growing linearly with the increasing current, as Dolegowski has proved experimentally [7].

The highest overvoltage can be awaited in the case of an instantaneous evaporation of the whole length of the fuse-element, with current-free interval. The current-free interval is caused by the fact that in a certain range of temperatures, e.g. for Cu between 2310 - 3500°C-, the vapours produced by the evaporation of the fuse-element are nonconducting. Thus, there occurs an ideal interruption of the circuit, and at the terminals of the melted fuse-element, appears the whole overvoltage given by the relation

$$U_p = L \cdot \frac{di}{dt} \qquad (4)$$

The rate of current rise di/dt is very high because it matters high overcurrents, and because the evaporation realizes in times non supassing 1 μs. The overvoltage can be as high as it breaks the discharge gap down. Another stage, i.e. evaporation of the wire with excess energy, so that the produced vapours are heated-up over the critical temperature becoming thus conducting, is characterized by the phenomenon that the current is not interrupted. Consequently, no current-free interval occurs. There occurs only one arc with one cathode and anode voltage drop. The value of the arc voltage will be determined, above all, by the voltage of the column, characterized by the high gradient (up to 100V/cm). Thus, the overvoltage lower than in the previous case can be awaited.

The preceding two cases of the interruption of the fuse - element, by means of its instantaneous evaporation, are only of theoretical importance. In fuses operating in existing networks current densities of the order 10^5 A/mm2 in the intervals shorter than 1 μs cannot be, in practice, attained.

Let us mention yet the last possibility, i.e. the adiabatic heating-up of the fuse-element preheated by the nominal current. In the starting stage, the distribution of the temperature was parabolic with the adiabatic heating-up being superimposed, so that the resulting distribution will have the form of a translated parabola. The melting of the fuse-element will not take place over the whole length, but only in its middle parts.If we compare the case of the short-circuit melting of the fuse-element from the cold and the warm stage (in both cases by means of the same short-circuit current), we find out, that the overvoltage will be lower with the fuse starting its function from the warm stage.

<u>FUSE-ELEMENT WITH CONTRACTED PARTS</u> In the case of the fuse-element with unvariable cross-section the number of interruption places and the height of the overvoltage depends on the value of the overcurrent as we saw in the previous paragraph. The overvoltages can attain considerable heights. For that reason, the up-to-date HRC LV fuses have fuse-element with contracted parts that predetermine places and number of arcs during melting. Theoretical consideration from the preceding paragraph, concerning the relation between the distribution of the temperature along the fuse-element and the number of interruption places, are partly valid even here : with parabolic distribution of the temperature, only the middle bridge melts and only one arc originates. With adiabatic heating-up, all the bridges remelt. To a demonstrable measure, this phenomenon can make itself felt only with fuses having a great number of bridges in a series.

Despite this, in fuses having a small number of bridges only, we also observe the influence of the preheating upon the overvoltage in breaking short circuits. In the case of PR type fuses with three bridges, it was experimentally found out that the mean value of the overvoltage coefficient decreased after preheating by nominal current by 8%, contrary to the case of operation from the cold stage. In this case, the decrease of the overvoltage cannot be explained by the decrease of interruption places. The fuse-element having been preheated, the fusing current decreased. The lowering of the current density in the moment of melting results, however, in lowering the arc-voltage per gap [7].

Let us refer to the question, how the design of the fuse-element influences the overvoltage. According to the theory, the number of bridges predetermines not only the number of arcs occuring after melting, but also the maximal overvoltage that can appear on the fuse. With increasing number of interruption places the overvoltage amplitude should according to the theory increase, too.

In our previous considerations, the fuse or its fuse-elements were taken into account separately without any respect to the influence of the external circuit. In fact, there is only a limited energy at disposal in the external circuit(mostly accumulated in the inductance), any the proportionality between the overvoltage amplitude and number of interruption places (length of the fuse-element, respectivelly)is valid only to a certain degree in dependence on the inductance of the circuit. Baxter [8] (Fig.1) has described this phenomenon and Hibner's [1] (Fig.2) recounted results confirmed it, too. With increasing number of interruption places increases also the energy, necessary fo their melting and for building up cathode spots, the process of melting itself is slowing down, and the part of energy which can manifest itself as the overvoltage is decreasing. Let us add to these problems one experience drawn from contact apparatuses. The division of the arc into a greater number of series small arcs contributes, after its entering a deionization grate, to limited overvoltage. The unstably burning arc shows numerous fluctuations of current and voltage caused, above all, by the great mobility of the arc column. Simplifying it we can say that the real length of the arc is being changed continuously. The gradient of the arc, as well, can change within large limits. On the other hand, the cathode and anode voltage drop is nearly constant in the large range of not only currents,but also of other conditions under which the arc burns. With the division of the arc into n-series arcs, the share of cathode and anode drops in the arc voltage increases, and in addition, with shortening the length of partial arcs, the possibility of the fluctuation of their length becomes smaller, which consequently results in considerable decrease of the arc voltage fluctuations.

THE INFLUENCE OF THE DESIGN OF THE FUSE ON THE OVERVOLTAGE

The influence of the filler has been studied only with the most common used filler - quartz sand - and namely, from the point of view of the granulation. Originally, Baxter published this relation [8]for copper wire, recently Hibner has done it for bands of different breadth. In all cases, the curve shows a maximum, the position of which dependends on dimensions of the fuse-element and on the granulation of the filler. The producer makes his choice of the granulation of the filler even from other standpoints (required breaking capacity, technology of filling the fuses, and economy) and possible high overvoltages reduces in another way, e.g. by the number of bridges. Technical literature dealing with the influence of other fillers than quartz sand is not known.

The use of copper instead of silver for the fuse-element does not influence substantially the limit overvoltage if the geometry of the fuse-element is retained. If we neglect the statistical fluctuations of the overvoltage coefficient in the range $\pm$ 0,1 the fuses with copper fuse-element shows the tendency to lower overvoltages.

The evaluation of the overvoltage must be carried out on the statistical basis, because the fuses show considerable dispersion of properties similar like all elements containing electrical arc. Statistical investigation of the overvoltages in the form of relative frequency diagrams in dependence on the overvoltage coefficient proved to be very useful.

The overvoltage coefficient is the relation of the overvoltage amplitude to the amplitude of the highest service voltage of the network, which lies usually by 1,1 U_n. On Fig.3a there is such a diagram for a member of the series of HRC fuses of the type PH (Czechoslovak production) with nominal current 50A, characteristic gTF, and on Fig 3b, the summary diagram for the whole series of fuses of the type PH. In both cases, the diagrams have the same shape corresponding to the normal distribution, and we can define two important coefficients of the overvoltage k:

- the most frequent coefficient of the overvoltage k^m, to which corresponds the greatest relative frequency,
- the limit coefficient of the overvoltage k^h that is the highest coefficient occurring in the set.

Analogous diagrams for other sizes of the series and types of fuses have a similar form, the approach to the normal distribution being the better the larger is the investigated set and the smaller is the difference of test parameters in individual experiments. In series of fuses, designed in the sense of IEC 269 as homogenous (proportionality of the cross-section of the fuse-element to its nominal current) not only the diagrams have the same shape, but also the most frequent and limit overvoltage coefficient have a constant value for all members of the series of fuses within the frame of statistical fluctuations($\pm$ 0,1) (see Fig.4 for the fuses, type PH, k^h). This is not the case in fuses where the homogenity of the series is not retained, as may be seen on Fig.5 (Roumanian fuses of the firm CILT).

INFLUENCE OF SERVICE PARAMETERS UPON THE OVERVOLTAGE

SERVICE VOLTAGE : In the preceding, we have shown that with a given design of the fuse-element, the overvoltage is influenced by the distribution of the temperature along the fuse-element, by the current and the inductance of the external circuit. The value of the overvoltage should be, consequently, constant with only the service voltage of the fuse being changed and other conditions unchanged. Experimentally found dependences of the overvoltage on service voltage are given by the producer and have a little increasing character. This phenomenon can be caused by different consumption of the energy necessary for loading parasite capacitances at the change of service voltage.

In the fuse with a shaped conductor the prospective current should have a very small influence on the overvoltage amplitude, because the influence of the current should show itself expecially in the value of cathode and anode voltage (see Equ. (3), the member of series arcs being predetermined. Experimentally found relations show within the frame of measurement accuracy and statistical dispersion independency of the overvoltage of the breaked current (Fig. 6,7). Influence of cos φ is small. It is caused by the decrease of the inductance and, consequently, by the amount of energy in the circuit (Fig. 8).

MEASURED VALUES OF OVERVOLTAGES (on the basis of measurements carried out by ourselves and those mentioned in technical literature) are given in Tab. 3. Fuses intended for the protection of semi-conductors show, of course, the lowest overvoltages while screw-plug cartridge fuses used for domestic installations the highest ones. The values attained in different countries do not differ substantially. We have found by means of the cathode oscillograph that the rate of rise of overvoltages lies by 650-9000V/ms, i.e.deep under the permissible rate of rise of normally used thyristors, which makes 200V/μs. Consequently, there is no reason for being afraid that electronic devices could be released unintentionally due to the operation of fuses.

Conclusion Measured values of the overvoltages with existing fuses allow us to draw the conclusion that the technique of fuses coped successfully also with the protection of semi-conductor devices. As far as the theory is concerned, the problems of the influence of the number of interruption places upon the overvoltage are to be solved for making possible to elaborate an exact computation program for fuses even from this point of view.

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REFERENCES

[1] Hibner J. : The voltage of single disrupt in a chain of arc intervals by short-circuit disintegration of stripe fuse-elements of fuses. International symposium of switching arc phenomena, Lodz,1970,p.226 - 231.

[2] Nasilowski J. : The process of short-circuit opening by a fuse with single-wire-element and explication of some phenomena observed during its operating. Ibidem, p. 210 - 215.

[3] Ossowicki J. : Attempt at systematic arrangement of mechanisms of wire fuse elements desintegration at overload. Ibidem, p. 204 - 209.

[4] Nasilowski J. : New observations of wire-explosions in fuses (in Czech). Elektrotechnický obzor, 1966, No 7, p.351 - 355.

[5] Kussy W. : Elektrische Niederspannungsschaltgeräte. Cram Verlag, Berlin 1950.

[6] Křesadlo Z. : The time of arc-origin in testing DC switches. (In Czech). Elektrotechnický obzor, 1950, No 5, p.95 - 98.

[7] Dolegowski M. : Spannungsverlauf an der einfachen Lichtbogenunterbrechung in den Sicherungen mit Sandlöschung und Einendungsschmelzstreifen. International symposium of switching arc phenomena, Lodz 1970, p. 219 - 225.

[8] Baxter H.W. : Electric Fuses. Arnold, London 1950

Tab. 1

Kind of desintegration	Overcurrent	Current deusity A/mm²	Sample oscillogram [3] Over-current	Over-voltage	k	Ref.
single - arc	<(5 to 8) In	335	2,05 In	300V	1	[3]
chaotic	(4 to 12) In	1340	8,3 In	300V	1	[3]
drop	(5 to 15) In	1670	10,3 In	343V	1,15	[3]
mixed	(12 to 17) In	2820	17,4 In	530 V	1,75	[3]
striated	> 17 In	62 500	385 In	1100 V	3,76	[3]
evaporation of the whole lenght with current-free interval	~ 60 In	10^4				[5]
	~ 1000 In	$1,8.10^5$				[6]

Tab. 2

Kind of desintegration	Empiric formula for h [mm]	Range of validity	Ref.
drop	$h = \frac{16}{3} d$	Ag, Cu wires in air, d<1mm	[4]
strip	h = 0,555 + 2,08d	Ag, Cu wires in sand	[4]
segment	h = 5,35	Cu wire, d = 1mm	[4]
of the band	h = 1,93 + 0,15b	Cu band, b = breadth	[1]

Tab. 3

Sort of fuses	Fuse origin	Maximal k^h	Maximal overvoltage V_m	Remark
HRC	Czechoslovakia	2,3	1650	
	Europe	2,4	1850	
	USA	1,95	1700	experiments
	USA	5,5	2000	catalogue
Semiconductor	Czechoslovakia	1,7	1200	
Screw - plug cartridge (type D)	Czechoslovakia	2,4	1900	
	Poland	4,3	2500	70 to 100 kA
	Holland	4,4	1400	

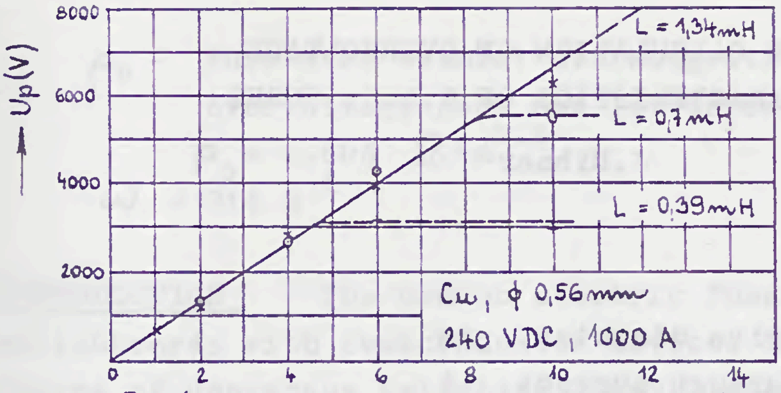

Fig. 1

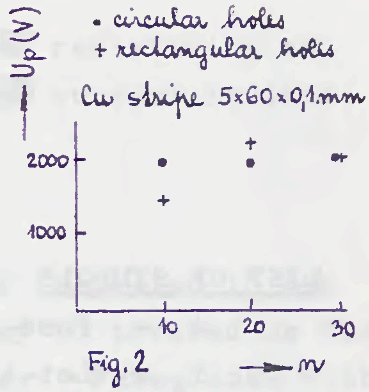

Fig. 2

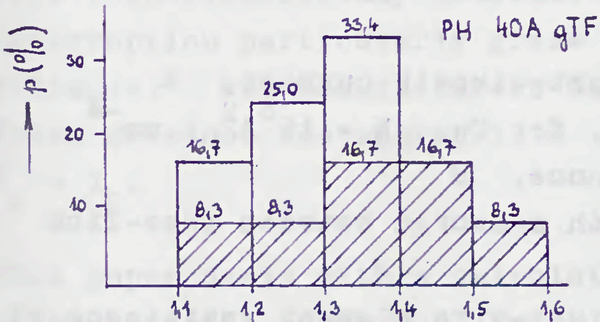

Fig. 3a

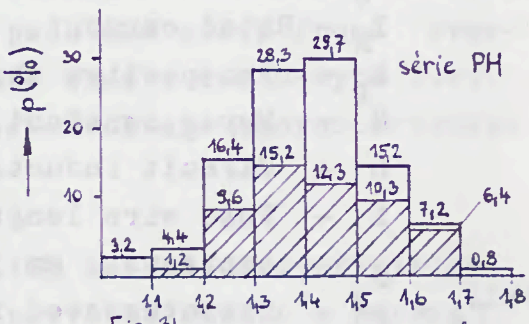

Fig. 3b

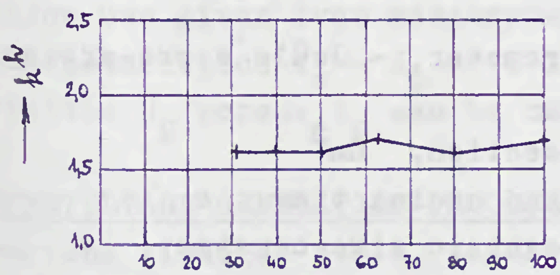

Fig. 4

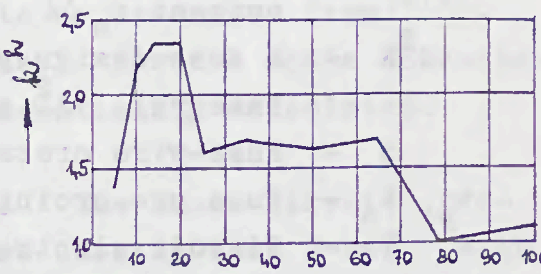

Fig 5

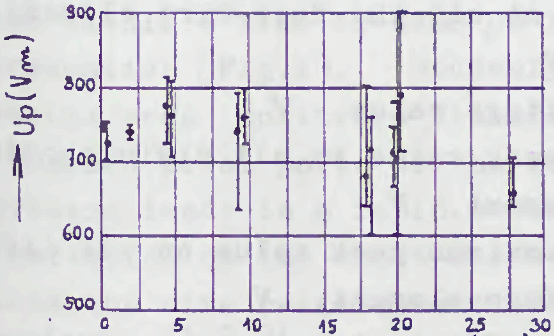

Fig. 6

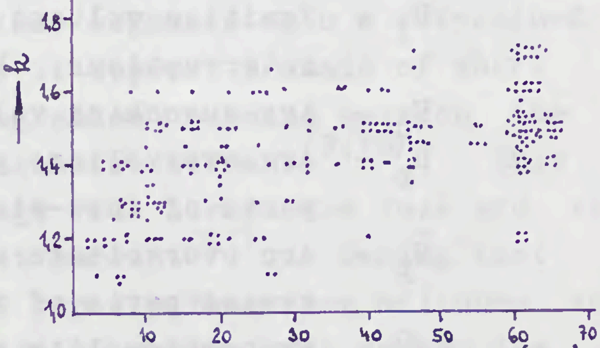

Fig. 7

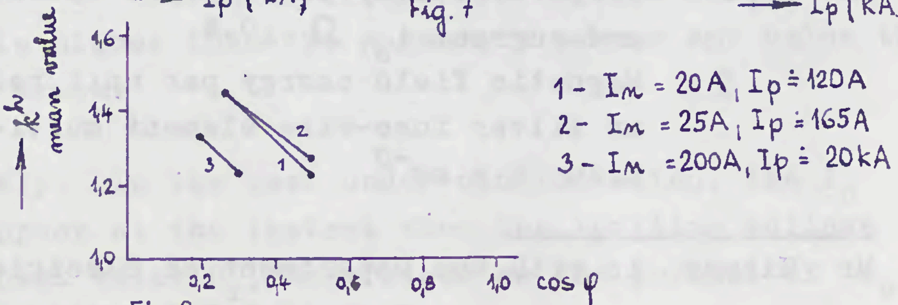

Fig. 8

THE CALCULATION OF OVERVOLTAGE CHARACTERISTICS OF H.R.C. FUSES

J.Hibner

LIST OF SYMBOLS

- d - Fuse-wire diameter, mm
- i_o - Let-through current, A
- $\hat{i}_o$ - Maximum let-through current, A
- I_N - Rated current, A
- I_p - Prospective short-circuit current, A
- K - Mayer constant, for Cu, $K = 10^5 A^2 \cdot s \cdot mm^{-4}$
- L - Circuit inductance, H
- l - Fuse wire length measured between fuse-link contacts, mm
- $r_o = \frac{U_p}{i_o}$ - Disintegrated fuse-wire element resistance at the instant of arc overvoltage peak value U_p and current i_o, Ω
- S^2K - A fuse design parameter, - Joule's pre-arcing integral, $A^2 \cdot s$
- S - Fuse-wire cross-section, mm^2
- t_p, t_a - Fuse pre-arcing and arcing time, s
- T - Circuit electromagnetic time constant, s
- U - Source voltage, V
- U_i - Ignition voltage at all the fuse-wire element interruptions, V
- U_q - Arc-quenching voltage value, V
- U_p - Arc overvoltage peak value on all disintegrated parts of fuse-element, V
- $\hat{U}_p$ - Arc overvoltage maximum peak value on all disintegrated parts of fuse-element, V
- β - Proportionality coefficient between overvoltage U_p and current i_o, $\Omega \cdot A^{0.5}$
- ε - Magnetic field energy per unit required for copper or silver fuse-wire element multi-arc disintegration $W \cdot s \cdot mm^{-3}$

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ρ_o - Fuse-wire element disintegration resistivity at overvoltage peak and let-through current instant, $\rho_o = 0.505\ \Omega \cdot A^{0.5}$

$\omega = 314\ s^{-1}$

INTRODUCTION The common electric fuses installed in the switchboards with semiconductor devices may be treated as the source of dangerous switching overvoltages. Fuse-links with wire fuse-elements may generate during short-circuit current interruption particularly great peak and steep front overvoltages. But manufacturers data sheets for D-type l.v. fuses give not the appropriate overvoltage characteristics $\hat{U}_p - I_p$.

This paper deals with a calculating method of overvoltage characteristic prediction. The previous author's papers (1÷6) enabled the U_p values calculation for a current i_o only which value was given from measurements or estimated from (7,8) characteristics $\hat{i}_o - I_p$ of a fuse. Now the whole characteristics $\hat{U}_p$ versus I_p can be mathematically calculated.

OVERVOLTAGE GENERATION PROCESS The short-circuit pre--arcing times of h.r.c. fuses are shorter than 5 ms. With large enough short-circuit current the fuse-wire disintegrates within a time of some μs into segments with a determined graduation (Fig.1). Suddenly it appears a chain of short serial arcs multi-arc disintegration burning between the remained metal parts of the fuse-wire element (9,10). This process leads to a rapid voltage rise across the fuse and to limitation of the short-circuit current (11). During that time the wire resistance rises rapidly from some miliohms to some ohms (1,2,3). Normally if the arc voltage during the arcing time is higher than the momentary source emf value the current will break.

Approximatively, in the case under consideration, the i_o value will appear at the instant when the ignition voltage reaches its peak value U_i, understood as the product of i_o

multiplied by γ_o. On the other hand, at the instant of final arc-quenching the quenching over-voltage U_q may appear. In the case of fuses with multi-arc disintegration its value normally is smaller than the ignition voltage U_i.

For d.c. and a.c. the element disintegration and overvoltage generation mechanism is analogous (Fig.2).

BASIC RELATIONS FOR THE OVERVOLTAGE CALCULATION According to the principle of the resistance method(1,2,3) Fig.2, the overvoltage can be calculated using the following relation:

$$U_p = \rho_o l \sqrt{\frac{i_o}{S}} = \frac{\rho_o l}{\sqrt{S}} \sqrt{i_o} = \beta \sqrt{i_o} \quad (1)$$

which is valid for

$$\mathcal{E} = \frac{L i_o^2}{2 l S} \geqslant 25 \ \frac{W s}{mm^3}, \quad i_o \geqslant 50 I_N \quad (2)$$

The relation (1) and conditions (2) are given in papers(2,3,6)

In order to get from relation (1) the characteristic $U_p - I_p$ it is necessery to involve a current i_o in parameter $S^2 K$ and the circuit current I_p.

The parameter β one may determine for a given fuse-link from the values ρ_o, l and S. The parameter should normally be given in manufacturers data sheets to enable the estimation of characteristic $U_p - I_p$.

A.C. $\hat{U}_p - I_p$ CHARACTERISTIC For low-current ratings up to abt 20 A the fuse-wire dia. is not greater than 0.4 mm. Than the S^2K value is low enough and $i_o < 0.5 \ I_p$, so one can write the following simplification

$$i = \sqrt{2} I_p \sin\omega t \approx \sqrt{2} I_p \omega t \quad (3)$$

For

$$\int_0^{t_1} i^2 dt = S^2 K \qquad (4)$$

from (3) it follows

$$\hat{i}_o = 11 \sqrt[3]{S^2 K I_p} \qquad (5)$$

The additional condition, which determines practically precise calculation results by using the relation (5) is

$$\frac{S^2 K}{\frac{2\pi}{\omega} I_p^2} < 0.01 \qquad (6)$$

From (1) and (5) we finally may get the relation $\hat{U}_p - I_p$

$$\hat{U}_p = 3.3 \beta \sqrt[6]{S^2 K I_p} \qquad (7)$$

Exceptly the condition 6 there must be yet fulfilled the conditions concerning the fuse wire disintegration energy but written in a different manner as function of parameter S^2K

$$\mathcal{E} = 16 \frac{L}{l} \sqrt[6]{S^2 K I_p^4} \cdot 10^3 > 25 \frac{Ws}{mm^3} \qquad (8)$$

$$S^2 K I_p > 94 I_N^3 \qquad (9)$$

<u>D.C. $\hat{U}_p - I_p$ CHARACTERISTIC</u> For the same assumption as for a.c. the short-circuit d.c. current shape for $t/T < 0.1$ one can write

$$i = I_p\left(1 - e^{-\frac{t}{T}}\right) \approx I_p \frac{t}{T} \qquad (10)$$

From (4) and (10) it follows

$$\hat{i}_o = 1.44 \sqrt[3]{\frac{S^2 K}{T} I_p} \qquad (11)$$

The dependence is valid for

$$\frac{S^2 K}{I_p^{\,2} T} < 0.1 \qquad (12)$$

From (1) and (11) we may get the relation for $\hat{U}_p - I_p$ characteristic

$$\hat{U}_p = 1.2\,\beta \sqrt[6]{\frac{S^2 K\, I_p}{T}} \qquad (13)$$

The additional conditions which should be taken into account beside (12) are the following

$$\mathcal{E} = 297 \frac{L}{l} \sqrt[6]{S^2 K \left(\frac{I_p}{T}\right)^4} > 25 \frac{Ws}{mm^3} \qquad (14)$$

$$\frac{S^2 K I_p}{T} > (35\, I_N)^3 \qquad (15)$$

EXEMPLARY $\hat{U}_p - I_p$ CHARACTERISTIC Fig.3 shows the exemplary $\hat{U}_p - I_p$ a.c. and d.c. characteristics for some D-type fuses Table 1 in range of 2 - 20 A calculated using the relations (7) and (13). The idendical characteristics can be drawn, if existing in dependence (1), i_o values will be calculated from characteristics $\hat{i}_o - I_p$ (7,8).

Table 1

Design parameters of D-type fuses Fig.1, for which the $\hat{U}_p = f(I_p)$ characteristics shown in Fig.3 have been calculated.

I_N	A	2	4	6	10	16	20
S^2K	$A^2 s$	4	24	65	300	894	2880
β	$\Omega A^{0.5}$	311	200	155	106	81	60

The carried out experimental test results with I_p = 1800 A and U = 260 V show a good agreement with calculations.

Generally it may be pointed out, that agreement between the calculated and measured $\hat{U}_p - I_p$ characteristics mainly depends from accuracy of i_o value determination, particularly for greater I_p values.

If the i_o values is accurate enough than the U_p value is accurate enough too. This conclusion goes from the author's examination of the dependence (1) in the following very wide parameter range:

- let-through currents from 0.1 kA to 20 kA
- current densities from 2 $kA \cdot mm^{-2}$ do 50 $kA \cdot mm^{-2}$
- source voltages from 0.5 U to 2 U
- energy per unit from 25 $W \cdot s \cdot mm^{-3}$ to 500 $W \cdot s \cdot mm^{-3}$
- circuit power factor $\cos\varphi$ or circuit inductance L in compliance with condition (2).

CONCLUSIONS The method suggested by the author makes possible the calculation of probable values of overvoltages generated by fuses with fuse-wire elements for any rated current in any electric circuit using formulae (1), if i_o value is known from measurements or from $\hat{i}_o - I_p$ characteristic

The maximum error statistically determined at a confidence level of 0.95 while using the formulae (1) for calculation of peak voltage does not exceed 16 %[2,3] when the conditions regarding the disintegration energy and the element disintegration density are complied with (2).

This same calculating method of $\hat{U}_p - I_p$ characteristic may be used, if there are known relations i_0 versus S^2K, I_p and T. In some cases, for which dependences[6,8,9] and[12,14,15] are fulfiled, one can obtaine the good results in the estimating of $\hat{U}_p - I_p$ from relations (7) and (13).

In order to enable the users to carry out overvoltage calculations on the basis of the formulae (1,7,13) the fuse manufacturers should make known some essential parameters of fuse elements such as the S^2K and β if more detailed parameters such as e.g. S, K and the quenching materials nature can not be given. In the lack of suitable catalogue data the fuse element parameters can be with sufficient accuracy determined by direct measurement of a dismantled fuse.

Practical application of the presented method of calculating overvoltages could diminishe labour consuming and expensive laboratory tests and accelerate working out catalogue data for fuses of any new design.

REFERENCES

1 Hibner J.: 'Calculation of over-voltages of low voltage fuses with strip fusing elements by the resistance gradient method' /in Polish/ Przegląd Elektrotechniczny 1968 No.10, p. 436-440.

2 Hibner J.: 'Calculation of overvoltage peak-values when breaking short-circuits by means of multi-strip fuses'. Sec International Symposium on "Switching Arc Phenomena". Łódź - Poland, 25-27 September 1973. Part: I. Conference Materials, SEP, Łódź, p.269-274. Part: II Post-conference materials, SEP Łódź, p.183-185.

3 Hibner J.: Resistance gradient method for calculating arc overvoltage peak values generated by short-circuit current

limiting /in Polish/. Dissertation T.U.Gdańsk 1973.

4 Hibner J.: Calculation of switching surges of apparatus fuses at direct current by the resistance method /in Polish/. Przegląd Elektrotechniczny, 1975 No.1, p. 22-24.

5 Hibner J.: Calculation of switching surges of apparatus fuses at alternating current. Przegląd Elektrotechniczny 1975 No.11 p.453-454.

6 Hibner J.: Calculation of overvoltages generated by fuses when limiting short circuit currents in low-voltage electric circuits. Fifth Iranian Conference on Electrical Engineering.Shiraz, October 27-30, 1975. Proceedings Vol.1, p.28-41.

7 Lipski T.: A graphical method of cut-off current estimation of the electric fuses /in Polish/. Przegląd Elektrotechniczny 1963, No.3, p.101-106.

8 Lipski T.: Low-voltage Fuses. WNT Warszawa 1068.

9 Nasiłowski J.: Phenomena Associated with the Desintegration of Conductors Overload by Short-circuit Current /in Polish/. Przegląd Elektrotechniczny, 1961, No.10, p.397-403.

10 Nasiłowski J.: Unduloids and striated disintegration of wires. Exploding wires. New York 1964, Vol.3. Plenum Press Chace W.G., Moore H.K.

11 Nasiłowski J.: The process of short-circuit opening by a fuse with single-wire fuse-element and explication of some phenomena observed during it´s operation. Symposium "Switching Arc Phenomena" SEP Łódź 1970, p.210-215.

12 Rauch W.: Strombegrenzung bei der Abschaltung von Wechselstron-Kurzschlussen durch Sicherungen ETZ-A 1959 H.16. S 543-547.

13 Wilkins R., Mc Ewan P.M.: A.C. short-circuit performance of uniform-section fuse elements PROC. IEE, Vol.122 No. 3, March 1975, p.285-288.

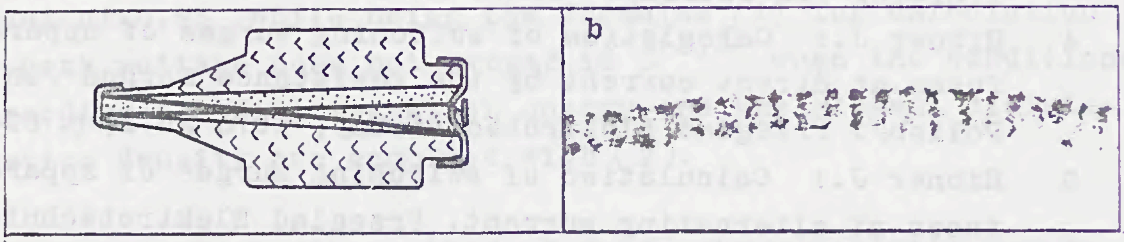

Fig.1. D-type fuse link with a wire element without notches (a) and element fragments after breaking a short-circuit (b)

b - vitrification with striated disintegration at the total element length when conditions (2) are complied with.

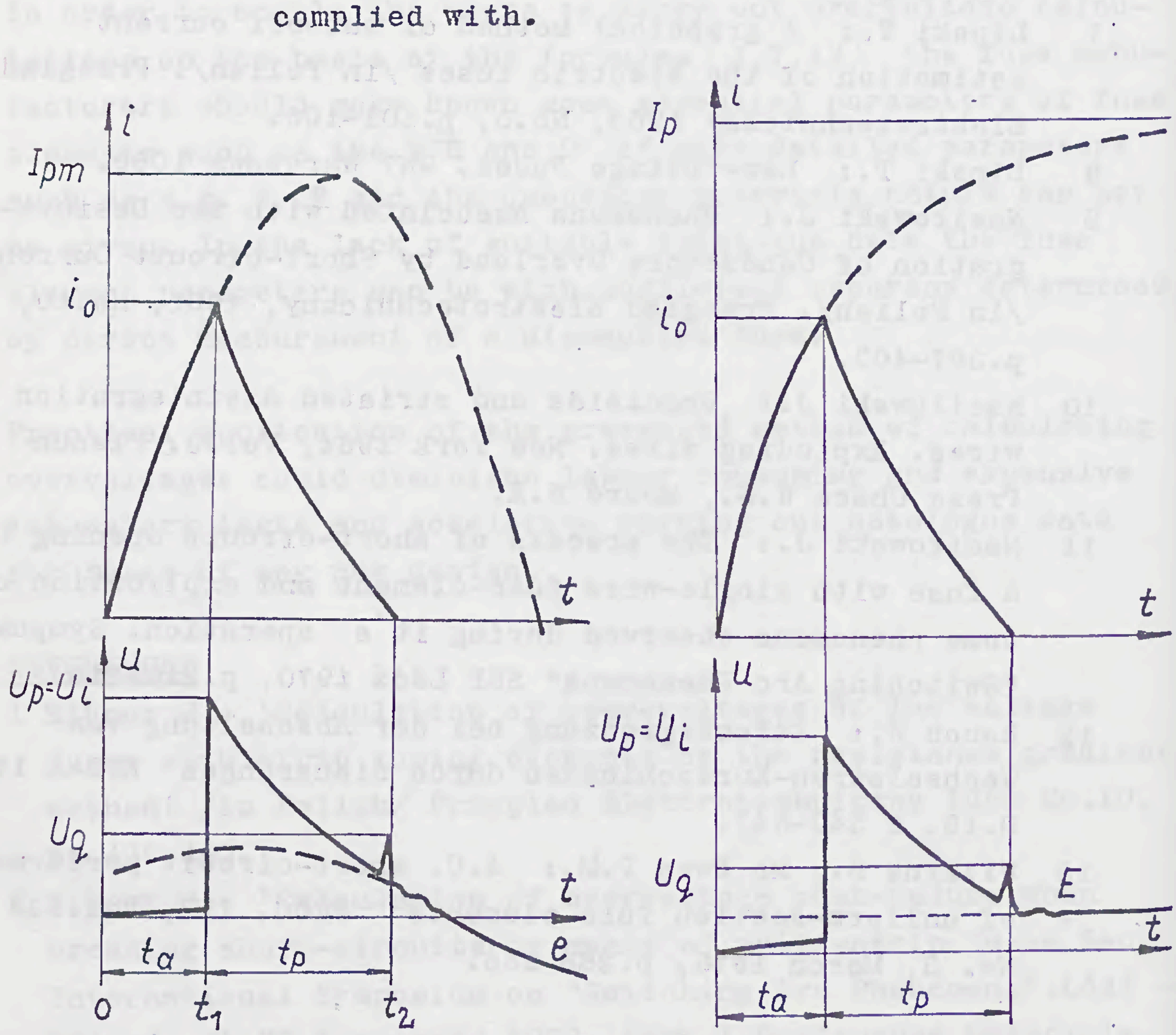

Fig.2. Simplified current and voltage course at D-type fuse operation in AC and DC circuits.

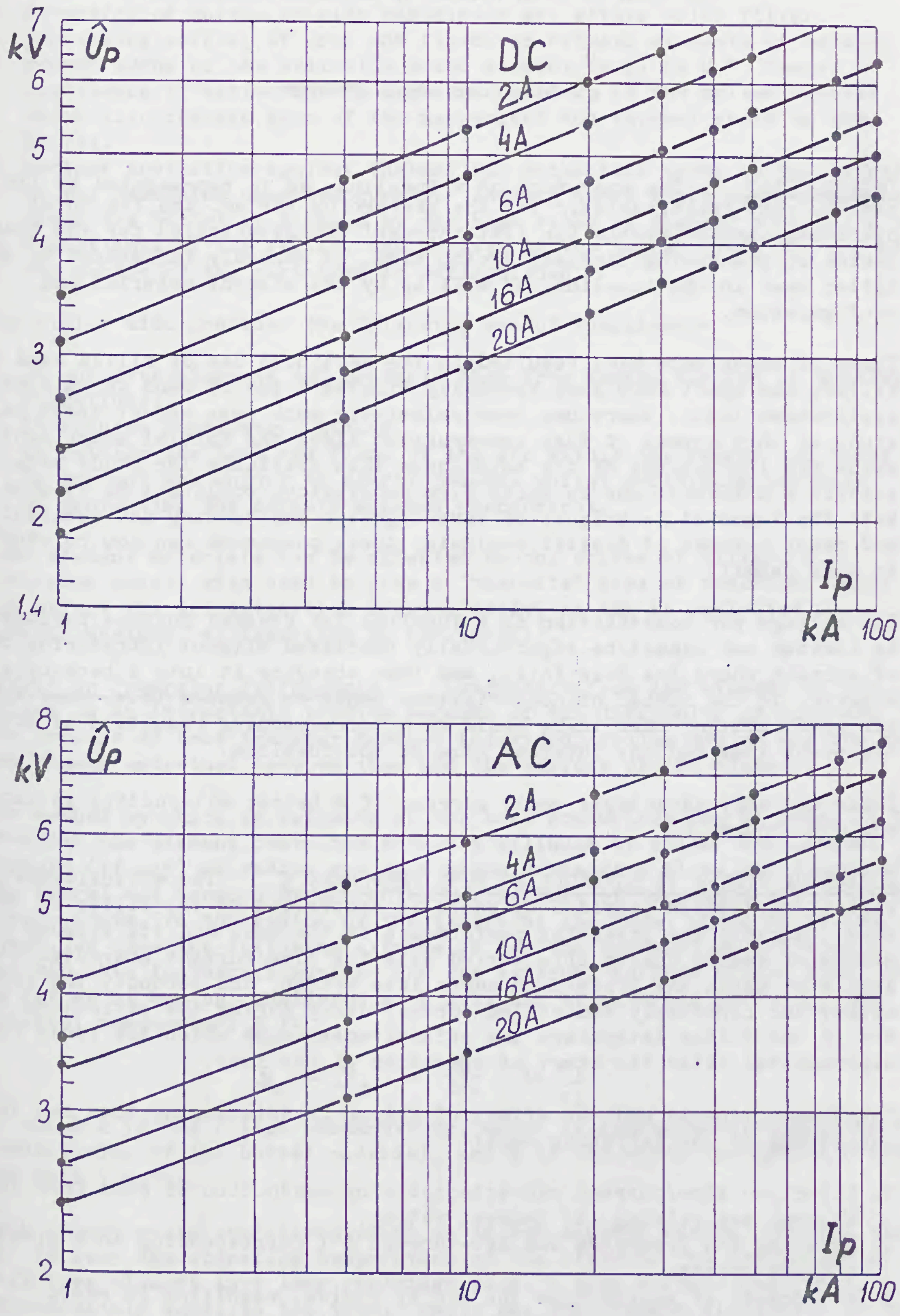

Fig.3. Fuse peak arc voltage $\hat{U}_p - I_p$ characteristic.
DC circuit, U_N = 500 V, T = 5 ms, $I_p \leqslant$ 100 kA.
AC circuit, U_N = 500 V, 50 Hz, $\cos\varphi$ = 0.1,
$I_p \leqslant$ 100 kA RMS.

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.

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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 :-

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

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:-

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

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 inclunces 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.

The Crowbar Method 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.

The Pulsed X-Ray Technique 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.

The High Speed Photography Method 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.

New Possible Techniques   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.

References:

1. K. Lerstrup, Int. Symp. Switching arc Phenomena, Lodz, 1971.
2. J. G. Leach, P. G. Newbery Proc. IEE 120, 9, Sept. 1973, 987 - 993.
3. R. Wilkins, P. M. McEwan Proc. IEE 122, 3, March 1975, 289 - 292.
4. H. W. Turner, C. Turner 2nd Int. Symp. Switching arc Phenomena, Lodz, 1973.

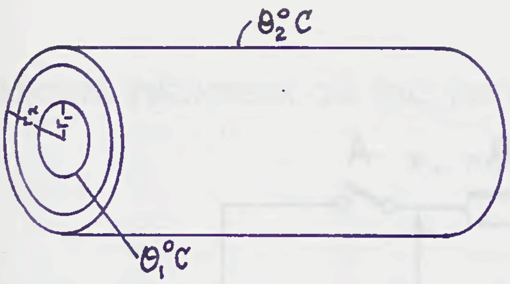


Fig 1. Conduction between Concentric Cylinders.

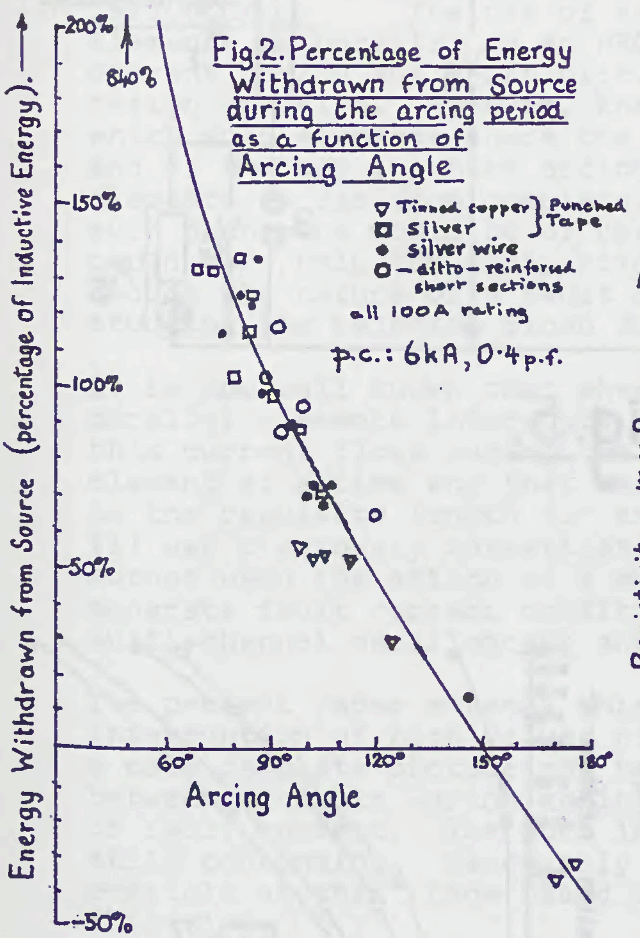


Fig.2. Percentage of Energy Withdrawn from Source during the arcing period as a function of Arcing Angle

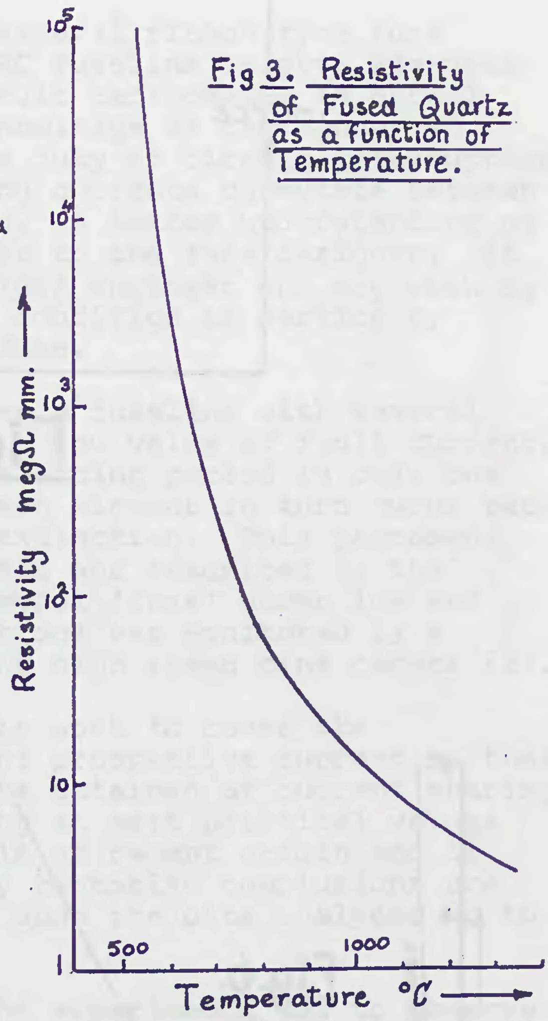


Fig 3. Resistivity of Fused Quartz as a function of Temperature.

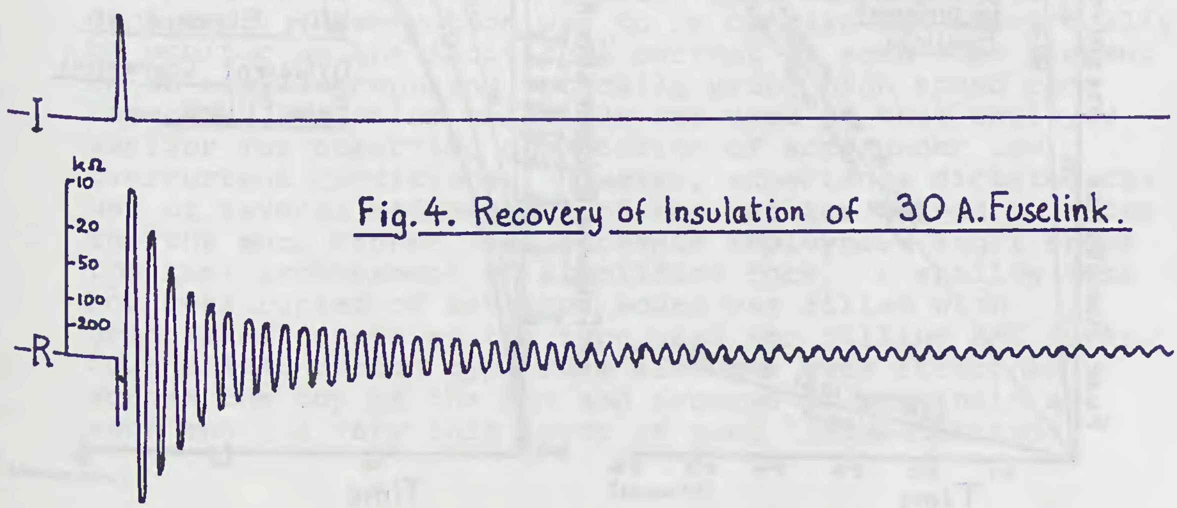


Fig. 4. Recovery of Insulation of 30 A. Fuselink.

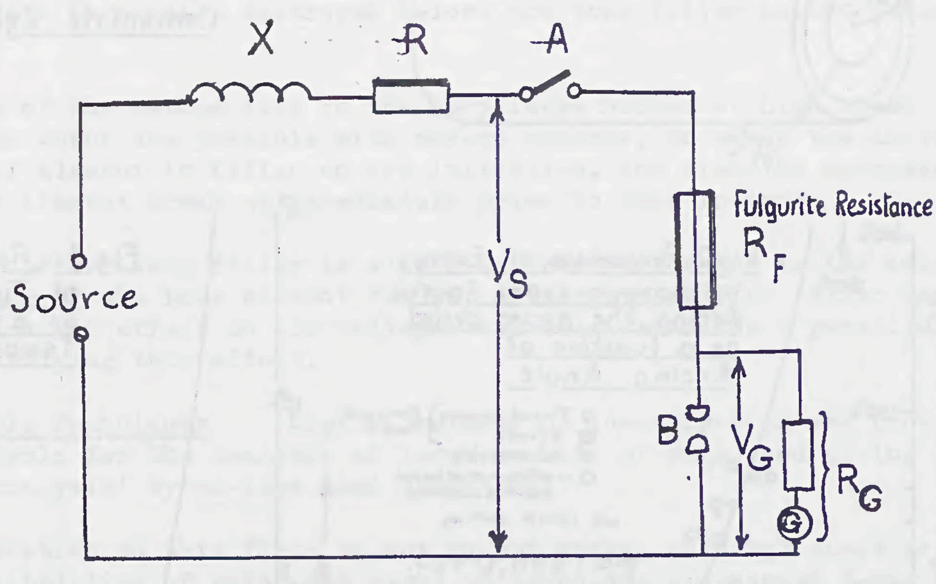


Fig. 5.

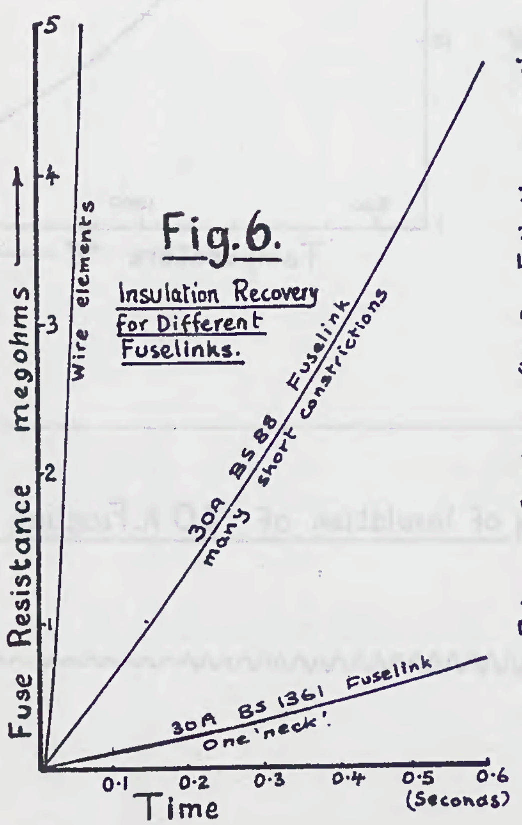


Fig. 6.
Insulation Recovery for Different Fuselinks.

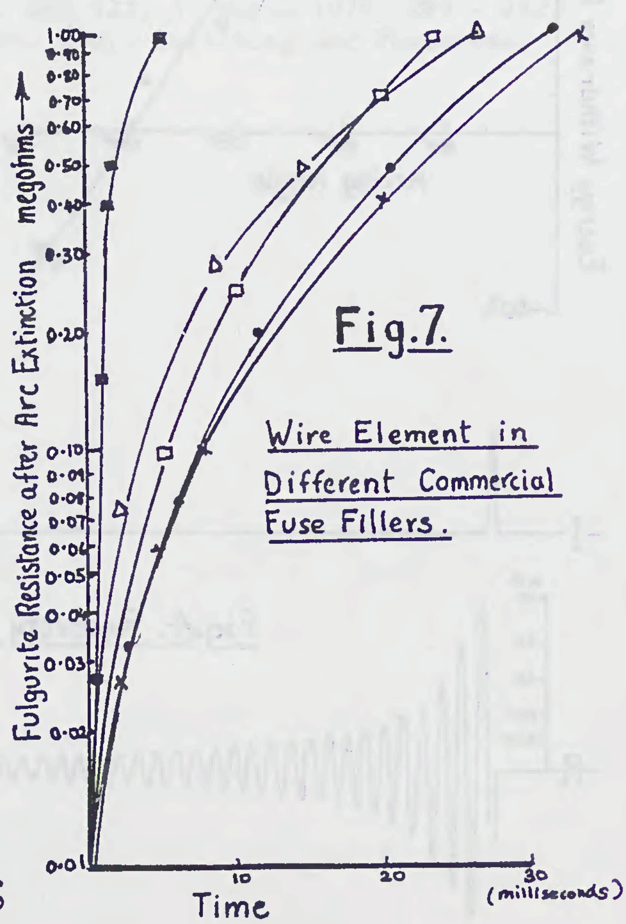


Fig. 7.
Wire Element in Different Commercial Fuse Fillers.

ARCING PHENOMENA IN HRC FUSES UNDER VARYING TEST CONDITIONS.

P. ROSEN

1.0 INTRODUCTION The use of several ribbon type fuse elements in parallel in an HRC fuselink to give adequate current rating and short circuit performance is normal design practice. However, knowledge of the manner in which such elements share the duty of circuit interruption and of the way in which arcing currents commutate between elements is far from complete. A better understanding of such phenomena would be of use to the fuse designer; it could also help the applications engineer who may wish to deduce the nature of a fault condition in service by studying the relevant blown fuse.

It is now well known that when a fuselink with several parallel elements interrupts a low value of fault current, this current flows during the arcing period in only one element at a time and that each element in turn burns back to the requisite length for extinction. This phenomena (1) was previously investigated and described by the author when the action of a model 'fuse' under low and moderate fault current conditions was monitored by a multi-channel oscillograph and high speed cine camera (2).

The present paper extends this work to cover the interruption of high values of prospective current so that a more complete picture may be obtained of current sharing between elements during arcing at most practical values of fault current. The work is of recent origin and is still continuing. Hence only tentative conclusions are possible at this stage based upon the data analysed up to this time.

2.0 TEST METHOD The aim of the experiments was to observe the pattern of arcing in a model fuse at varying current densities. Observation was to be carried out electrically by monitoring the individual current in each fuse element on an oscillograph and optically using high speed cine cameras. A similar technique was used to that employed earlier for observing commutation of arcs under low overcurrent conditions. However, experience dictated the use of several refinements of the earlier method to cater for the much higher test currents employed. Fig.1 shows the test arrangement in simplified form. A shallow test box constructed of asbestos board was filled with granulated quartz of the type used for filling HRC fuses. Four silver ribbon type fuse elements were stretched across the top of the box and secured to terminals at each end. A very thin layer of sand (later omitted) was sprinkled on top of the elements and a sheet of glass laid on top of the sand. Neoprene gaskets provided gas tight seals around the edges of the box and a thick perspex 'lid' was clamped down over the glass plate and rubber seals to complete the assembly. A filler hole at one end of the box allowed additional quartz to be introduced and compacted by vibration after assembly was complete. The box was mounted horizontally and the cameras viewed its transparent top from a distance of 2-3 metres via a mirror mounted at an angle of 45° above the box.

A schematic diagram of the test circuit is given in Fig.2 Limitation of laboratory supply facilities dictated the choice of 700 volts r.m.s. for the test voltage. The prospective test current was set to the required value by means of adjustable series resistance and reactance, with minimum values of 'R' being used so as to obtain the lowest values of power factor for each setting.

In general, power factors of less than 0.3 were obtained. The maximum available prospective current was 3200 amps. It was not possible to control the switching with respect to the point on voltage wave hence several shots with random switching were necessary at each current setting to give an adequate picture of events. A six channel electro-magnetic oscillograph provided individual current traces from each of the four fuse elements and also provided a record of total fuse current and arc voltage.

The fuse elements in the test box were of a type representative of modern practice. The emphasis of the investigations being directed towards high voltage fuse operation (since the earlier work had concentrated on the low overcurrent problems of h.v.fuses), therefore scaled down versions of a type in present use for fuses rated at 3.3kv were employed. The elements were 6.35 mm wide by 0.019 mm thick and had seven series reduced sections of 2.9×10^{-4} cm^2. The reduced sections were spaced widely apart (25cm) to obviate any chance of the arcs merging during operation. The four elements connected in parallel in the fuse test box were deemed to have a nominal current rating of 35 amps (by inference from the current which such elements would carry when built into a real fuse).

3.0 <u>CAMERA EQUIPMENT</u> In the earlier low overcurrent tests a cine camera running at 4000 frames per second gave an adequate record of the arcing commutation which took place during the comparatively long (10-500 milliseconds) arcing periods involved. The present tests at higher prospective currents required much greater camera speeds in order to record the extremely rapid variations in the initial pattern of arc build up. A cine camera running at 9000 frames per second was used for all the tests to give a relatively crude picture of the complete arcing period. This was supplemented for later tests by a cine camera run in 'streak mode'. In this camera the film was run continuously without an intermittent motion at a speed of 55 metres/second. The streak mode camera was placed at an angle to the array of fuse elements in the test box so that each of the 28 individual arcs at the element reduced sections appeared as a separate streak of light on the film (see Fig.4). Careful analysis of the dimensions and positions of each of these streaks enabled a complete picture to be built up of the growth and decay of the associated arc in the fuse element itself. An electronic camera was also used to supplement the information for certain tests. This gave a matrix of frames on polaroid film of a selected portion of the arcing period, the interval between frames being 1 microsecond. The cine cameras were fitted with a triggering device which closed the supply to the test fuse when the cameras reached the required speed. The electronic camera was itself triggered by a photo electric cell which caused scanning to commence once the first arc appeared.

4.0 TEST PROCEDURE In previous work, commutation of arcs between fuse elements had been explored over the range 1.7 to 6.0 times fuse rated current corresponding to pre-arcing reduced section current densities of 0.525 to 1.9kA/mm^2 per element. In the present work the range 12-90 times rated current was explored corresponding to element reduced section current densities of 3.75 to 26.7 kA/mm^2. At each current setting (see table 1) several tests were carried out to cover different switching angles and to ensure that adequate cine and oscillographic records were obtained. After each test the elements and fulgurite adhering to the glass cover plate were removed and photographed for later analysis (Fig.3).

During the course of the tests it was found possible to mount the elements directly on the underside of the glass cover omitting the thin covering layer of sand. This gave improved cine records without noticeably affecting the initial pattern of arc build up (although it is likely that the glass did have some effect on the later phases of the arcing period).

Table 1 - SUMMARY OF TEST SCHEDULE

No. of Tests.	Prospective Current	Pre-Arcing Current Density	Camera Records
6	450A	3.75kA/mm^2	A
6	600A	5.0 "	A
33	750A	6.25 "	A + B
15	3200A	26.7 "	A + B + C

A: Conventional cine camera run at 9000 F.P.S.

B: Streak mode camera run at 55 metres/second

C: Electronic camera at 10^6 frames second.

5.0 TEST DATA ANALYSIS

5.1 Tests at 450A These tests simulated a fault current of about 12.5 times the fuse current rating. From previous work it was known that, at up to 6 times rated current, the total arcing current was carried by each parallel element in turn, with no discernable overlap as the current switched from one element to another until all arc were extinguished.

In the present tests at 12.5 times rated current there was evidence of a transitional phase (Figs. 6c and 7). In a typical case arcing commenced at some reduced sections in two elements simultaneously. The current then switched consecutively to a third element and finally to the fourth element which cleared the circuit. The last element to clear, arced for a much greater proportion of the total arcing time than the others and so was responsible for the major part of the arc energy dissipated. In most tests two and sometimes even three elements were arcing simultaneously during some portions of the arcing period. The total period during which arc build up and commutation took place was of the order of 3 milliseconds, hence the 9000 F.P.S. cine camera was able to provide an adequate record of events unaided.

5.2 Tests at 600A These tests simulated a fault current of about 17 times fuse rated current. From Figs. 6d and 7 it will be seen that arcing took place in all elements more or less simultaneously. However, there was great disparity in the degree of arcing in the different elements and there were corresponding disparities in the sharing of current between elements at any given instant. This appeared in some measure due to the unequal rate of build up of series arcs in each element; once all 28 arcs had ignited, current sharing tended to equalise and all elements cleared simultaneously at the natural current zero.

5.3 Tests at 750A These tests simulated a fault current of about 21 times rated current. The current density of 6.25kA/mm^2 was a close approximation to that required for the maximum arc energy test (test duty 2) in most recognised fuse test specifications and on those tests where the closing angle happened to be between 0^o and 20^o after voltage zero a close agreement with the requirements of TD2 in IEC 282-1 was obtained.

The conventional cine camera was no longer fast enough to record the initial arc build up and so the streak mode camera was employed as a useful adjunct (Fig.5). The initial portion of each streak mode film was analysed to produce an arcing pattern diagram (Fig.6) and this in conjunction with the conventional film provided a complete record of the arcing period.

As is seen in Fig.6a and 7, arcing commenced in all four elements practically simultaneously. There was a rapid build up of the number of series arcs in all elements with little evidence of unequal current sharing. All 28 arcs were initiated in a period of about 140 microseconds from which point in time all four elements burned back equally to extinguish simultaneously at the natural current zero.

5.4 Tests at 3200A These tests simulated a fault current of 90 times rated current. From Figs 6b and 7 it is seen that although operation was generally similar to the 750A case the arc build-up period was much reduced - typically only about 80 microseconds. Burn back and arc extinction were correspondingly more rapid with the fuse current falling to zero well before the natural zero pause. It will also be noted that, as expected, the fuse exhibited 'cut-off' the peak current being well below the prospective value.

Some attempt was made to expand a portion of the initial arcing period to allow closer examination. The electronic camera used for this purpose provided 12 frames spaced 1 microsecond apart (unfortunately not reproducible here). They confirmed an impression gained from the streak mode films that individual arcs fluctuated rapidly in intensity (at least optically) over periods as short as 5-10 microseconds and that these fluctuations were completely random and unrelated to any given current path. The fluctuations in arc intensity could not be related to any discernible variations in the oscillographic traces.

5.5 Effect of Closing Angle It could be inferred from a study of the test data that the pattern of arcing is more closely related to the pre-arcing time than to the allied function of current density. Where the pre-arcing time was greatly extended due to closing the circuit onto a minor loop of current, considerable differences in arcing patterns were sometimes apparent; the general effect being to produce the kind of unstable element-to-element arcing pattern normally peculiar to tests at low current densities. Insufficient data has so far been obtained to confirm or quantify this aspect of the investigation. However, Table 2 summarises the pattern which appears to emerge from the tests done so far. The table suggests that arcing will be consecutive from element to element for pre-arcing times greater than 1000 microseconds and that it will generally be concurrent in all elements at once for pre-arcing times less than 500 microseconds.

Table 2 Pre-arcing Time	Tests giving 'Consecutive' Arcing	Tests giving 'Concurrent' Arcing
1 millisecond or more	15	-
500-1000 microseconds	3	8
Less than 500 microseconds	-	22

(Remainder of tests not relevant to above table).

6.0 CONCLUSIONS

6.1 At fault currents between 6 and 12 times fuse rated current a fuse of the type tested will operate in a mixture of consecutive (arcs in one element at a time) and concurrent (arcs in several elements at the same time) modes. The last element to clear will usually do so on its own and will have much heavier fulgurites than the others.

At fault currents in the region 12-20 times rated current, arcing will be concurrent but still very uneven as between one element and another. At fault currents above 20 times rated current, arcing will be wholly concurrent and will be similar in severity for all parallel elements. The period during which arcs are formed at each reduced section of the elements is very short compared with the total arcing time. Typically 140 microseconds at 21 times rated current falling to 80 microseconds at 90 times rated current.

6.2 Pre-arcing time appears to be a prime factor in determining arcing patterns. The longer the pre-arcing time the greater the likelihood of element-to-element commutative type arcing. Hence for a given level of fault current the arcing pattern of the fuse may vary depending upon the instant of closing the circuit with respect to voltage zero.

6.3 While it is recognised that the results of this investigation can only apply, strictly, to the element type and test conditions specified it is thought likely that the results are valid in practice. The extent to which this is the case will be investigated in future work.

ACKNOWLEDGEMENT AND REFERENCES

(1) Mikelucky H.W. I.E.E.E. Transactions Vol. PAS-84 No.12.

(2) Rosen P. Symposium on Switching Arc Phenomena 1973, Lodz, Poland.

Acknowledgements: Electricity Research Council.
GEC English Electric Co., Ltd.,

FUSE ELEMENT TESTING BOX

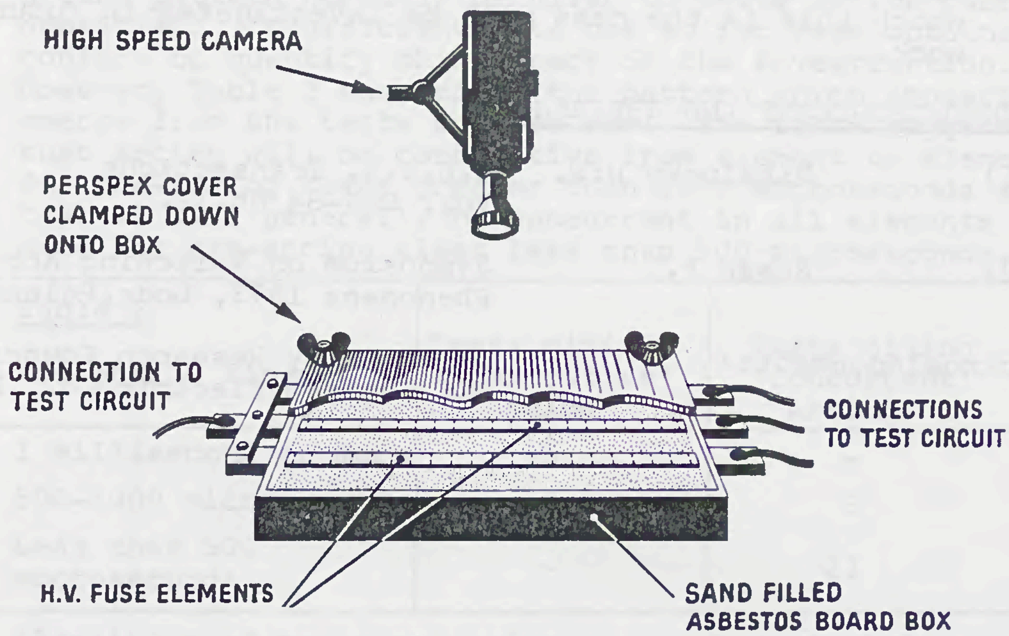


FIG.1.

BASIC TEST CIRCUIT

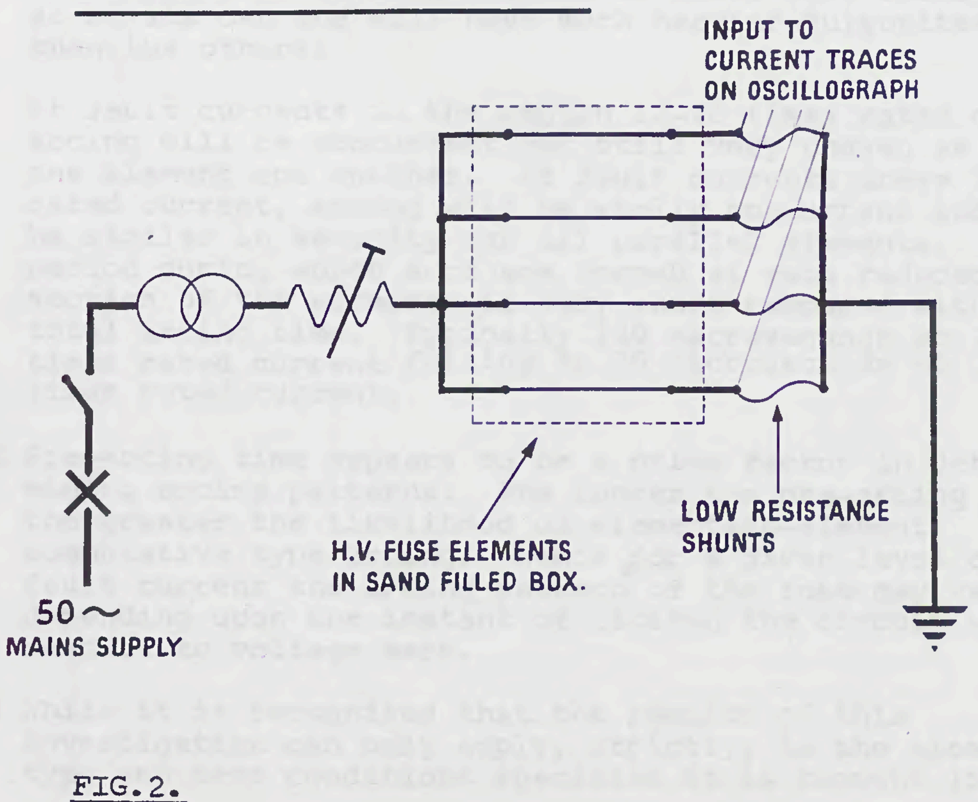


FIG.2.

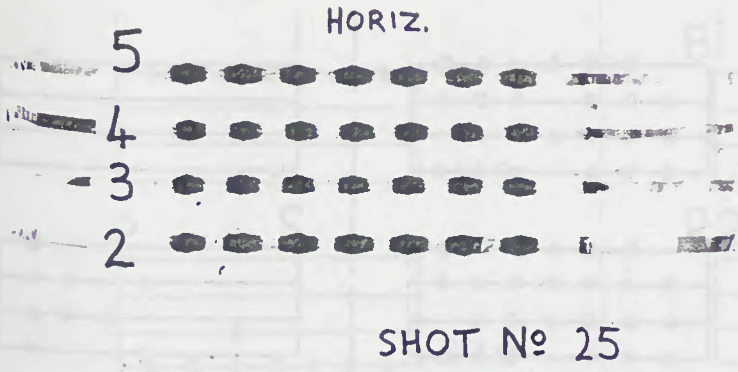


FIG. 3.

Set of elements after 750A test showing fulgurites.

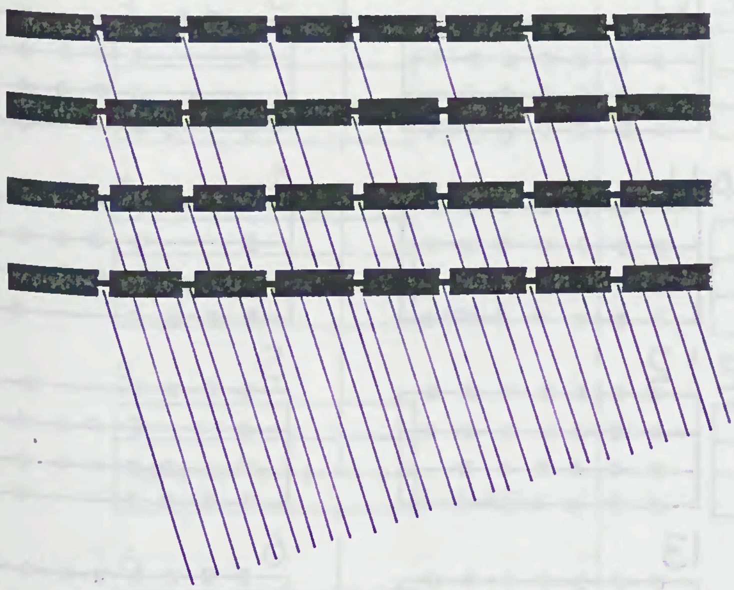


FIG. 4.

Diagram showing how streak mode camera scans elements to pick up individual arcs.

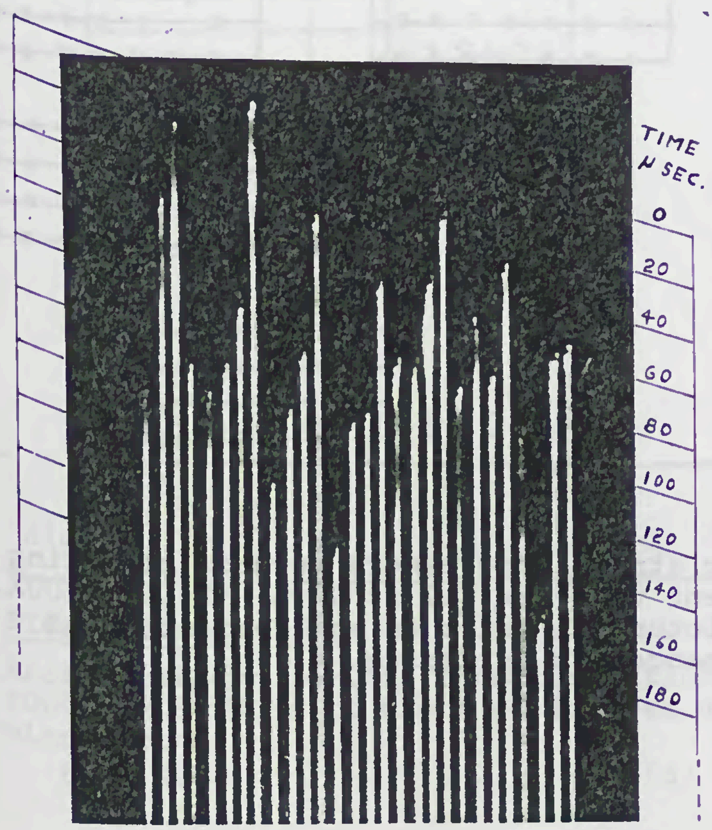


FIG. 5.

First 200 microseconds of streak mode film from fuse test at 750A.

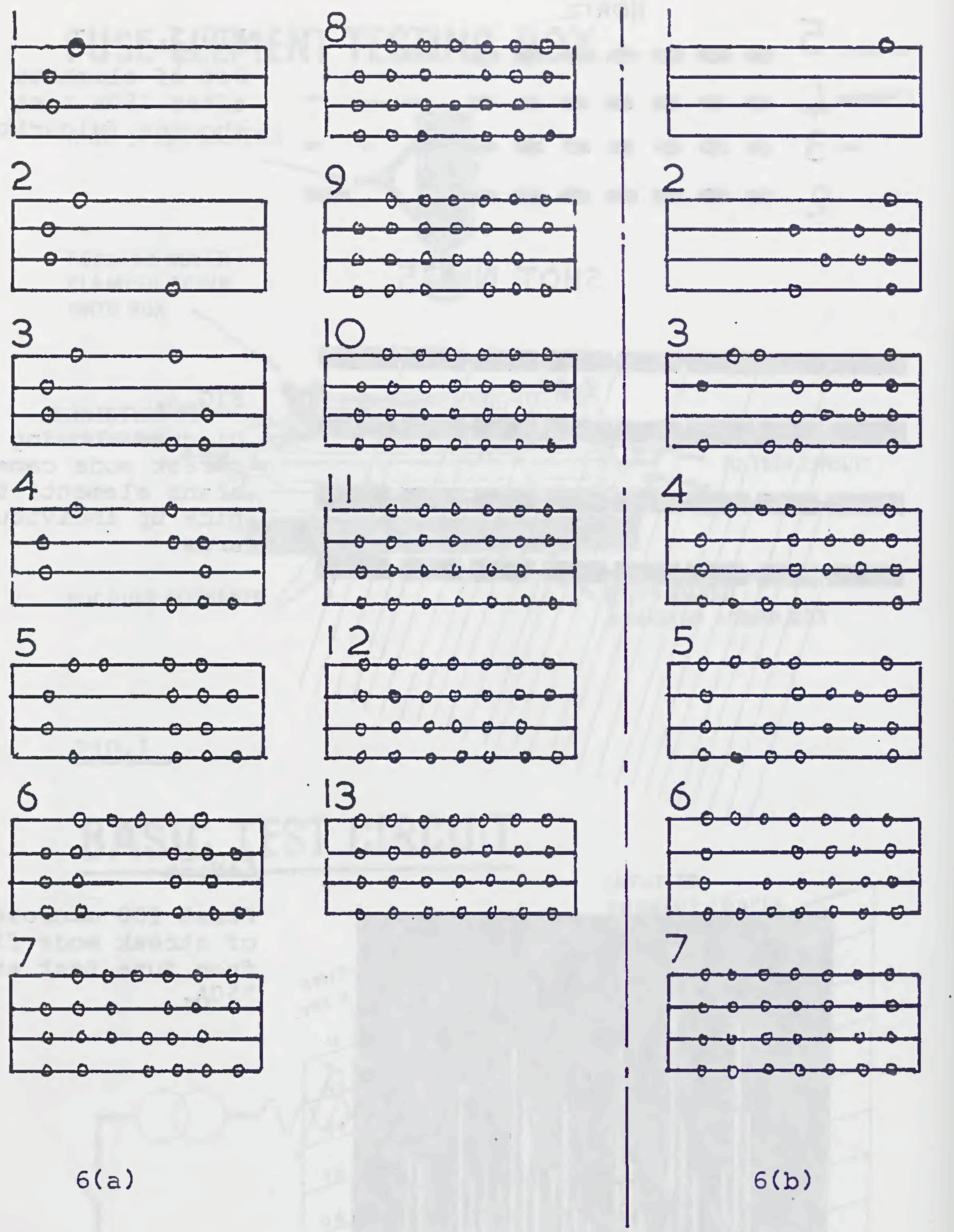
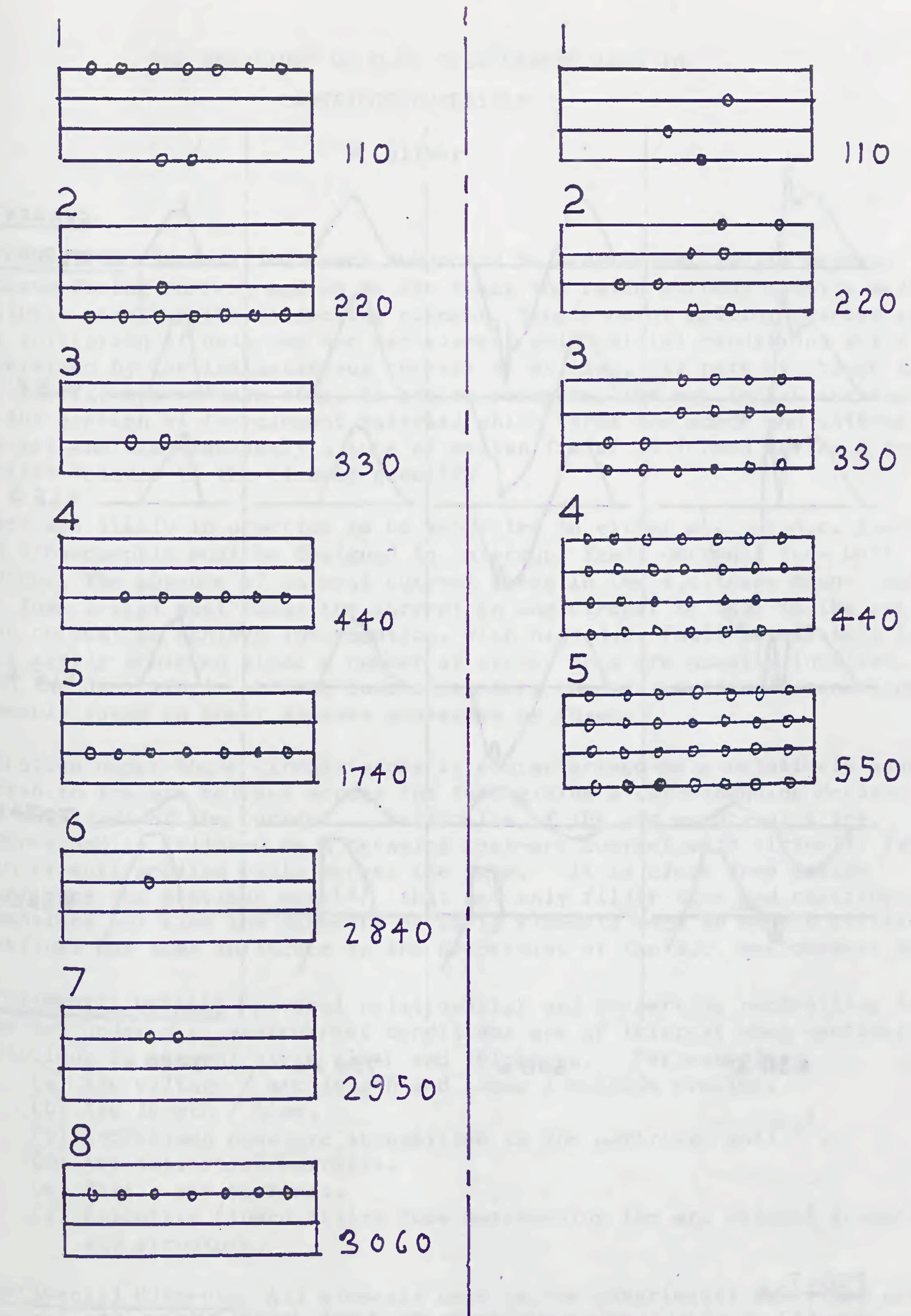


FIG.6

Reconstruction from streak mode camera records of arcing pattern in 4 element test box (a) at 750A, (b) at 3200A. In each case the picture is built up at 10 microsecond intervals from commencement of arcing.



6(c) 6(d)

FIG.6. (Continued)

Arcing pattern derived from conventional cine film run at 9000 F.P.S. No's to right of figures denote elapsed time in microseconds.

6(c) 450A 6(d) 600A

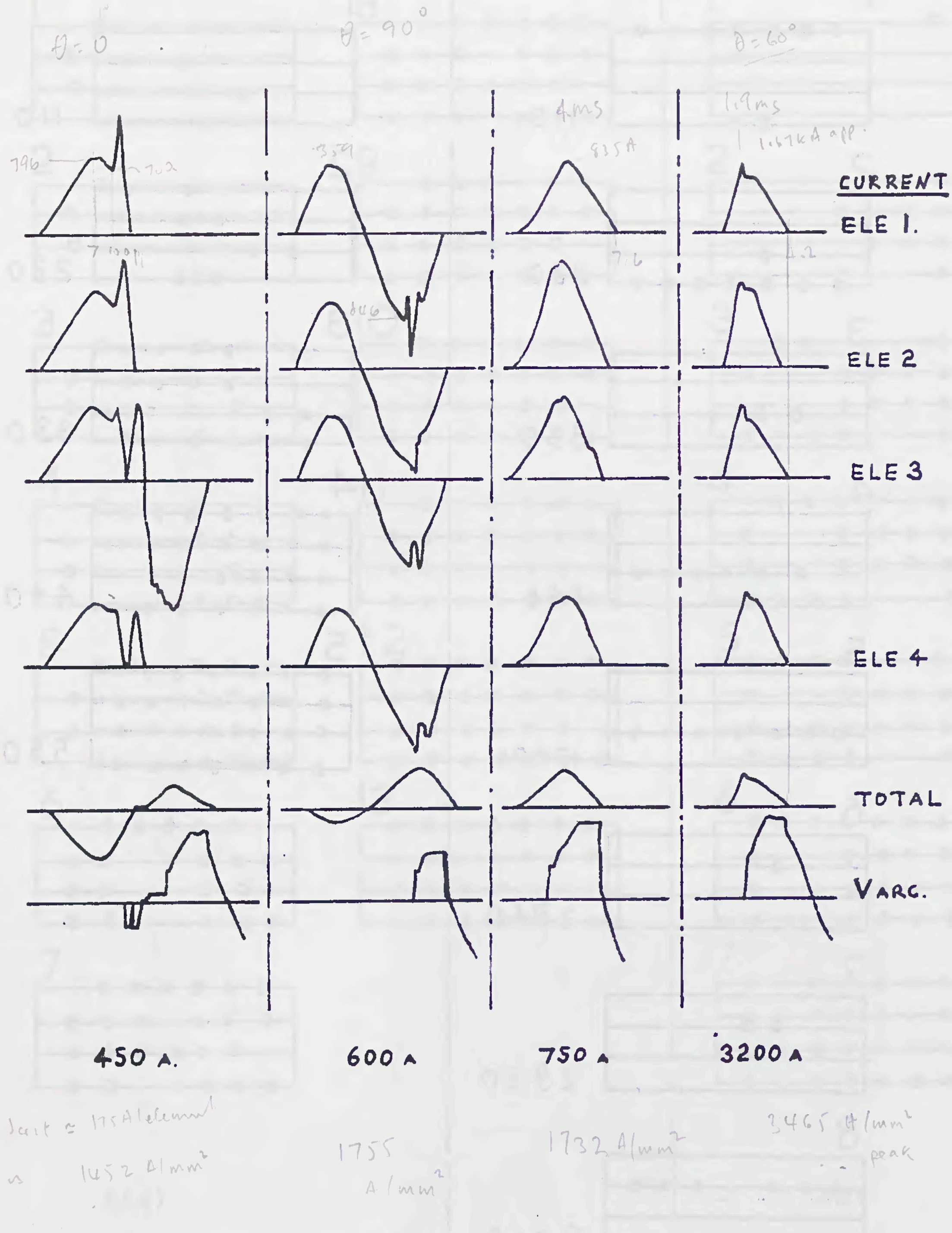


FIG.7..

Oscillographic records from typical test shots at prospective current levels in the range 450-3200 Amps.

THE BEHAVIOUR OF D.C. OVERCURRENT ARCS IN CARTRIDGE FUSELINKS

R. Oliver

INTRODUCTION Sand-filled fuses subjected to overcurrent faults between minimum fusing current and up to ten times the rated current usually melt at a single point on the conducting element. Single point melting results in the initiation of only one arc per element with initial conditions which are determined by the instantaneous current at melting, its rate of change and the initial arc voltage step. As arcing proceeds, the arc length increases by the erosion of the element material which forms the anode and cathode of the arc and simultaneously a tube of molten filler is formed having a cross-section related to the element geometry.

Fuses are likely in practice to be subjected to either a.c. or d.c. faults and consequently must be designed to interrupt fault currents from both sources. The absence of natural current zeros in the d.c. case means that the fuse arc(s) must cause the current in the circuit to fall to the extinction current to achieve interruption. With high d.c. fault levels this is more easily achieved since a number of series arcs are usually involved. With the d.c. single arc the fuse encounters the most difficult condition commonly found in power systems protected by fuses.

Operation under these circumstances is characterised by a relatively slow growth in the arc voltage across the fuse giving a corresponding decline in the magnitude of the current. Extinction of the arc occurs at a few amperes and is followed by a decaying post-arc current with virtually full open circuit applied volts across the fuse. It is clear from design experience and previous work[1] that not only filler type and cartridge dimensions but also the geometry of strip elements used in modern cartridge fuselinks has some influence on the properties of the d.c. overcurrent arc.

EXPERIMENTAL DETAILS Several relationships and properties controlling the fuse arc under d.c. overcurrent conditions are of interest when considering variations in element strip width and thickness. For example:

(a) Arc voltage / arc length and anode / cathode erosion.
(b) Arc length / time.
(c) Arc column pressure transmitted to the cartridge wall[2].
(d) Arc extinction currents.
(e) Post - arc currents.
(f) Fulgurite (fused filler tube surrounding the arc column) formation and structure.

Experimental Elements All elements used in the experiments described are of commercially available (99.97% purity) silver having a single reduced section at the mid-point as shown in Fig.1. The nominal dimensions for the range of strip elements used include strip widths up to 0.8128cm and silver thicknesses between 2.54×10^{-3} and 2.54×10^{-2}cm.

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Experimental Cartridge Fuse Standard cartridge fuselinks in commercial use often consist of a cylindrical ceramic tube or body containing element and filler sealed by end caps having an interference fit onto the outer diameter of the tube. This construction is not convenient for experimental work where high accuracy in the positioning of a single element along the axis of the cartridge is required and a large number of repeatable fuse operations are to be undertaken. In addition, the recovery of the delicate fulgurites after test with a minimum of disturbance during the dismantling procedure has to be arranged if an examination of length and structure is to be easily performed.

The design of the fuselink used is shown in Fig.2. All experimental work being done with the fuse mounted in the vertical position and filled with 99.7% silica sand having a mean grain size of 0.488 mm. compacted by a standard technique.

Power Circuit Fusing currents are obtained by the application of a 450 v nominal d.c. source to the R - L circuit shown in Fig. 3.

When required, a shorting thyristor is connected across the fuse and by presetting the gate circuit to provide the desired arc voltage trigger level the arc is extinguished before natural interruption by the fuse.

Circuit resistance and inductance are a resistor bank and fixed air-cored coil of 6.34 mH respectively, the latter remaining unchanged throughout the experimental programme.

Voltage and Current Measurements The fuse voltage is recorded throughout the pre-arcing, arcing and post-arc (recovery) periods. Generally this trace shows a very low deflection during the pre-arcing period, an increasing voltage with initial step during arcing and a steady recovery voltage usually exhibiting a small post-arc transient oscillation.

Current measurements are derived from two sources, the first by recording the voltage across a calibrated non-inductive shunt giving a trace deflection proportional to the current. The second method results from the need for good resolution of currents in the range from fusing currents of several hundred amperes down to extinction values of a few amperes and decaying post-arc currents in the order of milliamperes. The technique investigated and adopted for this purpose is the measurement of the forward volt-drop of three parallel diodes carrying the fuse current. Forward volt-drop values are determined for currents from 0.1 mA to 500 A and the calibration curve established by curve-fitting an 11th order polynomial having minimum variance.

Measurement of Arc Length To determine the final or interrupted arc lengths the fulgurites are removed and measured using a vernier microscope. All measurements being taken with reference to a datum line outside the arcing region and an accurately known distance from the initiation point of the arc. This allows total arc length and anode / cathode burnback values to be determined.

EXPERIMENTAL RESULTS Continuous oscillographic records of each fuse operation show the melting, arcing and post-arc currents, fuse voltage and cartridge wall pressure. (See Fig. 4). These traces, together with fulgurite length measurements provide the data source for the following results.

Arc Length at Natural Extinction Arc lengths at natural extinction show changes with both width and thickness of the silver strip elements but no significant effects are observed due to changes in initial fusing current.

Considering first the strip thickness it is apparent from Figs. 5 and 6 that reduction of this parameter decreases the final arc length significantly. Most of this decrease is observed in the lower half of the thickness range. Less scatter is found with the thinner sections despite the shorter arc lengths where measurement errors would tend to be more significant.

Strip width effect is demonstrated by again comparing the Figures 5, 6 and 7 where the three widths studies, namely 0.1524 cm, 0.3048 cm and 0.8128 cm show decreasing arc lengths respectively, with the exception of the thinnest material. Final arc lengths with the latter remain relatively constant at 3.5cm. for the three strip widths. One interesting anomaly is that shown by the widest strip where a maximum arc length occurs in the middle of the thickness range.

The curves discussed above are derived from results at a wide range of fusing currents, there being no consistent differences in the arc lengths of fuses subjected to the range of overcurrents being studied. Since the arcs are initiated at a predetermined point on the element it is possible to measure the extension of the arc in both anode and cathode directions. Figure 8 shows that differences in the anode and cathode burnback can occur with particular strip geometries. With the thinnest strip the cathode extension is approximately 1.6 times that for the anode and has a similar ratio for the three widths examined. With increasing thickness this effect becomes less apparent and for 1.3716×10^{-2}cm. and greater the anode and cathode burnback are equal. With arcs extinguished prematurely by use of the shorting thyristor at various stages in their growth, the anode burnback is found to be greater even before the arc voltage has reached 100 v for conditions where anode / cathode differences are observed in final length results. Where final arc lengths are equally attributable to cathode and anode burnback the same situation is found to prevail throughout the arcing period.

<u>Arc Column Electric Field</u> When the shorting thyristor system is used the average axial electric field between electrodes may be determined as the instantaneous voltage per cm. of arc length at the time of interruption. Field values determined in this way show a considerable variance for apparently similar experimental conditions. Changes in the average field as a function of strip width are not observed but the field is seen to increase as the thickness is reduced as shown in Figure 9.

When the arc is initiated in a fuse it is subject to different fusing currents and during arcing the current falls to low extinction currents. Possible variations in the average field with current were studied for one element form with two initial currents. Interruption of the arc at a number of arc voltage levels with both initial currents yields field-instantaneous current data shown in Figure 10. Experimental values are plotted on common axes for both initial currents and reveal that when the arc current falls to approximately 50 amperes further reduction in current is associated with a decline in axial field. This decline continues to fields corresponding to the band of recovery voltage / final arc length ratios found in fuses not subjected to premature extinction.

<u>Arc Extinction Current</u> Measurements of arc extinction currents taken at the commencement of the final voltage transient show a marked consistency

for all element geometry and fusing current conditions. No significant trends are observed, the arc extinction currents being in the range 1.5 to 7.2 amperes with a mean for all arcs of 3.45 amperes.

Post-arc Current The current flowing through the fuse immediately after extinction of the arc is carried by the fulgurite tube formation remaining These currents are in the range 10^{-3} to 1.0 amperes and increase with the cross-sectional area of the silver strip in the fuse.

Recovery voltage data corresponding to the instantaneous post-arc current allows the fuse resistance (R_f) to be determined. R_f is a function of fulgurite cross-section, length (y) and temperature and since the final length is known it follows that assuming most of the current is conducted by the fused silica :

$$R_f = \frac{U\,y}{A}$$

$$\text{hence} \quad \frac{y}{R_f} = \frac{A}{U}$$

where A, the cross-sectional area of the fused silica is not uniform along the length of the fulgurite and U, the resistivity of the silica is temperature dependent. Curves showing observed values of R_f for the range of element strips studied are given in Figure 11.

FUSE VOLTAGE - CURRENT - ARC LENGTH MODEL. It has been suggested[1] that the behaviour of the fuse arc may be modelled by assuming that the mass of electrode metal eroded is directly proportional to the electrical charge passing through the arc column. One further approximation is that the average axial electric field remains constant throughout the arcing period and this leads to the following equations:

$$V_D = L\frac{di}{dt} + iR + V_a \qquad (1)$$

$$V_a = E\,l_a + k_o \qquad (2)$$

$$l_a = \frac{c}{q}\int i(t)\,dt \qquad (3)$$

where V_D = applied voltage
t = time (secs)
L = circuit inductance (henries)
R = circuit resistance (ohms)
i = instantaneous current (amperes)
V_a = arc voltage
l_a = arc length (cm.)
E = axial electric field (v cm^{-1})
k_o = initial arc voltage
c = specific 'burn off' constant(cub.cm.per coulomb)
q = cross-sectional area of fuse element (sq.cm.)

Equations (1),(2) and (3) may be combined to form:

$$L\frac{d^2i}{dt^2} + R\frac{di}{dt} + \frac{c\,E}{q}\,i = 0$$

which may be readily solved to provide an analytical solution for the current flowing in the circuit. Examples of the use of this model may be found in Figures 4 and 7 where the virtues and limitations of the charge-controlled model are illustrated by the broken-line curves.

DISCUSSION AND CONCLUSIONS Experimental results indicate that the charge-controlled model is not entirely satisfactory in describing the fuse arc under d.c. overcurrent conditions. The main cause of this is the assumption that a constant average electric field is maintained throughout the arcing period when in fact the final arc length found experimentally suggests a decline in the field as extension of the arc progresses. This decline is confirmed by the comparison of fields in the early part of the arcing period with the voltage / final arc length ratios found at extinction.

Widest strips provide the nearest approximation to the model, the narrower elements having longer final arc length than might be expected. This is despite the indications that, in the latter case, the field is the same as for wider strip of the same thickness in the early part (>50 amperes) of the arcing period.

These findings suggest that there is a general division of the arcing behaviour into two phases, the first being at a field which remains constant or decreases only by a small amount, the second being subject to a significant decrease in field resulting in longer arcs than anticipated.

Considering the reasons for this decline of the field in the second phase, it is not sufficient to suggest that the fall in current is responsible since it would be more logical to expect the reverse effect under these circumstances. If the conditions of low current, $\frac{dl_a}{dt}$ and $\frac{di}{dt}$ immediately before extinction are approximated to a quasi steady-state, then increases in the field like those observed in the static characteristics of the wall-stabilised arc might be expected. In fact small increases in the field are only evident in the last 5 milliseconds of arcing before the post-arc voltage transient.

Behaviour of the fuse arc column in both phases is likely to be controlled by radial power losses to the surrounding gas and fused silica tube. The fact that thin strip generates higher axial fields in the first phase suggests that the radial losses to a silica tube of small dimensions are greater due to the closer proximity of arc column and tube wall. The field remaining reasonably constant implies that a stable power input-radial loss balance is achieved during the first phase. If the field is maintained virtually constant in this first phase by the loss mechanism then in the second phase the transfer of energy would appear to be subject to a progressive reduction in the ability of the arc column to dissipate the input power. Changes in the thermal conductivity of the surrounding gas and reduction in arc radius are both possible reasons for the decrease in axial field in the later stages of the arc. Other work(3) with arcs in SF_6 suggests that for arcs of radius 0.5 mm. between 10 and 100 amperes a similar reduction in field is observed

Extinction of the fuse arc occurs at approximately 3 amperes with the experimental conditions studied. Transition time from extinction current to post-arc current varies with element geometry from times too short to measure with the u.v. recorder time-base to a maximum of 4 milliseconds with large cross-section strips.

Post-arc currents provide an indication of the fulgurite condition immediately after extinction of the arc by allowing the resistance of the post-arc column and hot silica tube to be determined. Resistance per unit length of the fulgurite shows an approximately inverse proportionality to both width and thickness over a substantial part of the range of values studied. This suggests that the post-arc current is conducted mainly by the fused silica and it can be observed for several seconds after extinction, the current decaying typically to less than 100 microamperes as the fulgurite cools.

General observations on the behaviour of the arc show sudden drops in arc voltage followed by a steady recovery to previous levels with amplitudes up to 60 volts. These are greatest with the widest strip and rarely seen with the narrowest. Kroemer[1] observed these changes and attributed them to the shorting of the voltage probes by element metal projected from the electrode region. Since this probability is eliminated by taking the arc voltage measurements externally, it is likely that this phenomenon is due to arc transfer across the width of the strip to points providing shorter arc-length. These gross changes are superimposed on a rising arc voltage having a second fluctuating component, which being always present, has a variable frequency typically greater than 1 kHz and amplitude of 15-20 volts. This behaviour may be attributable to smaller movements of the cathode and anode regions of the arc which occur independently of the large lateral changes in position found with wide strip electrodes.

It is clear from this work that although the charge-controlled model of the fuse arc provides a good basis for the prediction of its behaviour under d.c. overcurrent conditions it is subject to error, principally caused by the constant electric field assumption.

Decreases in the second phase of arcing seems likely to be caused by changes in the energy transfer conditions between arc column and fused silica. Increased arc lengths at extinction resulting from this are the main reason for the d.c. overcurrent fault condition being considered the most onerous for a fuse to interrupt in practice.

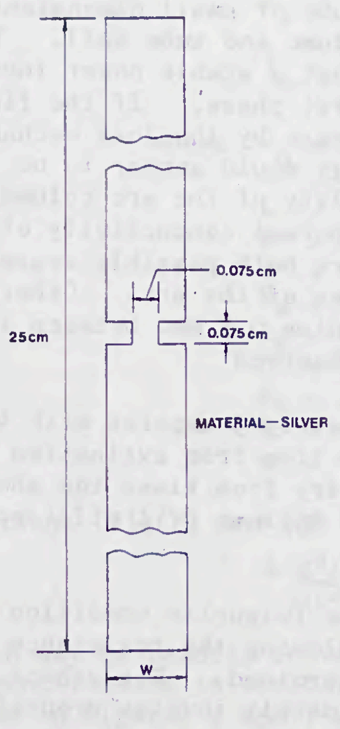

FIGURE 1

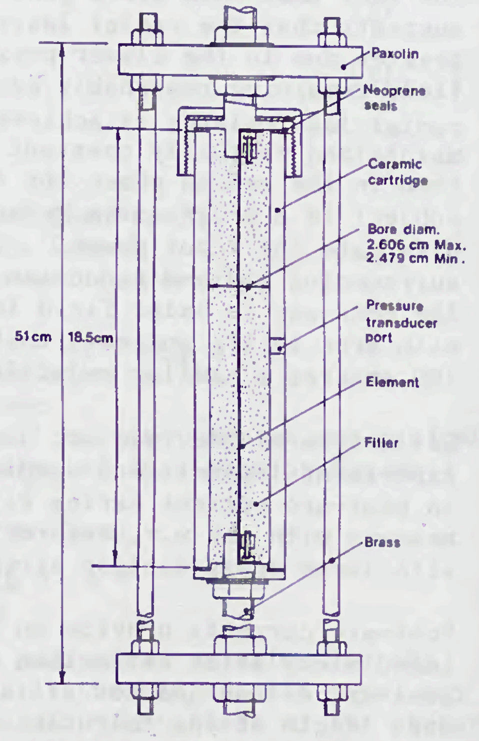

FIGURE 2

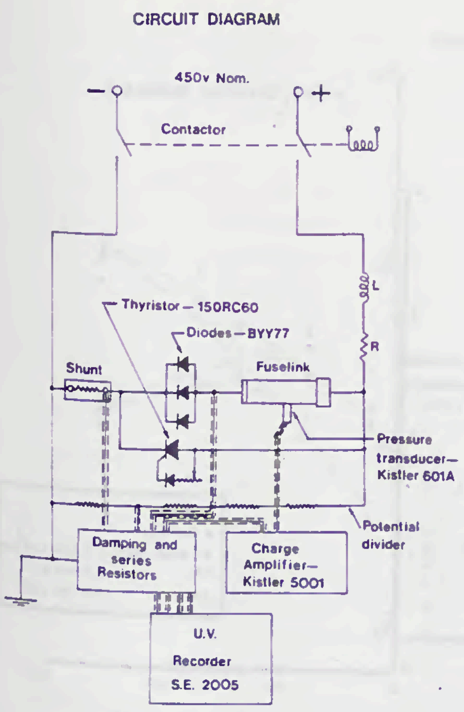

FIGURE 3

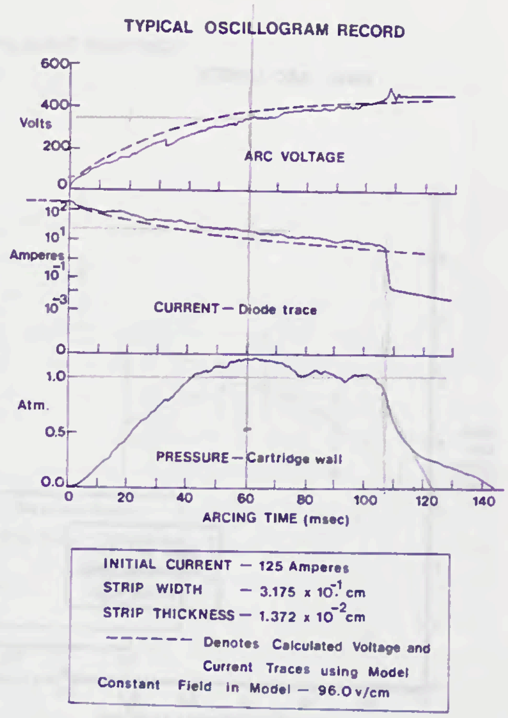

FIGURE 4

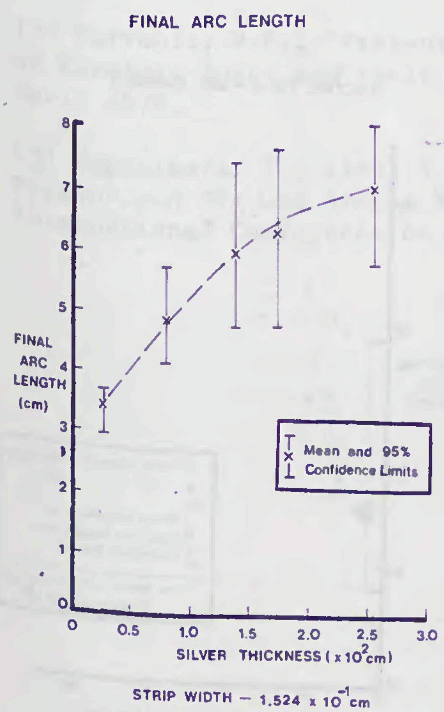

FIGURE 5

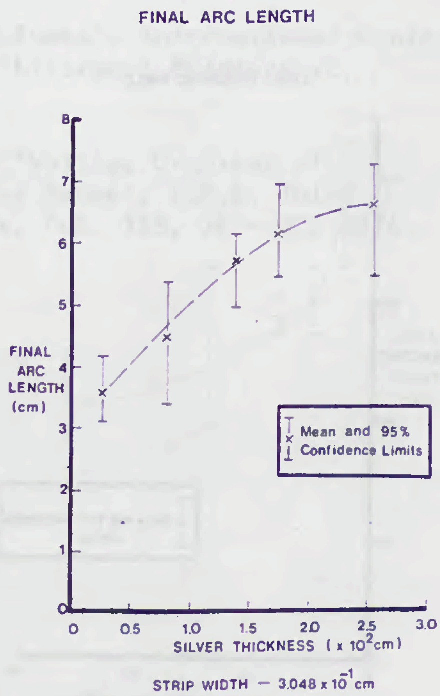

FIGURE 6

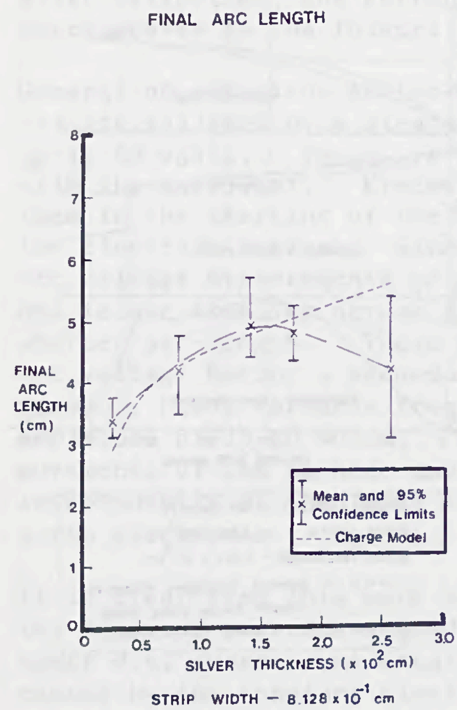

FIGURE 7

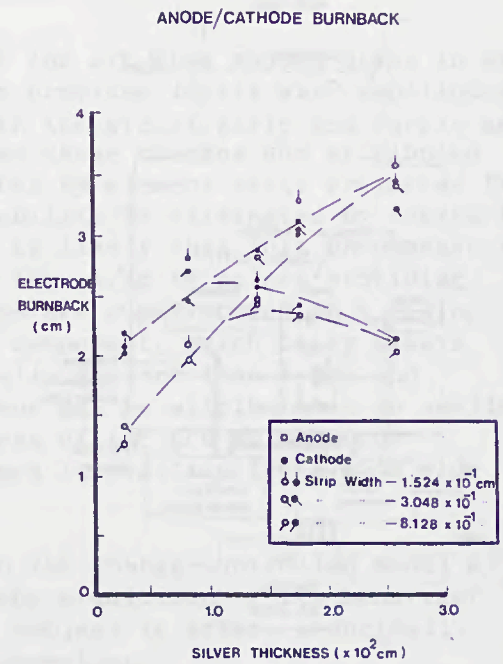

FIGURE 8

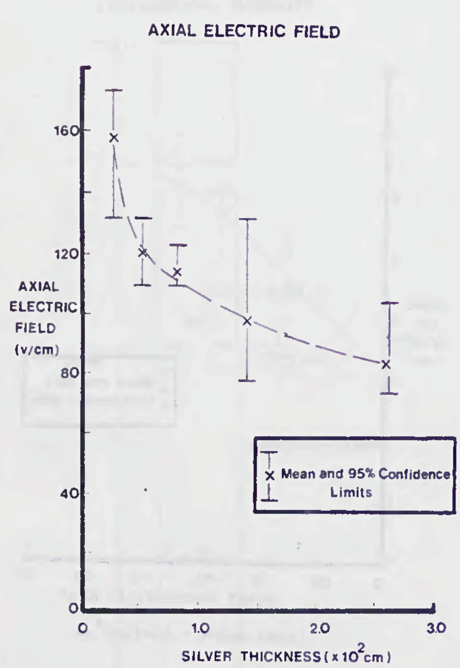

FIGURE 9

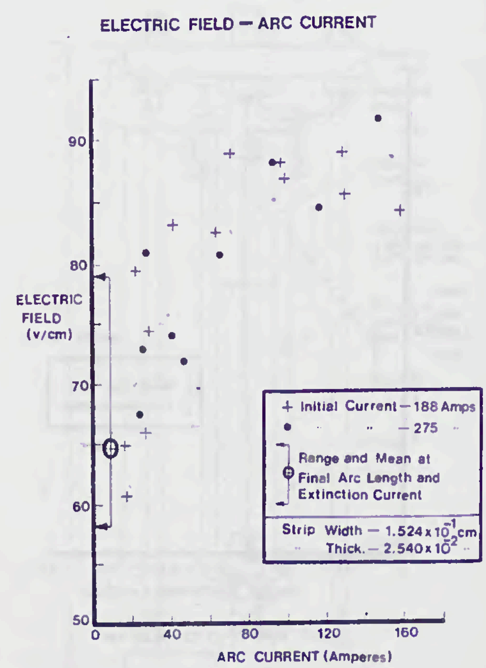

FIGURE 10

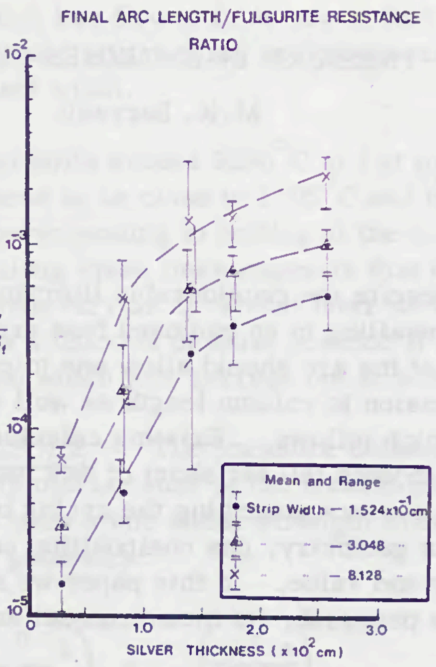

FIGURE 11

REFERENCES

(1) Kroemer, H., 'The Arc in Elements Fusing in Sand', Arch. fur Elecktrotechnik, Vol. 36, 455 - 470, 1942.

(2) Barrault, M.R., 'Pressure in Enclosed Fuses', International Conference on Electric Fuses and their Applications, Liverpool Polytechnic, April 1976.

(3) Sakakibara, T., Kito, Y., Miyachi, I., 'Voltage Gradient of Pressurised SF_6 Gas Arc in Very Low Current Range', I.E.E. Third International Conference on Gas Discharges, Pub. 118, 24 - 27, 1974.

PRESSURE IN ENCLOSED FUSES

M.R. Barrault

INTRODUCTION Despite the considerable literature on the subject, the physical conditions prevailing in an enclosed fuse arc column are still ill defined. A good understanding of the arc should allow one to predict the variations in electric field and extension in column length as well as the cut off current and dielectric recovery which follows. Existing calculations based on the charge controlled or similar models fall far short of this ideal largely because they ignore the crucial parameters governing the arcing behaviour. Among these we may list the column geometry, gas composition and pressure, wall temperature, current density and value. In this paper we shall examine some of the factors controlling the pressure, its measurement and evolution.

THE COLUMN PRESSURE The atmosphere in the arc column is derived from the evaporation of the element and also through wall ablation from the internal surface of the surrounding molten filler material (usually silica) tube. This tube is supported by the granular filler which cools the liquid silica thus increasing its viscosity and reducing its flow through the interstitial spaces. As a further consequence of this contact filler grains are melted and their mass added to that of the tube.

The bore of this tube which defines the geometry of the arc column is initially selected by the dimensions of the strip element. Thereafter the melting leads to an increase in available lumen area because of the voids present in the filler either intrinsically or through incomplete packing. For silica sand the ratio τ of the volume of fused silica to that of the original material is approximately 0.66. If a_f is the fully fused fulgurite cross section area t and w the element thickness and width then:

$$\text{Lumen area} \simeq (\tau - \lambda)\, tw + (1 - \tau)\, a_f$$

where λ is the fraction of element material entrapped in the fused section. ($\lambda \approx 1$) and we have neglected the initial set and compressibility of the surrounding material. As a first step we may assume that the quantity of molten fulgurite at a given axial station is proportional to the amount of energy dissipated there.

Combining this with a simple thermal conduction model for an arc of elongated cross section which has an electric field independent of current we find:

$$\text{Lumen area} = \sqrt{\frac{Q(1-\tau)}{\tau} Cw^2 + \text{an initial value}^2}$$

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Here Q is the charge which has flowed in an arc at that location and the initial value reflects the arc foot and initial filler set processes, C an arc material constant and w the element width.

Silica melts at 1705°C and boils around 2230°C at 1 at pressure, we may therefore expect the outer melted area to be close to 1705°C and the internal lumen wall to be at a temperature corresponding to boiling at the column pressure. A simple model developed along these lines suggests that the internal wall temperature should, at early times vary as QI whilst later on it should depend only on the current. Since QI is a function of axial position it is likely that strong axial flows are established which will average out in some way those variations.

CARTRIDGE WALL PRESSURE The pressure measured at the cartridge wall differs from that in the column because of the mechanical properties of the filler. Most sands will show some shear strength when under compression. As a result in cylindrical geometry:

$$\left(\frac{p_c}{p_a}\right)^{-1} = \left(\frac{r_a}{r_c}\right)^{\gamma - 1}$$

where γ, (< 1) is a constant for the sand p_c, r_c, p_a, r_a the cartridge and arc column pressure and radius. For spherical symmetry, likely to be approximated when the arc length is comparable with the cartridge diameter

$$\left(\frac{p_c}{p_a}\right)^{-1} = \left(\frac{r_a}{r_c}\right)^{2(\gamma - 1)}$$

In addition some pressure hysterisis will exist which could introduce a lag at the time when the column pressure is falling.

EXPERIMENTAL RESULTS: The cartridge pressure generated in the assembly described in (1) was measured using a piezoelectric transducer mounted through an aperture in the cartridge wall Figure 1.

A typical trace is illustrated Figure 2. It displays a slow rise reaching a peak well after maximum power and remains fairly constant until extinction. Examination of the fine structure shows that the pressure is able to respond quickly to both upwards or downwards changes in current indicating that hysterisis effects are not serious. Experiments using a thin plastic tube to simulate the silica tube substantiate this observation Figure 3 and shows that $\left(\frac{p_a}{p_c}\right) \simeq$ 2 to 3.

A correlation of peak measured pressure with peak dissipated power Figure 4 leads to broad support of the above considerations.

CONCLUSION: Arc column pressure measurements in the fuse situation are complicated by the transmission properties of the filler material. In particular measurements made with different cartridge diameters (2) not only reflect real changes in column pressure due to changes in initial lumen sizes but also changes in the ratio of $\frac{p_a}{p_c}$ - The considerable delay between the onset of peak pressure and the earlier peak power dissipation underlines the importance of thermal storage in the molten phase.

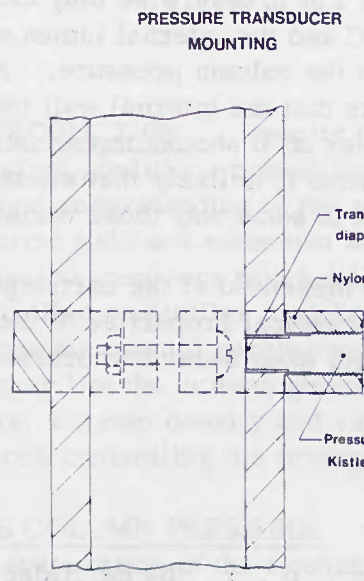

Figure 1

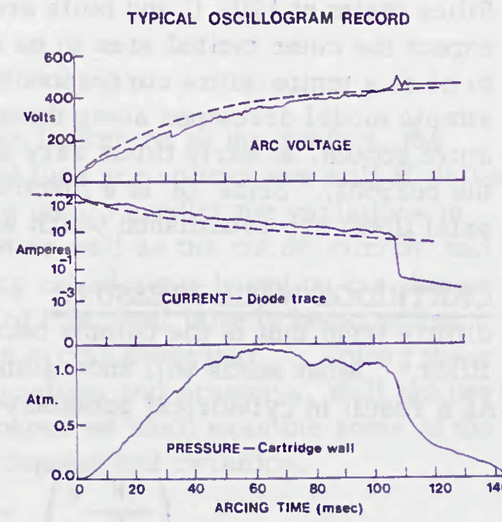

Figure 2

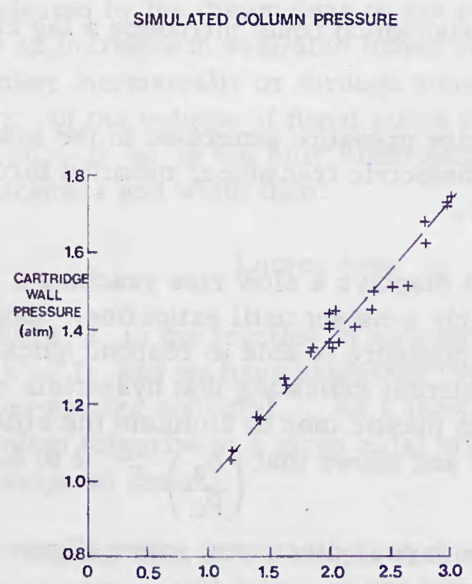

Figure 3

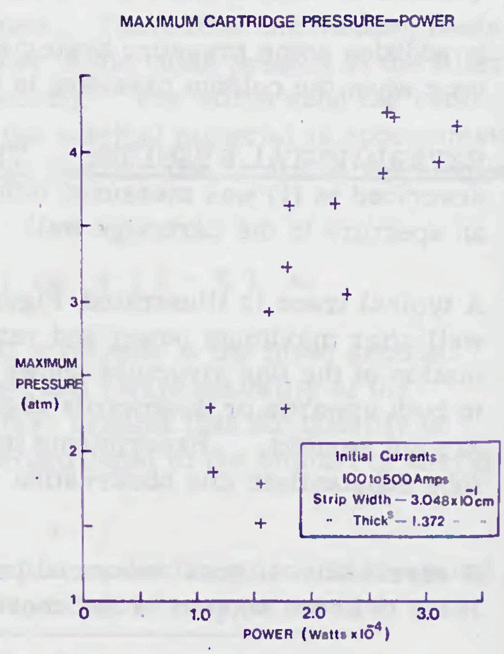

Figure 4

REFERENCES:

(1) Oliver, R. "The behaviour of D.C. overcurrent arcs in cartridge fuselinks"

(2) Baxter, "Electric Fuses" Edward Arnold and Co. 1950

SPECTROSCOPIC OBSERVATIONS OF ARCS IN CURRENT LIMITING FUSE THROUGH SAND

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Mitsubishi Electric Corporation

ABSTRACT Time-resolved spectroscopic observations have been made on arc in current limiting fuse with a silver element. The Ag I, Si I, II, and III lines have been observed successfully through quartz sand in pyrex tube.

As the result, it is suggested that the arc space in the fuse is composed mainly of S_iO_2 vapour. All of these lines appear simultaneously at the onset of arcing. Their intensities attain to the peaks within 1 μsec. Thereafter, the intensities of the Ag I and Si I lines decay rapidly within 10 μsec. While, the Si II and III lines hold high intensities during whole arcing period. The order of electron density and temperature in the arc of Si vapour have been estimated to be 10^{18} cm^{-3} from line-width and 2×10^4 °K from relative intensity ratio, respectively.

INTRODUCTION Current limiting fuse has been applied widely to electrical systems as an economical protective device. Although many works have been reported on the behavior of current limiting fuse, there are few reports concerned with the properties of the arc in the fuse except some theoretical considerations on the behavior of silver vapor in the quartz sand.[(1)(2)] But the current limiting phenomena of the fuse can not be understood without making clear the physical properties of arc space in the quartz sand. We revealed the fact that the spectroscopic observation of arcs in the fuse is successfully possible through quartz sand in Pyrex tube. This paper describes the results of spectroscopic investigation on arcs in current limiting fuse with a silver element.

EXPERIMENT

Test Circuit The test circuit is shown schematically in Fig. 1. The constants L,C and charging voltage V_o were chosen to be 1.55 mH, 1000 μF and 1.3 kV, respectively. A prospective short circuit current with the crest value of 1 kA and the frequency of 60 Hz was fed to the model fuse by closing the switch S. The voltage and current waveforms of the fuse were observed by an oscilloscope through a differential voltage divider and a coaxial shunt, respectively.

Model Fuse The cross-sectional view of the model fuse and the element are shown in Fig. 2. The barrel is made of Pyrex glass tube with the inner diameter of 15 mm and the length of 100 mm. The silver ribbon element has a single reduced section as shown in Fig. 2. Quartz sand was used as an arc quenching filler around the element. Three kinds of grain size, #32 ∿ 60, #16 ∿ 32, and #10 ∿ 16, were prepared for the experiment.

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In addition, the arcing phenomena of the same silver element stretched in air was studied for the comparison with that of the model fuse.

Spectroscopic Observation Arcs in the fuse were observed by making use of a spectrograph (Type GE 100 Shimazu) as shown in Fig. 1. The observations were carried out aiming at the arcing in the reduced section of the silver element. The calibration of wavelength dependence of the spectrograph including the three photomultipliers was done with a NBS standard lamp, and the relative intensity calibrations of the arc spectrum were performed by taking photographs of the spectrum through neutral filters of four different optical densities. The spectroscopic data were obtained by two methods, the time-integrated spectrogram and the time-resolved observation.

The time-integrated spectra were taken on the photographic plates (Kodak 103 aF) covering the wavelength of 3300 ∿ 5600 Å. Fig. 3 shows the intensity of time-integrated spectra as a function of the wavelength obtained by tracing the photographic plates using a microphotometer. Fig. 3 (a), (b) and (c) correspond to the cases of arcing in the quartz sand with the grain size, #32 ∿ 60, #16 ∿ 32 and #10 ∿ 16, respectively. In these cases, only the spectral lines of Ag I, Si I, Si II and Si III were detected as pointed out in the figures. Fig. 3 (d) shows the case of arcing in air. In this case O I, O II, N I, N II lines were detected as well as Ag I lines.

It is interesting to note that the O I and O II lines can not be observed in the case of arcing in quartz sand in spite of the fact that oxygen is contained in the filler as SiO_2. This problem is treated quantitatively in the discussion.

Time-resolved spectroscopic observation was performed on the basis of the results of the time-integrated spectra obtained above. Five spectral lines of Ag I 5209 Å, Si I 3905 Å, Si II 3858 Å, Si II 4130 Å and SiIII 4560Åwere selected from the spectra as typical lines of arc. Three lines, Ag I line and any two of Si I, II, III lines were detected simultaneously by three photomultipliers as the voltage outputs. Figs. 4 and 5 show the temporal changes of intensities of these lines during the short period just after the onset of the arcing, and during the whole arcing period, respectively. From the oscillograms obtained in Figs. 4 and 5, it is clear that all these lines appear simultaneously at the onset of arcing and their intensities attain to the peaks within 1 μsec. Thereafter the Ag I and Si I lines decay rapidly within 10 μsec, while the Si II line holds high intensity during whole arcing period.

DISCUSSION On the assumption of local thermodynamic equilibrium (LTE), the electron temperature, electron density, and mixing ratio of the Si I or S II to Ag I were determined from the data of the relative intensities of the spectral lines, and the composition of the arc space in the fuse and the arc pressure were also calculated using Saha equations, charge-neutral condition and the equation of the state.

The electron temperature was obtained from the relative intensity of the line pair, Si II 4130 Å and Si II 3858 Å, and the result is shown in Fig. 6. As shown in the figure, the electron temperature does not almost change with time, and the order of the electron temperature is about 2×10^4 °K.

By making use of the electron temperature in Fig. 6, the electron density was estimated from the line pair, Si II 4130 Å and Si III 4568 Å. As shown in Fig. 7 the electron density was kept nearly constant in the arc period as well as the case for electron temperature. The electron density was also estimated from the Stark broadening of the time-integrated spectral lines, Si I 3905 Å, Si II 3858 Å, 4130 Å and 5056 Å in Fig. 3.[3] Table 1 shows the result, and the electron density of the order of 10^{18} cm^{-3} obtained from the Stark broadening agrees with that from the relative intensity.

The mixing ratio of the three atomic species, Si I, II and Ag I, was also calculated from the relative intensities of the line pairs; Si I 3905 Å and Ag I 5209 Å, Si II 4130 Å and Ag I 5209 Å. Fig. 8 shows the results with the waveforms of the discharge current and arc voltage.

From the time-integrated spectra shown in Fig. 3, it is evident that the arc space in the fuse is composed of the atomic species, Ag I, II, III, Si I, II, III and O I, II, III. To determine the densities of these nine kinds of particles, use was made of six Saha equations for the each particle densities of Ag, Si and O, charge-neutral condition, the ratio 1 : 2 of the silicon to oxygen and the ratio 1 : 40 or 1 : 80 of Ag I to Si II obtained in Fig. 8. In the calculation, the advance of ionization limit of each species due to the electron concentration of 10^{18} cm^{-3} was taken into account. Calculated particle densities are shown in Table 2. The arc pressures calculated at the same time attained to about 6 atm and 5 atm corresponding to the ratio 1 : 80 and 1 : 40 for silver to silicon, respectively. From the calculated results, the reason why the spectral line of O I and II was not observed even by photographic plate of high sensitivity is explained as follows.

The intensity ratio of typical O II line, 4490 Å or 4061 Å, and Ag I line 5209 Å was calculated as given in Table 3, by making use of the particle densities in Table 2, the electron temperature 2 x 10^4 °K and the electron density 1 x 10^{18} cm^{-3}. The spectral intensities of O II lines are far lower than those of Ag I or Si II lines, since the excitation energies for most of O II lines are higher than those for Ag or Si lines. None of O I lines in the wavelength region from 3300 to 5600 Å were observed since the excitation levels of these lines disappear due to the reduction of the ionization energy caused by the high electron density of 10^{18} cm^{-3}.

REFERENCES

(1) L. Vermij, "Electrical behavior of fuse elements", Ph. D. Thesis, pp. 86-96, 1969.

(2) H. W. Mikulecky, "Current-limiting fuse with full-range clearing ability", IEEE Trans. Power App. Syst. PAS-84, pp. 1107-1116, 1965.

(3) H. R. Griem, "Plasma spectroscopy", McGraw-Hill, New York, 1964.

Table I. Electron density Ne calculated from half widths of SiI and SiII lines ($Te=2\times10^4$)

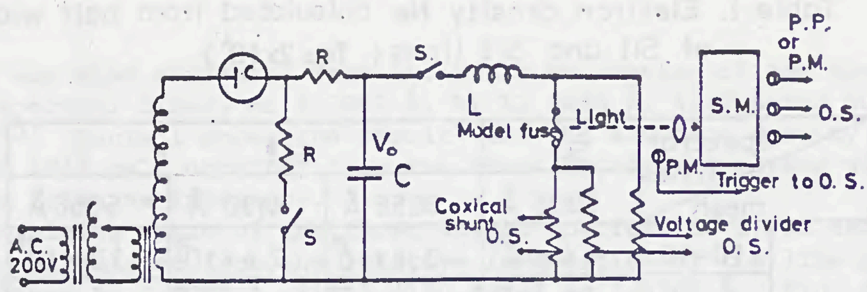
Spectral lines / mesh		SiI	SiII		
		3905 Å	3858 Å	4130 Å	5056 Å
Ne (cm^{-3})	10~16	1.4×10^{18}	3.8×10^{18}	2.4×10^{18}	1.2×10^{18}
	16~32	2.4×10^{18}	3.8×10^{18}	3.7×10^{18}	1.5×10^{18}
	32~60	1.6×10^{18}	2.5×10^{18}	2.0×10^{18}	7.4×10^{18}

Table 2. Calculated particle density for $Te=2\times10^{4}$ °K and $Ne=10^{18}cm^{-3}$

Mixing ratio / Species of particles	Particle density (cm^{-3})	
	AgI/SiII = 1/40	AgI/SiII = 1/80
Ag I	4.5×10^{15}	3.0×10^{15}
Ag II	1.3×10^{17}	8.6×10^{16}
Ag III	8.1×10^{16}	5.6×10^{16}
O I	9.6×10^{16}	1.3×10^{17}
O II	4.0×10^{17}	5.3×10^{17}
O III	3.0×10^{13}	4.0×10^{13}
Si I	7.0×10^{15}	9.3×10^{15}
Si II	1.8×10^{17}	2.4×10^{17}
Si III	6.3×10^{16}	8.3×10^{16}

Table 3. Calculated relative intensity ratio of spectral lines

Mixing ratio / Species of particle	Relative intensity	
	AgI/SiII=1/40	AgI/SiII=1/80
O II (4490Å) / AgI (5209Å)	3.7×10^{-5}	6.3×10^{-5}
O II (4061Å) / AgI (5209Å)	2.1×10^{-5}	1.4×10^{-4}
Si II (4130Å) / Ag I (5209Å)	0.95	1.5×10^{0}



C Capacitance , L Inductance , R Resistance
S Switch , O.S. Oscilloscope , P.M. Photomultiplier
P.P. Photogaphic plate , S.M. Spectrometer

Fig. 1. Schematic of experimental set up

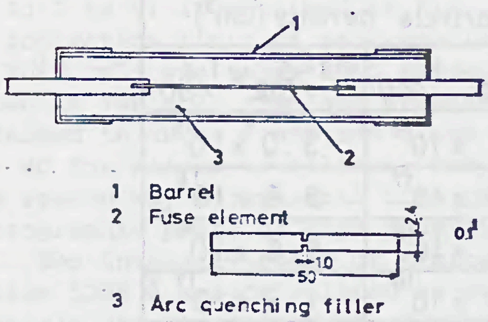


Fig.2 Cross-sectional view of model fuse

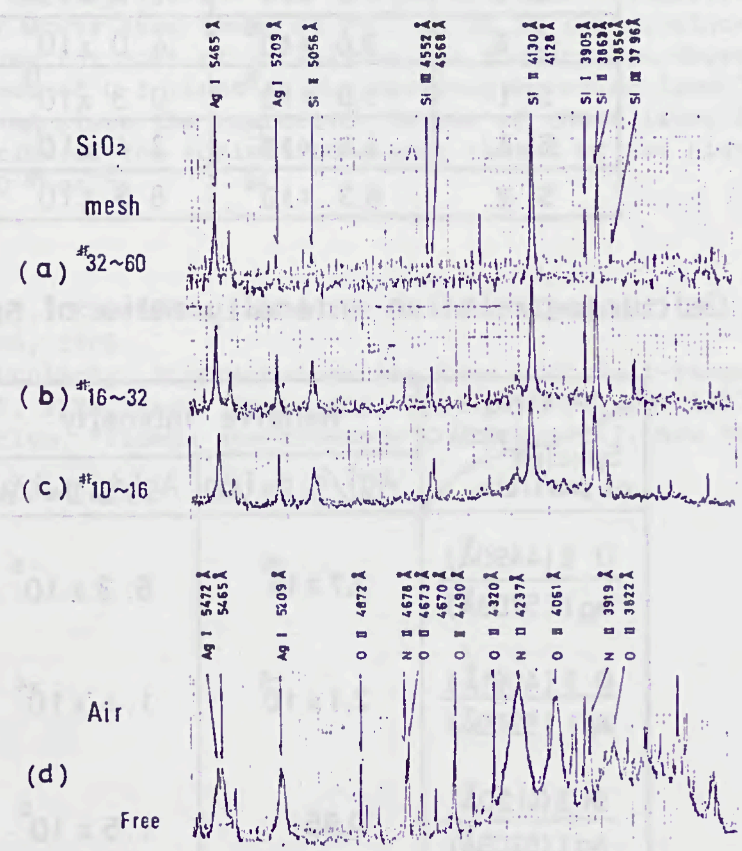
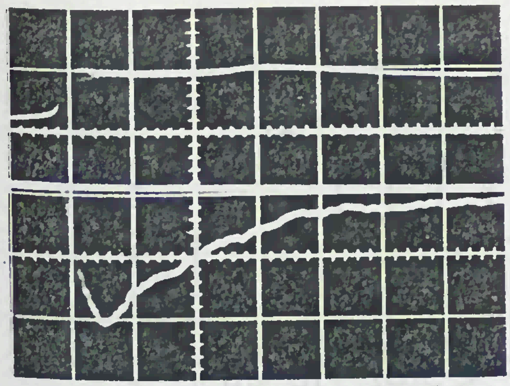
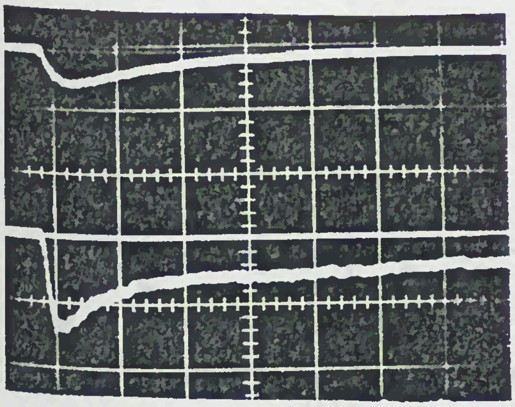


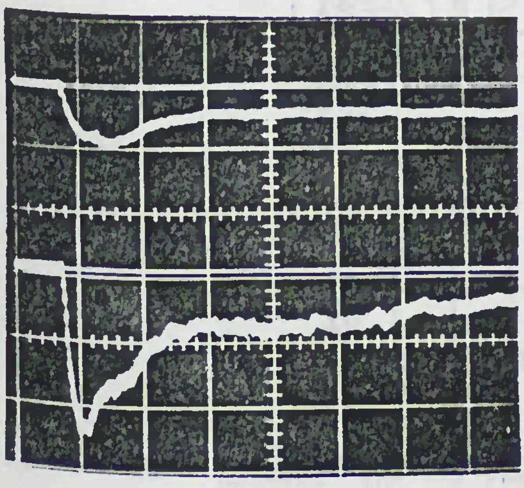
Fig. 3 Time integrated arc spectra in fuses



(A) Upper; Arc Voltage
53.4 V/div.
Lower; P.M.(AgI, 5209 A)
0.5 V/div.

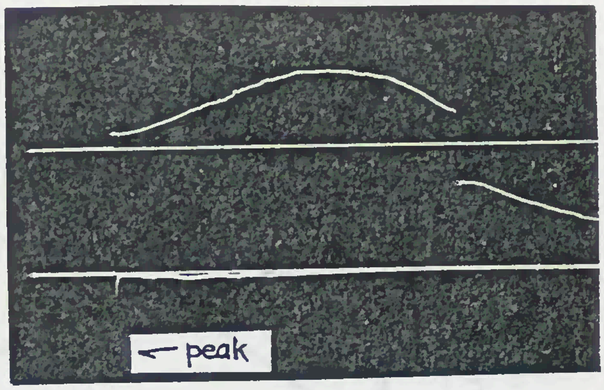


(B) Upper; P.M. (SiI, 3905 A)
0.2 V/div.
Lower; P.M. (SiII, 4130 A)
0.5 V/div.

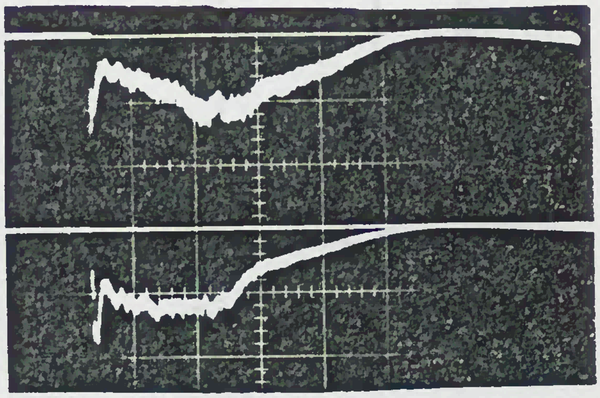


(C) Upper; P.M. (SiII 4130 A)
0.1 V/div.
Lower; P.M. (SiIII, 4560 A)
0.2 V/div.

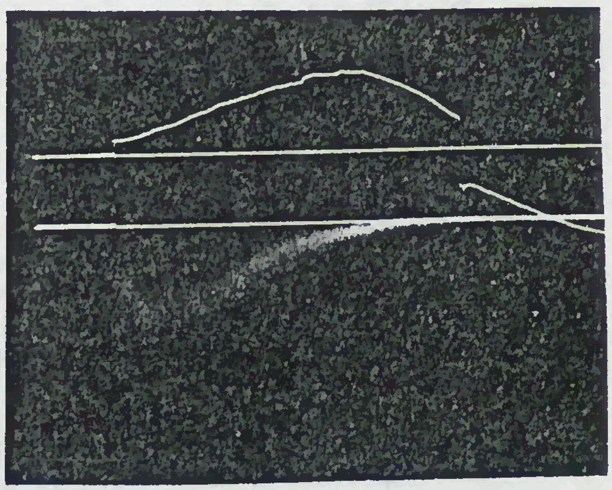
Fig.4 P.M.output intensity of spectral lines at onset of arcing.(Sweep; 2 μsec/div.)



(A) Upper; Arc Voltage
267 V/div.
Lower; P.M. (AgI, 5209 A)
0.5V/div.



(B) Upper; P.M. (SiI, 3905 A)
0.01 V/div.
Lower; P.M. (SiII, 4130 A)
0.2 V/div.



(C) Upper; Arc Voltage
267 V/div.
Lower; P.M. (SiIII,4560 A)
0.05 V/div.

Fig.5 P.M.output intensity of spectral lines during arcing period.
(Sweep; 0.5 msec/div.)

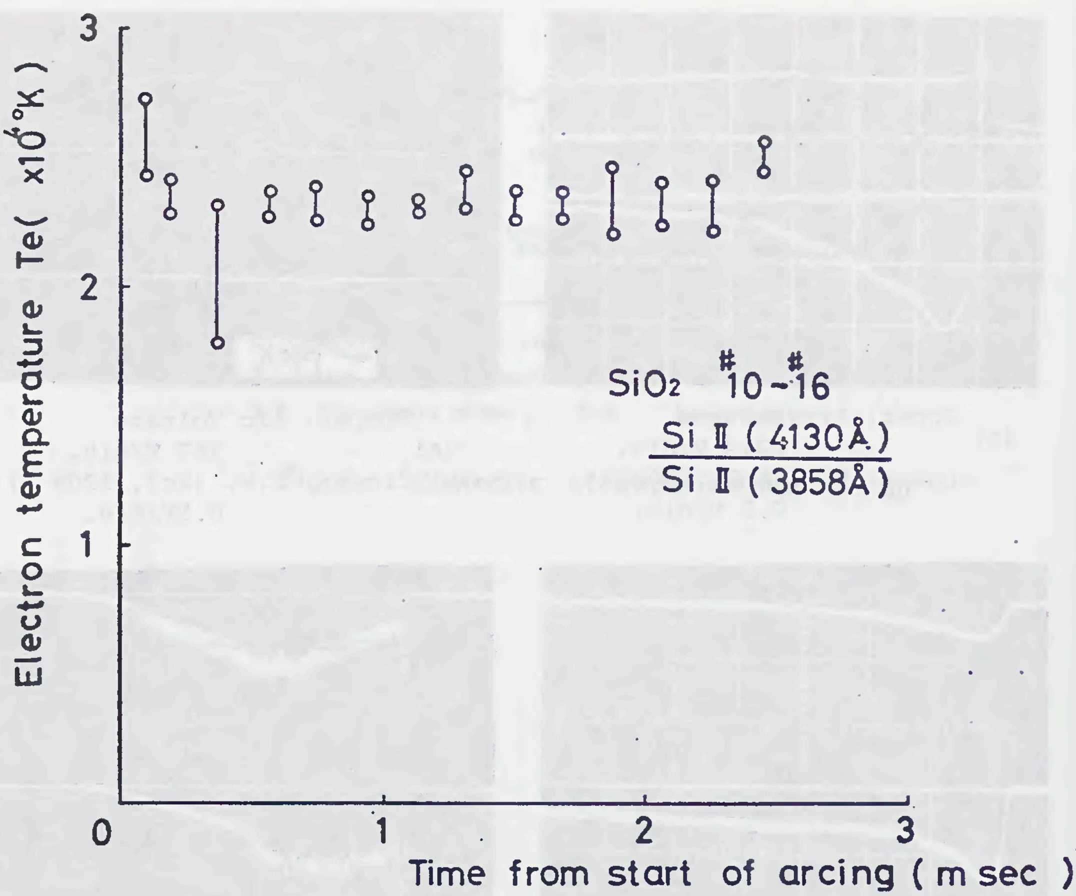


Fig. 6 Values of Te as a function of ta

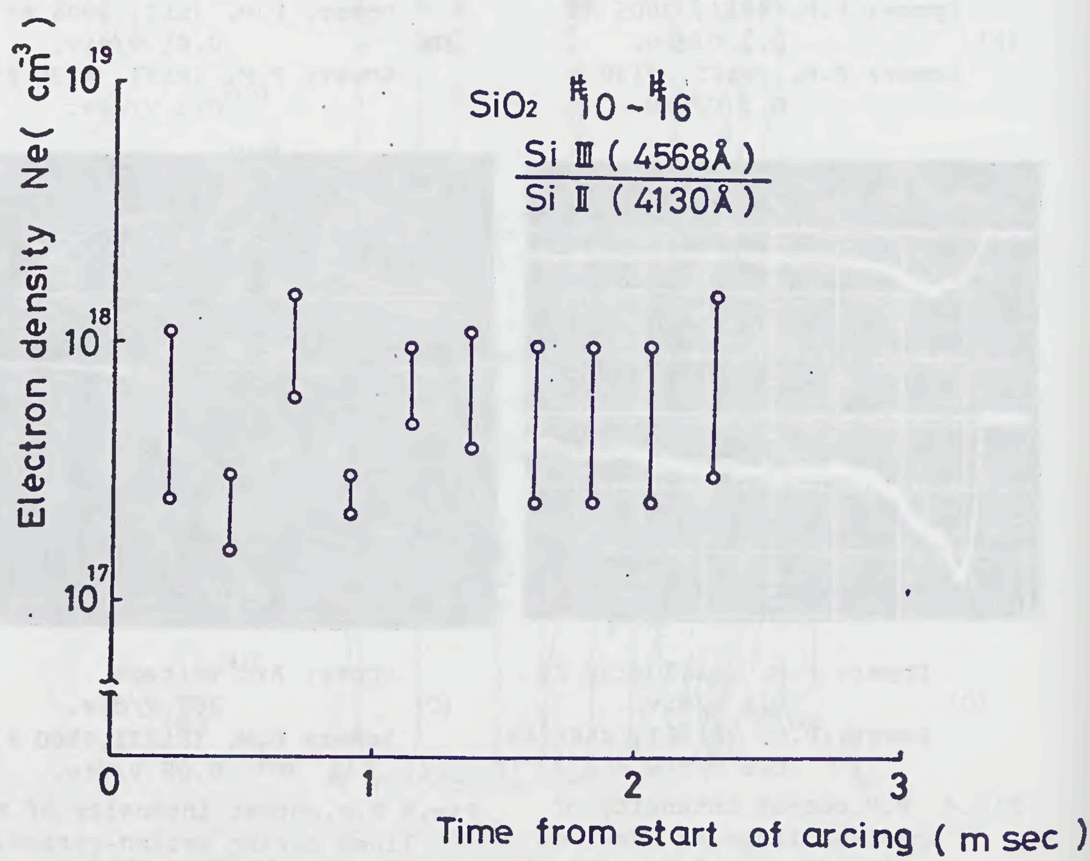


Fig. 7 Values of Ne as a function of ta

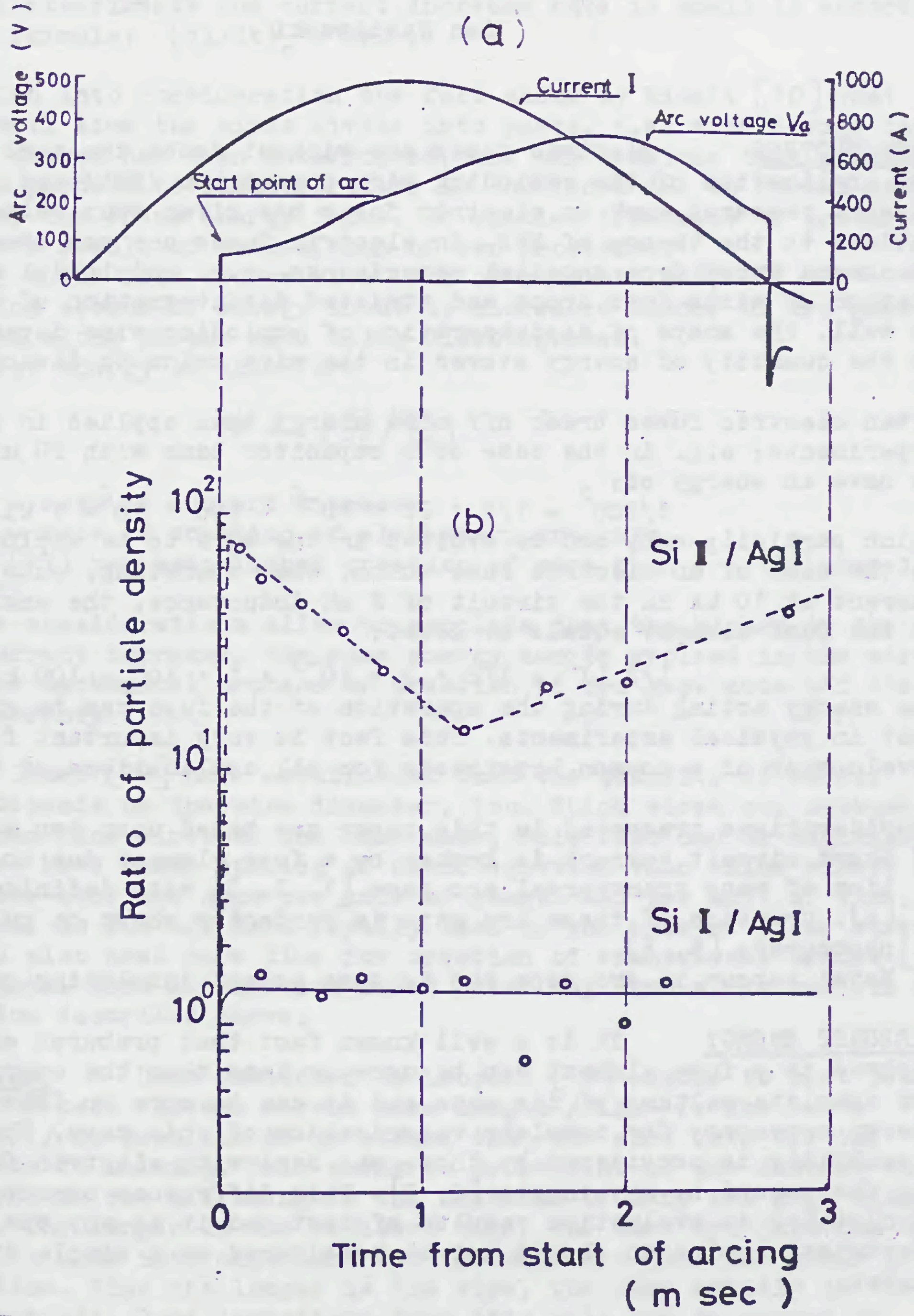


Fig.8 Typical waveforms of the discharge current and arc voltage, and the ratio of silicon to silver.

CHAIN OF ARCS AS DETERMINING FACTOR IN ELECTRICAL EXPLOSION OF WIRES

Jan Nasiłowski

INTRODUCTION Electric fuses are without doubt the earliest practical application of the exploding wire phenomenon /EWP/ and, for that reason, research work on electric fuses has given many valuable contributions to the theory of EWP. In electric fuses one can observe phenomena known from physical experiments, e.g. undoloidal disintegration of wires into drops and striated disintegration of conductors as well. The shape of disintegration of exploding wire depends probably on the quantity of energy stored in the wire prior to disintegration.

Often electric fuses break off more energy than applied in physical experiments; e.g. in the case of a capacitor bank with 20 μF at 10 kV we have an energy of:

$$1/2CU^2 = 1/2 \cdot 20 \cdot 10^{-6} \cdot 100 \cdot 10^6 = 1 \text{ kilojoule}$$

which partially only can be evolved in the wire to be exploded. While in the case of an electric fuse which, when operating, cuts off the current at 10 kA in the circuit of 2 mH inductance, the energy evolved in the fuse element equals at least:

$$1/2\ LI^2 = 1/2 \cdot 2 \cdot 10^{-3} \cdot 1 \cdot 10^8 = 100 \text{ kilojoules}$$

The energy acting during the operation of the fuse can be greater than that in physical experiments. This fact is very important for development of a common hypothesis for all applications of EWP.

Considerations presented in this paper are based upon two assumptions:

1/ Short circuit current is broken by a fuse element due to the creation of many transversal arc gaps [1, 2, 3] with definite spacing [4]. Creation of these arc gaps is perfectly shown on published photografs [5, 6].

2/ Metal vapour in arc gaps has to some extent insulating properties[7].

PREBURST ENERGY It is a well known fact that preburst energy evolved in a fuse element can be more or less than the energy necessary for complete melting of its mass and it can be more or less than the energy necessary for complete vaporisation of this mass. The first possibility is considered by those who deal with electric fuses [1, 8] and the second by physicists [8, 9]. This difference cannot be caused by mistakes in evaluation results of test and it is why the process of electrical explosion should not be considered as a simple transition of phases.

Technicians use, in their experiments, low voltage sources of power with inductances measured in milihenries; physicists as a rule apply

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high voltage capacitors with inductances measured in microhenries. Therefore, the transport of energy occurs with different rates. In physical experiments the current increases very rapidly, however in technical experiments the current increase rate is small in accordance with the formula: $(di/dt)_o = U/L$.

Taking also into consideration the fact shown by Eiselt [10] that during dwell time the wires divide into parts, i.e. when energy input from the source has been interrupted, one can conclude that once the initiated process of disintegration is continued due to forces independent of the fresh energy input. It enables treatment of preburst energy as a result of competition of two processes:
1/ energy input from source with rate of current load,
2/ breaking action of energy input by increased number of arc gaps created along of the wire being disintegrated.
Preburst energy is therefore

$$E = f\left(\frac{di}{dt} / \frac{\Delta n}{\Delta t}\right)$$

where
di/dt - rate of current increase,
$\Delta n/\Delta t$ - rate of creation of elementary arc gaps.
Maury [11] has established creation of more than $1 \cdot 10^5$ arcs in a second.
The above considerations allow to conclude that the higher is the rate of the current increase, the more energy can be evolved in the wire untill the mechanical process of creation of arc gaps cuts off the path of the current.

Nash and Olsen [12] have established that the quantity of energy evolved depends on the wire diameter, too. Thick wires can consume more energy than fine wires of the same mass. This fact can be explained. Fine wires have finer spacing of disintegration than thick wires, thus they create more arc gaps per unit of length and per unit of time, so the current is cut off more rapidly than in the case of thick wires, which can also need more time for creation of transversal cracks [4] and arc gaps. This explanation makes clear why fine wires can win the competition described above.

PEAK CURRENT Data published by Leopold [13] enable to plot peak current and peak voltage versus wire length /Fig. 1/. The curve $I_{1max} = f/1/$ is peculiar if we assume that the wire cuts off the current due to melting. This seems to be evident if one assumes that the current is cut off owing to the creation of many arc gaps along of the wire. The longer is the exploded wire, the more arc gaps can be expected to come into existence and the more arc gaps can occur in a unit of time. Thus the longer is the wire, the more rapidly is the current cut off. Some deviations from this rule can be caused by dispersion of spacing of disintegration.

Considering the relation $U_{max} = f/1/$, one can point out that the measured peak voltage is a sum of voltage drops on elementary arc gaps [1, 2]. The longer is the wire the more arc gaps can exist and the higher voltage can be recorded. Saturation of the curve $U_{max} = f/1/$ at a definite level will be explained with Baxter's plots of the peak voltage.

PEAK VOLTAGE H.W. Baxter /1904-1962/ has given some important plots [1] of peak voltage across the wire in the medium of quartz sand grains as function of design parameters of the fuse and as function of circuit inductance /Figs. 2-5/.

Operation of a fuse in short circuit conditions can be considered as a rapid process. During this process the magnetic field energy $1/2\ LI^2$ is transformed into energy of the electric field $1/2\ CU^2$. Rapid process means here that time of arcing is reduced to zero and one can assume the equality:

$$1/2\ LI^2 = 1/2\ CU^2$$

where: U-overvoltage, I-cut-off current, L-inductivity of the circuit, C-capacity of the circuit.
The above formula gives: $U = I\sqrt{L/C}$.
Taking into consideration the fact that after attenuation of the overvoltage across the fuse the voltage U_o, equalling the open circuit voltage remains, we obtain $U_{max} = U_o + I\sqrt{L/C}$
Baxter's plot of $U_{max} = f/l/$ can be commented as follows /Fig. 2/. It has been written earlier that proportionally to the wire length the peak voltage increases but in the circuit with constant circuit parameters /U_o, R, L, C/ the increase of peak voltage is stopped when the fuse wire is long enough. It means that the magnetic energy of the circuit has been exhausted and greater number of arc gaps cannot cause a further increase. Greater inductance of the circuit, nowever, results in saturation of the curve $U_{max} = f/l/$ at a higher level. The slant part of the curve displays that there can exist an average arc gap voltage u_1 and U_{max} cannot exceed: $U_{max} \leq u_1 \cdot n$, where n is the number of arc gaps.

Knowledge of the spacing of disinterration of copper wires in quartz sand [4] enables calculation of the average arc gap voltage as we know the total voltage /Fig. 2/.
The 0.022 in.dia. Cu wire has a spacing [4]:
$h_s = 0{,}555 + 2{,}08\ d$ /mm/
$h_s = 0{,}555 + 2{,}08 \cdot 0{,}022 \cdot 25{,}4 = 1{,}71$ mm
The average number of arc gaps along of a wire 6 inches long of this diameter is 89, so the average arc gap voltage:

$$u_1 = \frac{4100 + 4200}{89} = 46 \div 47{,}2 \text{ volts}$$

The next plot of $U_{max} = f/L/$ shown on Fig. 3, can be commented as follows:
The peak voltage increases with the increase of the inductance, initially, according to the formula $U_{max} = U_o + I\sqrt{L/C}$, because greater inductivity means greater magnetic energy of the circuit with other parameters being constant. The slant part of the curve $U_{max} = f/L/$ means that the wire of constant length, i.e. of constant average number of arc gaps will obtain higher voltage for each arc gap, but this voltage cannot exceed a definite value which should be considered as breakdown voltage of the chain of elementary arc gaps. When this breakdown voltage is reached the curve $U_{max} = f/L/$ stops its increase, because the wire of definite length cannot divide into more parts than it follows from the spacing of disintegration. When however longer wires were applied in Baxters experiments, the voltage reached accordingly greater values as it is shown in Fig. 3.

Data from Fig. 3 enable the following calculation of average arc gap voltage:

$$u_1 = \frac{3100}{\frac{4 \cdot 25{,}4 \text{ mm}}{1{,}71 \text{ mm}}} = \frac{3100 \text{ volts}}{59 \text{ arc gaps}} = 52{,}6 \text{ volts}$$

and

$$u_1 = \frac{1430}{\frac{2 \cdot 25{,}4 \text{ mm}}{1{,}71 \text{ mm}}} = \frac{1430 \text{ volts}}{29 \text{ arc gaps}} = 49{,}4 \text{ volts}$$

The above given three values of u_1 obtained from different experiments are similar. The differences are small and they can be explained as the result of dispersion of spacing.
Fig. 4shows a family of curves representing the relation $U_{max} = f/d/$. One can give the following explanation to the plot. The thicker is the wire the longer is the spacing of disintegration and at constant length of the wire the number of the elementary arc gaps decreases therefore, the value of the peak voltage decreases accordingly.

A reduction of the current in the circuit results in reduction of magnetic field energy, thus advantage of insulating properties of individual arc gaps is not wholly taken. This explains the observation that a reduction of the prospective current causes a reduction of the peak voltage. The results presented in Fig. 4 enable calculation of the average arc gap voltage for the highest curve as in table 1. The similarity of the obtained values cannot be accidental.

Table 1 Average arc gap voltage u_1 calculated after Baxters data [1/Fig. 55/] for prospective current of the circuit of 1500 amps.

Diameter of the wire		Spacing x/ h_s	Average number of arc gaps xx/ n	Peak voltage U_{max}	$u_1 = \frac{U_{max}}{n}$
inches	mm	mm		V	V
0,036	0,9144	2,45	21	1100	52,4
0,028	0,7122	2,03	25	1350	54,0
0,022	0,5588	1,71	30	1600	53,3
0,0148	0,3759	1,33	38	2050	53,9

x/ after formula: $h_s = 0{,}555 + 2{,}08\ d$ /mm/

xx/ for two inches long fuse wires

The curve in Fig. 5 can be commented in the following manner. Spacing of disintegration for wires in quartz sand depends on the size of grains [4, Tabl.3]. The spacing is the finest for grains with dimensions 0,2 - 0,4 mm, so the fuse wire of definite length surrounded by such a sand will produce during disintegration the greatest number of arc gaps and thus the highest peak voltage. Finer and thicker grains will produce longer spacing and thus will lower the peak voltage.

It has been shown [20] that in other than Baxters test conditions the average arc gap voltage can be much higher.

DWELL TIME Finite dwell time is not recorded in the case of electric fuses because such an event would mean unsuccesful operation of this device. Nevertheless, sometimes during desinn tests of fuses one can observe two pulses of current. It is overcome by application of longer fuse elements, i.e. by increasing the number of arc gaps. The same result can be reached by decreasing voltage of the power source. In the case of current pause, not transient overvoltage but a stabilised voltage of the source or residual voltage on a capacitor bank is the acting factor. When the chain of arc gaps can withstand acting residual voltage, the second current pulse cannot occur and the current pause lasts infinitely. When acting voltage is high enough breakdown of arc gaps between metal striations can occur; therefore the dwell time should depend on the acting average value of arc voltage. Interesting papers about current pause and the restrike mechanism in exploding wire discharge in air are given by Vlastos [21, 22, 23].
In the case of electric fuses with quartz sand filler, intensive cooling of liquid metal particles stabilises arc gaps after radial explosion [4], but in the case of explosion in air or in vacuum, radial flow of metal striae can eliminate many of arc gaps due to direct contact of metal particles. On the other hand, infrapressure which should exist in the axial postexplosion duct/seen excellent in fulgurites [4]/, will facilitate voltage breakdown along of this duct. Investigation od fulgurites [14] has shown that the postexplosion duct is not a postarc duct in the case of correct operation of the fuse, but it is when breaking capacity has been exceeded. In this case the striated structure in fulgurite vanishes. When to Eiselts [10] data /Fig. 6/ one applies a hypothesis that the duration of the dark pause depends on the average value of the acting arc gap voltage and one converts Eiselts results making assumption that the spacing of striae in air is a linear function of the wire diameter, e.g. h = 5d, one will obtain a family of curves Fig. 7 instead of one curve seen on Fig.6.

The accepted formula h = 5d is probably not correct in this case, but it is applied only in order to show the manner of argumentation and not exact values. We have no other papers about spacing of striae in air except of works of Arnold and Conn [15] and Coffman [24], but theese papers do not give formulae for calculation of average spacing versus wire diameter. Dark pause depends on residual field intensity in a uniform manner for all diameters of tested wires [10]:

$$\tau = f\left(\frac{U_p}{l}\right)$$

where U_p is residual voltage on capacitor acting on chain of arc gaps in the fuse element with length l.

The results of the tests give a hiperbolical plot /Fig. 6/, so

$$\tau = \frac{k}{U_p/l}$$

When spacing of disintegration is h one can write that l = nh where n is number of considered arc gaps, so

$$\tau = \frac{k\,h}{U_p\;/\;n} = \frac{kh}{u_1}$$

When spacing of disintegration is a linear function of the diameter d of the wire $h = \alpha + \beta d$ we can write

$$\tau = \frac{k(\alpha + \beta d)}{u_1} = k_1 + k_2 \frac{d}{u_1}$$

Main properties of the dwell time are as follows:

1. Duration of the dwell decreases when the acting residual average voltage u_1 increases.
2. Current pause vanishes when in given test conditions the fuse element is shorter than l_{min}, i.e. when the number of arc gaps is smaller than a certain n_{min}, because in this case the chain of arc gaps cannot withstand transient increasing overvoltage.
3. Current pause lasts infinitely, when in given test conditions the fuse element of a certain diameter is longer than a certain l_{max}, i.e. when the number of arc gaps is greater than a certain n_{max}, namely when chain of arc gaps between striae is able to withstand residual voltage acting in the process.
4. The dwell time in the zone between l_{min} and l_{max} increases proportionally to the wire length, i.e. to the number of arc gaps. The above remarks give a picture as shown on Fig. 8, based on experiments of Cnare and Neilson [16].
5. Increase of wire diameter results in increassing of l_{min}, because in this case we have less arc gaps in the chain.

RESISTANCE ANOMALY Resistance of the wire as a function of energy input during pre-arcing time increases more rapidly for that wire in which energy is evolved slower [17, 18, 19].
Usually and traditionally we consider exploding wires in pre-arcing time as metallic continuum subjected to uniform changes along and across the wire. This is not correct because we know that the wire melts from surface inwards and that transversal cracs are created along of the wire prior to creation of arc gaps.
These facts show that the resistance calculated simply from oscilogrammes is a mean value and we do not take into account these zones of locally increased resistance. Creation of mechanical cracks in wires needs some time, so when transport of energy is rapid enough we can evolve more of it without an additional resistance increase.

SHORT CIRCUIT OPENING Knowing phenomena in electric fuses with quartz - and filler one can give grid - description of the process of short circuit opening by means of a fuse with a single wire melting element /Fig. 9/. Left hand column in this grid presents events in the melting wire. Central column presents alterations of the current and magnetic field, right hand column shows alteratione of the voltage across the fuse.

SOME ADDITIONAL REMARKS TO THE GRID DESCRIPTION Short- circuit heats the melting wire. In an accidental point of the fuse wire the first arc gap comes into existence, and mechanical vibrations of the fuse wire devides due to vibrations into segments and a chain of elementary arc gaps with short arcs is brought about.

Increasing current, causes in the melting wire increasing pinch pressure which /when the current is cut-off and reduced/ results in radial expansion of molten segments between quartz - sand grains and in transformation of the wire into a tube /Fig. 10/. Internal duct of the slag /or fulgurite/ is not a post-arc duct in case of a fuse which broke correctly the short - circuit current. The slag shows no electrical conductivity in the longitudinal direction but some parts of it shows this conductivity in the transversal direction.

REFERENCES

1. H.W. Baxter, Electric Fuses, E.Arnold, London, 1950
2. A.E. Barrington, A criterion of arc formation in power systems Electrical Energy, 1957 p. 152.
3. J. Nasiłowski, The process of circuit opening with short circuit current by a fuse /Polish/ Przegl. Elektr. 1964 p. 21.
4. J. Nasiłowski, Unduloids and striated disintegration of wires EXPLODING WIRES vol. 3-1964.
5. W.G. Chace, The liquid behaviour of exploding wires. Phys. Fluids 2 : 230 /1959/
6. D. Zernow and G. Woffinden, The cinemicroscopic observation of exploding wires, EXPLODING WIRES vol. 1-1959.
7. O. Mayr, High voltage circuit breakers without oil /German/ Elektr. Zeitschrift 1934 pp. 757 and 791.
8. A.E. Barrington, The fusing of wires with heavy surge currents, Brit.J.Appl. Phys.7 : 480 /1956/.
9. I.F. Kvartschava et al.Determination of energy of electric explosion of wires /Russian/, Zhur, Exp.Teor.Fiz. 31:745 /1956/.
10. B. Eiselt, On the course of wire explosion /German/ Zs. f.Physik 132:54 /1952/.
11. E. Maury, Phenomena connected with the short circuit caused by fuse wires in a 220 kV network /French/, Rev.Gen.Electr. 1945 p. 131.
12. C.P. Nash and C.W. Olsen, Factors affecting the time to burst in exploding wires, EXPLODING WIRES vol. 2-1962.
13. H.S. Leopold, Effect of bridgewire parameters on explosive initiation, EXPLODING WIRES vol. 3-1964.
14. T. Lipski, Post-arc currents in quartz sand filled fuses /Polish/, Przegl. Elektr. 1964 p. 17.
15. H. Arnold and W.M. Conn, About distances in characteristic patern of exploding wires, EXPLODING WIRES vol. 2-1962.
16. E.C. Cnare and F.W. Neilson, Large exploding wires-correlation to small wires and pause time versus length dependency, EXPLODING WIRES vol. 1-1959.
17. R.C. Good, Resistance variation of exploding wires, EXPLODING WIRES vol. 3-1964.
18. R.C. Maninger, Prebust resistance and temperature of exploding wires, EXPLODING WIRES vol. 3-1964.
19. F.D. Bennet, G.D. Kahl, E.H. Wedemeyer, Resistance changes caused by vaporisation waves in exploding wires, EXPLODING WIRES vol. 3-1964.
20. J. Hibner, The voltage of single disrupt in a chain of arc intervals by short - circuit disintegration of strip-fuse elements of fuses.

Symposium "Switching arc phenomena" SEP, Łódź, Poland, 1970 pp. 226-231.

21. A.E. Vlastos, Current pause in exploding - wire discharges, J.Appl. Phys. 38 : 4993 /1967/.

22. A.E. Vlastos, Restrike mechanism of exploding wire discharges J. Appl. Phys. 39 : 3081 /1968/.

23. A.E. Vlastos, Restrike channel resistance of thin exploding wires J. Appl. Phys. 40 : 4752 /1969/.

24. M.L. Coffman, New evidence for standing waves in electrically exploded iron wires, EXPLODING WIRES, vol. 4 /1968/.

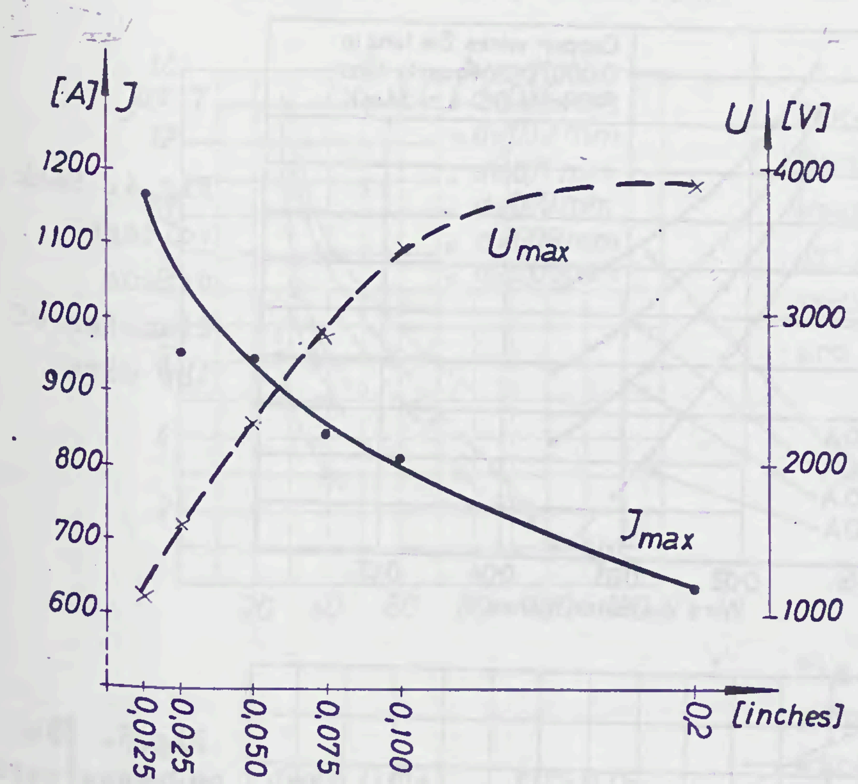

Fig. 1. First pulse peak current and peak voltage as a function of the wire length

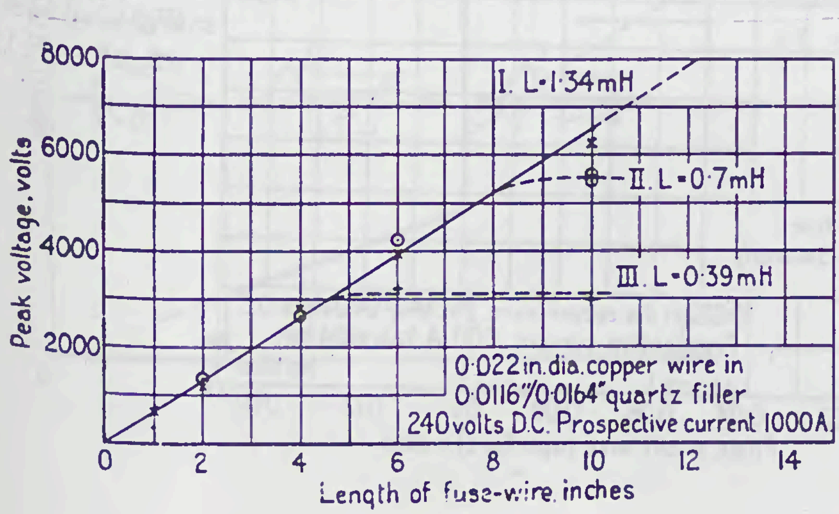

Fig. 2. Peak voltage versus length of the fuse wire

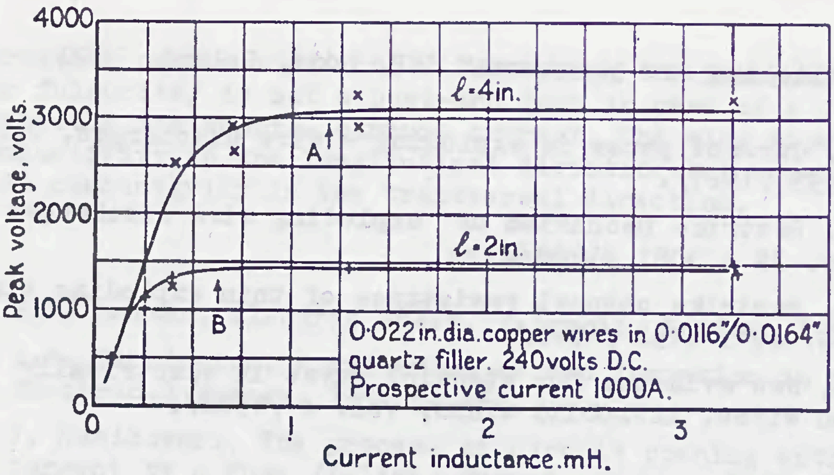

Fig.3. Peak voltage versus inductance of the circuit

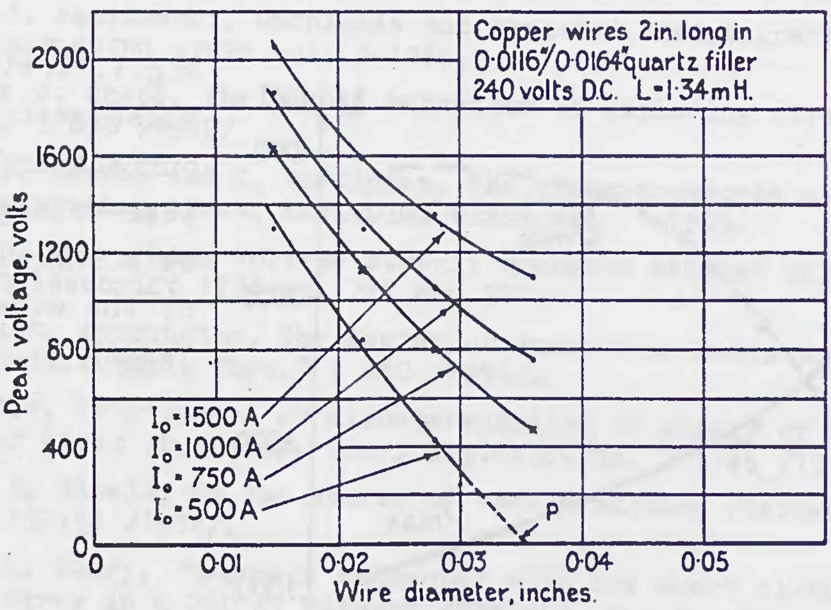

Fig.4. Peak voltage versus diameter of the wire

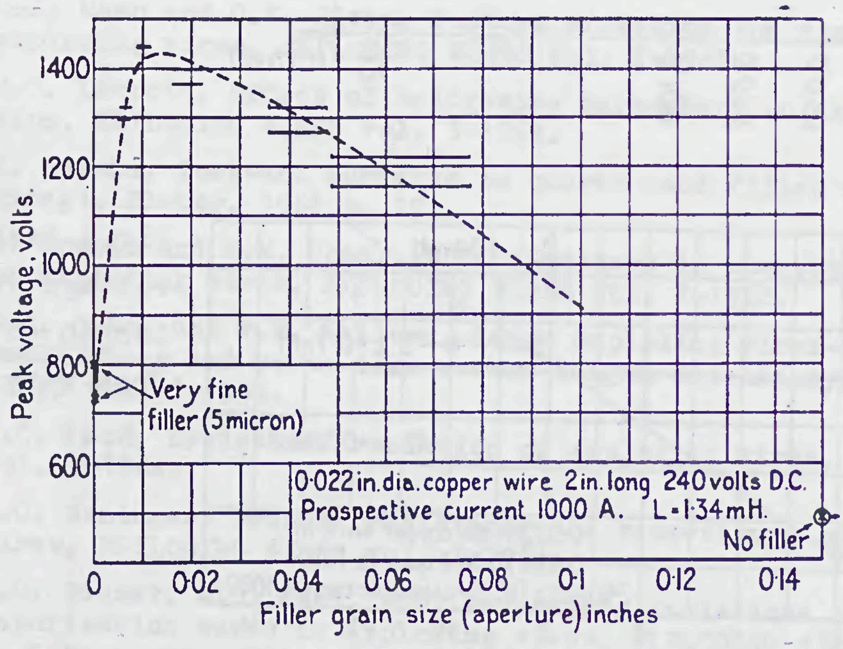

Fig.5. Peak voltage versus grain size of the filler

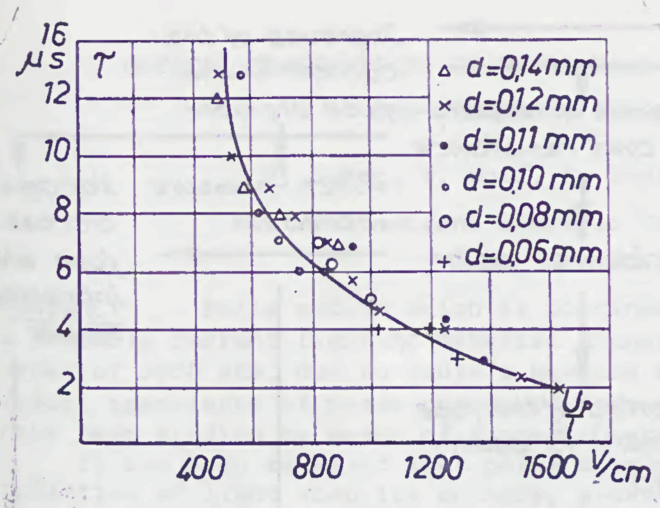

Fig.6. Dark pause duration versus residual field intensity

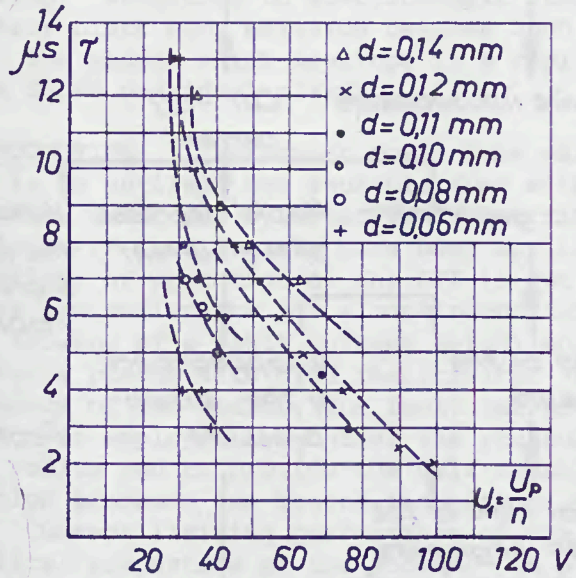

Fig.7. Dark pause duration versus average voltage acting on individual arc gaps

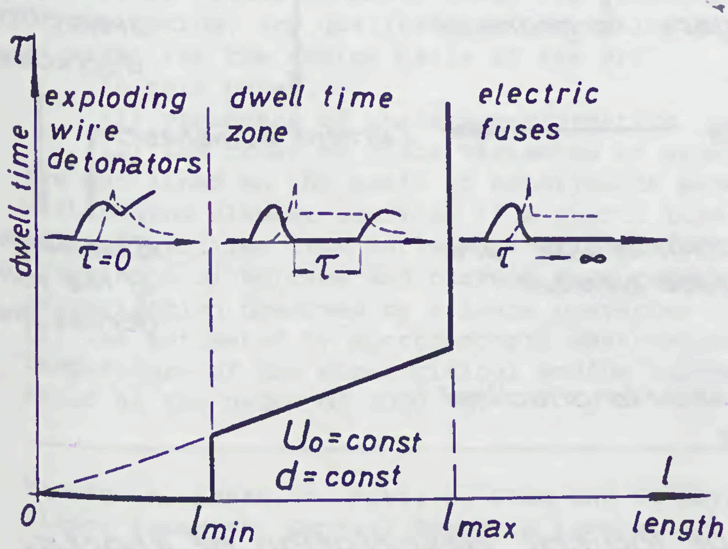

Fig.8. Application zones of exploding wires and dwell time zone as a function of wire length

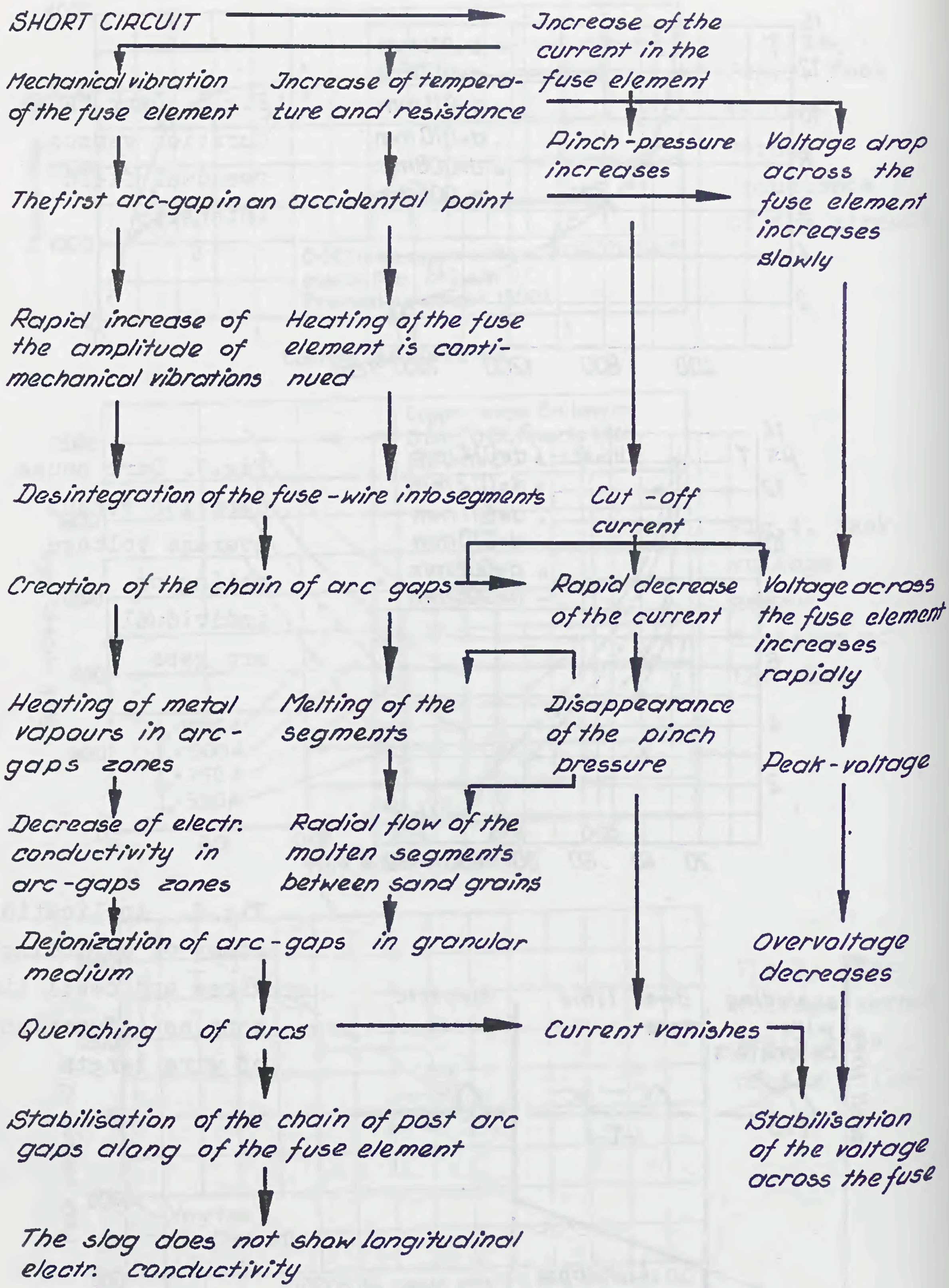

Fig. 9. Grid of logical description of short-circuit opening by a fuse wire in quartz-sand medium.

OPTICAL OBSERVATIONS OF ULTRA HIGH PRESSURE SODIUM ARC IN THE PERMANENT POWER FUSE

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ABSTRACT Solid sodium which is confined in a capillary in the PPF as a reusable current limiting material changes to high density vapour of the order of 3000 atm. due to Joule's heating by let-through fault current. Visual transients of phase change of sodium confined in a quartz capillary have been studied by means of a spectrometer and an image converter camera.

It has been revealed that phase change of sodium starts with the radiation of light when its enthalpy exceeds the value necessary for the boiling. According to spectroscopic studies, radiation of sodium is closely black body emission between 2000 and 5000 °K.

The plasma which develops in a capillary in the PPF has been profiled as a dense non-ideal plasma.

INTRODUCTION Permanent Power Fuse which is called by abbreviated name PPF is an entirely new reusable fuse with excellent current limiting performance developed by Mitsubishi Electric Corp., Japan. Since 1969, various PPF used devices have been applied to the actual field.(1)(2)(3). Principle of operation of the PPF is out lined below. The sodium which shows low resistance for a continuous current evaporates immediately on the flowing of a fault current establishing a high temperature and high pressure plasma with high resistivity. With abrupt change of the resistance of the sodium, the fault current is effectively limited. A piston is employed to control the pressure rise due to the expansion of the sodium and to provide the self-rehealing force to the expanded sodium by high pressure gas behind the piston.

Current limiting performance of the PPF depends greatly on supercritical properties of the sodium. In pre-arcing period of the PPF, phase transformation from solid to supercritical vapour develops within a few ms. Since little is known about the properties of supercritical vapour of the sodium, any qualitative information gives considerable contribution to establish the design basis of the PPF.

In this paper,

(1) processes of phase transformation, and

(2) the order of state variables of supercritical sodium vapour

are out lined on the basis of experiments made by a special model fuse with sodium element confined in a quartz tube.

(1) was profiled from estimation of electrical resistivity obtained from transients of voltage and current measurements and also from speed of vapourization observed by a image converter camera.

(2) was estimated by spectroscopic observations of the sodium arc. Temperature of the supercritical sodium vapour with radiation were estimated as the order of 4000 °K.

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The plasma in the PPF with such order of temperature and pressure belongs to dense strongly nonideal plasma (plasma for which the mean particle potential and kinetic energies are of the same order of magnitude), which has been studied by many scientists to get informations on the structure of the plasma, on the energy spectrum of the electrons and also on quantum mechanical phenomena peculiar to dense strongly heated media.(5)(6)(7) Any information obtained on the plasma in the PPF will give some additional knowledge of strongly nonideal plasma.

EXPERIMENTAL PROCEDURE

(i) MODEL PPF A quartz tube with inner diameter of d_o is O-ring shealed on both ends between copper terminals I and II as shown in Fig-1. Ar gas is filled at 10 kg/cm^2 behind the piston. Tests were made at d_o of 1 m/m. Radial emission of the sodium element was observed through the window of the model. Hereafter, the model PPF is abbreviated to PPF.

(ii) TEST CIRCUIT Fig-2 is a test circuit. The test circuit consists of a capacitor bank with total capacitance of 76000 μF charged to 100 to 400 V., inductance with 20 μH and controlled Thyristor to turn on short circuit current through the PPF. Tests were also made at capacitance of 16000 μF.

(iii) CIRCUIT CONDITIONS FOR THE TESTS Simplified skeleton circuit of Fig-2(a) is given in Fig-2(b). In Fig-2(b), the current through the PPF (denoted as N) and the parallel resistor R are denoted as i_1 and i_2, respectively. The voltage across the PPF is denoted by V_f. Fig-2(c) is a schematic drawing of a wave form of the current i_1 and i_2. The current through the PPF is transferred to the parallel resistor R after the abrupt increase of resistivity of the sodium element at i_c. In Fig-2(c), τ means the time for the current transfer from the PPF to the resistor. After the transfer of the current i_1 to R, the current i_f remains due to the voltage V_f. T_p means a pre-arcing period of the PPF. Process of the increase of the resistivity of the sodium element and streak observations have been investigated during $T_a + \tau$ under the circuit condition at C = 76000 μF keeping other conditions as given above. Spectroscopic observations for the plasma during $\tau + T_f$ have been made under the same circuit conditions of the capacity at C = 76000 μF. Spectroscopic observations have also been made for the plasma during τ by reducing the capacity of the capacitor bank to 16000 μF in order to diminish i_f or T_f down to be negligible. A resistor R connected in parallel with the PPF is employed to reduce the mechanical stresses impressed upon the quartz tube at the development of the high pressure plasma.(3) Voltage and current signals were derived to a computer aided digital data aquisition and analysis system.(4)

(iv) OPTICAL OBSERVATIONS Onset of light emission from the sodium element during pre-arcing period was detected by a photomultiplier (1P28).
Time resolved and time integrated spectroscopic observations were made by a spectrometer (GE-100 Shimazu, Japan) and a spectrographic dispersion unit (Model D2, Beckman-Whitley, U.S.A.) respectively. The time integrated record of spectra was made on photographic film (Kodak high speed film 2485). The dispersion unit covers wave length between 2000 to 10000 Å. The spectrometer (GE-100) is equipped with 3 channels of photomultiplier out puts. Each multiplier can be adjusted to arbitral spectral line which is selected among many lines because of its significance of

time resolved observations. Three traces of the multiplier out puts give time resolved records of the selected three lines.

The calibration of wave length dependence of the spectrograph including the films was done with a NBS standard lamp, and relative intensity calibrations of the arc spectrum through neutral filters of four different optical densities.

Axial speed of the development of vaporization of the sodium was observed by an image converter camera (IMACON, John Hadland).

RESULTS AND DISCUSSIONS

(i) FORMATION OF SODIUM PLASMA For the PPF with d_o of 1 m/m, resistivity was calculated from the measurements of voltage and current transients against energy input (Enthalpy) to a unit volume of the sodium as shown in Fig-3 by a solid line. In this case, the Enthalpy was calculated under the assumption that the temperature distribution of the element is axially and radially homogeneous during Joule's heating up to the point T and that heat conduction to the wall of quartz is negligible. In Fig-3, a dotted line is a theoretically calculated curve of resistivity. In the calculation, the resistivity vs. temperature curve which has been authorized up to a boiling point at atomspheric pressure is extrapolated to the boiling temperature of 1200 °C at 10 atm. This boiling point at 10 atm. is denoted as T in Fig-3. In Fig-3, each notation, S, SL, L and LV means phase of sodium, Solid, Solid + Liquid, Liquid, Liquid + Vapour, respectively. Zone of each phase is correspondingly related to Enthalpy axis. Point E in Fig-3 means that onset of light emission was detected by a photomultiplier at this point.

Experimental curve agrees well with the calculated curve up to point T. Homogeneous Joule's heating in these regions is experimentally supported. Homogeneity of the plasma up to the point T is also supported by the fact that the emission is not observed untill the point T.

Beyond the point T, calculation is made assuming that cylindrically symmetric core of vapourized sodium with resistivity of infinity grows radially. Such an assumption has already been introduced in a research of exploding wires of gold.(8)

Beyond the Point T, experimental curve exceeds considerably beyond the calculated curve. And Enthalpy required to get the same resistivity is smaller for the experimental curve than that for the theoretical curve.

An image converter camera is used for streak observation of the process of the development of the plasma. Fig-4 shows a typical streak photogram and illustration around the element of the model PPF. In Fig-4, the rapid growth of the emission finishes within 15 μs.

The resistance of the plasma varies from 100 to 410 m Ohm during τ and the averaged resistivity is 0.18 to 3.3 m Ohm-cm, assuming that the plasma is homogeneous in the quartz tube of d_o = 1 and length of 10 m/m.

It should be noted that the experimentally obtained value of the resistivity is smaller by almost two orders of magnitude than the classical resistivity.(9) The same order of magnitude of resistivity has been reported for dense non-ideal plasma of Cs(10).

(ii) SPECTROSCOPIC OBSERVATIONS FOR THE PLASMA DURING τ Spectroscopic observations of the sodium plasma in the model PPF have been made to estimate the order of physical state of the plasma.

The time integrated spectrogram obtained at the circuit condition of the second case shows that continuum spectra are observed over the wide range of the wave length between 2500 Å and 1 μ.

Typical spectra are given in Fig-5(a). Line spectra of Hg are superposed as reference lines. Current transients are coupled with each spectrum.

The time resolved spectrogram for three different lines with wave length of 4564. 4960 and 6090 Å shows that the sodium plasma emits the continuum spectrum during τ only when current abruptly decreases by an increase of the resistance of the sodium plasma.

Fig-5(b) shows temporal change of the intensity observed with one of three photomultipliers which is adjusted at 4563 Å. A corresponding current waveform is attached to Fig-5(b). Relative intensity of continuum spectra obtained by Fig-5(a) is given in Fig-6. Solid lines in Fig-6 give relative intensity of a black body radiation at the temperature of 3450 and 2000 °K. The experimental data plotted in Fig-6 agree closely with those of black body radiation. Good correlation is confirmed between the instantaneous value of the current at the beginning of the current limiting period and the estimated temperature. When the instantaneous value of the current is high, the estimated temperature becomes high due to high energy injection rate to the sodium.

The arc pressure can be roughly estimated to be the order of 10^4 atm, under the assumption that the plasma is ideal gas of the temperature 2000 $\sim$ 5000 °K and the particle density 1.7×10^{22} cm^{-3} of liquid sodium at boiling point. But reduced pressure $e^2\ n_e/6\rho_D$ (ρ_D; Debye radius) obtained by real gas effect(11)(12) for 10 % ionized plasma is the same order of the pressure calculated above. Therefore, it seems that the arc pressure during τ is far lower than 10^4 atm.

(iii) SPECTROSCOPIC OBSERVATIONS DURING $\tau + T_f$ For the plasma during $\tau + T_f$, self-reversal NaD line and other broadend sodium lines are observed on to the continuum spectra.

An example of the time integrated spectrogram is given in Fig-7(a). Time resolved observations of the spectral lines around NaD including 5890 Å were made as shown in Fig-7(b). One of NaD lines, 5890 which is recognized during the period τ disappears beyond T_f. While, 5915 and 5875 Å lines are recognized for 1 ms. getting into T_f period.

From these spectroscopic studies, it is deduced that the plasma during τ is closely black body and the plasma during T_f is considered to be optically thin, since the self-reversal NaD line and other broadend lines are observed during T_f.

The electron density in the plasma during T_f has been estimated to be the order of 10^{18} cm^{-3} from Stark broadening(12) of the spectral line of NaD which is given in Fig-7(b).

REFERENCES

(1) T. Ito et al: IEEE 1970 Summer Power Meeting Paper No.70 CP 601 PWR.
(2) T. Ito et al: IEEE 1972 Winter Power Meeting Paper No.C 72 103-5.
(3) T. Ito et al: IEEE Trans. Vol. PAS-92, No.4 July/August 1973 pp. 1292-1297.
(4) T. Miyamoto et al: IEEE Trans. Instrumentation & Measurement, Vol. IM-24 No.4 Dec. 1975 pp.379-384.
(5) F. Hensel, E. U. Frank Rev. Mod. Phys. 40 697 (1968).
(6) N. F. Mott: Phil. Mag. 13 989 (1966).
(7) V. A. Aleksev: Teplefiz. Vys. Temp. 8 641 (1970).
(8) T. J. Tucker: J. Appl. Phys. 32 1894 (1961).

(9) L. I. Grekov et al: Osnovnye Svoistva Nekotorykh Gazov Privysokikh Temperaturakh, Hoskenostroenie, 1964.
(10) S. G. Barol'skii et al: Soviet Physics JETP 35 94 (1972).
(11) A. B. Cambel et al: "Real Gases", Academic Press., New York & London, 1963.
(12) H. R. Griem: "Plasma Spectroscopy", McGraw-Hill, New York, 1964.

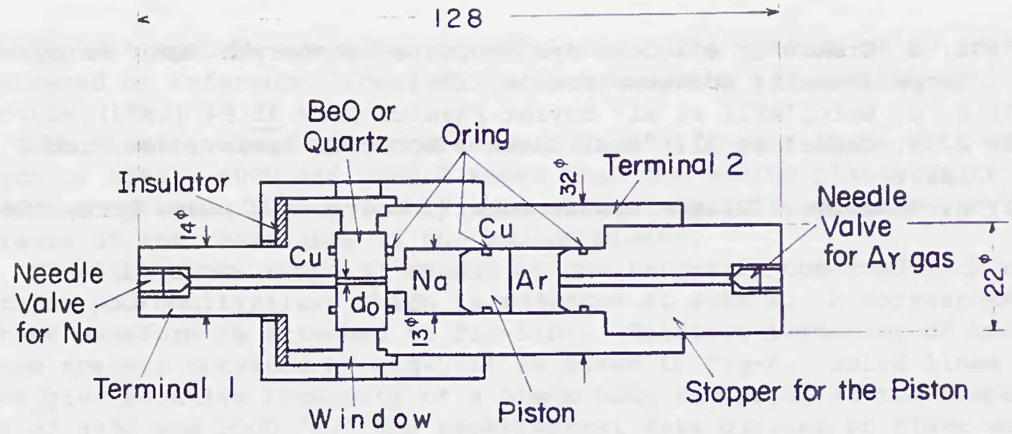

Fig.1 Cross sectional view of model PPF

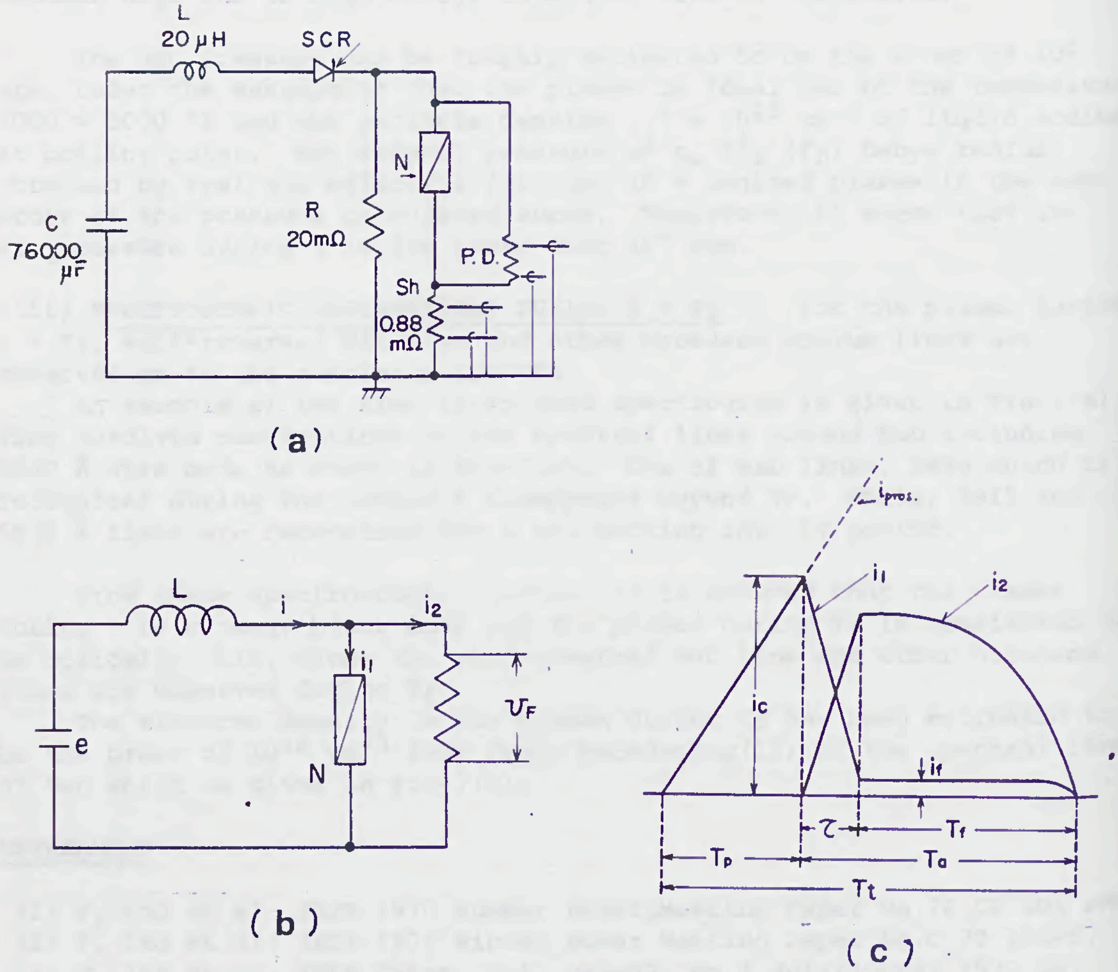

Fig.2 Circuit diagram and current waveform.
(a) Circuit diagram.
(b) Simplified skelton circuit of the test circuit.
(c) Schematic drawing of the waveform of i_1 and i_2.

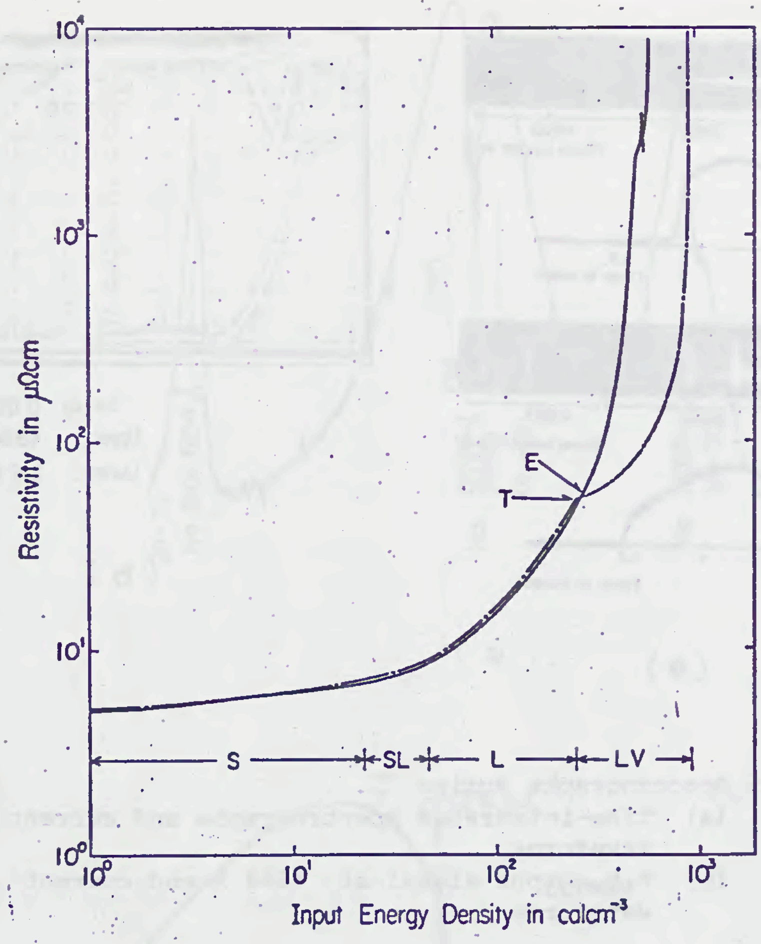

Fig.3 Resistivity of sodium in capillary versus input energy density.

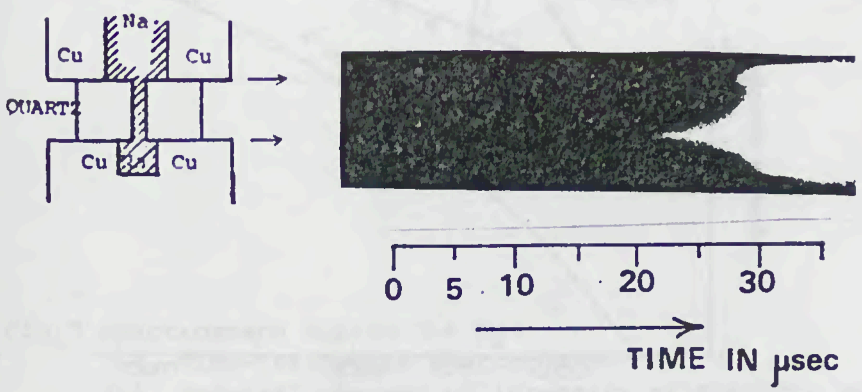

Fig.4 Streak photograph by image converter camera.

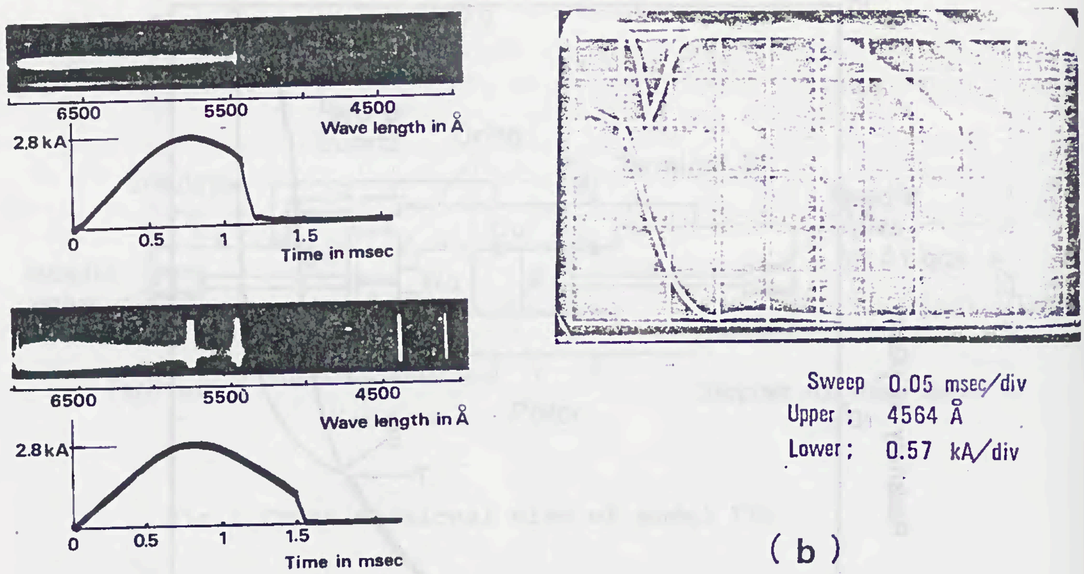

Fig.5 Spectrographs during τ.
(a) Time-integrated spectrographs and current waveforms
(b) P.M.output signal at 4564 A and current waveforms

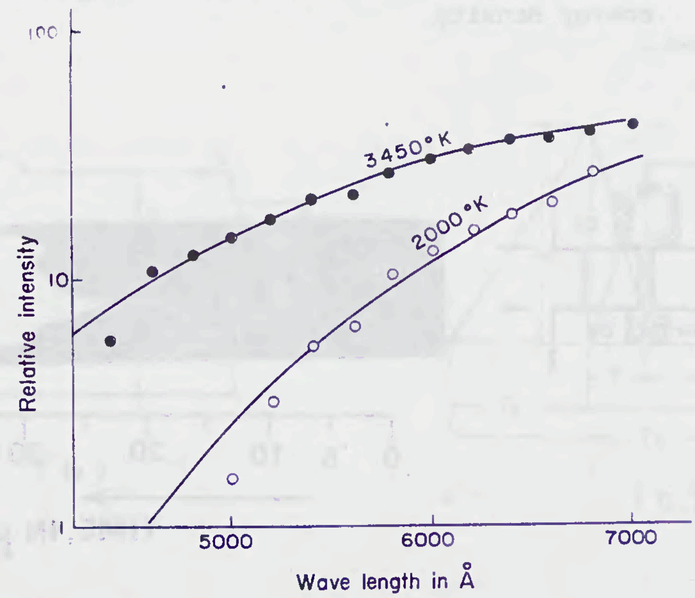

Fig.6 Relative intensity of continuum spectra. Solid curves show the relative intensities calculated for the black body.

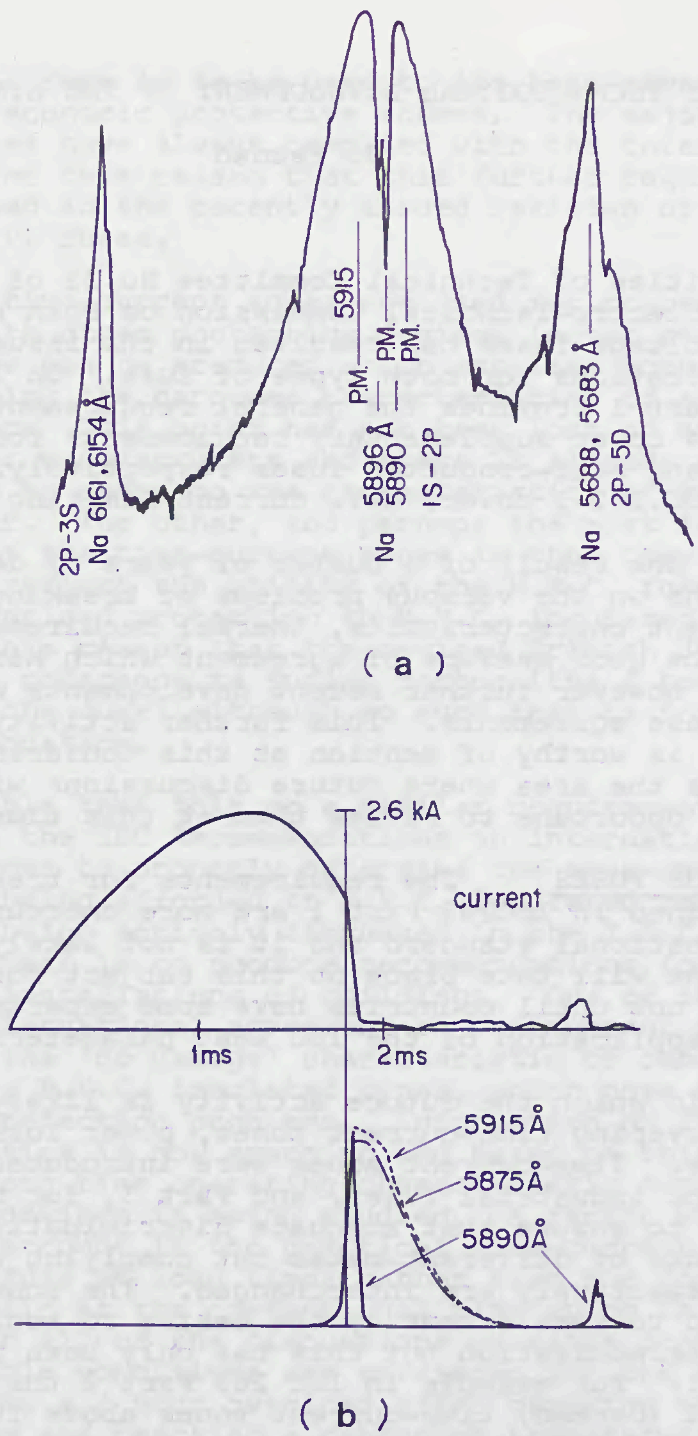

Fig.7 Spectrograph during $\tau + T_f$.
(a) Time-integrated spectrograph
(b) Temporal changes of intensity of spectrum around Na D lines.

THE TECHNOLOGICAL DEVELOPMENT OF THE H.R.C. FUSE

J. Feenan

The activities of Technical Committee No.32 of the International Electro-Technical Commission on both high voltage and low voltage fuses has resulted in the issue of a number of specifications for both types of fuse. On low voltage, IEC.269 Part 1 provides the general requirements and Parts 2, 3 and 4 cover supplementary requirements for industrial, domestic and semi-conductor fuses respectively. On high voltage IEC.282-1 covers H.V. current limiting fuses.

These are the result of a number of years of detailed discussions on the various problems of breaking capacity, Time-current characteristics, thermal requirements etc and reflect the good measure of agreement which has been reached. There are however further recent developments which extend beyond these agreements. This further activity on fuse standards is worthy of mention at this Conference because it highlights the area where future discussions will take place and it is opportune to review them at this time.

LOW VOLTAGE FUSES The requirements for breaking capacity now contained in IEC269 Part 1 are more onerous than in any previous national standard and it is not likely that further discussions will take place on this subject for some time. Certainly not until countries have some experience arising from the application of the IEC test parameters.

The area in which the future activity is likely to be centred is that covering time-current zones, power loss and power acceptance. Time-current zones were introduced into IEC 269 Part 2, for industrial fuses, and Part 3, for domestic fuses, primarily to ensure that adequate discrimination is obtained if fuselinks of different makes but complying with Part 2 or Part 3 respectively are interchanged. The zones were also influenced to some extent by the desire to achieve international harmonisation but this has only been partly successful. For example in IEC 269 Part 2 the GII (British) and the GI (German) time-current zones above 100 amps are identical for all practical purposes but for 100 amps and below they are distinctly different.

It is unfortunate that according to the IEC Recommendation a manufacturer can utilise the complete zones for a given current rating whereas there are many designs which can comply to a mean characteristic within a tolerance of ±10%. This fact has led to much criticism of these very wide zones and it is obvious that further attention will have to be devoted

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to them if a fuse is to be used to its best advantage to produce an economic protective scheme. The majority of British fuses have always complied with the tolerance +10% and it is for this reason that this further requirement has been retained in the recently issued revision of BS.88 covering L.V. fuses.

If the IEC time-current zones are used for co-ordination purposes with other protective devices (motor starters) arrangements can be produced which are less economic than that utilising the narrower characteristics of an individual manufacturer. This point has not been lost on some motor control gear manufacturers and there is already a tendency to continue to refer to the characteristics of the individual manufacturer. The other, and perhaps the most important criticism of the time-current zones is that they do not accurately reflect the ability of the H.R.C. fuse to provide adequate overload protection to P.V.C. insulated cables and it is for this reason that the revised British Standard retains the reference to fusing factor (the 4 hour operating current of the fuse) although no such test is included in the IEC Recommendation.

It is probable that this or a similar requirement will be included in the IEC Recommendations on international wiring rules in order to properly determine the over-current protection being afforded to P.V.C. insulated cables. This subject is being actively discussed in the I.E.C. Committee TC64 whose task is to produce recommendations for the electrical installations of buildings. One of the factors on which international agreement on overcurrent protection depends is the 'no damage' characteristic of cables, particularly P.V.C. insulated types, which pose the most difficult protection problems. Information on these characteristics is now emerging and based on this the desirable long time operating characteristic for all protective devices is being studied. A factor which has to be taken into account is the <u>practical</u> time-current characteristic of a fuse at long times rather than the <u>conventional</u> characteristic at the <u>conventional time</u> which is used at present. In all of the discussions on cable protection the worst possible conditions are envisaged for the cable i.e. subjection to a 4 hour overload after carrying rated current continuously and reaching a conductor temperature of 70°C. This is being compared with the operating characteristic of a fuse starting from cold. Furthermore in the case of GII fuses the time-current characteristic is at present established on a <u>fuselink</u> mounted in a <u>conventional</u> test rig. Although the work of TC64 on this subject is not yet complete, it is probable that the agreement reached will be similar to that which has been accepted in U.K. for many years. This means that fuses with a fusing factor of 1.5 or less in accordance with British Standard BS.88 can provide complete protection to P.V.C. insulated cables when the current rating of the fuse is equal to or less than the current rating of the cable, thus simplifying fuse selection. This statement is supported by at least 15 years satisfactory practical experience.

A further problem which is being investigated by Committee TC64 is the protection to be afforded to persons against electric shock in the event of a fault. Various types of installation conditions have been considered together with the desirable characteristics of the various protective devices. The rule regarding the application of fuses in this context is, however, fairly simple. It has been agreed that for fixed installations on TN systems (low impedance earthed system such as is used in U.K) adequate protection against shock is provided if the earth loop impedance is low enough to cause the fuse to operate within 5 seconds when a phase-to-earth fault is applied. A review of typical installations in U.K. has already shown that this requirement for ensuring shock protection by the use of fuses is already met in the vast majority of cases without the need for supplementary earth bonding. Although it is the responsibility of the installer to select the necessary protection in accordance with these rules, these requirements do impinge upon the desirable time-current characteristic for a fuse as well as for other protective devices.

It is obvious from the foregoing that when further consideration is given to the time-current characteristics of low voltage fuses it will be necessary to consider a more practical representation of service conditions than those upon which the present characteristics are based.

DIMENSIONS A supplement to IEC269 Part 2 in Report form will soon be issued containing the dimensions of British industrial fuses at present contained in BS.88 and the German NH type fuses at present contained in DIN43620. It has been agreed that these two sets of dimensions are in such widespread use that they reflect the best compromise to international standardisation for the present and possibly for the foreseeable future. It is recommended that uncommitted countries choose one or the other of these sets of dimensions. Dimensional standardisation of domestic fuses is in a much more fluid position and it is further complicated by the uncertainty of the time-current characteristics which may ultimately be required arising from the deliberations of IEC TC64. At the recent IEC Meeting in The Hague it was decided to collect, as a first step, sets of standard dimensions of domestic fuses in popular use and it is possible that arising from this a Report will be issued as a supplement to IEC 269 Part 3 containing such dimensions. Until this position is reached, it has been decided in U.K. to retain British Standards BS.1361 and BS.1362. Fuses to these two British Standards comply with the technical requirements of Part 3 and therefore there is no immediate necessity to review these Documents until the international situation is clarified.

This dimensional problem has occupied many hours of discussion at I.E.C. Fuse Meetings and little progress has been made towards unified dimensions. This is not surprising when agreement has not yet been reached on one set of desirable and practical time-current characteristics.

It is more important that this target is achieved first of all. It is also questionable whether any useful purpose will be served by further debating unified dimensions for fuses in a Technical Committee. User preference is a more likely solution. It certainly gives more scope for technical progress.

POWER LOSS AND POWER ACCEPTANCE In IEC269 Part 2 and 3 maximum power loss values have been agreed for fuselinks of standardised dimensions, but it must be realised that they have been obtained from existing designs of fuselinks. They are also established, of necessity, in a conventional manner and in free air. Although this is a reasonable first step it should be viewed with caution. The natural next step is to consider power acceptance of associated devices (fuse-holders, fuse-switches etc). There is a body of opinion which suggests that such equipment must accept these maximum power loss values but this tends to ignore important and practical considerations, some of which are:-

1. The power loss of a fuselink will increase when it is enclosed.

2. No attempt has been made to restrict the power loss values of fuselinks.

3. Conversely there are designs of fuse switches appearing on the market which take advantage of the fact that there is as yet no temperature limit specified for fuse terminals in enclosed fuse switches.

4. The thermal limitations of associated equipment should not be based on test at rated current alone.

5. In the majority of instances there is a load or diversity factor to consider which has a beneficial affect on the combination and should not be ignored.

There is a need for further consideration of this problem in I.E.C.so that a solution is reached which more accurately reflects practical considerations. This was obvious from comments made in various low voltage product committees at the recent I.E.C. Meeting in The Hague and at least one Working Group has been charged with giving further consideration to this problem.

The problems confronting I.E.C. on time-current characteristics and power loss are concerned with practical considerations and the fuse committee cannot solve them in isolation. There is a need for a collaborative effort from the various low voltage product committees to produce the best solution and it is in this way that further progress will undoubtedly be made in the I.E.C. deliberations of low voltage fuses.

H.V. FUSES There have in the last few years been noticeable technological advances in high voltage fuses, the most interesting being the H.V. motor circuit fuse. The reason for the rapidly increasing popularity of this fuse is a) its improved time-current characteristics and repetitive withstand capability and b) the introduction of vacuum contactors and motor switching devices (MSD) as an acceptable technical alternative to circuit breakers, with obvious economic advantages. The motor circuit fuse was first mentioned in I.E.E. Paper No. 6353P October 1970 but there have been rapid advances in design since that time. Some indication of this effort can be appreciated from the information presented in Figure 1. This gives recommendations for fuse selection for various repetitive starting duties and has been based on a series of pulsing tests on various sizes of fuses conducted over a long period of time (in excess of two years) followed by a detailed physical examination, including metallurgical examination of the fuse elements. Figure 2 compares old and new elements showing the different form of the new element and the stress relief feature achieved by bending it at specific points along its length in a precise manner. There is a marked improvement in the ability of a given fuse element to withstand repetitive current pulses when stress relieving is introduced. Figure 3 compares the performance of straight and stress-relieved elements when subjected to a given duty cycle. This information ensures the proper selection of fuses for high voltage motor circuits and eliminates premature operation which occurred in previous designs because of their inability to cope with an onerous repetitive starting duty. Fuses are now available in current ratings up to 630 amps at voltages up to 11kV and 1000 MVA.

This is undoubtedly a success story for the British H.V. fuse industry and it is interesting to note that U.K. are now formulating proposals for inclusion in I.E.C. to cover such fuses for both time-current characteristics and repetitive pulse withstand requirements.

SEMI-CONDUCTOR FUSES Since their inception in the 1950's the demand for such fuses has steadily increased at an appreciable rate and with it the demand for higher current and voltage ratings together with the requirement for faster characteristics. These fuses are now recognised internationally in the recently published IEC269 Part 4 "Supplementary Requirements for Fuselinks for the Protection of Semi-conductor Devices" which incidentally covers both

H.V. and L.V. fuselinks

The increase in knowledge of the design limits of semi-conductor devices has led to a simpler method of fuse selection for standard applications and a desire to explore the ultimate limits of utilisation of such fuselinks, particularly the very fast acting types, in order to achieve maximum economy from solid state equipment.

One of the greatest problems is the apparently infinite variety of applications which exist. Furthermore the methods of assessing no-damage limits of semi-conductor devices and determining the protection afforded by semi-conductor fuses are not yet fully aligned although considerable progress has been made. I.E.C. 269 Part 4 specifies for the first time an internationally accepted method for determining and presenting fuse performance based upon A.C. tests. This will be of great assistance to the user because there had been a tendency in different countries to use a different test basis for the determination of such data as I^2t values, arc voltage characteristics etc.

The application problem will, it is hoped, be further eased with the publication of an Application Guide still under discussion in I.E.C. and further consideration will be given to formulating D.C. tests on an internationally agreed basis to augment the A.C. tests already specified.

There is, however, one problem on which progress is difficult. This concerns the highly repetitive duty cycle to which some applications are subjected. An example of this is a rolling mill drive commonly used in steel production. Such applications also require very fast acting fuses and the combination of these two opposing requirements has led to intensive investigations into obtaining the best solution. One of the most interesting discoveries has been the considerable improvement in pulse withstand capabilities of fast acting fuses by the inclusion of stress relieving configurations such as those described earlier on H.V. fuses. Here again the length of the fuse element is a factor in deciding when to introduce such a feature but because the 'necks' of semi-conductor fuse elements run at much higher temperatures than more conventional fuses it is obviously more critical in such fuses.

The element material and basic design philosophy used also have an appreciable influence on the ability to withstand repetitive over-loads and investigations are not complete at the present time. Nevertheless a part of the Application Guide has been devoted to this problem and manufacturers are issuing more precise guidance than previously.

The dimensions of semi-conductor fuselinks in the U.K. are virtually standardised for voltage ratings up to 600V AC and current ratings up to 600 amps. These dimensions, which ensure non-interchangeability with industrial and domestic fuses, will appear in the British Standard version of IEC 269 Part 4 namely BS.88 Part 4. Above this range of current and voltage ratings, however, the constantly changing demand for fast acting fuses of different current and voltage ratings has led to novel arrangements in an attempt to satisfy this demand on an economic basis. One such method is shown in Figs. 4 & 5. It is possible, by utilising standard modules to produce a wide range of fuselinks of different configurations. Fast operation is ensured because the maximum cooling surface is presented to the surrounding air. It is possible, with this form of construction, for the equipment designer to design his own fuse. Figure 6 presents per-module data on I^2t together with the appropriate factor for the desired multiple arrangement. (Factor A = $(\text{Number of Modules})^2$).

The precise configuration is not critical because the resistance of a single module swamps that of the contact resistance in the end terminations and the constant given in the published data provides an adequate safety margin to counter the slight effect of current inbalance in the different dispositions of modules in any grouping.

The use of high volume standard modules makes this an attractive proposition for both manufacturer and user by avoiding the delay and relatively high cost resulting from the production of special bodies, end caps, etc., necessary for special fuses.

<u>CONCLUSIONS</u> It is reasonable to claim that, within the range of voltage and current ratings at which the majority of cartridge fuses are used, technology is sufficiently advanced to enable the achievement of the primary function of fault interruption without much difficulty. Present design efforts are concentrated more on the achievement of high volume production at economic unit price coupled with more consistent and sophisticated characteristics to suit particular requirements. These two objectives tend to oppose each other and can only be achieved by the use of precision components and a high degree of quality control. The degree to which these objectives are being achieved is evident from the wide ranging protection within precise limits provided by the modern H.R.C. fuse at a cost which makes it the most economic and effective fault protective device available today.

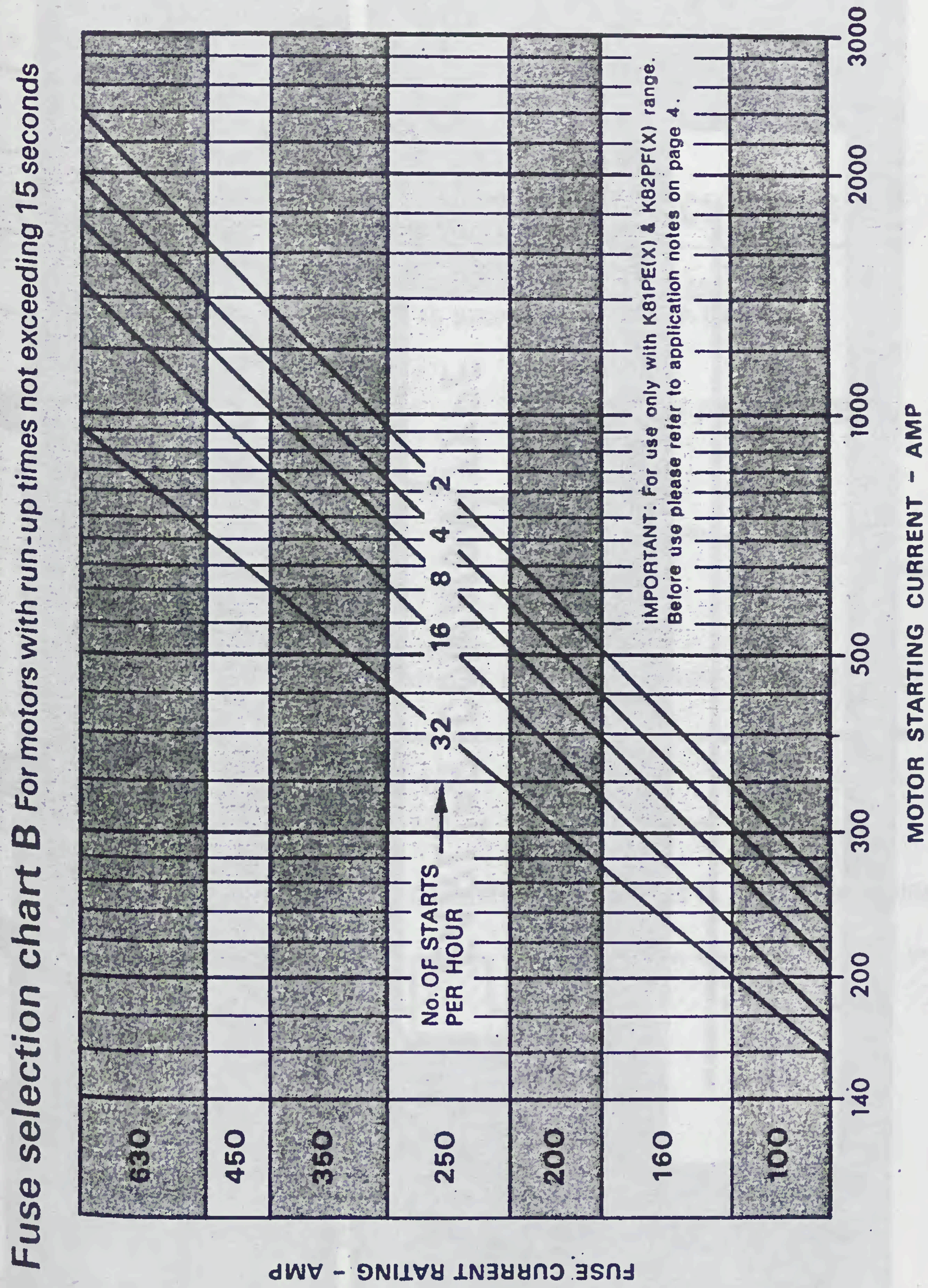


FIG.1 Example of H.V. Motor Circuit Fuse selection chart for various repetitive start conditions.

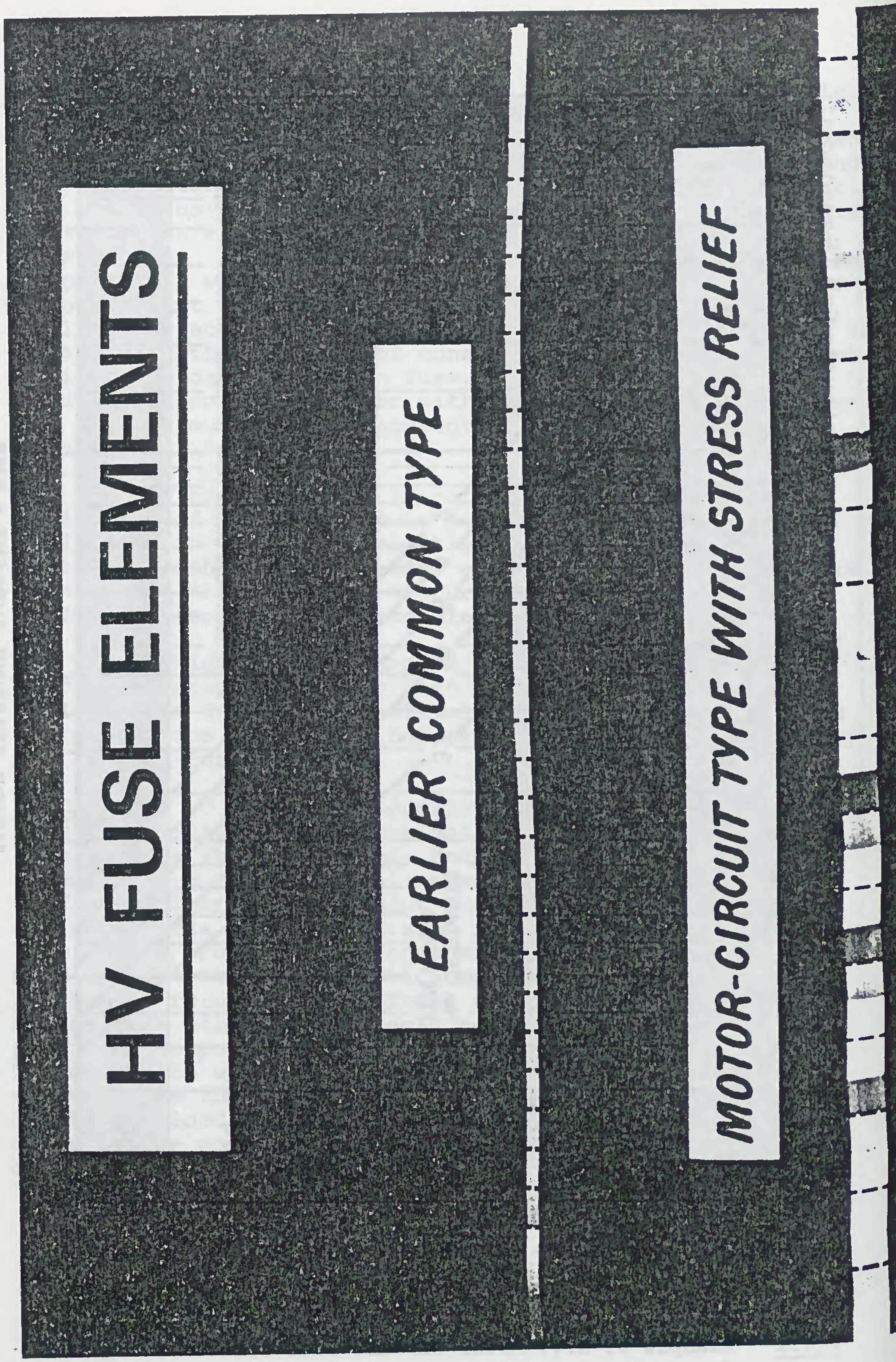


FIG.2 Comparison of old and new H.V. fuse elements for motor circuit protection.

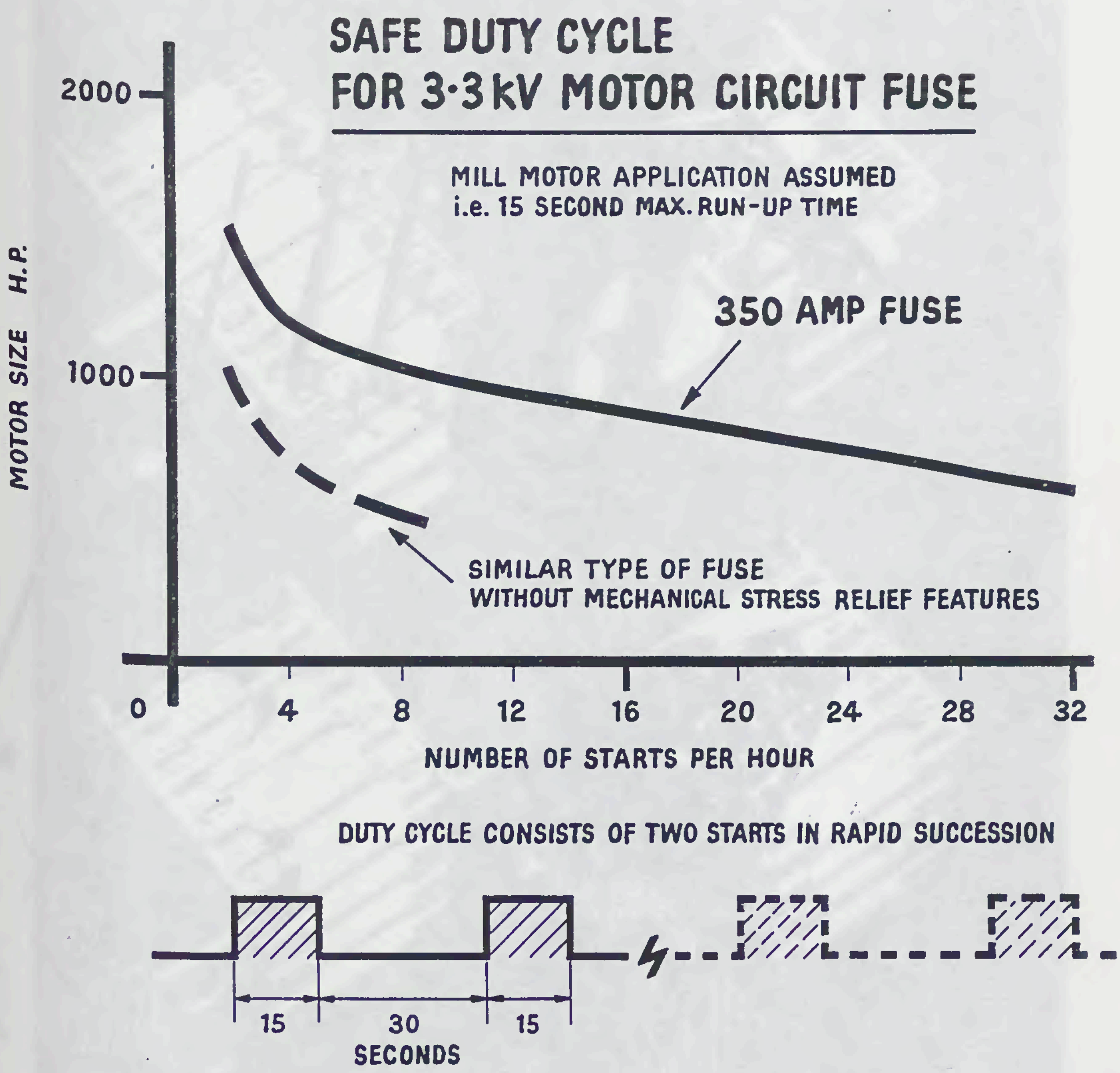


FIG.3 Improvement in repetitive pulse withstand ability of fuse elements by inclusion of stress relief features.

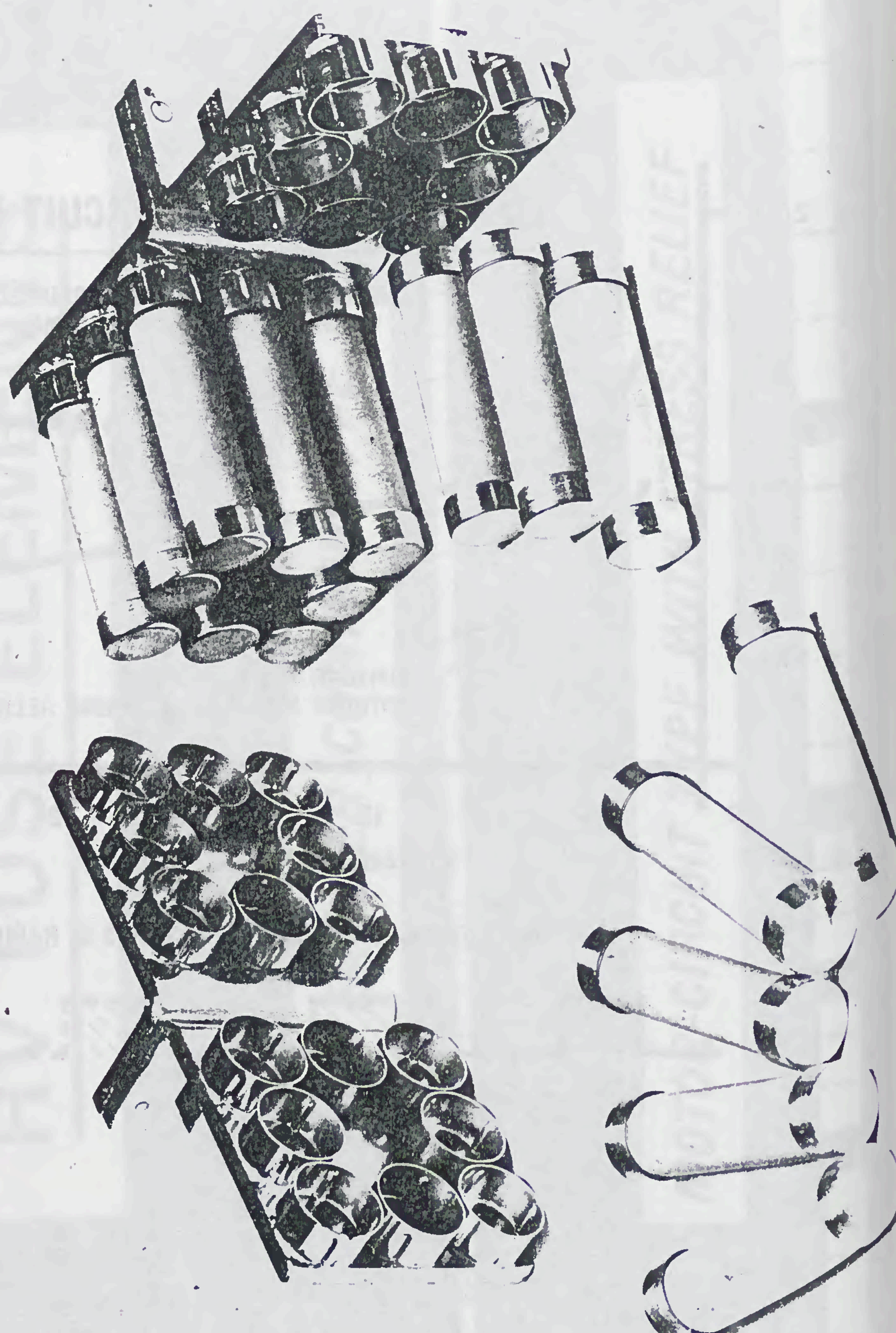


FIG.4 Modular construction of "GSH" multibody fuselinks.

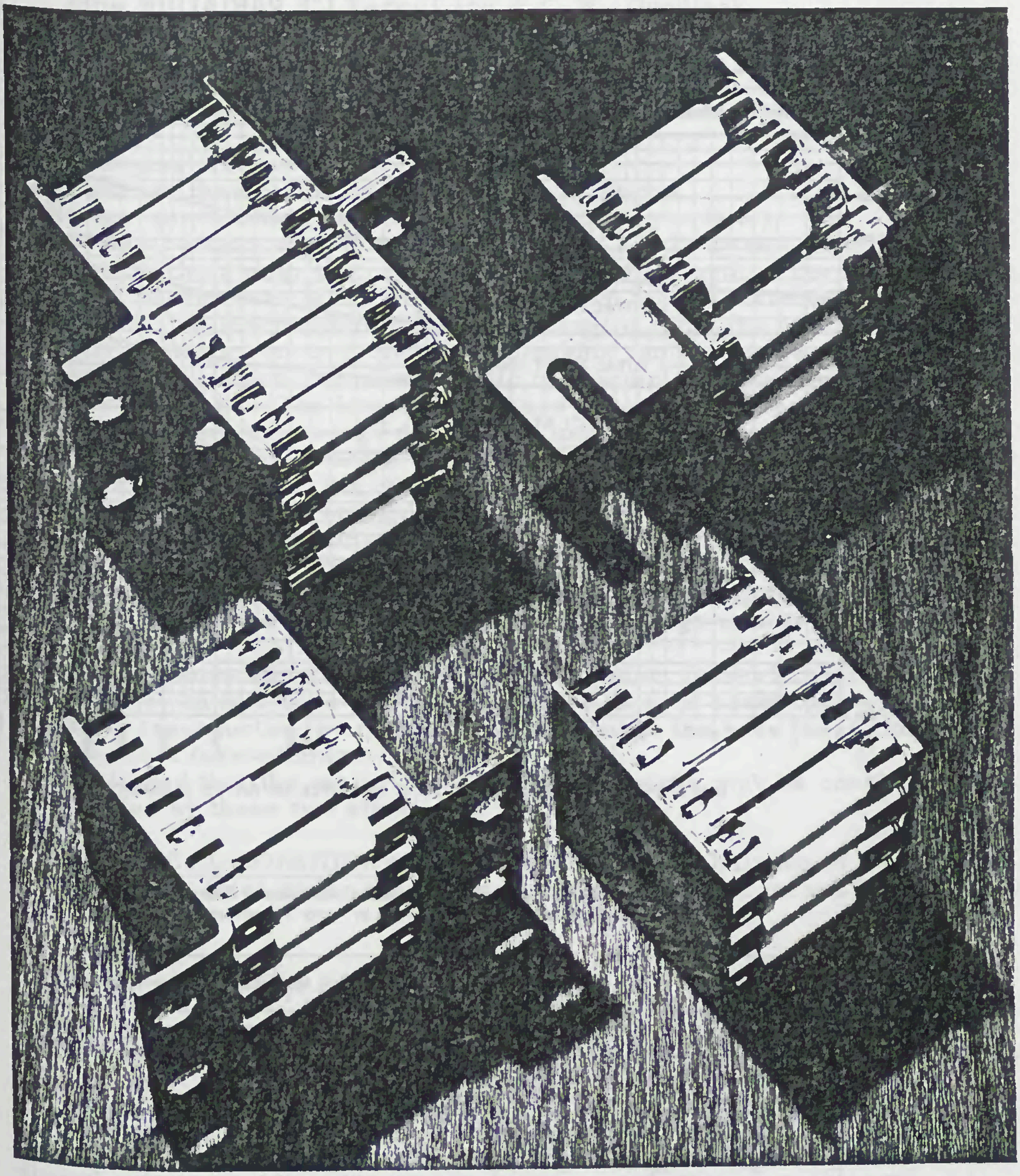
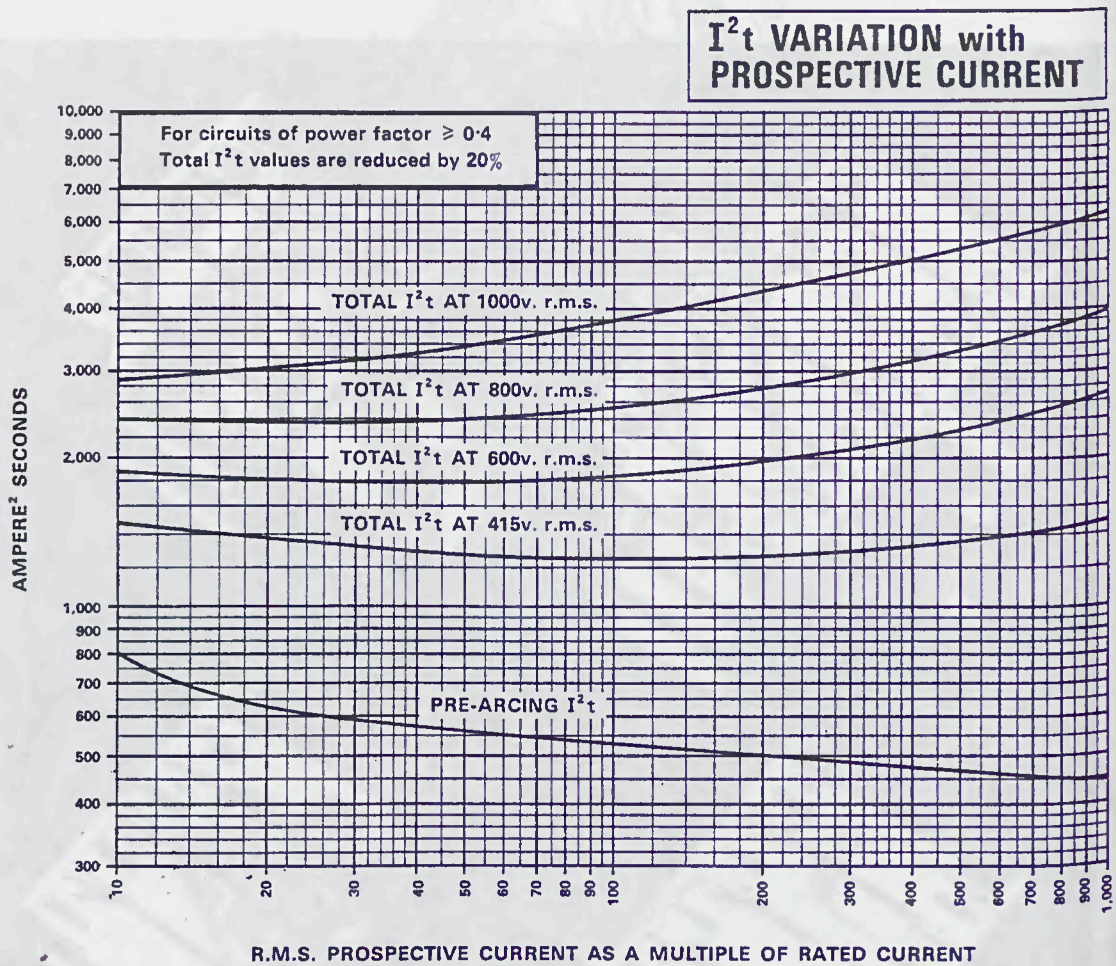


FIG.5 Arrangement of "GSMJ" fuselinks up to 800A, 800V RMS A.C. showing versatility of multibody principle.



Pre-arcing I^2t or Total I^2t of given fuse rating is obtained by reading off value on appropriate curve and multiplying by Factor 'A' from Table below.

Fuse Rating Amp.	63	120	180	240	300	350	400	460	520	580	630	680	800	1000	1200
Factor 'A'	1	4	9	16	25	36	49	64	81	100	121	144	256	400	576

FIG.6 Per-module I^2t data for "GSMK" fuselinks for voltages up to 1000V A.C.

CURRENT-LIMITING CAPABILITY AND ENERGY DISSIPATION OF HIGH-VOLTAGE FUSES

L. Vermij and H.C.W. Gundlach

INTRODUCTION Important characteristics of a fuse are amongst others:

- the nominal current
- the energy dissipation under nominal conditions
- the current-limiting capability (cut-off characteristic).

These basic characteristics are determined partly by the same parameters, such as e.g. the cross-section and the length of the fuse-element, physical parameters of the material of which the fuse-element is composed, the mechanism of the heat transfer from the fuse-element to its surroundings, the maximum permissable temperatures, etc. That means that the above mentioned basic characteristics are not independant from each other. The aim of this paper is to show the relationship existing between the energy dissipation under nominal conditions P_n on the one hand and the nominal current I_n and current limiting capability or cut-off current I_c on the other hand.

Two situations will be studied, viz.

- fuse-elements consisting of a long, homogeneous conductor of constant cross-section (long fuse-element).
  In this case the heat generated in the fuse-element under steady-state conditions will be transported to its surroundings mainly in radial direction.
- Fuse-elements consisting of a number of short fuse-elements connected in series. In this case the heat generated in each short fuse-element is mainly transported (by metallic conduction) to the ends (heat sinks) of each short fuse-element.

It is believed that the majority of practical designs may be considered to be bounded by these two situations.

THEORETICAL CONSIDERATIONS The energy-balance of a current-carrying fuse-wire under steady-state conditions, that means if $\partial T/\partial t = 0$, is given by:

$$\lambda \frac{d^2T}{dx^2} + J^2 \rho_0 (1 + \beta T) - GT = 0 \qquad (2.1)$$

where $T(x)$ is the temperature at a place x (see Fig. 1), J is the current density $[Am^{-2}]$, λ is the heat conductivity of the wire-material $[W.m^{-1}.K^{-1}]$, ρ_0 is the specific resistance at ambient temperature $[\Omega m]$, β is the temperature coefficient of the specific resistance $[K^{-1}]$ and G is the total heat flux per unit length and per degC in radial direction to the surroundings of the conductor $[W.m^{-3}.K^{-1}]$. The value of G can be determined experimentally for a given case [1].

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Eq. (2.1) is valid for a conductor with length $L = 2\ell$ connected to two metal blocks (see Fig. 1) having a heat capacity which is large compared with the heat capacity of the conductor.
Introducing the boundary conditions $\frac{dT}{dx} = 0$ at $x = 0$ and $T = 0$ at $x = \pm \ell$, it can be derived that

$$T(x) = \frac{b}{a} \left[\frac{\cos x \sqrt{a/\lambda}}{\cos \ell \sqrt{a/\lambda}} - 1 \right] \tag{2.2}$$

where $a = J^2 \beta \rho_0 - G > 0$
$b = J^2 \rho_0$

In the case of short fuse-elements, where the heat transfer from the fuse-element is mainly determined by heat conduction to the ends of the fuse-element, it can be shown that $J^2 \beta \rho_0 \gg G$ [1]. Further, the maximum temperature T_m will exist at $x = 0$. So, in this case of short fuse-elements we obtain:

$$T_m = \frac{1}{\beta} \left[\frac{1}{\cos \alpha \ell} - 1 \right] \tag{2.3}$$

where

$$\alpha = J \sqrt{\frac{\beta \rho_0}{\lambda}}$$

In the case of long current-carrying conductors, the maximum temperature T_m is not influenced by axial heat transfer to the ends of the conductor. So then we have

$$T_m = -\frac{b}{a} = \frac{J^2 \rho_0}{G - J^2 \beta \rho_0} \tag{2.4}$$

Introducing the melting temperature T_s and assuming $T_m = T_s$, the equations (2.3) and (2.4) give an expression for the minimum fusing current density J_s for short and long fuse-wires respectively. From eq. (2.3) it can be seen that J_s depends also on the length $L = 2\ell$ of the fuse-element. This dependency is shown graphically in Fig. 2 for the metals Ag, Al and Pb. From eq. (2.3) and (2.4) also the ratio $q = T_m/T_s$ can be computed as a function of the ratio $p = J/J_s$. The results are given in Fig. 3 for short and long fuse-wires respectively.

The energy dP generated in a small part dx of a fuse-element with cross-section A can be written as

$$dP = J^2 \rho_0 \left[1 + \beta T(x) \right] A \cdot dx$$

Introducing eq. (2.2), assuming $J^2 \beta \rho_0 \gg G$ and integrating over the entire length $L = 2\ell$, one can derive for the total energy P generated in a short fuse-element:

$$P = 2 \sqrt{\frac{\lambda}{\beta \rho_0}} \cdot A \cdot J \cdot \rho_0 (1 + \beta T_m) \sin \alpha \ell \tag{2.5}$$

For the current I holds: $I = J \cdot A$. Further, $T_m = qT_s$ $(q < 1)$ can be introduced. If nominal current conditions are considered, for which $I = I_n$, $\alpha = \alpha_n$, $q = q_n$ and $P = P_n$ are valid, we get

$$P_n = 2\sqrt{\frac{\lambda}{\beta\rho_0}} \cdot I_n \cdot \rho_0 (1 + q_n \beta T_s) \sin \alpha_n \ell \qquad (2.6)$$

The value of q_n belongs to a value $p = p_n = J_n/J_s < 1$. These values of q_n and p_n can be derived from Fig. 3a for different metals.
From eq. (2.3) it is clear that $\cos\alpha\ell$ and consequently also $\sin\alpha\ell$ depends only on β and T_m. So under nominal current conditions, where $T_m = q_n T_s$, the factor $\sin \alpha_n \ell$ is a constant. That means that P_n according to eq.(2.6) seems to be independant of the length of the fuse-element, but depends only on q_n (or p_n), and on the physical parameters β and T_s. This conclusion, which has been confirmed by experiments, is valid as long as the radial heat transfer from the fuse-wire may be neglected, as is the case for short fuse-elements.

The energy dissipation of a <u>long</u> current-carrying conductor, for which it is assumed that its temperature T equals T_m over its entire length (this leads to a conservative estimate), can be written as

$$P_n = J_n^2 \rho_0 (1 + \beta T_m) A.L$$

where L is the total length of the conductor.
Substituting $I_n = AJ_n$ and $T_m = q_n T_s$ and introducing eq.(2.4) for $J = J_n$, we obtain

$$P_n = L I_n \sqrt{q_n T_s G \rho_0 (1 + q_n \beta T_s)} \qquad (2.7)$$

In this case the energy dissipation P_n does depend on the length of the conductor L, as would be expected.

Under short-circuit conditions the behaviour of a fuse-element can be fairly well described with Meyer's relation

$$\int_0^{t_s} J^2 dt = C_M$$

where t_s is the melting time and C_M represents Meyer's constant which is determined by physical constants of the material of the fuse-element. Defining the action integral

$$K_M = \int_0^{t_s} i^2 dt \qquad (2.8)$$

where i is the instantaneous value of the current flowing through the fuse-element, it follows with $i = AJ$:

$$K_M = A^2 C_M \qquad (2.8a)$$

The cut-off current I_c can be computed from the above equations by computing the value of i at $t = t_s$. The value of the minimum fusing current I_s and, at a given A, also the value of J_s depends on the length of the fuse-element, as demonstrated with Fig. 2.
If for a short fuse-element $I_s = A_s J_s$ is valid, and for a long fuse-element $I_{s\infty} = A_\ell J_{s\infty}$, and we require $I_s = I_{s\infty}$, then it follows that

$$\frac{A_\ell}{A_s} = \frac{J_s}{J_{s\infty}}$$

where A_ℓ and A_s are the cross-sections of long and short fuse-elements respectively.
In the foregoing it is shown that, keeping I_s constant, the cross-section can be reduced if the length of the short fuse-element is reduced. Reducing the cross-section means, however, a reduction of K_M according to eq. (2.8a) and, consequently, a reduction of I_c. So, also the ratio I_c/I_s or I_c/I_n can be reduced by reducing the length of a short fuse-element.

With the help of the above theoretical considerations it is possible to find a relation between the energy-dissipation P_n, the cut-off current I_c and the nominal current I_n of a fuse under a variety of conditions. This will be the subject of the next section.

COMPUTATIONAL RESULTS AND CONCLUSIONS The above mentioned relationship between P_n, I_c and I_n has been computed for long fuse-wires and, neglecting the energy transfer in radial direction, for short fuse-wires.

Assuming a certain cross-section A which is constant over the entire length of the fuse-wire, it is possible to compute the nominal current I_n of long fuse-elements from eq. (2.4) for a given metal, after introducing values for $q_n = T_m/T_s$ and G. With the same parameters the energy dissipation per unit length P_n/L can be computed from eq. (2.7), as well as the value of the action integral K_M according to eq. (2.8). If the current i in eq. (2.8) is assumed to be a symmetrical sine-wave current with peak value $\hat{I}$, a value of I_c can be found with the chosen parameters. Fig. 4 and 5 show results of such computations for long silver wires and long sodium wires respectively. Experimental evidence suggests that for G a value of $2 \times 10^6 W.m^{-3}.K^{-1}$ has to be taken, which value has been introduced in our computations. Further, for silver wires $q_n = 0.2$ ($T_m = 192$ degC) has been introduced, which seems to be a practical value. For sodium wires we introduced $q_n = 0.9$ ($T_m = 88$ degC).
As an example: Fig. 4 shows that a long silver fuse wire with $I_n = 200A$, subjected to symmetrical (50Hz) short-circuit currents with peak values $\hat{I} = 20kA$ and 40kA will cut the current at values $I_c = 18kA$ and 24kA respectively, providing the arc-voltage is sufficiently high. The energy dissipation in this fuse wire at $I = I_n$ will be approximately 9.5Watts/cm. Fig. 5 shows that under equal circumstances a long sodium wire with $I_n = 200A$ will cut the current at $I_c = 10kA$ and 12kA respectively. In this sodium wire the energy dissipation at $I = I_n$ amounts to appr. 8.6 Watts/cm. This example demonstrates that long sodium wires show a remarkable reduction of I_c compared with silver wires, whereas the eneregy dissipation is almost equal in both cases. If in the case of a long silver wire the value of G can be made three times larger than assumed earlier, and if we assume $q_n = 0.6$ ($T_m = 576$ degC), then the cut-off current will be almost equal to that of the long sodium wire under the above mentioned conditions. However, the energy dissipation of the long silver wire at $I = I_n$ will now amount to 30 Watts/cm.
A dramatical reduction of I_c, compared with long fuse-elements, can be obtained by applying short fuse-elements, as can be seen from a comparison of Fig. 4 and 5 with Fig. 6 and 7. The latter figures have been computed for short fuse-wires which are subjected to a short-circuit current with a peak value of 20kA. Fig. 6 shows for example that short

silver fuse-elements with L = 2mm and L = 10mm cut the current at values I_c = 2kA and I_c = 6kA respectively, if $\hat{I}$ = 20kA. Further Fig. 6 and 7 show that at I_n = 200A the energy dissipation amounts to 28 Watts per element for silver and 17 Watts per element for sodium, irrespective of the length of the fuse-element. For comparison, figures 6 and 7 show I_c as a function of P_n/L and I_n for long fuse-elements ($L \rightarrow \infty$). It turns out that the energy dissipation of short fuse-elements is in general larger than P_n at $I = I_n$ of long fuse-elements per equal length.

As a conclusion one can state that the total energy dissipation at $I = I_n$ of a chain of short fuse-elements in series is determined by the number of short fuse-elements and not by the total length of these short fuse-elements. This energy dissipation is larger and can be much larger than the energy dissipation of a long fuse wire with equal total length. In general, a fuse requires a minimum length of the fuse-element in order to be able to generate an arc-voltage which is sufficiently high. Also the required dielectric strength (resistance) after interruption of the current makes a certain length necessary. So one can state that the nominal voltage for which a fuse is designed requires a certain minimum total length of the fuse-element. Once this length is given, the minimum energy dissipation at $I = I_n$ will be obtained with a fuse-element which consists of a homogeneous conductor of constant cross-section. Improving the current-limiting capability by deviding the total required length into a number of short fuse-elements in series, which is especially desirable at high values of the nominal current, is only possible at the expense of a higher energy dissipation at $I = I_n$. In general one can state that the lower the cut-off current is, the higher the energy dissipation will be.
The value of the energy dissipation, even at high nominal currents, does not offer serious problems as long as low-voltage fuses are considered. High-voltage fuses, however, require much greater lengths of the fuse-elements, and this will lead to much larger values of the energy dissipation. If a maximum permissable value for the energy dissipation of high-voltage fuses exists, as will be the case with built-in fuses, only small nominal currents are possible. In general, it can be stated that it is hardly possible to built high-voltage fuses with high nominal currents (hundreds of amps) and with improved current-limiting capability in accordance with present design methods, which can meet practical requirements with respect to the energy dissipation under nominal current conditions. Improvements can only be made if the arc-voltage per unit length and the dielectric strength per unit length after current-interruption can be increased. In this respect it may be remarked that research work carried out by amongst others Salge[2] and Huhn [3] , with the aim to gain more insight in the parameters influencing the arc-voltage, seems to be very important.

REFERENCES

[1] L. Vermij: Holectechniek 5 (1975) 3, 76..81

[2] J. Salge: Int. Conference on Energy Storage, Compression and Switching, Torino, November 1974.

[3] P. Huhn: Dissertation (1971), Techn. Universität Hannover.

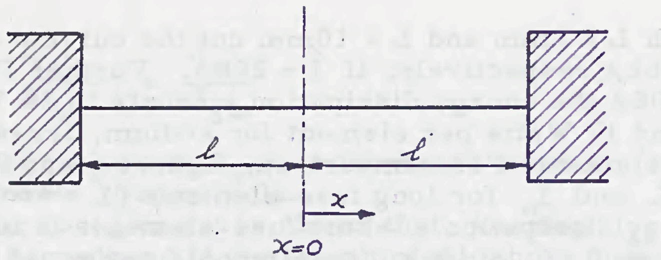

Fig. 1.

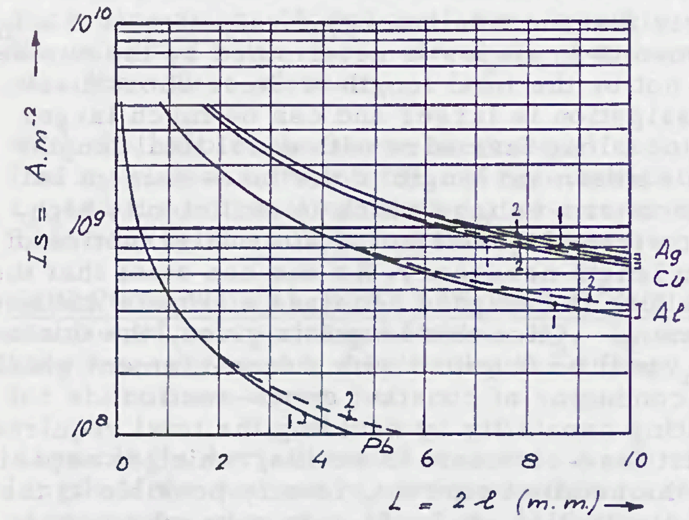

Fig. 2. The minimum fusing current density J_s as a function of the total length $L=2\ell$ of a fuse-element for the materials silver, copper, aluminium and lead. Curves 1 have been computed neglecting the radial heat transfer (G = 0) Curves 2 have been computed with $G = 6.10^6\ W.m^{-3}.K^{-1}$.

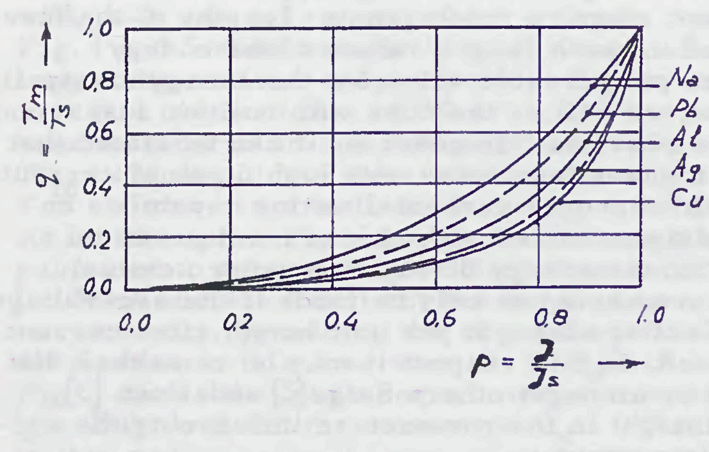

Fig. 3a. The ratio between the maximum temperature T_m and the melting temperature T_s, as a function of the ratio between the current density J and the minimum fusing current density J_s for short current carrying conductors and for the materials silver, copper, aluminium, lead and sodium.

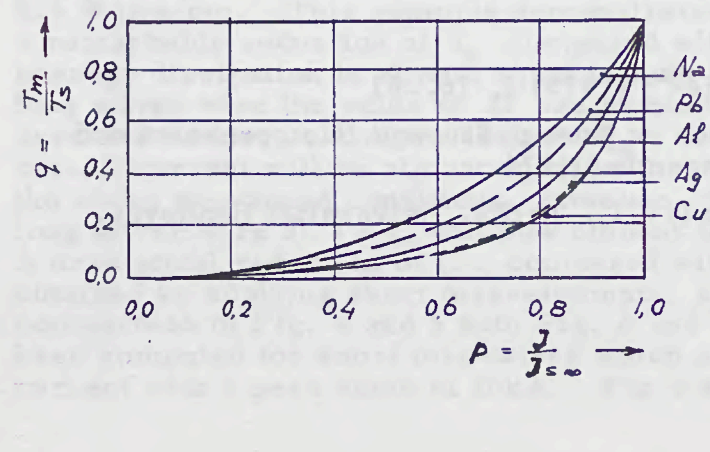

Fig. 3b. The ratio T_m/T_s as a function of the ratio J/J_s for long current-carrying conductors and for the same metals as Fig. 3a.

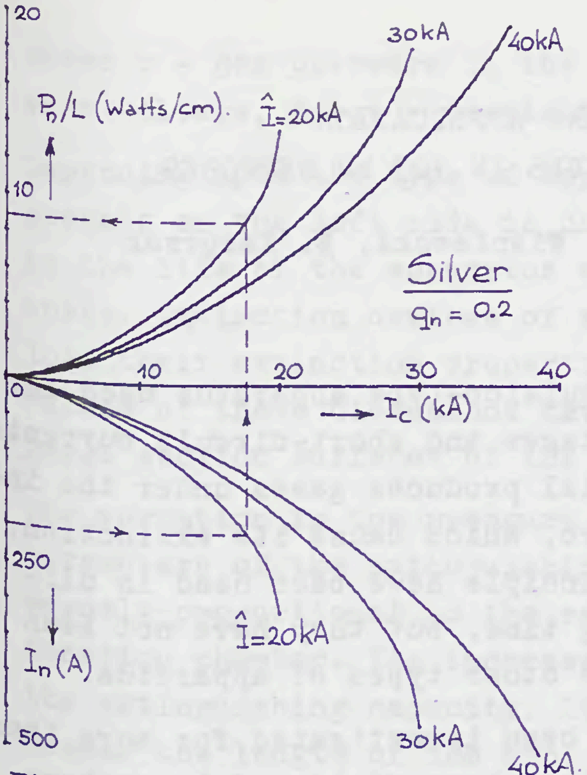

Fig. 4

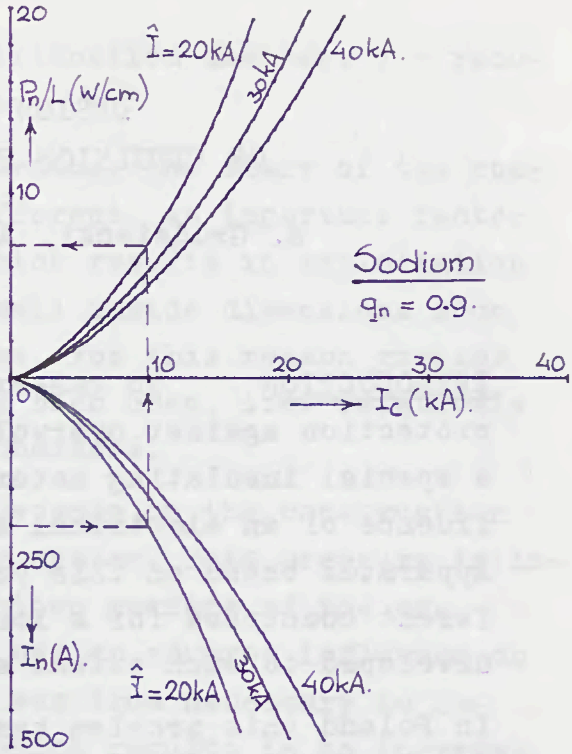

Fig. 5

Cut-off current I_c of long fuse wires (Ag and Na) as a function of the nominal current I_n and the heat dissipation per unit length P_n/L. Peak value of prospective current $\hat{I}$ is parameter.

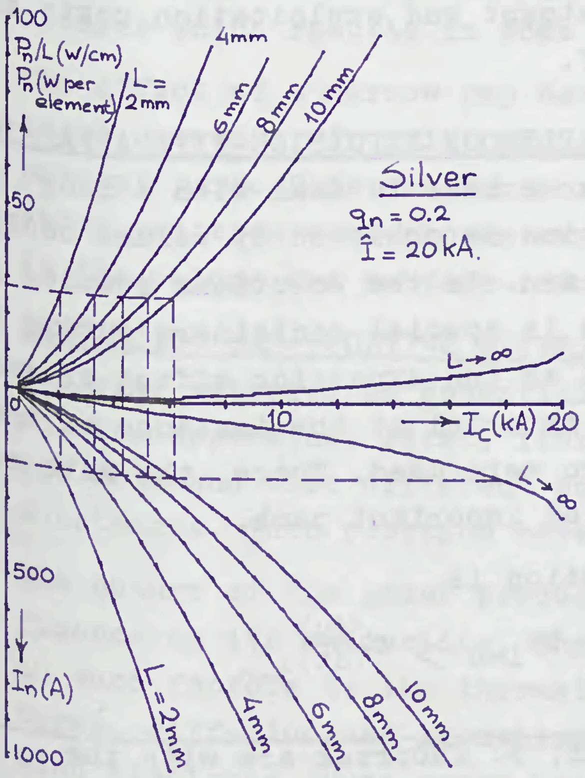

Fig. 6

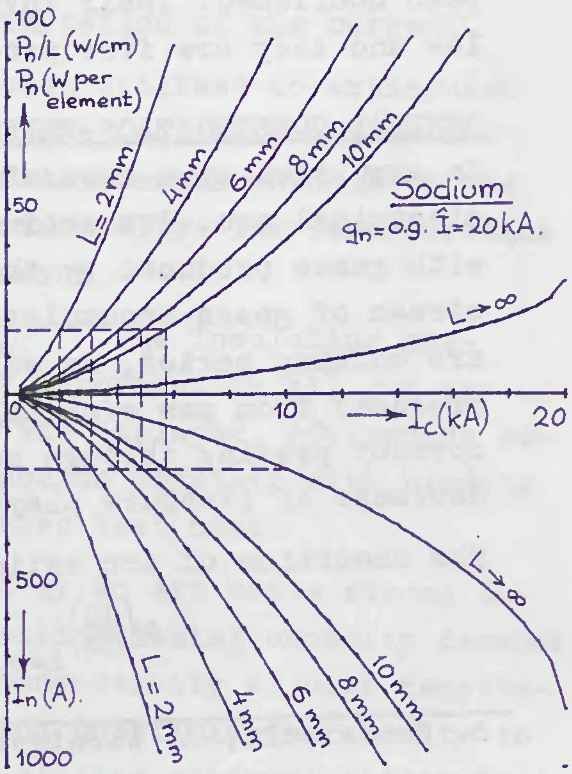

Fig. 7

Cut-off current I_c of short fuse wires (Ag and Na) as a function of I_n and P_n per short fuse-element, in a circuit with prospective current with peak value $\hat{I} = 20$ kA. Length L of short fuse-element is parameter.

DESIGN AND APPLICATION OF EXPULSION FUSES IN 123 kV NETWORKS

S. Grudziecki, A. Wiśniewski, B. Kacprzak

INTRODUCTION In gas-expulsion-type apparatus used for protection against overvoltages and short-circuit currents, a special insulating material produces gases under the influence of an electrical arc, which cause its extinction. Apparatus based on this principle have been used in different countries for a long time, but they have not been developed to such extent as other types of apparatus.

In Poland this problem has been investigated for more than 20 years. On the basis of long-term field and laboratory research, the usefulness of their application as apparatus of universal use, with moderate technical parameters has been confirmed. Their investment and exploitation costs are low and they are fire proof.

GENERAL CONSTRUCTION PRINCIPLES OF EXPULSION-TYPE APPARATUS

In expulsion-type apparatus we have to deal with a long electrical arc. Its extinction is achieved by volume cooling with gases produced by the arc. In the solutions studied a stream of gases accumulated in special containers during the arc burning period, as well as the expansion effect of gases produced from gas evolving material at the instance of the current passing through zero were used. There, the rate of decrease of pressure plays an important part.

The condition of arc extinction is

$$a\left(\frac{dp}{dt}\right)_{i=o} + bp_{i=o} > c\left(\frac{du}{dt}\right)_{i=o}$$

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where p - gas pressure in the extinction chamber, u - recovery voltage, a,b,c - constants.

Depending upon the type of apparatus, the share of the components on the left side is different. An important factor is the life of the apparatus which results in exploitation costs. Extinction devices of small inside dimensions soon lose their extinction properties. For this reason greater values of these dimensions have been used, i.e. relatively large section surfaces of the chambers.

The variation in the pressure depends on the construction parameters of the extinguishing system. This pressure is inversely proportional to the section surface of the extinction chamber. Its increase has an adverse influence on the extinguishing capacity. It was thus necessary to increase the length of the arc, which results in an increase of the power and consequently in an increase of the pressure and a decrease of the recovery-voltage gradient. Owing to the increase of the arc length the voltage drop on it increases which results in some limitation of the current.

The effect of a narrow gap has been utilised to extinguish small currents. In this case surface cooling plays an important part. Construction parameters corresponding to the above relation were chosen experimentally. The same pertains to the volume and surface insulation.

INSULATING GAS-EVOLVING MATERIAL The insulating gas-evolving material is essentially important in all gas-expulsion apparatus. First, fibre was employed, afterwards boric acid and then different compounds together with binding substances. Pure plastics have also been used.

The nature of the gases produced by an arc has a strong influence on its extinction. The extinguishing capacity depends on such factors as the thermal conductivity at high temperatures, diffusion and recombination coefficients, ability to bind electrons. Most gases have similar extinguishing capacities. Hydrogen is specially good owing to a high thermal conductivity at arc temperatures and large diffusion coefficient. An essential problem is the state of the surface of the gas-evolving material after the arc extinction. The conducting deposits may lead to arc reignitions.

A new gas-evolving material has been applied. It comprises an inorganic component $Al_2O_3 \cdot 3\ H_2O$ and an organic one as a binding agent. Under the action of an arc a quick water vapour evolution occurs. The organic component is also decomposed, giving hydrogen and carbon. As the average temperature of the gases exceeds 1300 K, a reaction takes place :

$$C + 2\ H_2O \rightarrow CO + H_2 - 31{,}4\ Cal$$

Then the formation of the C deposit becomes difficult. The reaction is endothermic, which assists in the extinction of an arc. Indeed, this reaction also takes place near the passage of the current through zero, and some part of the thermal energy accumulated in the arc column may be absorbed. The hydrogen produced in this reaction, together with that from the decomposition of the organic component, plays an important part in the extinction process. The organic component besides the binding and the production of gases, plays an additional role. It renders impossible the creation of a high temperature resistant layer of Al_2O_3 .

The investigations have shown that superficial insulating properties of this material do not change under the influence of the electric arc. The ability to expand gases is less than in the case of other materials. This is why apparatus using such a material have suitable gas containers in order to give an adequate gas stream during the zero-value of the current. Research has shown that the consumption of this material is lower than that of others.

<u>THE 123 kV FUSE SHORT-CIRCUITING SWITCH</u> On the basis of the above principles of the arc extinction and gas evolving material, different types of apparatus for the protection against atmospheric overvoltages and against short-circuit current, as well as apparatus for switching purposes have been built. One of them will be described as follows.

<u>Design</u> 123 kV lines are now distribution lines. For economic reasons simplified stations with short-circuiting switches are being used more and more instead of circuit-

breakers /Fig.1/. In these stations relatively small short-circuit currents occur. A disadvantage of the short-circuiting switches is the overloading of the circuit-breakers in principal stations. This and some other exploitation disadvantages lead to limiting the number of the simplified stations. In order to eliminate these disadvantages and to apply the simplified stations more extensively, a new type of apparatus has been studied, this comprising a short-circuiting switch and expulsion fuses. It is presented schematically in Fig.2. In Fig.3 a cross-section of the expulsion-type fuse is shown. A fuse-link of silver foil is placed on a gas-evolving rod of such diameter, that there is no corona. The arc is produced in a gap between the rod and the gas-evolving tube. A gas-container facilitates the arc extinction. The gas-evolving tube is strengthened mechanically with epoxy-glass tube.

<u>Application</u> The scheme of a simplified station is shown in Fig.4. The 123 kV fuse-short-circuiting switch is realised in a three-phase scheme. Each phase comprises two series-connected fuse elements and one short-circuiting switch. The short-circuiting switches of each phase are combined together and driven by a common spring mechanism. The cooperation of the fuses with the short-circuiting switches consists in the fact that the short-circuiting switches released by the overcurrent protection always cause three-phase ground short-circuits, eliminated afterwards by the fuses. Reversed functioning is also possible. The melting of a fuse may occur in one phase following a fault in the network. One fuse element of each phase is mounted rotationally and rotates after melting under the influence of gravitational force, releasing the short-circuiting switch mechanism in the last phase of the motion, which causes three-phase short-circuit. This short-circuit is afterwards eliminated by other fuses.

The switching off and on of the station is realised with an isolating switch with a switch closer. The switch closer has an automatic block system which makes the switching on and off of the load-current impossible. The fuse-short-circuiting switch, as opposed to the existing simplified solutions, switches off the faulty station at once, without the action of the automatic reclosing in principal stations. Then a fault in one station is not felt by other stations connected to the same transmision line. The ground short-circuit current during the functioning of the fuse-short-circuiting switch is very small, resulting from the asymetry and can be neglected. This is important because of ground voltage drops /security reasons/. Besides, the short-circuit duration is small, resulting from the functioning of fuses. It is also possible to apply 123 kV fuses in important stations, as a reserve protection.

Tests These fuse elements are constructed in such a manner that they do not melt under overload currents. They act only under short-circuit currents. For example in Fig.5 the pre-arcing time/current characteristic of the fuses for 63 A rated current is shown. Proper coordination between the time/current characteristics of the 123 kV fuses and those of the 123 kV and 17,5 kV overcurrent protection devices is ensured.

The short-circuit current breaking tests were made in the - laboratory /oscillograph records in Fig.7/ and in 123 kV net-works with the grounded neutral /osc.rec.in Fig.8/. In Fig.6 the arcing times are shown. They are always lower than one cycle. There are no dangerous overvoltages.

CONCLUSION The above described fuse-short-circuiting switch is a useful apparatus for the protection of the simplified stations in the distribution 123 kV networks from both technical and economic reasons.

REFERENCES 1. Grudziecki S.: Nowy materiał izolacyjno-gazujący, Piorun i Ochrona odgromowa, Acta Technica Gedanensia nr 2, GTN, 1963.

2. Grudziecki S.: Zespół odłącznika i bezpieczników wysokiego napięcia typu napowietrznego, Opis pat.PRL nr 45690, 1961.

3. Grudziecki S., Wiśniewski A., Kacprzak B.: Bezpiecznikozwiernik wysokiego napięcia, Opis pat. PRL nr 62422, 1968.

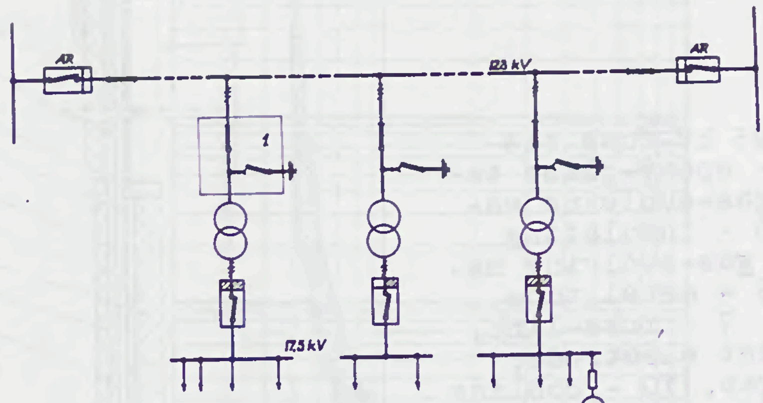

Fig.1. Scheme of the 123/17,5 kV network with simplified stations. 1 - short-circuiting switch with coupled isolating switch. AR - automatic reclosing.

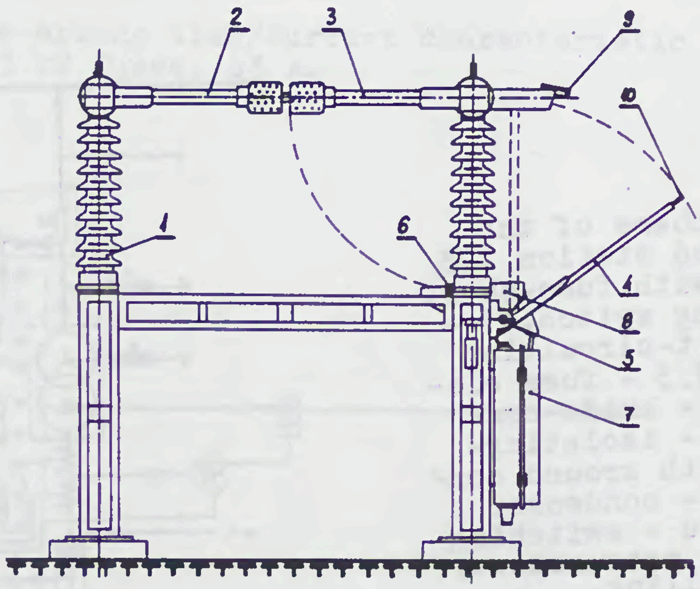

Fig.2. 123 fuse short circuiting switch. 1 - stand-insulator, 2 - immovable fuse element, 3 - rotationally mounted fuse element, 4 - short-circuiting switch knife-contact, 5 - drive-shaft, 6 - lock release device, 7,8 - casings, 9 - immovable contact, 10 - arcing contact.

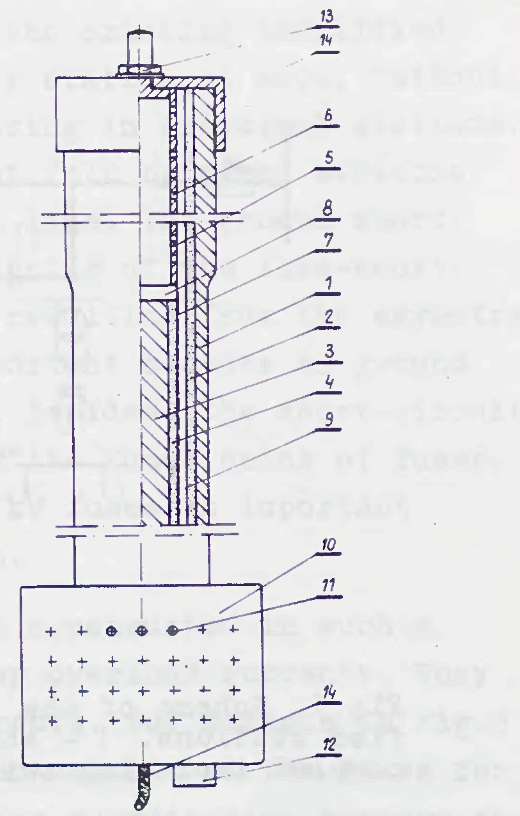

Fig.3. 123 kV-fuse element. 1 - epoxy-glass tube, 2 - gas-evolving material, 3 - insulating rod, 4 - gas-evolving material, 5 - metal tube, 6 - hole, 7 - fuse-link, 8 - contact electrode, 9 - air-gap, 10 - cooling device, 11 - hole, 12 - contact, 13 - nut, 14 - flexible cable.

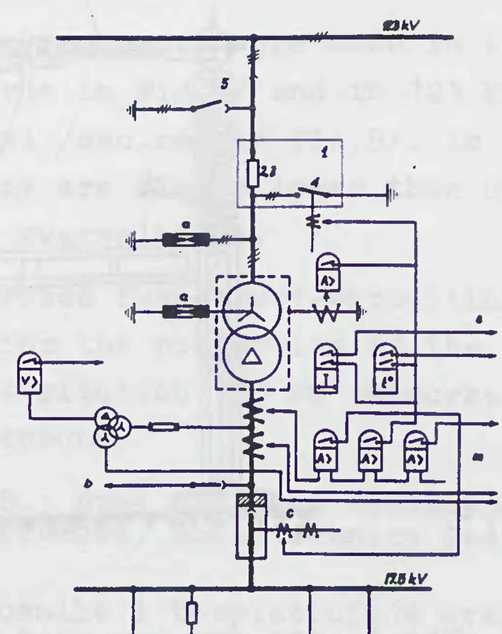

Fig.4. Scheme of the simplified station 123/17,5 kV with fuse-short-circuiting switch. 1 - fuse short-circuiting switch, 2,3 - fuse elements, 4 - knife-contacts, 5 - isolating-switch with ground contacts, b - condenser battery, c - switching coil, m - measurement, s - sygnalling.

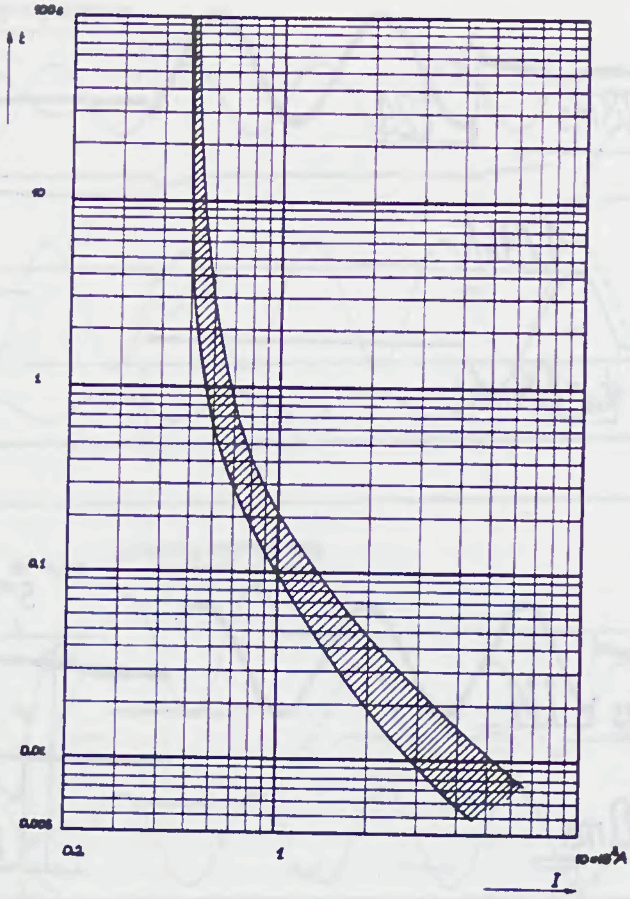

Fig.5. Pre-arcing time/current characteristic of the 123 kV fuses, 63 A.

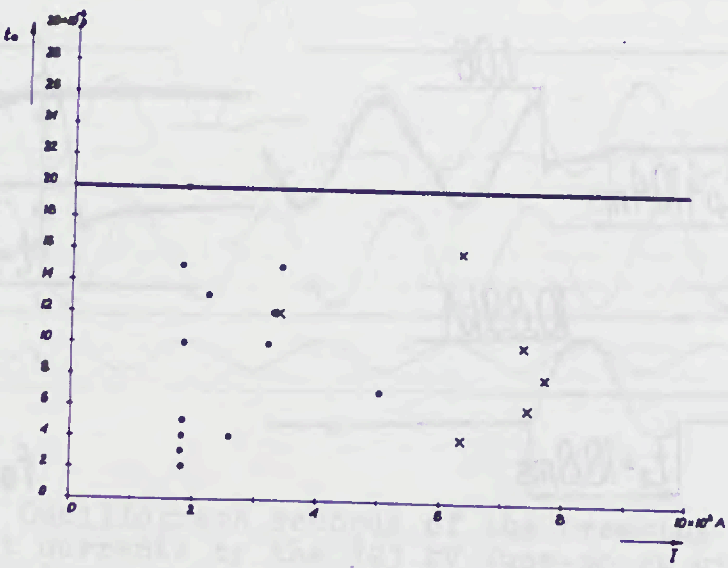

Fig.6. Arcing time versus current of the 123 kV fuses. Different rated currents ; x - laboratory tests ; • - field tests.

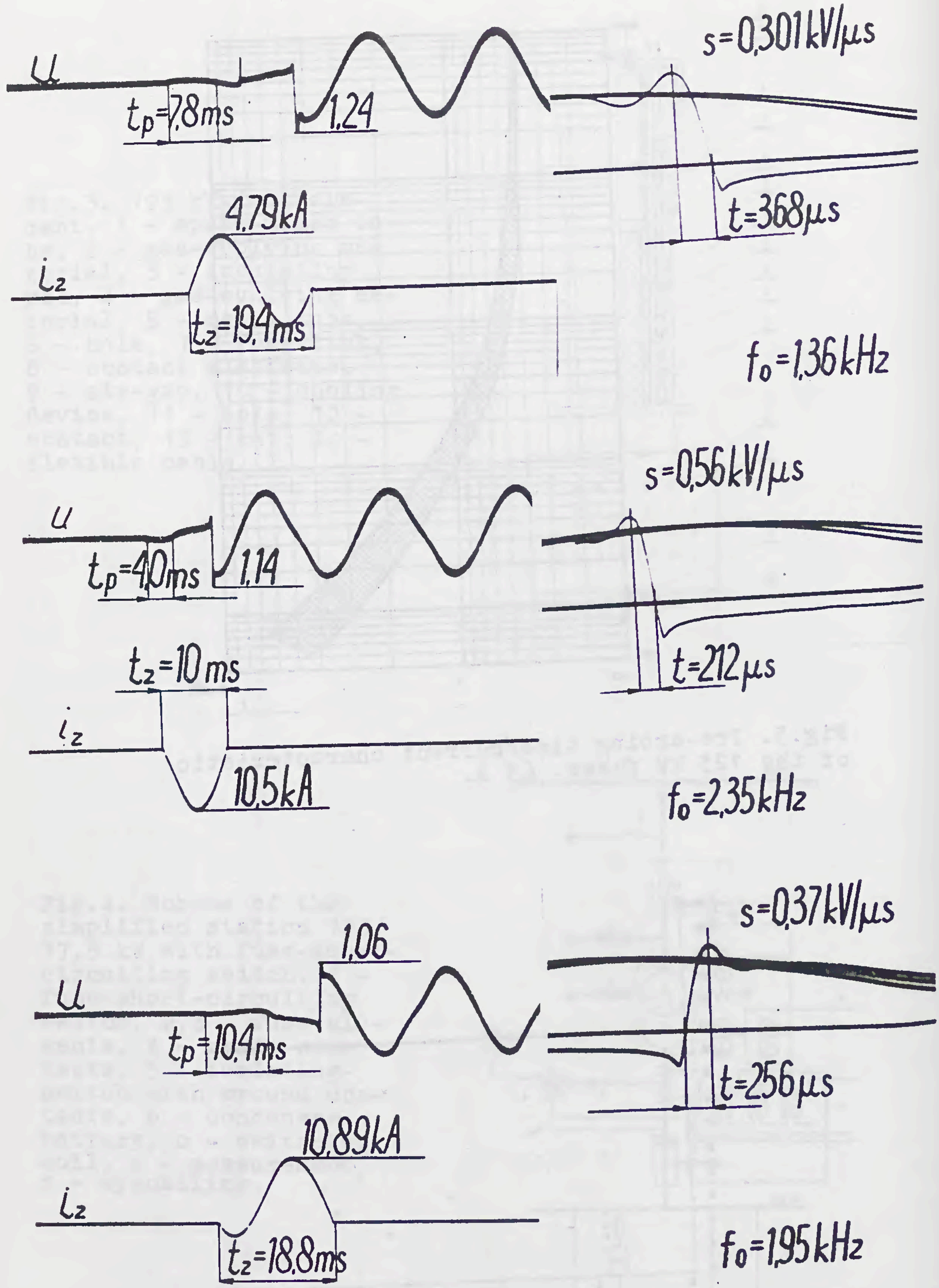

Fig.7. Oscillograph records of the breaking of short-circuit currents by the 123 kV fuse-short-circuiting switch. Phase to ground recovery-voltage. Laboratory tests.

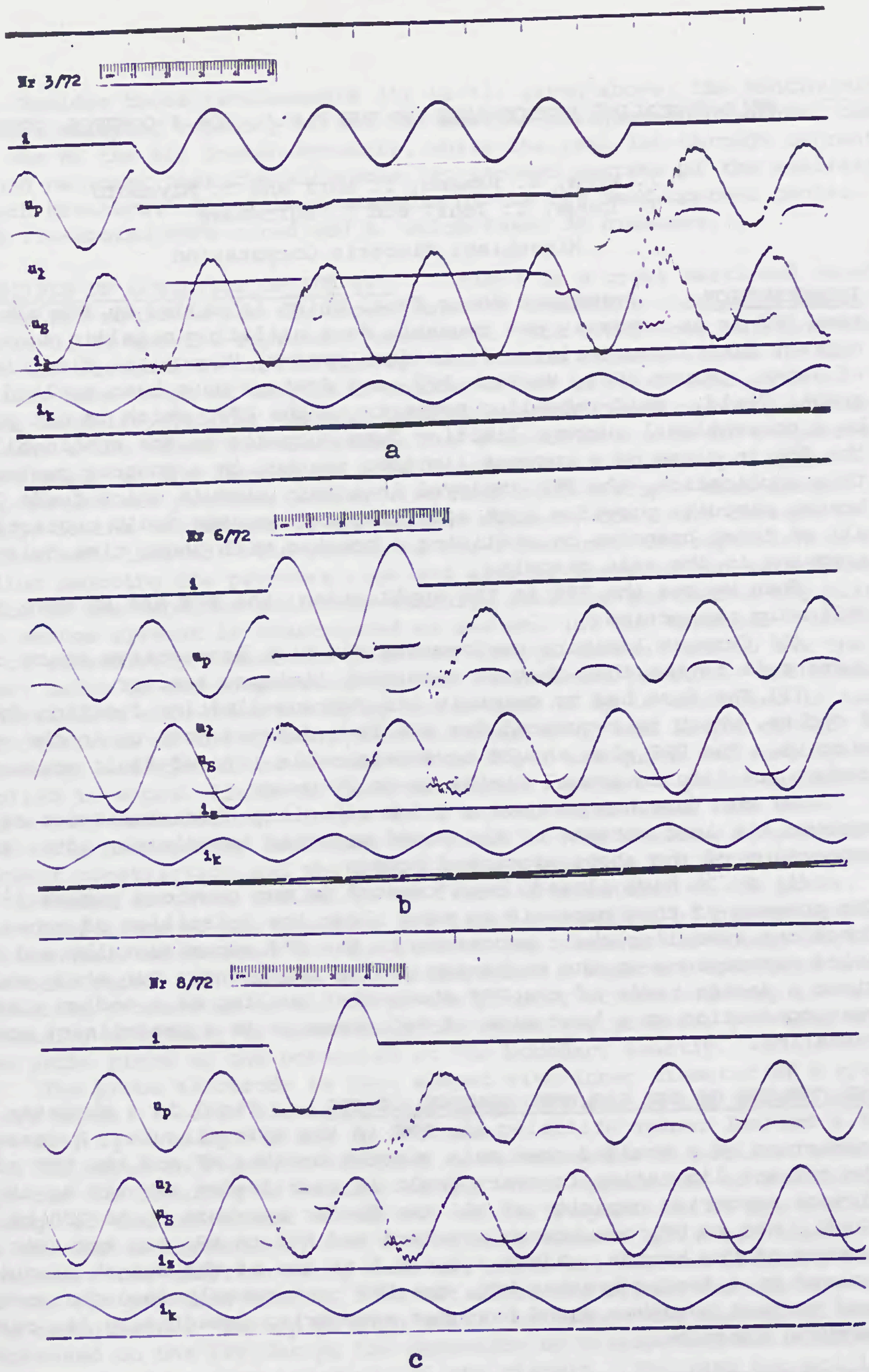

Fig.8. Oscillograph records of the breaking of short-circuit currents by the 123 kV fuse-short circuiting switch. Phase to ground recovery-voltage. Tests in 123 kV networks with the grounded neutral; a - 1800 A, b - 3200 A, c - 3400 A.

SELF-REHEALING PERFORMANCE OF THE P.P.F. FOR A CONTROL CENTER

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** T. Inoue, I. Ishii and T. Shirasawa

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INTRODUCTION Permanent Power Fuse, which is called by the abbreviated name PPF is an entirely new reusable fuse utilizing metallic sodium as a current limiting material. It is developed by Mitsubishi Electric Corp. of Japan. Since 1969, various PPF used devices have been applied to the actual field. Self-rehealing property of the PPF, which is not possessed by a conventional current limiting fuse suggests us the applicability of the PPF in place of a current limiting reactor in a control center. In this application, the PPF employed in a main circuit which feeds 20 to 30 branch circuits provides both selective and cascade fault protection to all of those branches by utilizing a breaker with short time delayed trapping in the main circuit.

When we use the PPF in the application, the PPF has to have the following properties.

(1) Current limiting performance for high prospective short circuit current is better than that of a current limiting reactor.

(2) The fuse has to maintain its current limiting function for about 3 cycles, which is requested for the time delayed back up in the main circuit. The PPF also should have reasonable life of fault protection during its life in actual fields up to 30 years.

(3) The fuse has to have a quick rehealing characteristics so as to recover the load current of the sound branches immediately after the disconnection of the short circuited branch.

(1) & (2) have already been treated in our previous papers.[(1)(2)(3)] The purpose of this paper is to make clear the definition of rehealing functions revealing their processes in the PPF experimentally and to give brief discussions on the mechanism of the rehealing. Our study which has given a design basis of the PPF shows that cooling of a sodium element by heat conduction to a heat sink of BeO ceramics is a predominant power of rehealing.

THE OUTLINE OF THE PPF USED CONTROL CENTER Fig-1 is a skeleton circuit of a control center utilizing the PPF in the main circuit. A cascade connection of a moulded case main circuit breaker NF and the PPF provides the current limitation to every fault in each feeder circuit so as to elevate rupturing capacity of all the feeder breakers up to 200 kA. at 460 V. NF1 to NF_n are branch breakers and MS1 to MS_n are magnetic contactors of the branch. After a fault A at one of the branch circuits is removed by a feeder breaker NF1, the PPF continuously feed the normal load current to other sound branches recovering immediately its current carrying functions.

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Besides those requirements (1) to (3) given above, the continuous current carrying capacity of the PPF must be designed to be higher than the sum of the all branch breakers, while the peak let-through current should be lower than the allowable let-through current of the smallest branch breakers. Fig-2 is an example of the PPF used control center with fin-cooled PPFs rated 800 A. which feeds 30 branches.

PRINCIPLE OF OPERATION OF THE PPF Fig-3 is a cross sectional drawing of the PPF modified for the experiments of rehealing characteristics. In Fig-3, TI and TII represent terminals. The continuous current flows from the terminal TI to TII through the sodium element inside of the ceramic tube (made of beryllium oxcide) which is reinforced with an outer metallic cylinder through another special ceramics. The sodium element which shows low resistance for a continuous current evaporates immediately on the flowing of a fault current establishing a high temperature and pressure plasma with high resistivity. With abrupt change of the resistance of the sodium element, the fault current is effectively limited. The piston in Fig-3 controls the expansion of the sodium reducing the pressure rise and also it provides the self-rehealing force to the expanded sodium by the high pressure gas behind the piston. The sodium element is constricted at one end (of the terminal-I-side) so as to effectively reduce the peak let-through current and to fix the start point of the evaporation at the constricted portion. The current constriction with diameter of d_1 and length of ℓ_1 is connected in tandem with the rest of the element with diameter of d_2 and length of ℓ_2. The structure and dimensions of the PPF in Fig-3 are quite the same as those applied in actual fields in control centers, except a probe electrode and a lead extended out of the PPF. Experimental model PPFs were specially prepared by inserting the probe at the boundary between the current constriction and the rest of the element. The probe electrode is intended to catch variations of floating potential at the probe.

Difference of the specific and local properties of plasma between the constricted section and the rest of the element was suggested in our previous paper (3). Since this difference is expected to affect the rehealing properties in the PPFs, the probing at the boundary is essentially necessary to understand the rehealing process, provided that the probe picks up the potential at the boundary exactly.

The probe electrode is disc shaped with inner diameter of 8 m/m and 5 m/m thick. Sodium element of the model PPF tested has dimensions of $d_1 = 3.5$, $\ell_1 = 7$, $d_2 = 6$ and $\ell_2 = 30$ m/m.

As shown in Fig-1, a resistor R_p is connected in parallel with the PPF for the lowering of voltage surges which appear due to the abrupt change of the resistance of the PPF at the evaporation of the sodium. As the PPF is essentially not a switching element but a non-linear resistor, the addition of R_p does not lower the current limiting function of the PPF provided that R_p does not seriously affect the current limiting performance. The R_p is also useful to reduce the mechanical stresses impressed on the PPF during the operation by dissipating the electrical energy stored in the inductance of the circuit. The last but not least, another important function of R_p is to feed necessary power to the feeder branches within its heat capacity whenever the power supplying is effective to attain the maximum service continuity against the branch feeders. Especially, when resistance of the PPF is higher than R_p, R_p shares the function of the power supply. It is needless to say that R_p does not have continuous current carrying function since the resistance of the PPF is always extremely lower than R_p for the continuous current.

THE SELF-REHEALING FUNCTION In the PPF used control center, the maximum service continuity should be provided to sound branches after the removal of a short circuited branch. Continuity of the supply of load current must be sustained to the sound branches without break. The parallel connection of the sodium element and R_p should provide the load current. To supply the load current under low ohmic drop across the sodium element shunted by R_p, resistance of the sodium element should become low enough as soon as possible after the current limiting operation. The load current means both the rated continuous current and over load current.

Generally, the over load current flows through the main circuit transiently when various types of perturbations occur on the bus line (V_B in Fig-1) voltage. Among these perturbations, instantaneous break due to high speed reclosing on h.v. primary line, and drop of line voltage caused by the fault at one of branches are included. The latter perturbation is caused by the fault at one of branches. In clearing the fault, the sodium element should evaporate and limit the fault current. In this case, over current always flows through the hot sodium element just after its current limiting operation.

Since the magnitude of the over current becomes considerable value when many motors are driven in feeder branches, it has been quantitatively estimated by means of a digital simulation program SCAP-M developed by Mitsubishi Electric Corp. assuming various types of perturbations with various durations. The calculated results shows that the maximum over current is about 1800 A. peak for a motor of 460 V. 90 kW. and it decays within 200 ms. finally to a rated continuous load current of 160 A. Such a transient rush over load current integrated over every motor in sound branches should be fed through the hot sodium element. The sodium element should recover its initial resistance for the continuous supply of the rated total load current.

It is thus requested for the element in the PPF for a control center to recover its initial resistance supplying the over load current through the element of itself during it is still hot.

Hereafter, the rehealing characteristics of the sodium element from high temperature current limiting plasma to transcritical liquid of sodium are investigated experimentally chosing the magnitude of the over load current as a parameter.

TEST CIRCUIT Fig-4 is the test circuit. In Fig-4, NFB which simulates the short circuited branch breaker and the resistor RL which simulates the over load current of other sound branches are connected in parallel each other.

At first, S and NFB are closed. The closing switch S initiates the fault through the PPF and NFB. The prospective short circuit current was adjusted to 60 kA asym. peak for all test cases.

After the arcing time of one half cycle, NFB removes the fault disconnecting the circuit of itself. Immediately after that, the current is continuously transferred to the resistor RL. Each of I_N, I_{NFB} and I_R is current through the sodium element, NFB and the resistor respectively. I_{NFB} limited by the PPF was 30 kA. crest. I_R from 140 A to 6000 A rms was tested. Variations of the potential of the probe electrode were measured with V_1 and V_2 by grounding one end of the sodium element at E.

EXPERIMENTAL RESULTS AND DISCUSSION Fig-5 and 6 are typical oscillograms which contain transients of V_T, V_2, I_R, I_N, I_T, I_{NFB} from the beginning of the fault untill the sodium element finally recovers current carrying capability of I_R after the clearing of the fault. I_R in Fig-5 and 6 is 140 A. and 3520 A. respectively. In these figures, v_T and v_2 are magnified signals of V_T and V_2.

Typical current wave forms are schematically shown in Fig-7. Fig-7 corresponds to the oscillogram of Fig-6 at I_R = 3520 A. In Fig-7, I_{NF} is limited effectively untill I_{NF} is interrupted finally at point X. I_N does not instantly recover I_R at X but at point Y. While, I_T in Fig-7 demonstrates that the over load current I_R starts to flow continuously at Z just after the finish of current limitation for the first major loop of the fault current. I_R is supplied through R_p as is illustrated clearly by the wave form of I_{Rp}. The continuity of the supplying of the over load current beyond X until Y is attained through R_p. Beyond the point Y, I_N fully recovers I_R and I_{Rp} disappears. In other wors, I_N is quite the same with I_R beyond the point Y. The resistivity of the sodium element is considered to be low enough to let-through I_R at the point Y. It should be noted that I_N recovers I_R instantly at the point X when I_R is smaller than 1200 A.r.m.s.

Fig-8 and 9 represent variations of the resistivity of the sodium element against time. X and Y correspond to each notation in Fig-7. The resistivity is expressed by a ratio P/P_o, where P_o means a resistivity of the solid sodium at 0 °C. (4.5 μΩ•cm). Point A in Figures of 8 and 9 corresponds to the point of the abrupt decrease of I_N just after the peak let-through current. Point B corresponds to the first current zero of I_N for Fig-8 and to the second current zero of I_N for Fig-9. $P\ell_1$ and $P\ell_2$ represents the variation of P/P_o at the current constriction and at the rest of the element respectively.

From Figures 8 and 9, the followings are deduced.

(1) Self-rehealing of the sodium element is performed in 2 steps with double time constant. The first and fast time constant is observed at point B untill the sodium reheals to transcritical liquid through a phase transition. This first time constant is the order within 1 ms. The second time constant of the order of 50 ms. is observed beyond the point B, where the element reheals under liquid phase.

(2) In the first step rehealing, the resistivity changes widely from high temperature plasma with P/P_o of the order of 10^3 to the transcritical liquid with that of 35.

(3) When I_R is small, sodium element reheals to transcritical liquid at t = X. When I_R is larger than 1200 A. the element reheals to the same state at t = Y. Since I_R is supplied continuously through R_p during $X < t < Y$, service continuity is satisfactorily sustained still in this case.

(4) Beyond the point B, after the sodium element recovers to transcritical liquid state, both $P\ell_1$ and $P\ell_2$ decrease steady even when I_R flow through the element and $P\ell_1$ is slightly higher than $P\ell_2$.

The self-rehealing capability of the sodium element were revealed to be satisfactory within the range of I_R tested.

Fig-10 represents variations of $P\ell_1/P_o$ with I_R, setting point B in Figures of 8 and 9 at t = 0. For all cases, the fast decrease of $P\ell_1/P_o$ at t = 0 laps in a line. The first time constant is within 1 ms. for all cases even when I_R up to 6000 A.r.m.s. flows through the sodium element.

A characteristic of P/P_o vs. temperature is attached to Fig-10. Continuous increase of P/P_o is expected up to the temperature of a transcritical point of the sodium[4][5] pressurized with the high pressure gas behind the piston. The value of the gas pressure is denoted on the curve at each corresponding transcritical temperature. Beyond the transcritical temperature, definition of phase, gas or liquid, becomes to be impossible. Since sodium in the PPF is pressurized at 100 atm. by the high pressure gas behind the piston, the transcritical conditions are T_C = 1700 °C and P/P_O = 35.

Digital simulation was made on the process of the decrease of P/P_O below P/P_O = 35 in a liquid phase. Radial heat conduction from the sodium element coaxially confined in a BeO ceramic tube to the wall of the ceramics was treated on a digital computer simplifying the problem by utilizing cylindrical symmetry of the PPF. The initial conditions for the sodium element were chosen at P/P_O = 35 and transcritical temperature T_C = 1700 °C with enthalpy at T_C.

The calculated results are given in Fig-10 by C_1 and C_2. Each of C_1 and C_2 corresponds to experimentally obtained curve of 1 and 2 respectively. The calculations were made for the initial decrease of the resistivity just after the transcritical point. Considerable fast decrease of $P\ell_1/P_o$ in a liquid phase is explained from the calculation. These agreements suggest that cooling of the sodium element by heat conduction to a heat sink of BeO is a predominant power of rehealing.

According to a survey on the number of branches of motor circuit, capacity of motors in the branch circuits of actual control centers in the fields and to the results of the analysis made by the digital simulation method on the magnitude of the over current, it has been concluded that the PPF is satisfactorily applicable to the main circuit of a control center rated 800 A.r.m.s., if the PPF has a capability of rehealing, supplying a over current of 400 A.r.m.s. for a duration of 30 ms.

Steady rehealing capability of the PPF is demonstrated in Fig-10 up to 5340 A. r.m.s. Although data are not shown in Fig-10, successful rehealing were confirmed under I_R up to 6000 A. and its duration of 200 ms.

Magnitudes of I_R tested are plotted with their durations on the cold start over current vs. time characteristic of the PPF as shown in Fig-11. It should be noted that the cold start over current vs. time characteristic is very close to the plots, especially to I_R of 6000 A.r.m.s. for a duration of 200 ms.

The current limiting operation enabled by the super critical plasma of the sodium does not have an influence on the over current carrying capability of the sodium element.

In other words, the over current carrying capability of the PPF is given always by its over current vs. time characteristic for a cold start even immediately after a current limiting operation.

The self-rehealing properties of the PPF thus revealed in this paper have given a coordination design basis of the PPF for control centers which provide both selective and cascade fault protection up to 200 kA keeping the maximum service continuity against sound branches.

REFERENCES

(1) T. Ito, T. Miyamoto, N. Takano: IEEE 1970 Summer Power Meeting Paper No.70 CP 601 PWR

(2) T. Ito, T. Miyamoto and Y. Wada: IEEE Winter Meeting 1972 Paper No. C72 103-5

(3) T. Ito, T. Miyamoto, Y. Wada, T. Mori and H. Sasao: IEEE Winter Meeting 1973 IEEE Trans. Vol. PAS-92, No.4 July. August 1973 pp. 1292-1297
(4) NASA Tech. Note: NASA-TN-D-2849 (1965)
(5) F. Hensel: Proc. 2nd International Conf. at Tokyo, Properties of Liquid Metals pp.357-363 (1973)

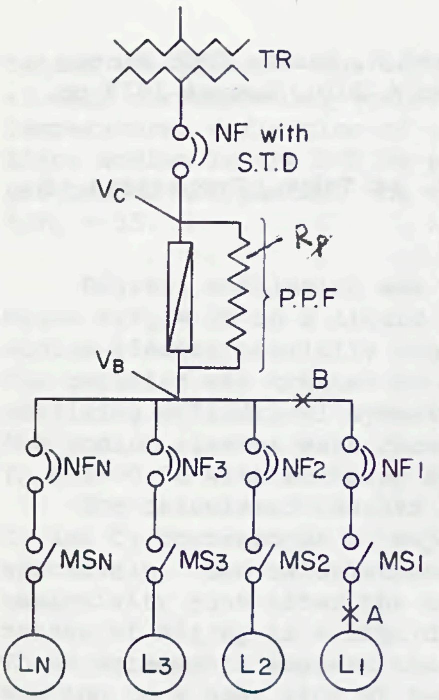

Fig-2. Outside view of the PPFused control center

Fig-1. Skeleton circuit diagram of a control center utilizing the P.P.F

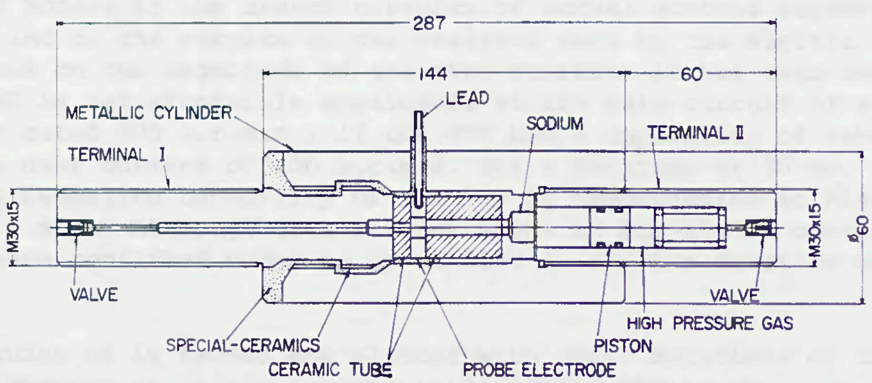

Fig-3. Cross sectional drawing of the P.P.F with a probe electrode

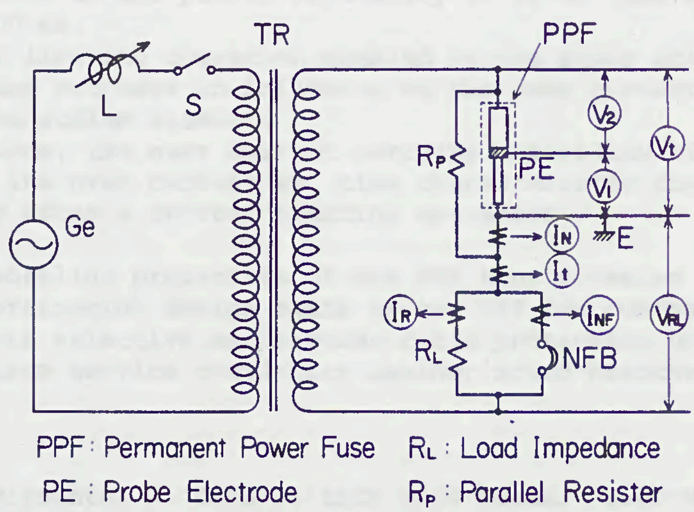

Fig-4. Equivalent test circuit for the rehealing characteristic of the P.P.F

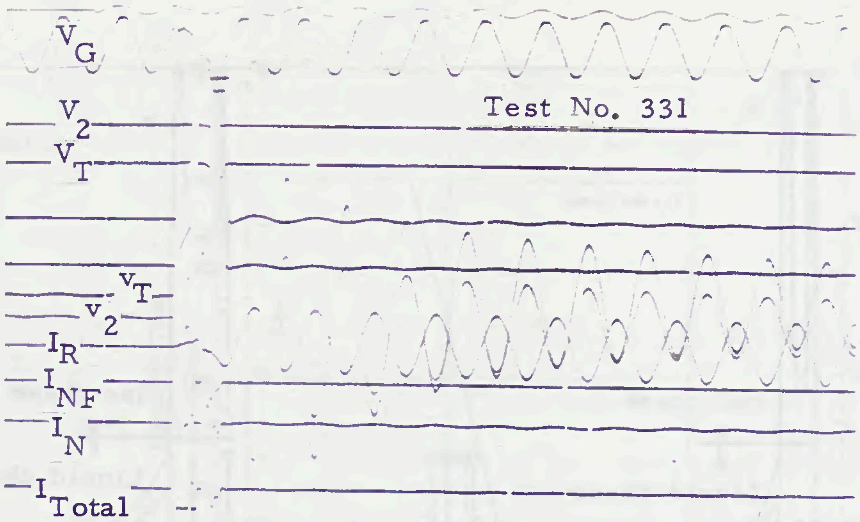

Fig-5. Typical oscillogram of a equivalent test at I_R = 140A_{rms}

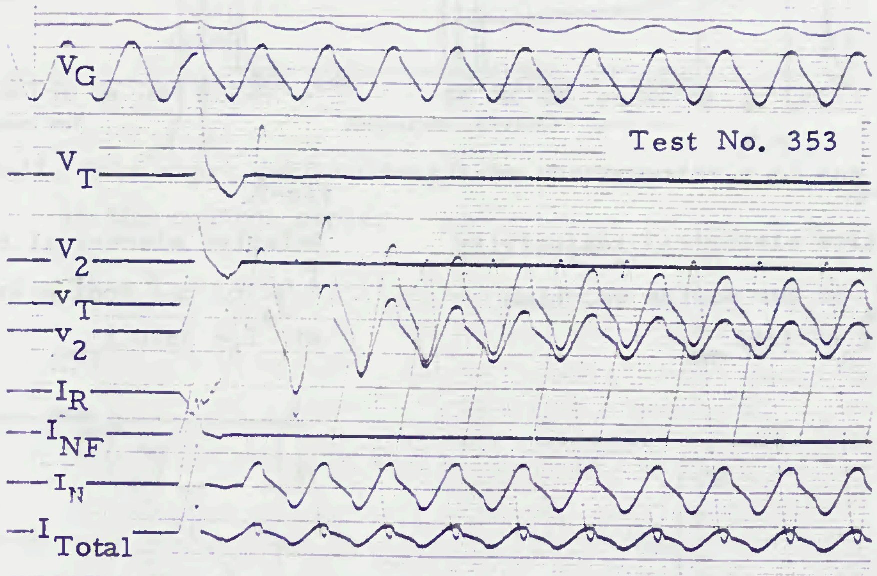

Fig-6. Typical oscillogram of a equivalent test at I_R = 3520A_{rms}

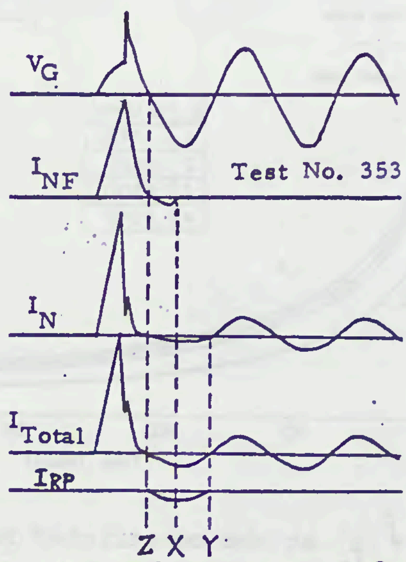

Fig-7. Voltage and current waveforms during the first few cycles (correspond to Fig-6.)

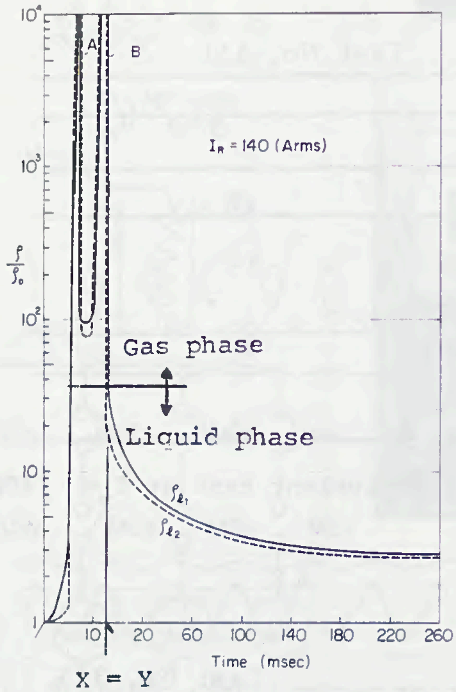

Fig-8.

Relative electrical resistivity ρ/ρ_o of the Sodium vs. time at I_R = 140A_{rms} .

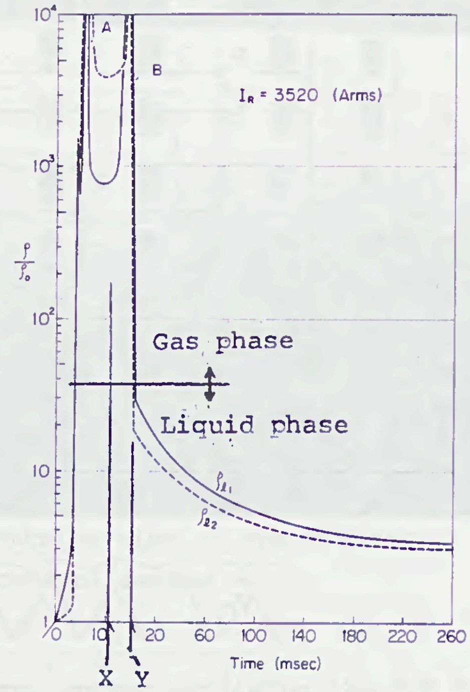

Fig-9.

Relative electrical resistivity ρ/ρ_o of the Sodium vs. time at I_R= 3520 A_{rms}

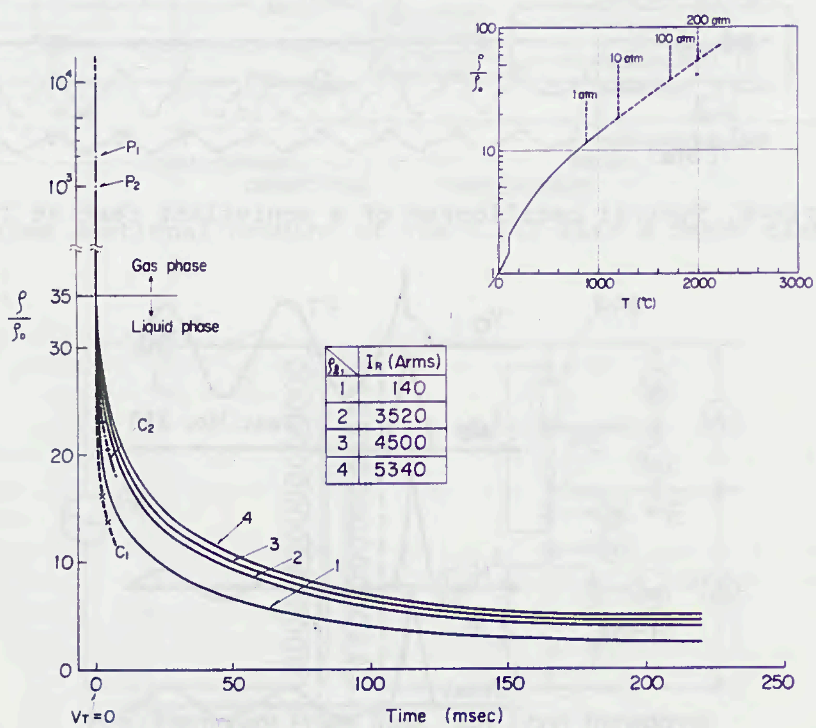

Fig-10. ρ/ρ_o at the constricted portion vs. time and characteristic of ρ/ρ vs. temperature (4) (5)

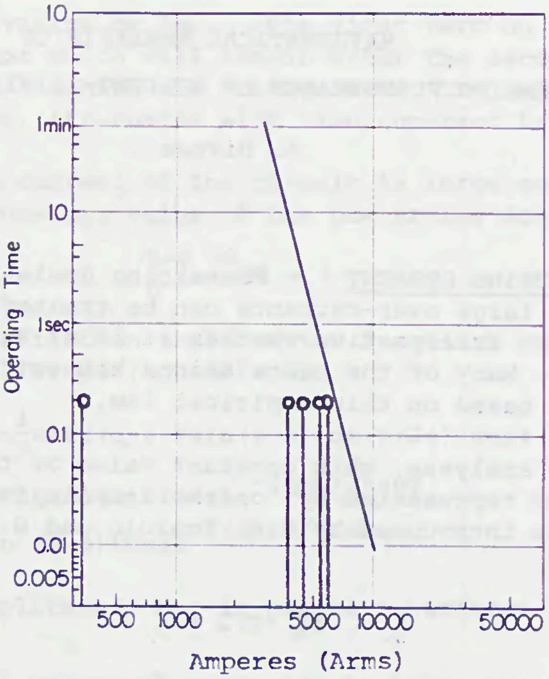

Fig-11. Cold start over current/time characteristic of the P.P.F in the control center

MATHEMATICAL ANALYSIS OF BREAKING PERFORMANCE OF CURRENT- LIMITING FUSES

A. Hirose

ONE-HALF-CYCLE FUSING CURRENT Pre-arcing Joule-integral of a fuse-link for sufficiently large over-currents can be treated as a constant specific to that fuse-link, irrespective whether it is of current-limiting or of expulsion type. Many of the calculations hitherto made on pre-arcing phenomena have been based on this empirical law.

In the following analyses, this constant value of the pre-arcing Joule-integral shall be represented by "one-half-cycle fusing current" $I_{T/2}$ [A] of the fuse-link, as introduced by S.B. Toniolo and G. Cantarella. It is defined by

(1) $$I_{T/2}^2 \cdot T/2 = K$$

where T denotes one period of the power frequency in seconds and K means the constant Joule-integral of the fuse-link in $A^2 \cdot s$. Re-writing (1), we get

(2) $$I_{T/2} = 10\sqrt{K} \quad \text{for 50 Hz, and}$$
$$= 11\sqrt{K} \quad \text{for 60 Hz.}$$

In most cases, these values are nearly equal to one-half-cycle fusing current on the time-current characteristic; however, for semi-conductor fuses and for micro-fuses, these values are often considerably smaller than the current given by the time-current characteristic.

Also, in the followings, all currents in a.c. and d.c. circuits shall be expressed in multiples of $I_{T/2}$ of the fuse-link to be put in the circuit. This manupulation makes the results of mathematical analyses applicable to wide varieties of circumstances: a single formula or a single diagram will now be able to cover wide range of prospective current combined with varieties of ratings of fuse-links.

MAKING ANGLE DIAGRAM When the source voltage $e=\sqrt{2}E \sin(\theta+\psi)$, where $\theta= 2\pi t/T$, is applied to a fused circuit of power factor angle ϕ at the instant t=0 or θ=0, the following current will flow in the circuit:

(3) $$\bar{i} = \sqrt{2}\bar{I}[\sin(\theta+\psi-\phi) - \sin(\psi-\phi)\varepsilon^{-\theta/\tan\phi}]$$

where both the instantaneous value of current and the prospective current are expressed in terms of $I_{T/2}$ of the fuse-link in the circuit and the short lines over the symbols indicate that these quantities have been made

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dimension-less by dividing by $I_{T/2}$. The first term on the right side of (3) gives a.c. current which will remain after the second term has subsided, lagging angle ϕ behind the voltage wave; the second term, canceling the first term at $\theta=0$, attenuates with time constant $L/R = T\cdot\tan\phi\,/2\pi$.

When the prospective current of the circuit is large enough, the fuse will operate giving the constant value of the pre-arcing Joule-integral, i.e.

$$(4) \qquad \int_0^{\theta_0-\psi} \bar{i}^2 d\theta = \pi$$

where θ_0 is the arc-initiation angle of the fuse-link on the voltage wave. Putting (3) into (4), we get[Appendix A]

$$(5) \qquad \bar{I}^2 = \pi[\theta_0-\psi-\frac{1}{2}\sin 2(\theta_0-\phi)+\sin(\psi-\phi)\cos(\psi+2\phi)/\cos\phi$$
$$+4\sin\theta_0\sin\phi\sin(\psi-\phi)\varepsilon^{-(\theta_0-\psi)/\tan\phi}$$
$$-\sin^2(\psi-\phi)\tan\phi\,\varepsilon^{-2(\theta_0-\psi)/\tan\phi}]^{-1}$$

Eq.(5) is rather complicated, but it can be re-written in the simplified form of

$$(6) \qquad \bar{I} = f(\theta_0,\psi,\phi)$$

which indicates that there exists a definite relationship among the prospective current in terms of $I_{T/2}$, arc-initiation angle Θ_0, making angle ψ on the voltage wave, and the power factor angle ϕ. Thus, if two parameters are specified, the relationship between the other two factors can be represented in a single diagram.

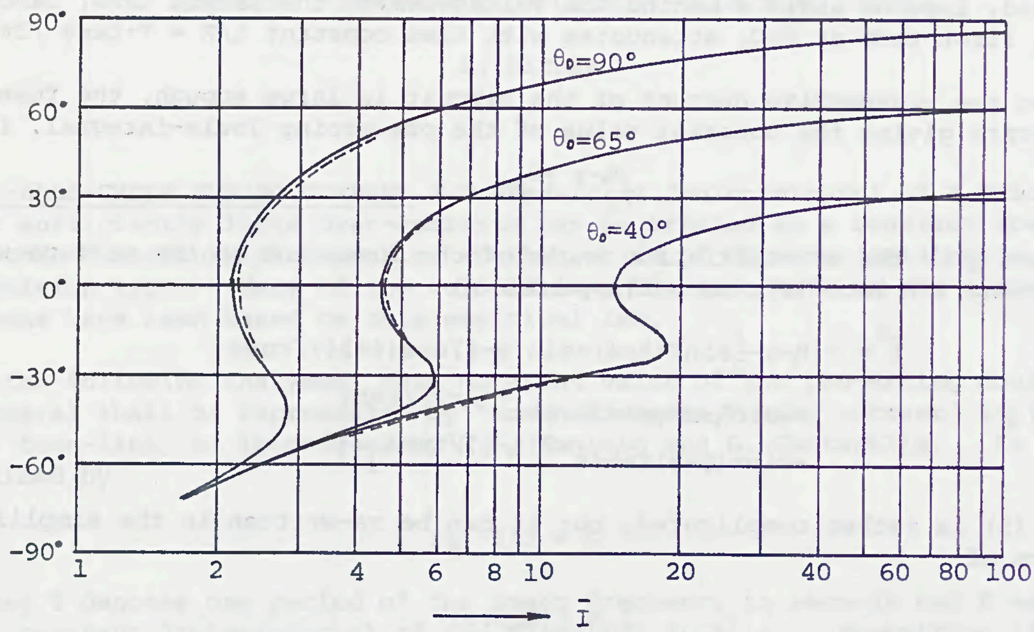
IEC Publications 269-1 and 282-1 prescribe regarding the breaking capacity tests that the arc-initiation angle θ_0 shall be from 40° to 65° for one test and from 65° to 90° for two tests. In answer to this requirement, Diagram 1 on top of the following page has been prepared, which represents the computed relationship between the making angle ψ and the breaking current in terms of $I_{T/2}$, taking the arc-initiation angle θ_0 as parameter and assuming the power factor of the test circuit as 0.05. The dotted lines are for power factor 0.15, which indicates the effect of the power factor is so small.

This Diagram indicates that for breaking capacity tests for $\bar{I} = 50$, the making angle of the test circuit should be chosen at about 45° for one test and at about 70° for two tests. This is applicable also for the case where the test frequency is 60 Hz, provided $I_{T/2}$, or the divisor of $\bar{I}$, is correctly calculated from (2).

It is noted that the IEC specification for the arc-initiation between 40° and 65° is impossible to be met for the test currents less than 4.5 in $\bar{I}$. Furthermore, if the current were less than 2.2, even the confinement of the arc-initiation between 65° and 90° becomes practically impossible.

<u>GENERALIZED CUTOFF CHARACTERISTIC FOR A.C.</u> Cutoff current of a current-limiting fuse-link having wire-elements, usually, coincides with the instantaneous current in the circuit at the instant of the arc-initiation. Thus, the latter should be examined in place of the cutoff current.

Diagram 1



So-called "cutoff characteristic" is composed of two parts: the lower inclined part where the cutoff may take place, and the higher inclined part where the cutoff never occurs. In any case, the cutoff current for a given prospective current is the maximum let-through current that could flow in a circuit for the most unfavourable making angle.

First the lower inclined portion should be studied. As stated before, the cutoff current of wire-element fuse-links can be deemed as equal to the instantaneous current $\bar{i}_o$ at the arc-initiation, which is given by substituting $\theta+\psi=\theta_o$ into (3). However, it should be simplified in the form,

$$\bar{i}_o = f_1(\bar{I},\psi,\theta_o,\phi).$$

This means that the instantaneous current $\bar{i}_o$ at the arc-initiation is to be determined by making angle ψ and the arc-initiation angle θ_o for given values of $\bar{I}$ and ϕ. On the other hand, ψ and θ_o are related with each other just for the same values of $\bar{I}$ and ϕ by means of (5) or Diagram 1. Thus, it is possible to get the relationship,

(7) $$\bar{i}_o = f_2(\bar{I},\psi,\phi).$$

Since the cutoff current indicated on the cutoff characteristic is the maximum value, which corresponds to the most unfavourable making angle,

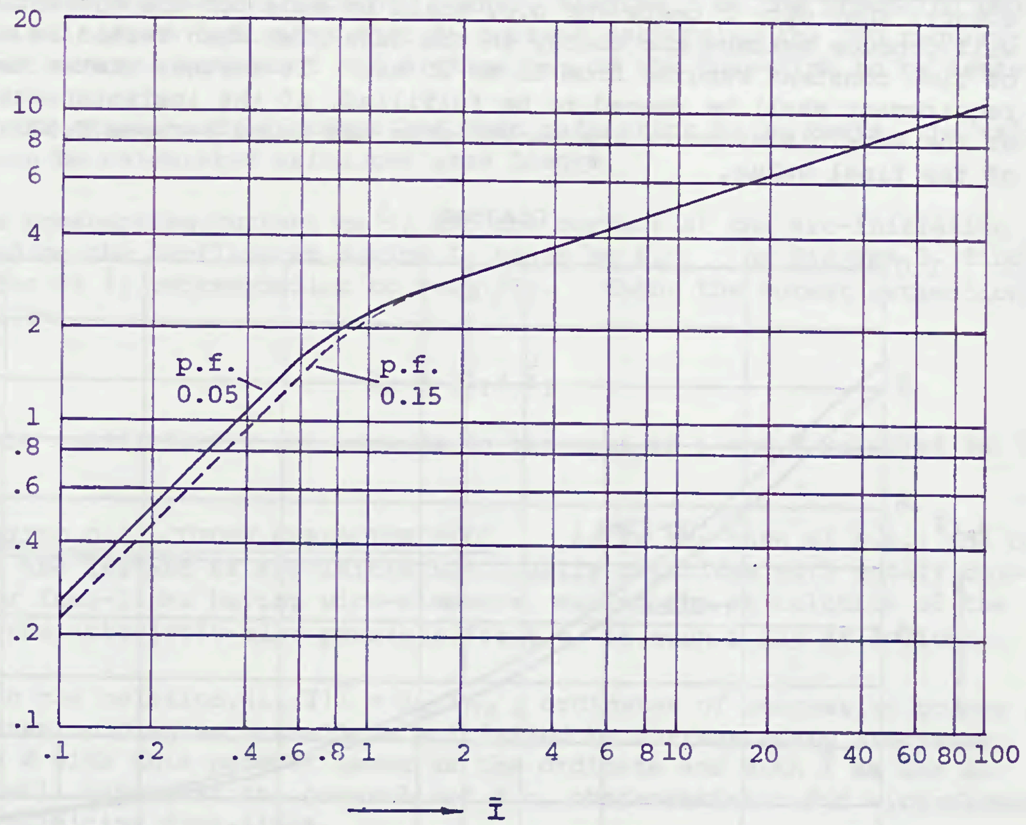
(8) $$\partial\bar{i}_o/\partial\psi = 0.$$

Combining (7) and (8) and eliminating ψ, we obtain ultimately

(9) $$\bar{i}_o = F(\bar{I},\phi)$$

which just indicates the lower inclined portion of the a.c. cutoff characteristic of wire-element fuse-links. Diagram 2 on the next page shows the result by a digital computer. [Appendix B]

Diagram 2



For the highly inclined portion, where cutoff never takes place, the computation should start directly from (3) or from its simplified form

$$\bar{i} = g(\bar{I},\psi,\theta,\phi).$$

Now, for given $\bar{I}$ and ϕ, the instantaneous value of current is a function of ψ and θ. Thus, the maximum let-through current must satisfy the following two conditions:

$$\partial\bar{i}/\partial\psi = 0$$

$$\partial\bar{i}/\partial\theta = 0$$

Combining all three equations, we get

(10) $$\bar{i}_{max} = G(\bar{I},\phi)$$

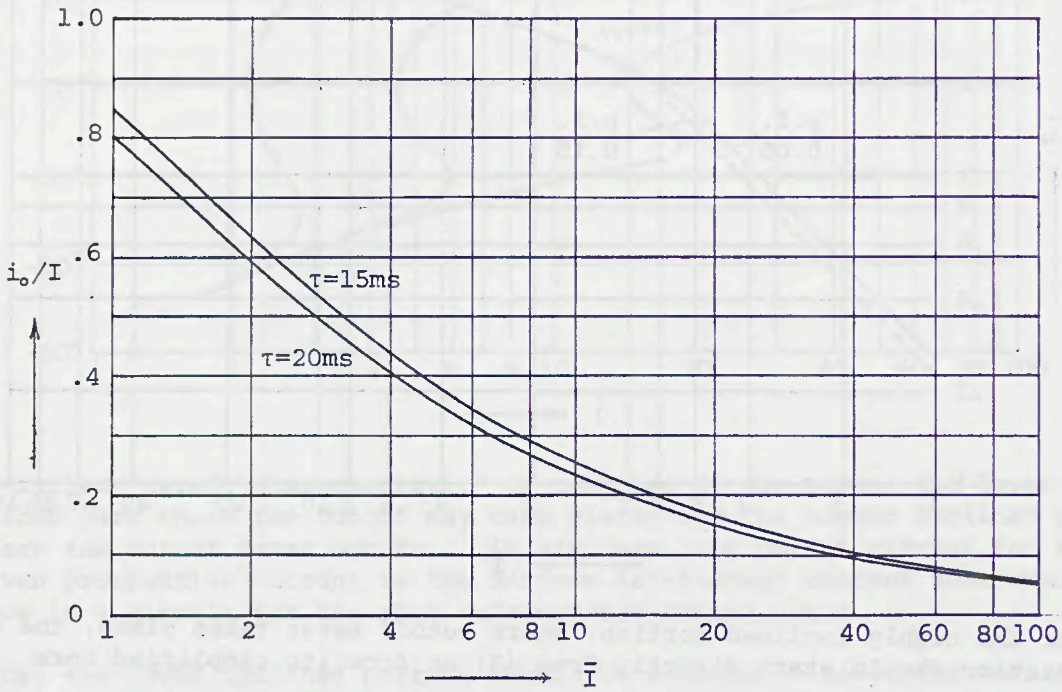
which represents the highly inclined portion of the Diagram.

It would be note-worthy that this portion is essentially independent of fuse-links, because it indicates the current in the circuit before the arc initiates in the fuse-link.

Though the direct application of this Diagram is limited to the wire-element fuse-links, it will also serve as a guidance in preparing cutoff characteristics of strip-element fuse-links.

ESTIMATION OF I_2 FOR D.C. TESTS   IEC-Publication 269-1 specifies, in effect, that duty 2 tests for d.c. shall be made for the current which will produce maximum arc energy in the fuse-link when tested in a circuit of time constant ranging from 15 to 20 ms. It further states that this requirement shall be deemed to be fulfilled, if the instantaneous current at the arc-initiation on the oscillogram was found between 0.50 and 0.80 of the final value.

Diagram 3



However, some estimation of the value of I_2 would be welcome to engineers in the test laboratories. This can be made as follows:

Let the rising d.c. current be represented by

(11) $$i = I(1 - \varepsilon^{-t/\tau})$$

where I is the d.c. prospective current and τ is the time constant of the test circuit.

The arc will start at the instant when the pre-arcing Joule-integral of the fuse-link reached its specific constant value. Thus, the following equation applies:

$$I^2 \int_0^{t_o} (1 - \varepsilon^{-t/\tau})^2 \, dt = I_{½}^2 \cdot T/2$$

where t_o and τ denote the pre-arcing time and the time constant, respectively.

Making the integration and re-arranging the result, we obtain [Appendix C]

(12) $$\bar{I} = \left(\frac{-T/\tau}{2\ln(1-\gamma) + 2\gamma + \gamma^2}\right)^{0.5}$$

where $\bar{I} = I/I_{½}$, $\gamma = i_o/I$

γ in the last formula is just the ratio of the current at the arc-initiation to the prospective current. Thus, Diagram 3 on the preceding page is obtained, which indicates that I_2 current satisfying the IEC requirement must situate between 1 and 3 times $I_{\tau/2}$ of the fuse-link to be tested.

If, on the other hand, I_1 tests had been made prior to I_2 tests, the value of I_2 can be calculated using the same Diagrm.

Let the prospective current be I_1 and the current at the arc-initiation measured on the oscillogram during I_1 tests be i_{o1}. On Diagram 3, find the value of $\bar{I}_1$ corresponding to $\gamma=i_{o1}/I_1$. Then, the surest estimation of I_2 will be

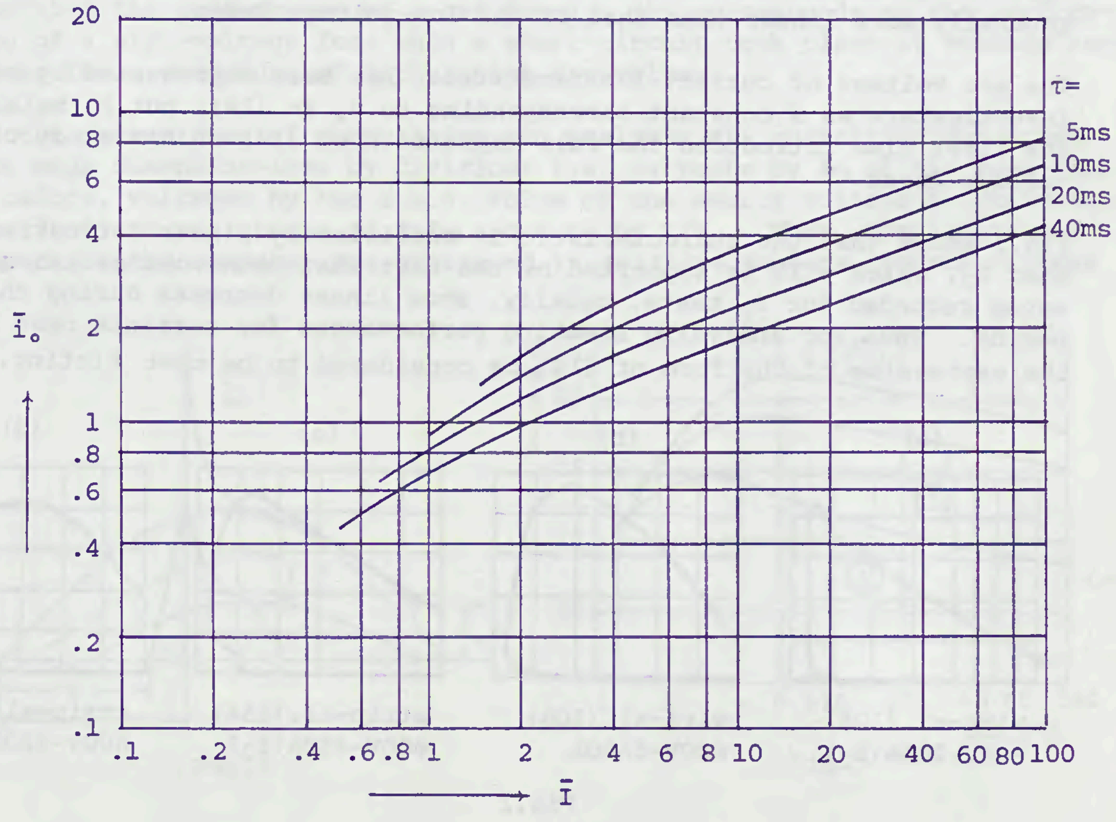
(13) $$I_2 = 2I_1/\bar{I}_1$$

where the coefficient 2 corresponds to the mean of 1 and 3 referred to above.

GENERALIZED D.C. CUTOFF CHARACTERISTIC As in the case of a.c., the current at the instant of arc-initiation usually coincides with cutoff current for fuse-links having wire-elements, making the calculation of the cutoff characteristic also possible for d.c. in such a way as follows:

Noticing the relation, $(i_o/I)\bar{I} = i_o/I_{\tau/2}$, ordinates of successive points on the curves on Diagram 3 shall be multiplied by corresponding abscissae. Diagram 4 with this product taken as the ordinate and with $\bar{I}$ as the abscissa will give just the generalized d.c. characteristic for wire-element current-limiting fuse-links.

Diagram 4



It should be noted that compared to a.c. cutoff characteristic where power factor of the circuit played a minor role, d.c. cutoff current is appreciably affected by the time constant of the circuit.

<u>REPRESENTATION OF V-I CHARACTERISTIC OF ARCS IN C.L. FUSES</u> The arc confined in sand has a peculiar V-I characteristic compared to the arcs in open air or in gases. The small area of the tunnel left behind the vapourization of fuse-element confines the arc so narrowly as to give the arc very high current-density. At the same time, sand granules on the inner wall of the tunnel cools the arc so intensely by fusion and vapourization that the arc voltage is appreciably higher than that of the free arc.

Another distinguished feature of the arc in sand is its positive resistance characteristic as indicated in the oscillograms in Fig. 1, where voltage across the fuse-terminals was taken as ordinate and current as abscissa. Referring to the oscillogram (a), current starts at the bottom left and goes right horizontally to the bottom right, where the fusion occurs and the voltage jumps up to the top right. This voltage spike limits the current, and both current and voltage decrease along the nearly straight line down to left, where some residual voltage is recognized.

These oscillograms suggest us that the V-I characteristic of c.l. fuses might be represented by

(14) $$v_a = v_o + ri$$

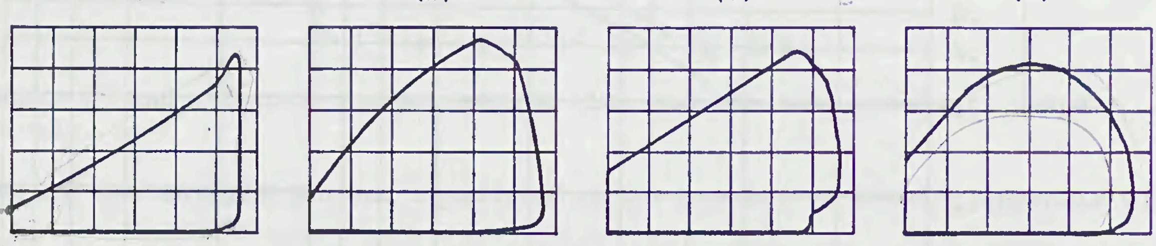
for fairly wide range of breaking currents.

In our experience the V-I characteristic of low-voltage wire-element fuses are more linear than that of fuses having strip-elements with many holes. Further, it is considered that the characteristic of high-voltage fuses are generally more linear than that of the low-voltage fuses.

The arc voltage of current-limiting fuses has been represented by many investigaters as a constant corresponding to v_o in (14), but F. Meier for the first time introduced the full expression of (14) in his study of low-voltage fuses.

Fig.1 shows that the characteristic is sufficiently linear for currents near I_2, which will be supported by the fact that both voltage and current waves recorded for I_2 tests, usually, show linear decrease during the arc period. Thus, for analysing breaking performances for currents near I_2, the expression of the form of (14) is considered to be most fitting.

(a) (b) (c) (d)



wire-el.(10A) 600V-200A(I_2) | wire-el.(10A) 600V-5600A | strip-el.(15A) 600V-480A(I_2) | strip-el.(15A) 600V-5600A

Fig.1

SIMULATION OF THE BREAKING PERFORMANCE BY ANALOGUE COMPUTER The breaking performance of a current-limiting fuse, when the arc voltage v_a is expressed by (14), can be reduced simply to the problem of the circuit theory. Furthermore, it can even be simulated by an analogue computer which operates in principle, as follows:

After closing the switch S_1 in Fig.2 at a pre-set making angle ψ, the 2nd power of the current through the circuit is integrated by the computer till it reaches the pre-arcing Joule-integral of the fuse-link to be tested. The computer stops here and the switch S_2 is opened to introduce the arc voltage into the circuit. The computer re-starts and begins to integrate the product of v_a and i, until the current reaches zero. The voltage and the current waves throughout the computation are recorded by the pen-oscillograph.

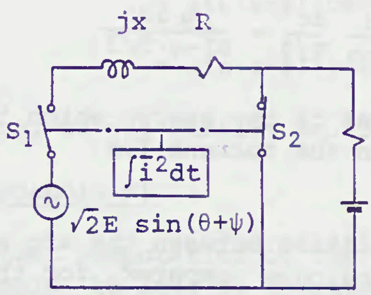


Fig.2

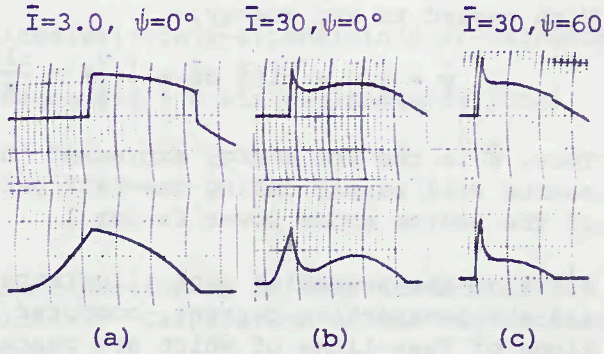


Fig.3

Some of the wave forms furnished by the computer are shown in Fig.3. (a), corresponding to the I_2 test, shows the upward swell of the current wave which indicates that the given arc voltage was too small. The computer simulated the performance of a bad fuse! (b) corresponds to the performance of a high-voltage fuse when a short-circuit took place at voltage zero. (c) is for a good fuse of rather high arc voltage.

For the convenience of computation and analysis all quantities concerned were made dimension-less by division: i.e. currents by $I_{T/2}$ of the fuse-link as before, voltages by the r.m.s. value of the source voltage E, resistance by a fictious resistance of $E/I_{T/2}$ and time by T/2. Thus, the inputs and outputs of the computer are expressed in relative numbers, source voltage

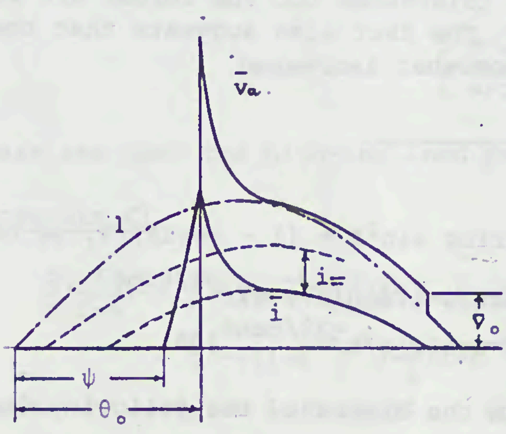


Fig.4

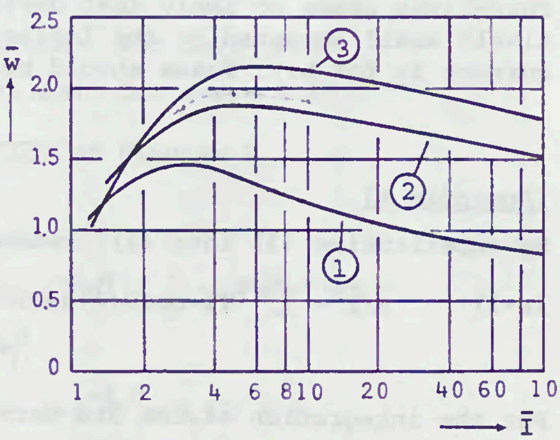


Fig.5

expressed by 1. In the followings all the quantities made dimension-less are indicated by a short line over corresponding symbols.

Thus, e.g. arc voltage is expressed by

$$\frac{v_a}{E} = \frac{v_o}{E} + \frac{rI_{T/2}}{E} \cdot \frac{i}{I_{T/2}}$$

or by

$$\bar{v}_a = \bar{v}_o + \bar{r} \cdot \bar{i}$$

where $\bar{v}_a$ is the ratio of the arc voltage to the r.m.s. value of the source voltage E and $\bar{r}$ corresponds to the voltage drop in terms of the source voltage E, in a resistor of r[Ω] carrying current $I_{T/2}$.

With regard to arc energy,

$$\bar{w} = \int (\bar{v}_o + \bar{r}\bar{i})\bar{i}\ d\bar{t} = \int \left(\frac{v_o}{E} + \frac{rI_{T/2}}{E} \cdot \frac{i}{I_{T/2}}\right) \frac{i}{I_{T/2}} \frac{dt}{T/2} = \frac{\int v_a\, i dt}{EI_{T/2} \cdot T/2}$$

Thus, $\bar{W}$ is the arc energy expressed in multiples of the energy which the source will supply during one-half period, when the current $I_{T/2}$ of the source under power factor 1.

Fig.5 on the preceding page illustrates the relation between the arc energy and the prospective current, computed by the analogue computer, for three kinds of fuse-links of which arc characteristics are shown in the Table.

fuse-links	#1	#2	#3
value of $\bar{v}_o$	0.60	0.35	0.35
value of $\bar{r}$	0.70	0.50	0.40

The values of $\bar{v}_o$ and $\bar{r}$ for #1 corresponds to the V-I characteristic of a l.v. fuse-link, while the other two are for h.v. fuses.

The computation indicates that the arc energy increases with the decrease in the values of $\bar{v}_o$ and $\bar{r}$ and that the current corresponding to the maximum arc energy moves rightwards. It also indicates that at the same time the top of the hill becomes flat. This is partly supported by the fact that the arc energy of a l.v. fuse increases when tested under increased voltages, which signifies values of $\bar{v}_o$ and $\bar{r}$ decrease in inverse proportion to E or the test voltage.

The fact that h.v. fuse-links have, in general, lower $\bar{v}_o$ and $\bar{r}$ than l.v. fuse-links seems to imply that design tolerances for the former are relatively small compared to the latter. The fact also suggests that the test current I_2 for h.v. fuses should be somewhat increased.

[Appendix A]

By substituting (3) into (4), remembering $\sin^2 A = (1 - \cos 2A)/2$, we have

(A-1) $$\pi/\bar{I}^2 = \int_0^{\theta_0 - \psi} [1 - \cos 2(\theta+\psi-\phi) - 4\sin(\psi-\phi)\sin(\theta+\psi-\phi)\varepsilon^{-\theta/\tan\phi} + (1-\cos 2\psi-\phi)\varepsilon^{-2\theta/\tan\phi}]\, d\theta$$

For the integration of the 3rd term in the brackets, the following formula

$$\int_0^{x_0} \sin(x+a)\varepsilon^{-bx} dx = \frac{1}{1+b^2}[\cos a + b\sin a - (\cos\overline{x_0+a} + b\sin\overline{x_0+a})\varepsilon^{-bx_0}]$$

should be consulted. Substituting $x=\theta$, $x_o=\theta_o-\psi$, $a=\psi-\phi$ and $b=1/\tan\phi$ in the formula and remembering $\sin(A+B)=\sin A\cos B+\sin B\cos A$, we have

$$\int_o^{\theta_o-\psi}\sin(\theta+\psi-\phi)\varepsilon^{-\theta/\tan\phi}d\theta = \sin\phi[\sin\psi-\sin\theta_o\,\varepsilon^{-(\theta_o-\psi)/\tan\phi}]$$

Integrating also the other terms in brackets in (A-1), we get

$$\text{(A-2)}\quad \pi/\bar{I}^2 = \theta_o-\psi-\frac{1}{2}\sin 2(\theta_o-\phi)+[\frac{1}{2}\sin 2(\psi-\phi)-4\sin\psi\sin\phi\sin(\psi-\phi)+\tan\phi\sin^2(\psi-\phi)]$$
$$+4\sin\theta_o\sin\phi\sin(\psi-\phi)\varepsilon^{-(\theta_o-\psi)/\tan\phi}-\tan\phi\sin^2(\psi-\phi)\varepsilon^{-2(\theta_o-\psi)/\tan\phi}$$

Terms between the brackets in (A-2) can be re-arranged as follows:

$$\frac{1}{2}\sin 2(\psi-\phi)-4\sin\psi\sin\phi\sin(\psi-\phi)+\tan\phi\sin^2(\psi-\phi)$$
$$=\sin(\psi-\phi)[\cos(\psi-\phi)-2\sin\psi\sin\phi]+\sin(\psi-\phi)\tan\phi[\sin(\psi-\phi)-2\sin\psi\cos\phi]$$
$$=\sin(\psi-\phi)[\cos(\psi+\phi)-\tan\phi\sin(\psi+\phi)] = \sin(\psi-\phi)\cos(\psi+2\phi)/\cos\phi$$

Thus, we get finally Eq.(5).

[Appendix B]

Actual computation of the low-inclined portion is so complicated that it should be left to computer specialists. Calculation of the high-inclined portion, however, is relatively simple.

Since, $\quad \partial\bar{i}/\partial\theta = \sqrt{2}\,\bar{I}[\cos(\theta+\psi-\phi)+\sin(\psi-\phi)\varepsilon^{-\theta/\tan\phi}/\tan\phi] = 0$

and $\quad \partial\bar{i}/\partial\psi = \sqrt{2}\,\bar{I}[\cos(\theta+\psi-\phi)-\cos(\psi-\phi)\varepsilon^{-\theta/\tan\phi}] = 0$

Subtracting the 2nd from the 1st equation, we get

$$\text{(B-1)}\quad \sqrt{2}\bar{I}[\sin(\psi-\phi)/\tan\phi+\cos(\psi-\phi)]\varepsilon^{-\theta/\tan\phi}=0$$

or $\quad \sin\psi = 0$, or $\quad \psi = 0$

Putting this into (B-1), $\quad \cos(\theta-\phi) = \cos\phi\,\varepsilon^{-\theta/\tan\phi}$ is obtained.

Solving this equation with respect to ψ for given values of ϕ, and substituting these values of ψ and ϕ into Eq.(3), we get

$$\bar{i} = \sqrt{2}\bar{I}(1.86) \quad \text{for } \cos\phi = 0,05$$
$$\bar{i} = \sqrt{2}\bar{I}(1.63) \quad \text{for } \cos\phi = 0.15$$

These are just the high-inclined portion of Diagram 2.

[Appendix C]

$$\frac{2}{T}\left(\frac{I}{I_{T/2}}\right)^2 = \int_o^{t_o}(1-\varepsilon^{-t/\tau})^2\,dt = t_o-2\tau(1-\varepsilon^{-t_o/\tau})+\frac{\tau}{2}(1-\varepsilon^{-2t_o/\tau})$$
$$= t_o-\tau(1-\varepsilon^{-t_o/\tau})-\frac{\tau}{2}(1-\varepsilon^{-t_o/\tau})^2$$

Since $\quad -t_o/\tau = \ln(1-i_o/I)$, and $\quad 1-\varepsilon^{-t_o/\tau} = i_o/I = \gamma$

Eq.(12) is obtained.

THE ROLE OF THE SEMI-ENCLOSED FUSE IN CIRCUIT PROTECTION

P. Morrell

'Additional security is obtained by Mr. Edison by inserting in every branch wire a 'Safety catch,' which is a short piece of lead wire that instantly melts if the strength of the current exceeds a certain value.'

(Comment on the Rules of the U.S. Board of Fire Underwriters, 1881).

This, the first fuse, invented by Thomas A. Edison in 1880, consisted of a 'weak spot' within the circuit intended to prevent overheating and destruction of conductors by excessive currents.

The device consisted of a piece of lead wire inserted in the circuit which was designed to melt when the current reached a pre-determined value. Its purpose was to protect the generator from damage due to excessive current and prevent damage to the building if short circuiting occurred between imperfectly insulated conductors.

Much time was devoted by engineers to the determining of wire diameters in order to prevent damage to lamps from over-voltage which frequently occurred with the early generators.

It was considered necessary to use lead wires for fuses as its low melting point resulted in a very small amount of damage to the surroundings when the fuse operated.

Circuit loadings increased rapidly with the years and the related higher current ratings required the use of copper for the fuse wire for currents in excess of approximately 5 amperes.

The operation of the copper wire fuse produced globules of molten copper and there was the fear that this would ignite the wood bases and cases then in use. This resulted in development aimed at containing the molten copper and one of the first improved types enclosed the copper wire element in a porcelain tube. The first British Patent which specifically referred to a fuse of high melting point wire, either silver or copper, in a porcelain tube was taken out by Laurence, Paris & Scott in 1889 (No. 6332). A later important development by the GEC, in the name of Hugo Hirst, is contained in British Patent No. 2249 of 1896. This covered the use of asbestos-covered fuse wire to minimise the effects of 'blow.'

Many stages followed in the development of fuses, they are generally well known to those involved in the fuse industry, and it is not the intention of this paper to cover them further.

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Circuit protection devices developed along three main lines (1) Semi-enclosed fuses (2) HRC Cartridge fuses and (3) Circuit breakers. The use of semi-enclosed fuses continued in the U.K. and Commonwealth countries, but gradually in other parts of the world the emphasis moved from semi-enclosed fuses towards miniature circuit breakers whilst the development and use of the HRC cartridge fuse became universal.

The definition of a 'semi-enclosed fuse' taken from British Standard 3036: 1958 is, 'A fuse in which the fuse element is neither in free air (other than the air in any external containing case not forming part of the fuse) nor totally enclosed.' Normally a semi-enclosed fuse is of the rewireable type using an element of tinned copper wire and it has become standard practice to refer to a semi-enclosed fuse as 'a rewireable fuse.'

In the U.K. the use of semi-enclosed fuses for domestic circuit protection is widespread and figures supplied by manufacturers of both semi-enclosed and HRC cartridge type fuse units suggest that up to 90% of the market is for semi-enclosed fuses whilst the remaining 10% is probably divided equally between HRC cartridge pattern and miniature circuit breakers.

A somewhat different pattern of use appears for industrial pattern semi-enclosed fuses and the figures supplied by manufacturers of both semi-enclosed and HRC cartridge patterns show that the degree of usage varies with the rated current of the unit.

The smallest size of industrial fuse has a normal current rating of 20 amps and this size together with the next larger size i.e. the 30 amp rating use approximately 70% semi-enclosed fuses compared with 30% HRC cartridge type.

The proportion of semi-enclosed fuses in use decreases with increased current rating being about 60% for the 60 amps rating and about 50% for the 100 amp rating. At a current rating of 200 amps, all fuses are of the HRC cartridge pattern, manufacturers having discontinued production of this rating in semi-enclosed pattern some years ago.

The performance of the semi-enclosed fuse is often queried and some engineers appear to be prejudiced against their continued use.

Semi-enclosed fuses commercially available have somewhat reduced breaking capacity ratings compared with HRC cartridge fuses, but the absence of any significant problems associated with these reduced breaking capacity ratings amply demonstrates that they are perfectly satisfactory for all normal applications. Their breaking capacity ratings are very similar to those applying to many miniature circuit breakers where the breaking capacity rating is seldom criticised.

Domestic pattern semi-enclosed fuses normally have a rated breaking capacity of between 1000 amperes and 2000 amperes depending on current rating and individual manufacturer.

This breaking capacity applies to all current ratings and as the physical dimensions of all current ratings are often identical the breaking capacity is not related to the size of element wire fitted and is achieved over a wide range of element sizes.

Industrial pattern semi-enclosed fuses differ from the domestic pattern in several ways, not least of which is physical size. The need for a longer wire element due to the higher voltage and current ratings dictates a larger unit which automatically allows for higher breaking capacity values.

Typical values are as follows:-

20 amp rating	-	2000 amperes
30 amp rating	-	2000 amperes
60 amp rating	-	2000 amperes to 4000 amperes
100 amp rating	-	4000 amperes to 6000 amperes

Economically the semi-enclosed fuse cannot be equalled and in these days when economy is of paramount importance it would be imprudent to dismiss this important factor without giving due consideration to the level of circuit protection necessary for any particular installation.

They have a further advantage which is not always appreciated - that of being less often maltreated. The dangerous expedients adopted by ignorant users to 'repair' blown cartridge fuses, such as wrapping them in silver paper, or soldering wire between the outside of the cartridge end caps, has proved, in practice, to cause more trouble than the risk of them overwiring semi-enclosed fuses.

One of the principal reasons for the abuse of cartridge fuse is that a replacement is not always readily available whereas a short length of copper wire as used for the repair of a blown semi-enclosed fuse is usually easy to obtain. It is quite true also that most users are ignorant of the consequences of such abuse to cartridge fuses.

Manufacturers of various types of protection equipment have all seen classical examples of the maltreatment of blown cartridge fuses and the damage caused to the equipment when another fault condition occurs, but cases where damage has been caused by mistreatment of semi-enclosed fuses are unknown. Most manufacturers of semi-enclosed fuses will endorse the view that evidence of problems due to their inherent lower breaking capacity is practically nil, we believe this to be due to the fact that cognisance has always been taken of the overall limitations of the fuse and they are therefore installed in situations where a device with a higher breaking capacity is not necessary.

In the majority of domestic situations quite low prospective short circuit currents are realised due to the resistance of the distribution cables, it is also a fact that most fault conditions occur in equipment at the end of the circuit cable and not at the distribution board. There are some special situations such as high rise blocks of flats where prospective currents can be much higher and in these situations the use of the semi-enclosed fuse is restricted.

Semi-enclosed fuses have a maximum fusing factor value of 2.0 when fitted with the size of element wire specified by the manufacturer. This requirement originates from the IEE Regulations for the Electrical Equipment of Buildings (8th Edition), 1924 which specified that with 100% over-current a fuse should blow within one minute with a fuse-wire of tinned copper, or within two minutes with a fuse-wire of lead/tin alloy.

A test to check the blowing current of a fuse was incorporated in British Standard 88 dated 1931, this specification being the one covering 'fuse cut-outs for ordinary duty.'

Following the issue of this British Standard work was carried out by the Electrical Research Association to investigate the possibility of using one size of wire for all semi-enclosed fuses of a given current rating. Although there was some divergence from a mean size among fuses of different makes due to design expediency, the variation was not usually more than one standard wire gauge. The result of this work was a list of mean sizes for various current ratings and this formed the basis of a table of recommended wire sizes incorporated in the 10th (1934) edition of the IEE Regulations for the Electrical Equipment of Buildings.

This table still appears in modified form in the latest (14th) edition of those regulations, the wire sizes now being expressed in metric values and sizes of lead/tin alloy elements having been deleted.

In 1958 British Standard 3036 was issued, this being devoted entirely to semi-enclosed fuses, and this specification is still current at the present date. Work is in hand to amend the specification in line with present day practice and also to introduce metric values where necessary. BS 3036 contains a great deal of useful information to the electrical engineer and its appendices which comprise a large part of the standard give expert guidance on the use of semi-enclosed fuses.

Standards for semi-enclosed fuses have been issued by certain Commonwealth countries as follows:-

Australia - SAA AS 3135 - 1973. This specification, in metric units, covers semi-enclosed fuses for A.C. circuit with a maximum current rating of 100 amperes and a maximum rated breaking capacity of 4000 amperes.

India - IS 2086 - 1963. This specification covers semi-enclosed fuses with a maximum current rating of 100 amperes and a maximum rated breaking capacity of 4000 amperes.

South Africa - SABS 174 - 1955. This specification covers 'rewirable' type fuses in current ratings up to 100 amperes maximum for both A.C. and D.C. circuits. The maximum breaking capacity rating is 4000 amperes.

New Zealand - NZS 1951. This is British Standard BS 3036: 1958 endorsed for use as a New Zealand Standard.

In conclusion it appears that semi-enclosed fuses will be used in large quantities for many years to come and this fact should be recognised by everyone associated with the electrical industry. That they will eventually be superseded by other protective devices whether it be circuit breakers or HRC cartridge fuses, seems, on balance,to be likely but the change over could take many years to accomplish. It has been suggested in some quarters that the change over should be effected by legislation, but with a device which performs its function with so few problems, we feel that any change should be allowed to come about as dictated by the combination and interaction of many technical and economic considerations as they emerge, rather than be forced by mandatory measures however well intentioned.

OVERCURRENT PROTECTION OF CABLES BY FUSES

S. B. Toniolo, G. Cantarella and G. Farina

SUMMARY Fuses can provide thermal protection of cables by preventing excessive duration of overcurrents exceeding the current-carrying capacity. Their protective action,however, generally implies a reduction of the current suitable for normal uninterrupted duty, with respect to the current-carrying capacity of the protected cable. Appropriate criteria for co-ordination may allow for a better utilization of the conductor in the cable.

GENERAL Cables in defined conditions of installation and use are characterized by a definite current-carrying capacity, i.e., the largest current they can carry in continuous duty without suffering deterioration of the insulating material by ageing in excess of that related to an assumed life duration in service.

A permanent load exceeding the current-carrying capacity of the cable results in a predictable reduction of the prospective life; a single temporary overcurrent of definite duration also results in a predictable reduction of the prospective life of the cable.

A suitable overcurrent protecting device should then prevent permanent over loads, within the necessary tolerance with respect to the current-carrying capacity of the cable, and it should interrupt major overloads or short-circuit currents within definite limits of duration, also within the necessary tolerance with respect to the presumed acceptable reduction of the prospective life of the cable for each allowed temporary overcurrent.

These are the requirements of an adequate overcurrent protection: as such they do not take care of the current, the protecting device is able to let flow through the protected cable in normal uninterrupted duty. Obviously a further requirement has to be introduced, related to the current allowed in normal service, which shall not be subject to undue interruptions.

The ideal overcurrent protective device should allow flowing in normal uninterrupted duty any current up to the current-carrying capacity of the protected cable, and it should operate to interrupt in due time any current exceeding, no matter how much, the current-carrying capacity of the cable itself.

FUSES AS OVERLOAD PROTECTING DEVICES Fuses complying with a definite Standard

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operate according to time-current characteristics lying within the standard operating band.

A conventional upper limiting value of time is considered by the Standard, in correspondence of which a lower limiting value is allowed for the higher non-fusing current I_{nf} and an upper limiting value is allowed for the lower fusing current I_f. The actual value of the current causing an individual sample of standard fuse to melt and to interrupt the current in the conventional time will certainly exceed I_{nf} without reaching I_f. The above conventional time is different for different sizes of fuses, and shall be intended as a time approaching the time required for substantially steady thermal conditions to be attained by the fuse with the conventional non-fusing current I_{nf}.

This does not mean that the fuse, having attained substantially steady thermal conditions with the current I_{nf}, is capable of carrying such a current for a time indefinitely exceeding the conventional time: the temperature rise of the fuse, although less than that necessary to reach the melting temperature, is high enough for causing accelerate ageing of the fusing element due to structural alterations. Consequently the permanence at such high temperature causes the operating characteristics of the fuse to drift towards the left (lower currents for same times), eventually bringing the fuse to melt with the conventional non-fusing current carried for sufficiently sustained duration. The duration necessary for accomplishing such an effect depends upon the design, the structure, the materials and the ambient circumstances of the fuse, and it cannot be generally defined with the accuracy and the tolerances applicable to the time-current characteristic within the range of substantial overload or short-circuit currents. In view of co-ordination for overload protection intended to prevent with sufficient accuracy excessively accelerate ageing of the cables, reference should then be made to the conventional fusing current I_f, which should not exceed the current-carrying capacity of the cable to be protected.

It shall be noted that such a criterion takes into account any possible actual operating characteristic of standard fuses; nevertheless it is excessive for the large majority of fuses belonging to a standard mass production, for which the standard band is allowed, and the actual fusing current for the conventional time can be expected to be less than the conventional fusing current I_f.

It shall moreover be noted that also for a fuse having its actual operating characteristic passing close to the limiting point of the conventional fusing current I_f, a current less than, but approaching such a value will eventually bring the fuse to melt after durations not too far from the conventional time, due to the effect of accelerate ageing caused by currents approaching I_f.

As a conclusion the co-ordination for overload protection may be deemed to comply with safety requirements even if the current-carrying capacity of the cable to be protected is slightly exceeded by the conventional fusing current I_f, e.g., if the condition is adopted, that the current-carrying capacity of the cable is not less than the mean value between the conventional non-fusing current I_{nf} and the conventional fusing current I_f.

The consequence of such a criterion is that, for a number of individual fuses complying with the rules, a possibility of allowing more sustained temporary overloads may arise: this results in a predictable reduction of the prospective life of the protected cable, which may be contained within predetermined tolerances.

It should be stressed that the allowance by which the current-carrying capacity of the cable to be protected against overloads may be exceeded to a reasonable extent by the conventional fusing current of the protecting device is based on the peculiarity of fuses, the operating characteristics of which are subject to a substantial drift towards lower currents for same durations when high temperatures are maintained. The same criterion does not apply for protecting devices having operating characteristics similar to those of fuses, but realized on different principles, as are those of circuit-breakers.

CURRENT IN ININTERRUPTED DUTY FOR OVERCURRENT PROTECTIVE DEVICES The upper limiting value of current, a fuse is capable to carry in permanent service without suffering too accelerated ageing due to permanence of excessive temperature rise, is assigned to the fuse as rated current I_n.

The extent, to which the cross-sectional area of the conductor in the cable can be utilized in normal service, is indicated by the ratio between the rated current of the fuse I_n and the current-carrying capacity of the cable I_z.

Let us consider standard fuses for which the ratio I_f/I_n is 1.6; I_{nf}/I_n is 1.3. If the condition for overload protection is taken:

$$I_z = \frac{I_f + I_{nf}}{2}$$

this means:

$$I_z = 1.45\ I_n$$

and the utilization of the current-carrying capacity of the cable is expressed by the ratio:

$$\frac{1}{1.45} \simeq 0.7$$

BEHAVIOUR OF FUSE AT CURRENTS INTERMEDIATE BETWEEN I_f AND I_{nf} As a consequence of the effect of accelerate ageing of fuses with sustained loads exceeding the rated current I_n but lower than the conventional fusing current I_f, the time-current characteristics may present a reliable operating zone also for times substantially exceeding the time related to the thermal time-constant in view of a steady condition.

Experimental results on ordinary standard fuses, reported on diagram of figure 1, related to rated currents of 50 A, show that fuses operate within times not exceeding 5 hours with currents of 1.3 I_n, (i.e. with the conventional non-fusing current I_{nf}).

This may be taken into account in co-ordinating fuses with cables in particular conditions of application. In domestic and similar applications, e.g., the normal service conditions are such as to allow considering the maximum duration of any condition of sustained load as limited to a definite number of hours. Within such a maximum duration, the overload can be determined, which the cable having a given current-carrying capacity I_z is able to withstand, without suffering excessive deterioration with respect to the pre-determined life duration.

In the assumption that such an overload capability of the cable be $k_1 I_z$, and that the current causing with certainty the fuse to melt within an upper limiting value of time, longer than the conventional time, be $k_2 I_n$, thermal protection of the cable will be ensured by the condition:

$$k_2 I_n = k_1 I_z, \text{ as a maximum for } I_n,$$

if the maximum expected duration of any sustained load condition of the cable to be protected does not exceed the upper limiting value of operating time taken into account for the fuse with the current $k_2 I_n$.

In the case where k_1 can be taken equal to k_2, under the above conditions a fuse having rated current I_n equal to the current-carrying capacity I_z of the cable is suitable for overload protection.

FUSES AS OVERCURRENT PROTECTION UP TO SHORT CIRCUIT   In principle the criterion of overcurrent protection is to limit the duration of the overcurrent in order to contain the thermal stress of the insultating material of the protected cable within the stated limit, to which the prospective life duration is related.

In particular, for overcurrents large enough to allow assuming the thermal phenomenon to be adiabatic, the condition means that the maximum total I^2t let-through shall not exceed a pre-determined limiting value. Fuses allow complying with this condition, since the maximum total I^2t let-through can be deemed to remain substantially constant from the current value, for which the adiabatic condition of operation starts holding, up to the current of their rated short-circuit breaking capacity.

CONCLUSIONS   Co-ordination for overcurrent protection (overload and short circuit) is appropriate when the time-current characteristic of the cable to be protected (current-carrying capacity for indefinite duration, durations admitted for single overcurrents as a function of the pre-determined life duration and of the pre-determined number of temporary overcurrents) lies at the upper side of the standard operating band of the protecting fuse. That generally implies reduced utilization of the conductor in the cable in normal service.

Particular conditions of application, however, can be found for which a better utilization of the conductor in the cable can be achieved.

An example is given by domestic and similar application, for which a fuse having rated current I_n equal to current-carrying capacity I_z of the cable can be deemed to be suitable, as a limit, for overload protection, under the specified conditions of service.

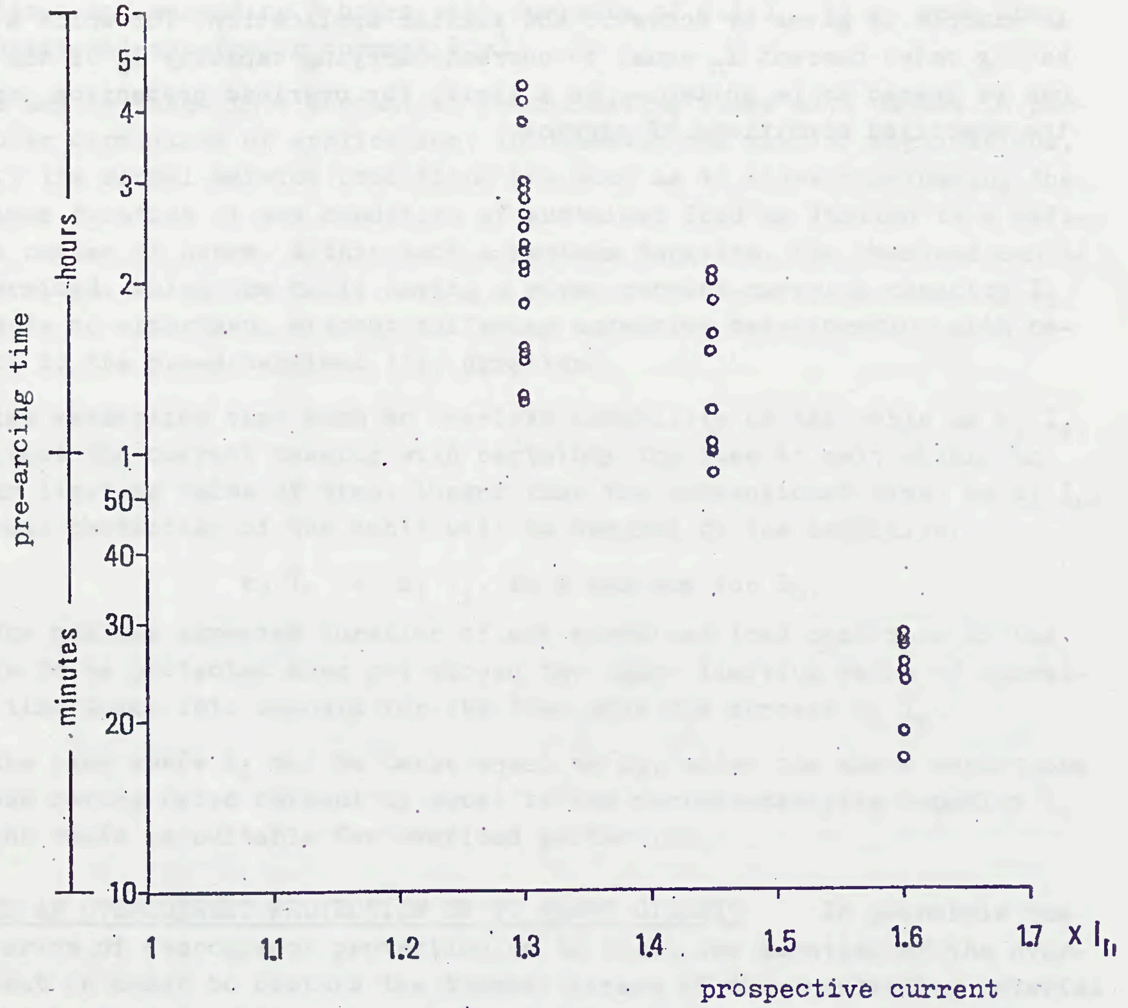

Fig. 1
Pre-arcing time of fuses rated 50 A, 500 V, 50 Hz, as a function of the test current

THE PROTECTION OF INDUSTRIAL CAPACITOR BANKS BY CURRENT LIMITING FUSES

By M.J. Smart and B. Wadcock

1.0 INTRODUCTION Capacitors are widely used for industrial power factor correction throughout the world, the advantages of using them being widely appreciated particularly in this era of expensive energy.

Capacitors for this application are generally protected by fuses and the application of these fuses presents problems to the fuse and capacitor designer because of the particular phenomena associated with capacitor banks. This paper describes these phenomena and how they are overcome in industrial applications at system voltages up to 11kV and bank ratings up to about 3Mvar.

2.0 GENERAL REQUIREMENTS Power Capacitor banks are always made up of series-parallel arrangement of capacitor sections, each section being protected by a fuse. The purpose of this fuse is to disconnect the faulty section in the event of its failure and permit the remaining healthy sections to continue functioning normally. The fuses selected for this duty must take account of the following requirements.

Transient Current Withstand On energisation of a capacitor a large inrush current occurs. This inrush current is limited only by the inductance and resistance in the energising circuit. For a single capacitor this source reactance is represented by the system impedance and approximately the peak inrush current can be calculated from the formula.

$$I \text{ peak inrush} = \sqrt{\frac{\text{System Fault level (kVA)}}{\text{Capacitor rating (kvar)}}} \times \text{capacitor rated peak rated current}$$

For a multi-section capacitor bank the inrush current into the first section is as for a single section bank, but for the second and subsequent sections there occurs a large interchange of energy between bank sections resulting in large inrush currents limited only by the inductance and resistance between the bank sections. This transient current is of high frequency and would normally decay within 10-20 milliseconds of inception. Any fuses incorporated in the capacitor circuit must of course withstand this current without deterioration.

Continuous Current Withstand Because the impedance of a capacitor is inversely proportional to frequency it will tend to receive a relatively high proportion of currents of frequency higher than system power frequency. This fact is particularly important in view of the present increasingly large scale use of power electronic equipment which is

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inherently harmonic generating. It is recognised in the current issues of most national specifications, BS1650 : 1971 typically laying down that the continuous current rating of a power capacitor should be 1.15 x current at rated voltage and frequency for medium voltage capacitors, this factor being increased to 1.3 x for high voltage capacitors. Because a capacitor also normally has a positive capacitance tolerance of 10%, these factors have to be increased respectively to 1.265 x and 1.43 x nominal power frequency current rating. This continuous overcurrent withstand must be incorporated into all associated capacitor equipment, in particular the capacitor fuses.

Discharge Withstand When a number of individually fused capacitor sections are connected in parallel, then on failure of one of these sections, the power frequency fusing current in the fuse of the faulty section will be that which results from short-circuiting the complete group of capacitors. In addition if, as is most likely, the short circuit occurs when the group of capacitors is charged to some voltage greater than zero the fuse of the faulty section must clear successfully against the resulting high frequency discharge current, and the fuse of each of the healthy sections must withstand the contribution to this discharge current from its own section.

3.0 FUSE TYPES As stated in Section 2.0 above capacitor banks are made up of series-parallel arrangement of capacitor sections, each section protected by a fuse. In practice capacitors are manufactured in standard unit sizes, these units being connected together to form a bank. Each unit in turn is made up internally of a number of elements or windings. Element voltages at present can be up to about 1.5 to 2kV so that units of voltage rating below this normally have all their elements connected in parallel. These units are generally protected by internal fuses, one fuse being connected in series with each element. Because of the comparatively large number of capacitor elements connected in parallel in this arrangement, it is relatively simple and economical to design an internal fuse to fulfill all the requirements of Section 2.0, above and in fact internal element fuses are usually used at these voltages. These are of course incorporated inside the units at the time of manufacture. Internal fuses can only disconnect dielectric failures, and for other faults, such as failure of the major insulation between the element pack and the unit case, they are not effective. External fuses are therefore normally necessary in addition to the internal fuses, and these are best incorporated in the incoming connections to the complete bank as described in Section 4.0 below.

For power factor correction capacitor banks of voltage rating above about 1.5kV to 2kV it is necessary to use capacitor units with two or more windings in series within the unit. Because of this series connection of elements there are correspondingly less elements connected in parallel in each element group within the unit and the design of an element fuse complying with the requirements of Section 2 is more difficult, unless an uneconomically large total number of windings per unit are used. In addition the internal fuse is not effective in disconnecting major insulation faults as described above. It is thus preferred practice to use external fuses for these applications, one fuse for each capacitor unit. The practical choice for an external fuse is then between a non-current limiting expulsion fuse and a current limiting h.r.c. fuse. The expulsion fuse is cheaper than the h.r.c. fuse and has a time/current characteristic (time plotted vertically) which is less steep, with the result that for a given ability to withstand high frequency transients its current rating and fusing time with the power-frequency fault current are both less. However the breaking capacity of an expulsion fuse is usually less than the fault level of the system where a capacitor is installed, and therefore the use of such a fuse is limited to those cases where the capacitor units are series connected in such a way that the power frequency fault current occurring upon unit failure is limited by the series connection. Since capacitor units are available with a single phase rating of up to 15kV, series connection of capacitor units is not normally necessary at industrial voltages up to this level unless the bank is sufficiently large to justify the use of the expulsion fuse on economic grounds. Thus capacitor banks of up to 3Mvar and higher at these voltages can be made up of capacitor units connected in parallel directly across the system line connections each with current limiting h.r.c. fuses connected so as to disconnect a faulty unit from the supply upon failure. Since the unit is connected directly across the system, the prespective power-frequency fault current is decided by the system fault level. For banks up to 3Mvar the discharge energy due to the short-circuit of parallel connected capacitors which occurs when a unit fails is negligible, so that only power-frequency fusing current need be considered in choice of fuse. Since the prospective power-frequency fusing current is large, being limited only by system impedance, correct operation of the fuse is ensured even if its rating considerably exceeds its normal operating current. Since a current limiting h.r.c. fuse normally has to be oversized to ensure correct high-frequency transient withstand this is an important advantage. It is emphasised that the connection of capacitors must be such as to ensure that capacitor failure results in system short circuit to obtain this advantage, and arrangements where power frequency fault current is limited by series connection of capacitors, such as in unearthed star arrangements, must be avoided.

4.0 LOW AND MEDIUM VOLTAGE ARRANGEMENTS Capacitor banks in the low and medium voltage range are assembled using capacitor units with individual output ratings up to 50kvar. These units can be two terminal type for single or two phase operation, or, three terminal type for three phase operation.

In the case of the two terminal units the elements are all parallel connected. In the three terminal units all elements are arranged in three groups with elements parallel connected, and the three groups arranged in a delta configuration.

Fig. 1A indicates the internal connection arrangement of elements for a typical two terminal capacitor unit rated 10kvar, 415 volts, 50Hz.

Fig. 1B indicates the internal connection arrangement of elements for a typical three terminal capacitor unit rated 50kvar, 415 volts, 50Hz.

Larger ratings of capacitors are achieved by parallel connection of multiple single unit assemblies.

These capacitor banks are usually controlled by suitably rated switches or contactors which are provided with line connected current limiting fuses.

Fig. 1C indicates the connection arrangements for a 100kvar, 415V, 3 phase, 50Hz capacitor bank complete with isolator, contactor, and line connected HRC type fuses.

5.0 HIGH VOLTAGE ARRANGEMENTS In high voltage capacitor banks, capacitor units up to 200kvar 15kV output rating are now commonplace Each unit usually comprises capacitor elements without fuses, these elements being arranged in a series/parallel grouping to meet the specified or required voltage rating.

Individual capacitor units of the three terminal type are available for working voltages up to 3.3kV 3 phase, and beyond this up to 15kV, two terminal types only are usually available.

Fig. 2A indicates the internal connection arrangement of elements for a typical three terminal 150kvar, 3.3kV 50Hz capacitor unit, and Fig. 2B the internal connection arrangement of elements for a typical two terminal 200kvar, 11kV 50Hz capacitor unit.

For capacitor banks of rated voltage above 3.3kV, two terminal capacitor units are used in multiple series/parallel grouped assemblies to achieve the desired rating.

For example a 600kvar, 11kV 3 phase capacitor bank could be arranged using 3 - two terminal capacitor units of individual rating 200kvar 11kV arranged in a delta configuration and protected by 3 line connected fuses. See Fig. 3A.

These capacitor units and fuses are normally accommodated in one of three ways.

a) Within a welded steel tank type construction complete with cable entry box. This tank is usually oil-filled to aid cooling and is ideal for difficult or exposed environments.

b) Within a fabricated sheet, steel cubicle complete with cable entry chamber.

c) In an open busbar arrangement where the capacitor units and associated line fuses are supported by a galvanised steel framework.

Higher capacitor bank ratings are achieved by addition of further two terminal capacitor units and fuses parallel connected in the delta configuration. For cubicles and open busbar designs the preferred arrangement is, as shown in Fig. 3C, with the units connected in delta in groups of three, with the fuses in the line connection to each delta group of units.

An alternative arrangement, is to connect the fuses within the delta as shown in Fig. 3B. Fuses connected in this fashion do not protect the arrangement for earth faults so that line fuses are required in addition for this purpose. This connection arrangement is usually used for oil-filled tank-type capacitors, where the physical arrangement makes it preferable.

Where line fuses are provided in addition to unit fuses it is important to ensure discrimination between the unit and line fuses. This can result in large line fuse ratings bearing in mind the 2 x factor which has to be applied to the unit fuse rating in accordance with Section 6.0 below.

6.0 FUSE RATING The fuses used in association with capacitors should have a rating which ensures the following requirements are satisfied:-

a) The fuse rated voltage and interrupting capability corresponds to the rated voltage of the system to which they are connected, and system fault level at the point of connection of the capacitor bank.

b) The fuses must be capable of handling the capacitor discharge currents, and also the capacitor bank/unit inrush transients as described in Section 2. On this point it is generally accepted, (based on practical operating experience) that for low and medium voltage capacitor banks line fuses of rating 150% of the capacitor current rating will accommodate without deterioration these discharge and transient inrush currents.

Because high voltage capacitors involve the use of fuses with smaller continuous current ratings and the ability of these fuses to withstand transient inrush and discharge currents is disproportionately less than for larger fuses, factors of 200% or more may be necessary. Fuse size can be significantly influenced again if back to back capacitor bank switching is employed. However in general for low and medium voltage capacitor banks because of the relatively small bank sections and high interconnecting inductance a fuse of 150% capacitor current rating will be satisfactory. For high voltage capacitors special steps may have to be taken to ensure sufficient transient withstand is incorporated in the fuses.

The consequences of incorrect rating, resulting in partial fuse failure caused by capacitor inrush or discharge current, is that when normal current is returned to the fuse, the fuse is no longer capable of its assigned duty, and overheating followed by complete and probably damaging fuse breakdown occurs. It is particularly important to avoid this in oil-filled tank capacitor designs.

c) The line fuses of the capacitor bank should discriminate with the fuses farther back in the supply system. In particular this may significantly influence the size of cable to a capacitor bank if correct protection of this supply cable is to be achieved.

The unit fuses of capacitor units within a capacitor bank should also be rated to achieve discrimination between the fuse protecting the faulty capacitor and those protecting the healthy capacitors. This on delta connected banks as recommended in this paper is easy to achieve as outlined in Section 3.0.

7.0 CONCLUSIONS Current limiting fuses offer considerable advantages when used for protection of industrial power factor correction capacitors in that they can generally allow capacitor requirements to be met by a physically small, simple installation. However to ensure reliable and correct operation of the installation it is important that the fuses are applied correctly as outlined in this paper.

Capacitor failure rates are considerably less than 0.1% per year and to ensure fuse operation matches this performance is particularly important.

Many years of experience of applying fuses in accordance with these guidelines have been acquired, and provided they are followed reliable and trouble free capacitor installations should be achieved.

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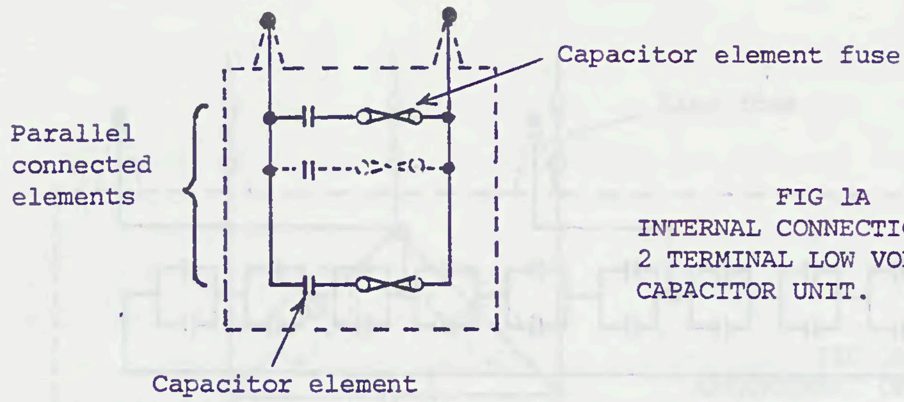

FIG 1A
INTERNAL CONNECTIONS FOR 2 TERMINAL LOW VOLTAGE CAPACITOR UNIT.

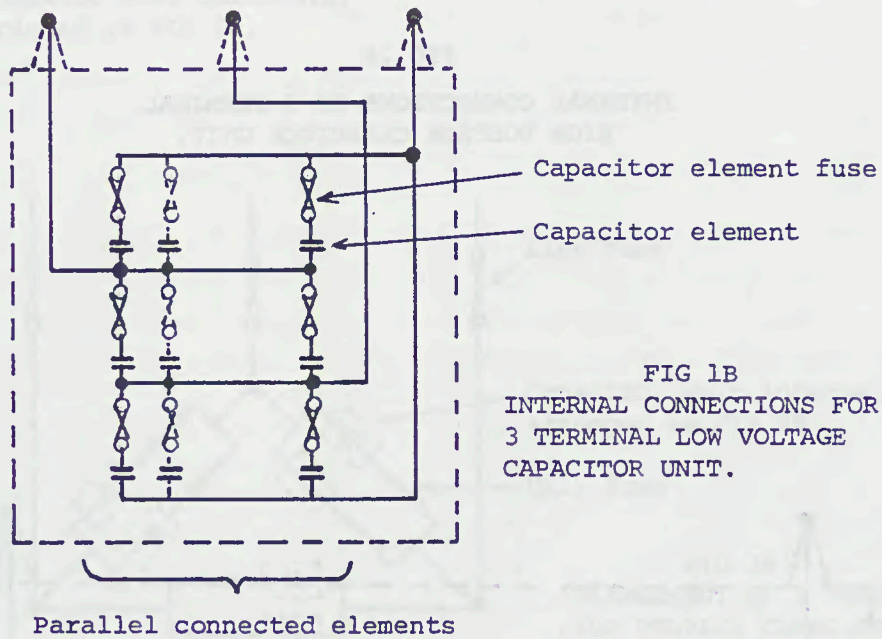

FIG 1B
INTERNAL CONNECTIONS FOR 3 TERMINAL LOW VOLTAGE CAPACITOR UNIT.

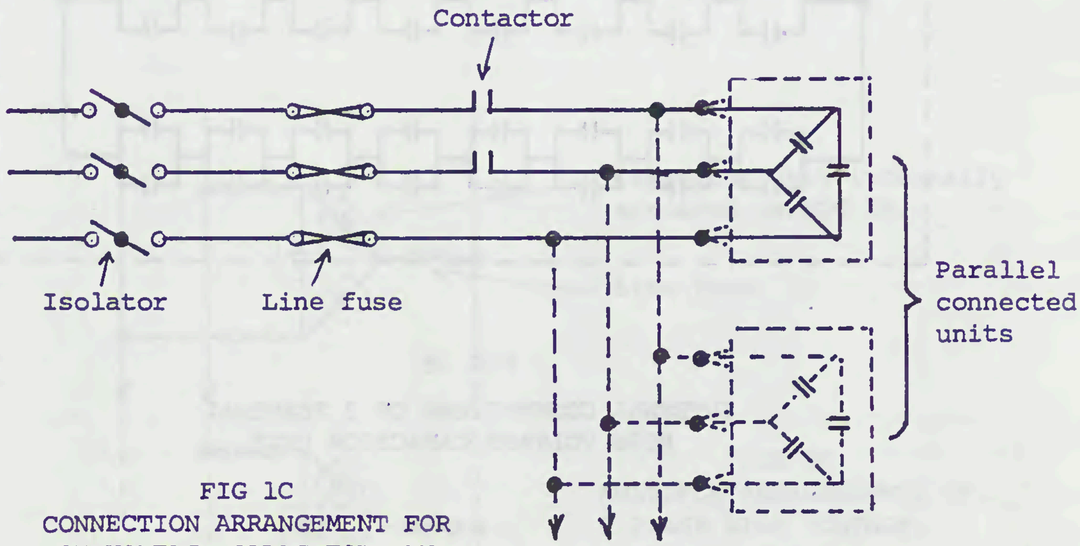

FIG 1C
CONNECTION ARRANGEMENT FOR LOW VOLTAGE CAPACITOR BANK.

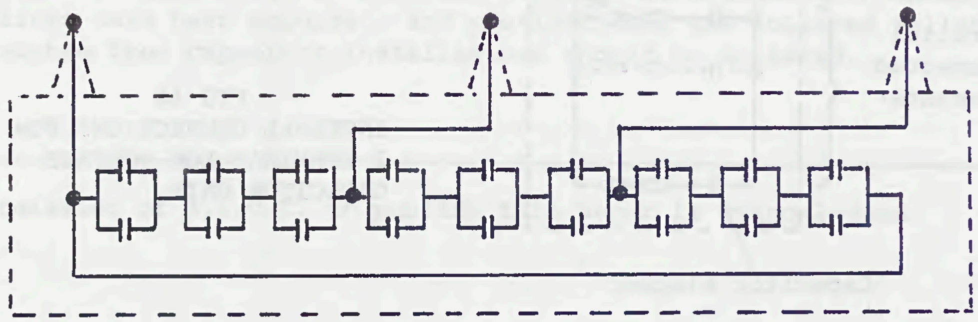

FIG 2A

INTERNAL CONNECTIONS OF 3 TERMINAL
HIGH VOLTAGE CAPACITOR UNIT.

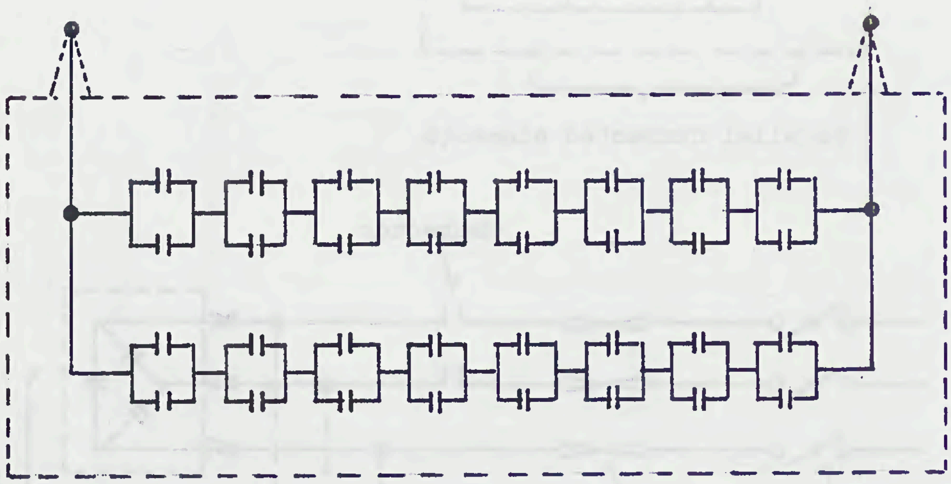

FIG 2B

INTERNAL CONNECTIONS OF 2 TERMINAL
HIGH VOLTAGE CAPACITOR UNIT.

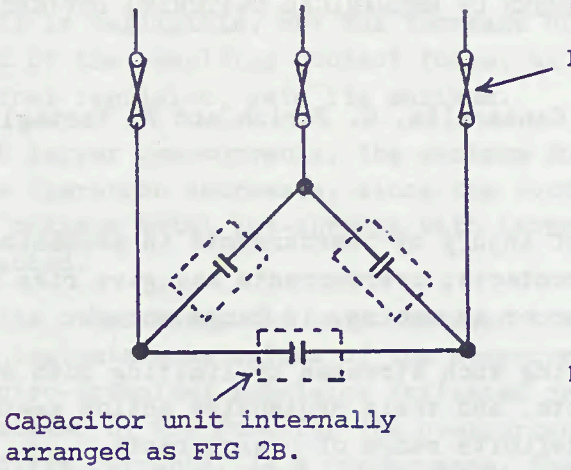

FIG 3A
ARRANGEMENT OF 3 PHASE
HIGH VOLTAGE CAPACITOR BANK.

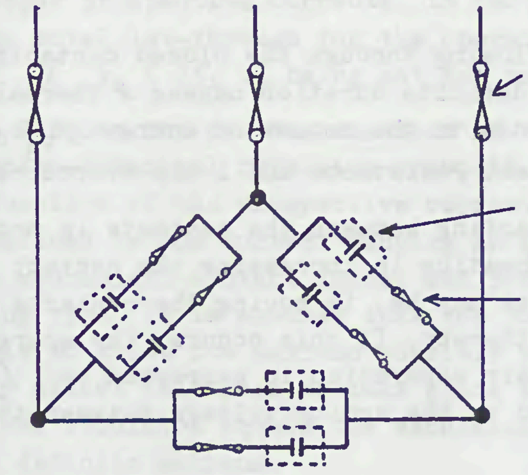

FIG 3B
ARRANGEMENT OF 3 PHASE
HIGH VOLTAGE CAPACITOR BANK
WITH LINE & UNIT FUSES.

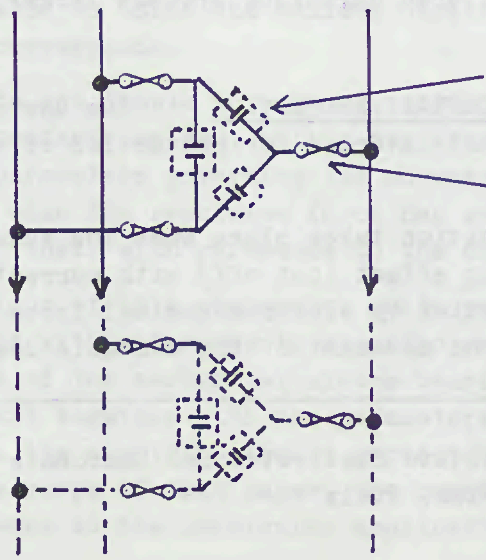

FIG 3C
MULTIPLE ARRANGEMENTS OF
3 PHASE HIGH VOLTAGE
CAPACITOR BANKS.

PROTECTION BY FUSES OF MECHANICAL SWITCHING DEVICES

S. B. Toniolo, G. Cantarella, G. Farina and M. Tartaglia

SUMMARY A weighty risk of injury by overcurrents in mechanical switching devices concerns their contacts; overcurrents may give rise to stresses leading them to weld together or to arcing, if large enough.

Fuses are suitable for limiting such stresses by limiting both duration and peak value of the overcurrents, and their protective action meets the most severe conditions within a definite range of overcurrents.

For larger overcurrents the severity does not increase any more, or it even decreases.

Experimental results are given to confirm this behaviour.

GENERAL An overcurrent flowing through the closed contacts of a mechanical switching device for a definite duration causes a thermal stress of the contacts, which corresponds to the amount of energy $\int_{t_d} r_c i^2 \, dt$, if t_d is the duration, r_c the contact resistance and i the overcurrent.

The electro-dynamical force acting between the contacts is proportional to i^2 and co-operates with the heating in increasing the contact resistance, until it succeeds, if the case may be, in moving the contacts so causing their separation and arcing thereby. If this occurs, the energy acting between the contacts during their separation is expressed by $\int_{ta} v_a \, i \, dt$, if t_a is the arc duration and v_a the arcing voltage between the moved contacts.

A value of overcurrent may be individuated for a definite mechanical switching device, starting from which the separation of the contacts by electro-dynamical force initiates since such a force prevails on the contact force. Larger overcurrents for unaltered durations produce larger repulsion forces for longer durations.

CURRENT-LIMITING FUSES FOR CONTACT PROTECTION The use of current-limiting fuses is of most practical interest for protection of mechanical switching devices.

An apparently prominent condition takes place when the fuse is such as to initiate its current-limiting effect (cut off) with currents around the value, for which contact separation by electrodynamical force starts [1]. By such values of overcurrent the movement of the contacts does not take place,

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or it is negligible, but the increase of contact resistance due to reduction of the resulting contact force, as a consequence of the electro-dynamical repulsion, gets its maximum.

With larger overcurrents, the maximum duration allowed for them by the fuse operation decreases, since the condition of substantially constant I^2t maximum total let-through with increasing prospective currents is approached.

On the other hand, the ratio between the duration of the time, for which the instantaneous values of the overcurrent exceed the value by which electro-dynamical repulsion initiates prevailing, and the total duration permited by the fuse for the overcurrent increases with increasing prospective currents. As a consequence, the amount of energy acting between the displaced contacts is expected to increase for overcurrents moderately exceeding the value by which electro-dynamical repulsion starts to prevail, but it stops increasing and even it starts decreasing with larger and larger prospective currents. In fact the condition of constant I^2t maximum total let-through for the operation of the fuse implies decreasing of $\int_{t_a} v_a\, i\, dt$, v_a being not too variable with increasing currents.

Figure 1 shows the maximum duration of the time, for which the force due to electro-dynamical repulsion prevails on the mechanical contact force, as a function of the prospective current, for a mechanical switching device defined by the current causing an electro-dynamical repulsion equal to the mechanical contact force, and protected by a fuse of the current-limiting type. It is assumed that the current is made with a making instant, suitable to allow its maximum possible value to be attained, and that the cut off effect initiates to take place at the current for which electro-dynamical repulsion equals the mechanical contact force. The diagram shows a well definite maximum.

The conditions of maximum stress for the contacts are to be expected to occur within a range of overcurrents included between a value around that for which electro-dynamical repulsion equals the mechanical contact force and the value to which the maximum duration of arcing between displaced contacts corresponds.

If contacts are liable to welding, the most favourable conditions for getting the contacts welded, within the above range of overcurrents, depends upon the parameters governing the movement of the contacts back to touch together, when the repulsion force has subsided, then upon the time required for that, with reference to the duration of the current.

The behaviour of this phenomenon can be predicted with adequate accuracy by calculation with reference to specific defined conditions, among which the parameters of the mechanical system bearing the contacts have to be taken into account together with the parameters governing the behaviour of the current in the electric circuit protected by definite fuses [2, 3, 4, 5]. Within the scope of this paper, the consideration is limited to the behaviour of fuses in the particular application.

EXPERIMENTAL RESULTS As an experimental confirmation of the above considerations, tests have been carried out taking as typical mechanical switching device contactors of ordinary construction and of different current ratings, protected by standard fuses of current-limiting type and of different ratings.

For testing, fuses were replaced by an appropriate special device [6], suitable for reproducing the intended operating characteristics of fuses with appropriate accuracy, i.e. within a tolerance appreciably more restricted than that admitted by the Standards on fuses (IEC Publ. 269-1/2).

Diagram of figure 2 shows the results of tests on a contactor rated 50 A, for which the current (r.m.s. value) causing electro-dynamical repulsion substantially equal to the mechanical contact force is 5 kA. The contactor is protected by a standard fuse rated 125 A, for which the maximum total let-through I^2t in adiabatic conditions of operation is about 95 kA^2s.

The instantaneous values of the current through the contactor and of the voltage across the contacts, the final values of I^2t let-through, resulting by $\int_t i^2 dt$, of energy stressing the contacts, resulting by $\int_{t_a} v_a i \, dt$, and $\int_t r_c i^2 \, dt$ were recorded at each test by the appropriate application of a computer [7]. The amount of this energy is reported in ordinate of the diagram, where the prospective test current is in abscissa. The making instant of the test current was pre-determined for each test with the aim at attaining the maximum expected total I^2t let-through.

When welding of contact occurs, it may result in a definite reduction of the amount $\int r_c i^2 dt$, for unaltered total I^2t let-through, due to the reduction of the contact resistance following the welding. In other cases the end of the let-through current leaves the contacts welded together, but the amount of energy required for this result is appreciably higher, as corresponding to $\int v_a i \, dt$. In such cases welding has occurred when contacts have come back to touch together, after a time of arcing due to repulsion. In many other cases, with higher currents, the arcing energy $\int v_a i \, dt$ did not give rise to welding.

CONCLUSIONS It may be stated as a conclusion:

a) when contacts are liable to welding, the most appropriate fuse [1] for protection is that, for which the current-limiting effect (cut off) initiates with currents approaching the value, by which electro-dynamical repulsion starts prevailing on the mechanical contact force.

According to the ratio between such a current and the rated current of the mechanical switching device, the above criterion may imply (and it implies in general for mechanical switching devices of particular design, as are contactors) de-rating of them with regard to normal service current, since fuses of rated current less than the rated current of the protected mechanical switching device are required.

Appropriate design of the mechanical switching device may reduce this inconvenience or overcome it at all. If contacts are less liable to weld ing, fuses of larger rated current can be used, but they allow for higher deterioration due to arcing during overcurrents.

b) tests for checking suitability of co-ordination between fuses and mechanical switching devices to be protected are to be made with currents around the value, which initiates contact separation by electro-dynamical repulsion, in moderate excess to this value.

Test at higher currents, up to the prospective current for which the combination of the mechanical switching device with the fuses is required to be suitable, are not strictly required when the above specified tests are passed successfully, since stresses on contacts and likelihood of welding, if the case may be, do not increase or even they substantially decrease with increasing currents, when fuses are characterized by operation with maximum total I^2t let-through being constant at large overcurrents.

REFERENCES

[1] - Toniolo, S.B. and Cantarella, G.: "Protezione di contattori mediante fusibili" L'Elettrotecnica, n. 3bis, vol. LV, 1968.

[2] - Wilkins, R.: "Generalised short-circuit characteristics for h.r.c. fuses" Proc. IEE, Vol. 122, No. 11, November 1975, pp. 1289 - 1294.

[3] - Toniolo, S.B. and Cantarella, G.: "Conditions of maximum arc energy in operation of current-limiting fuses" IEEE Trans., 1969, PAS - 88, pp. 94 - 99.

[4] - Kaufmann, R.H.: "The magic of I^2t" IEEE Trans., Vol. IGA - 2, No. 5 - Sept./Oct. 1966, pp. 384 - 392.

[5] - Cantarella, G.: "L'interruzione di corrente alternata mediante fusibili - L'energia trasformata nell'arco" L'Elettrotecnica, n. 4, Vol. XLVII, 1960.

[6] - Toniolo, S.B. and Cantarella, G.: "Simulation of fuse performance for co-ordination and testing purposes" Proc. IEE, Vol. 122, No. 5, May 1975, pp. 501 - 503.

[7] - Farina, G.: "Computer data acquisition and processing in short-circuit laboratories" Acta IMEKO 1973, Vol. I, pp. 607 - 618.

[8] - Boehne, E.W.: "Performance criteria for current-limiting power fuses - II" Trans. Am. IEE, 1946, 65, pp. 1034 - 1044.

[9] - Lerstrup, K.: "The current limiting fuse with special reference to discrimination and breaking capacity" Ingeniøren, 1958, pp. 13 - 20.

[10] - Baxter, H.W.: "Electric fuses" (Arnold 1950).

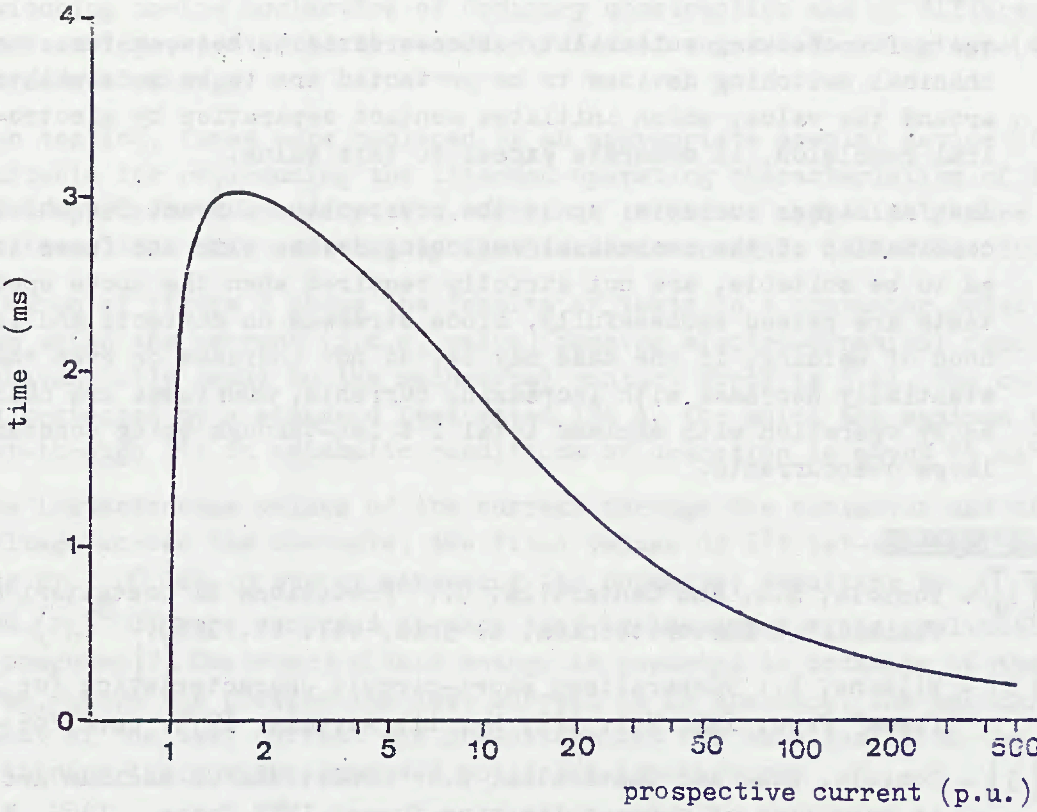

Fig. 1

Maximum duration of the time for which the force due to electrodynamical repulsion prevails on the mechanical contact force, as a function of the prospective current, for a given power factor ($\cos\varphi = 0.2$). Prospective currents are referred to the r.m.s. value of the current for which these forces are equal

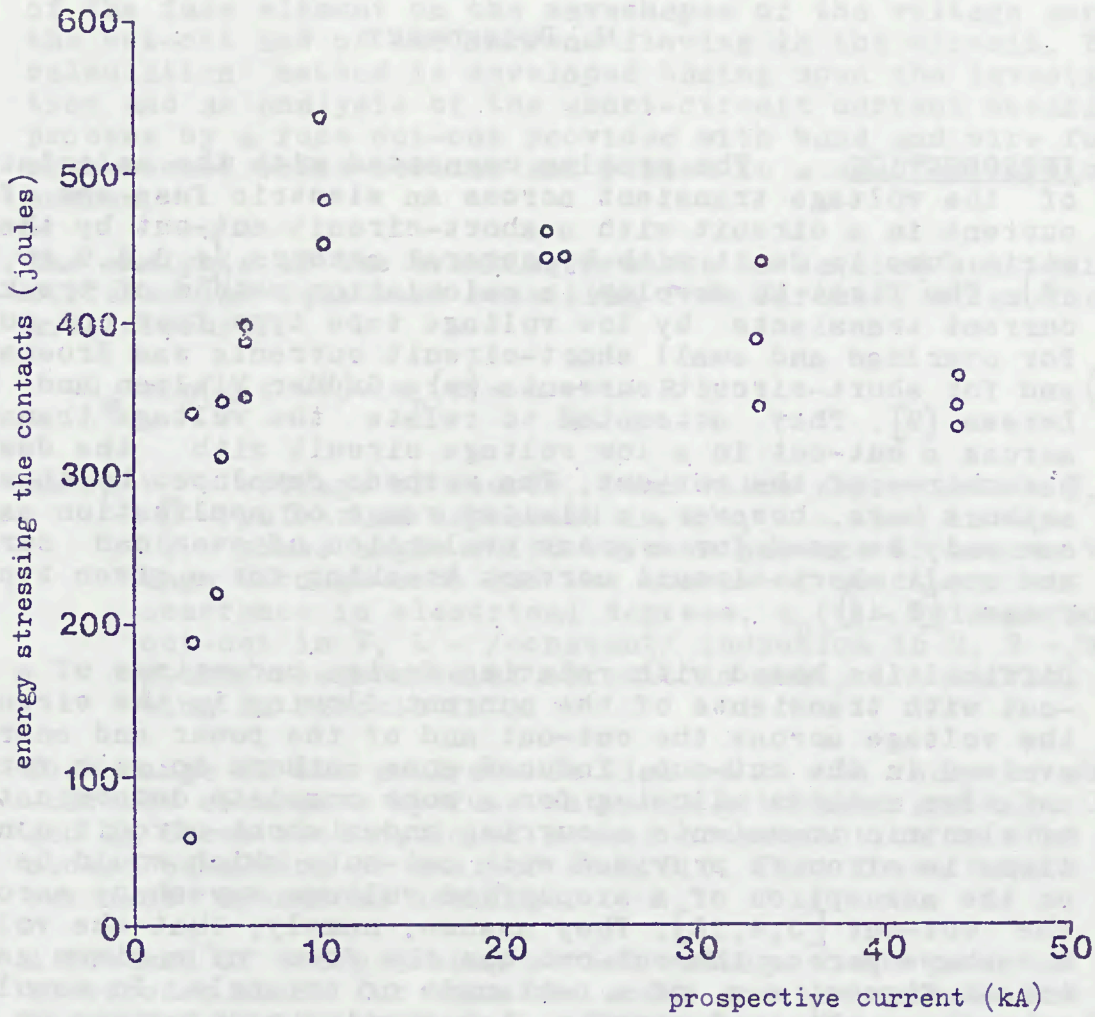

Fig. 2
Energy stressing the contacts of a contactor rated 50 A, as a function of the prospective test current

CALCULATION OF THE COURSE OF THE CURRENT AND VOLTAGE OF A CURRENT-LIMITING FUSE

M. Dołęgowski

INTRODUCTION The problem connected with the calculation of the voltage transient across an electric fuse and of the current in a circuit with a short-circuit cut-out by the electric fuse is dealt with by several authors [1,3,4,9,10,11,12, 16]. The first to develop a calculation method of breaking current transients by low voltage tape type fuse cut-outs for overload and small short-circuit currents was Kroemer [11] and for short-circuit currents were Gruner Nielsen and Holm Lersen [9]. They attempted to relate the voltage transient across a cut-out in a low voltage circuit with the design parametres of the cut-out. The methods developed by these authors have, however, a limited range of application as they can only be used for a gross evaluation of overload current and small short-circuit current breaking for a given type of fuses. [9,11]

Difficulties bound with relating design parametres of a cut-out with transients of the current flowing in the circuit of the voltage across the cut-out and of the power and energy evolved in the cut-out, induced some authors to seak for calculation methods allowing for a more complete determination of electric transients occurring under short-circuit conditions in circuits provided with cut-outs which would be based on the assumption of a simplified voltage waveshape across the cut-out [3,4,12]. They assume, namely, that the voltage waveshape across the cut-out has the form of a given geometrical figure, e.g. of a rectangle or triangle. In result these authors obtained certain interesting conclusions on arc extinction, on the limitation of the short-circuit current and the influence of the voltage waveshape on the breaking performance value and of the Joule integral value.

The above quoted authors do not state what design parametres of a cut-out influence the appearence of a given voltage waveshape occurring across it. Therefore, as results from the survey presented, the up-to-date calculation methods do not allow, in practice, for the calculation of current and voltage transients appearing on a current limiting cut-out having complex design parametres of the fuse, especially, for the case of short and heavy overloads.

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Under these circumstances, a calculation method is suggested which would take into account the effect of the dimensions of the fuse element on the waveshapes of the voltage across the cut-out and of the current flowing in the circuit. This calculation method is developed basing upon the investigation and an analysis of the short-circuit current breaking process by a fuse cut-out provided with band and wire fuses with necked cross-section and placed in a sand extinction medium.

The analysis of the breaking process is carried out using differential equations resulting from Kirchoff´s law for an a.c. circuit:

$$U_m \sin(\omega t + \psi) - u_p(t) = L \frac{di}{dt} + R\, i \qquad (1)$$

where U_m - voltage of source, peak value expressed in V, ω - pulsation expressed in 1/s, t - time in s, ψ - phase angle shift between passage of source voltage through zero and the moment of short-circuit occurance in electrical degrees, $u_p(t)$ - voltage across cut-out in V, L - /constant/ induction in H, R -/constant/ resistance of circuit in ohms, i - current flowing in circuit in A.

The range of the analysis is limited to the case of short--circuit clearance by fuse cut-outs with band and wire Cu and Ag fuses with ratio of necked cross-section to that not necked equalling or smaller than 0.6. The fuses have a number n of identical neckings.

A the end of every arcing period voltage drops occur at the electrodes which for both the anode and the cathode are represented by the voltage U_B. The number of arcs equals the number n of neckings. Under these assumptions, the relation describing the voltage waveshape across the cut-out can be expressed by the following equation:

$$u_p = n\left(U_N + l \cdot E\right) \qquad (2)$$

where u_p - voltage across cut-out in V, n - number of neckings of fuse number of arcs, U_B - voltage drop at electrodes in V, l - length of a single arc in cm, E - electric field strength, average voltage gradient in V/cm.

Substituting expression (2) in equation 1 we obtain:

$$U_m \sin(\omega t + \psi) - L \frac{di}{dt} - Ri = n\left(U_B + lE\right) \qquad (3)$$

In result of an analysis made and of laboratory tests the quantities U_B, l and E could be determined as a function of certain physical parametres characteristic for the arc in the cut-out and as well as for the geometrical dimensions and the material of the fuse including copper and silver fuses.

LABORATORY TESTS A series of indentical cut-out models, provided with Cu and Ag fuses having shapes and dimensions according to fig.1, were prepared. The fuses were immersed in quartz sand of 0.2 to 0.4 mm grain size. The fuses were tested in the test circuit specified in fig.2.

The power of the source and the constants R and L of the test circuit fig.2 allowed for the obtention of the following test parametres foreseen by the programme: prospected current I_p=0.3 to 60 kA, cosφ = 0.1 to 0.35, recovery voltage U_p=100 to 240 V or 600 to 1800 V.

The tests of cut-outs by the method of arcing stoppage were carried out switching on by the short-circuiting switch Z_1 the circuit with cut-outs B_1 and B_2 and, thus, initiating in the cut-out B_1 the arcing process. Next, at a given moment after the appearance of the arc the arcing process was stopped by closing the switch Z_2. During the test series of identical cut-outs the latter switch was closed at different delay times in reference to the moment of arc firing. These times were chosen so as to assure a uniform distribution of times to closing of the switch. The tests carried out by this method are illustrated by oscillogrammes of fig. 3.

ANALYSIS OF TEST RESULTS

Determination of voltage U_B The voltage drop U_B at the electrodes of an arc appearing within a cut-out was determined by extrapolation of the function U=f(l) see fig. 4 to its intersection with the axis of ordinates.

It may be seen in this figure that at small arc length the voltage increments are approximately proportional to arc length increments. Thus, we can write:

$$u_p = U_B + l \frac{du}{dl} \qquad (4)$$

where u_p - voltage across cut-out in V, U_B - voltage drop at electrodes in V, l - arc length in cm, du/dl = E - electric field strength in arc column in V/cm.

The quantities U_B and E in expression (4) are functions of tests parametres /of the current/ and of design parametres of the fuse [5,6,7,8]. When investigating relation (4) it was stated that:

a/ for the range of current densities throughout the fuse cross-section S not exceeding 8 kA/mm^2, U_B is a function of the current, U_B = f(i)- see fig. 6,

b/ for the range of current densities thronghout the fuse cross-section S of 8 to 20 kA/mm^2, U_B is a function of the current density throughout the fuse cross-section, U_B = f (i/s) - see fig. 7.

The function $U_B = f(i)$ represented in fig. 6 is an exponential relation.

Establishing in the diagramme the origin of the system of coordinates at the point of 20 A the relation $U_B = f(i)$ may be represented by an analytic equation by the expression:

$$U_B = \triangle U_1 + k\, i^{\vartheta} \quad (5)$$

where U_B - voltage drop at electrodes in V, $\triangle U_1$ - constant component of the voltage drop at electrodes equalling 20±5V, k - coefficient equalling 1,5, ϑ - exponent equalling 0.39.

Fig.6 represents the relation $U_B = f(i/S)$. It may be seen that for the range of current densities of 8 to 20 kA/mm^2 the relation can be represented as a straight line of a slope $\rho_B = 4.18 \pm 0.25 \cdot 10^{-5} \Omega \cdot cm^2$. The extrapolation of this straight line to its intersection with the axis of ordinates determines the point $\triangle U_2 = 30 \pm 5$ V.

The analytic form of the equation of the regression line for the relation $U_B = f(i/S)$ for the current density of 8 to 20 kA/mm^2 may be represented by the following expression:

$$U_B = \triangle U_2 + \frac{i\, \rho_B}{S} \quad (6)$$

where $\triangle U_2$ - component of voltage drop at electrodes independent of current and equalling 30±5V, ρ_B - slope of straight line in Ω cm^2, S - fuse cross-section equalling the arc cross-section S_B in the electrode zone in mm^2. 8

It results from expression (6) that for the current density range of 8 to 20 kA/mm^2 the slope of the straight line, is constant and has the dimension of resistivity of the electrode zone expressed in Ω cm^2 (and not in Ω cm as the deepness of the electrode zone was not established).

As can be seen, U_B can be calculated from the expressions (5) or (6). In doubtful cases, the relation $S_B = f(i)$ is decisive under the following form

$$S_B = c_1 \cdot i^{\varepsilon} \quad (7)$$

in which the coefficients c_1 and ε amount to:

$c_1 = 1.05 \pm 0.1\ 10^{-3}$, $\varepsilon = 0.730 \pm 0.03$.

Thus, when the cross-section S_B calculated from expression (7) equals or exceeds the cross-section S, $S_B \geq S$, expression (6) obliges, and when the cross-section S_B is smaller than the cross-section S, $S_B < S$, the expression (5) is valid.

Determination of arc length l. The velocity of elongation of the arc depends on the material of the fuse, its temperature, the cross-section and the power of the arc. The energy necessary for fusing a section of length dl /neglecting the emission of heat to the ambiance as it is a short-circuit that we are considering/ results from the heat balance equation:

$$dl \cdot S \left[C_v \cdot \Delta T + h + h' \right] = c_2 i^2 R_B \cdot dt \qquad (9)$$

where dl - elementary length of fuse in cm, S - crosssection of fuse in cm^2, C_v - specific heat of metal in solid state per unit volume $\frac{Ws}{^\circ C\ cm^3}$, h - latent heat of fusion of metal per unit volume $\frac{Ws}{cm^3}$, h' - empirically determined quantity taking into account the energy of vaporisation of the metal and that of transformation of the thermal energy into the kinetic energy of metal vapour $\frac{Ws}{cm^3}$ [7,8] $\Delta T = T_1 - T_2$, T_1 - - metal fusion temperature, T_2 - temperature of fuse heated by Joule's heat, C_2 - proportionality factor, i - current A, R - resistance of electrode zone of arc in ohms, dt - time in s.

After transformation expression (9) takes the following form:

$$\frac{dl}{dt} \left[C_v \cdot \Delta T + h + h' \right] = \frac{C_2\, i^2\, R_B}{S} \qquad (10)$$

Expression (10) represents the relation between the thermal power evolved within the fuse and the power density at the electrodes. The following data are necessary for solving this relation:

$\frac{dl}{dt}$ - velocity of arc elongation in cm/s corresponding to the instantaneous value of the current i, see fig. 5,

T_2 - temperature of fuse heated by Joule's heat corresponding to the instantaneous current value i,

R_B - resistance of electrode zone of arc as function of current.

These data have been determined from the short-circuit tests considered in Chapter 2.

The elongation velocity of the arc or of the arc gap dl/dt corresponding to the instantaneous value of the limited current i and at the moment t_1 is determined from the diagramme of fig. 5 as the slope of the tangent to the curve $l=f(t)$ at the point having coordinates t_1 and l_1.

The temperature T_2 of the fuse heated by Joule's heat corresponding to the instantaneous value of the current and at the moment t_1 can be determined from the expression:

$$T_2 = \frac{\exp \frac{\alpha \varrho_o}{S^2 C_v} \int_{t_o}^{t_1} i^2 dt - 1}{\alpha} \tag{11}$$

where T_2 - temperature of fuse in ^oC, ϱ - resistivity of the fuse metal in ohm·cm, α - temperature factor of resistance in solid state $1/^oC$, C_v - specific heat of the metal of the fuse in $\frac{Ws}{^oC\ cm^2}$.

Expression (11) results from Mayer's formula [15].

For an arc resistance R_B in the electrode zone the following expression may be suggested:

$$R_B = \frac{U_B}{i} \tag{12}$$

By substituting in equation (10) the expression (12) we obtain the following relation:

$$\frac{dl}{dt} \left[C_v \cdot \Delta T + h + h' \right] = \frac{C_2\, i\, U_B}{S} \tag{13}$$

in which the factor C_2 determined by the method of minimum squares amounts to:

$$C_2 = 0.18 \pm 0.01$$

By transforming expression (13) we obtain the relation between the arc elongation velocity on current, temperature and the fuse material constants having the following form:

$$\frac{dl}{dt} = \frac{C_2\, i\, U_B}{S \left[C_v \cdot \Delta T + h + h' \right]} \tag{14}$$

After separating the variables and integration we obtain:

$$l = C_3 + \int_{t_z}^{t_1} \frac{C_2\, i\, U_B\, dt}{S \left[C_v \cdot \Delta T + h + h' \right]} \tag{15}$$

where l - length of fusion of fuse element in cm, t_z - firing moment, t_1 - moment at which the arc attains the length l_1, C_3 - constant having the dimension of the arc length in cm. It determines the necking length p.

<u>Determination of voltage gradient E</u> It results from the author's works that at the beginning of the breaking process the voltage rate of rise du/dt depends on the arc power p and on the value of Joule's energy evolved in the fuse at the moment of occurrence of the short-circuit, i.e. that a correlation exists between the voltage rate of rise and

the arc power [6,8]

$$\frac{du}{dt} = f(P)_{T_1 = \text{constant}} \tag{16}$$

Taking expression (16) into account and differentiating expression (2) we obtain for the initial section of the process for growing current values

$$\frac{du}{dt} = \frac{d \cdot U_B}{dt} + \frac{dl}{dt} E + \frac{dE}{dt} l = f(P) \tag{17}$$

The arc power can be expressed by:

$$P = \frac{i^2}{G_k} \tag{18}$$

where G_k - conductivity of arc gap.

Conductivity of the arc column is a function of the current [10,16]

$$G_k = f(i) \tag{19}$$

Introducing to the formula (18) expression (19) we obtain

$$P = i^2 f(i) \tag{20}$$

or

$$P = f_2(i^\beta) \tag{21}$$

Substituting in equation (21) the expression (17) and taking into account that the voltage drop at the electrodes U_B in a wide range of current variation, hence, also of time up to the moment considered, changes but slightly. In consequence, the index dU_B/dt appearing in expression (17) is very small and we can assume

$$\frac{dU_B}{dt} = 0$$

and after setting E before the parenthesis we obtain:

$$\frac{du}{dt} = E\left(\frac{dl}{dt} + \frac{dE}{dt}\frac{l}{E}\right) = f_2(i^\beta) \tag{22}$$

It may be seen from 22 that the voltage variation rate across the cut-out depends on two components:

- the component resulting from arc length increase at a constant voltage gradient,

- the component resulting from the voltage gradient increase at a constant arc length.

By transforming expression (22) to the form:

$$E = \frac{f_2(i^{\beta})}{\frac{dl}{dt} + \frac{dE}{dt}\left(\frac{1}{E}\right)} \qquad (23)$$

we obtain the relation between the electric field strength and the current as well as the quantities $\frac{dl}{dt}$ and $\frac{dE}{dt}$ characteristic for the extinction performance of the cut-out.

Introducing in the expression (23) $\frac{dE}{dt} = 0$ (E=const.) we obtain the relation between the electric field strength and the current as well as the fusion velocity of the fuse.

$$E = \frac{f_3(i^{\beta})}{\frac{dl}{dt}} \qquad (24)$$

Introducing in expression (23) $\frac{dl}{dt} = 0$ (l=const.) we obtain the current at a constant length of the arc (This case occurs after a complete fusion of the fuse element and before the arc extinction within the cut-out .

$$E = \frac{f_4(i^{\beta})}{\frac{dE}{dt}\left(\frac{1}{E}\right)} \qquad (25)$$

Respective numerical data for the relations E = f(i) according to the expressions (24) and (25) were established from tests. Numerical data for the relation E=f(i) according to the expression (25) were obtained from the analysis of oscillogrammes of current breaking at a constant length of the arc. This analysis allowed for plotting the diagramme E = f(t) represented in fig.8. This relation can be expressed as an exponential function:

$$E = E_o \exp t/\theta_1 \qquad (26)$$

where E - electric field strength in V/cm, E_o - electric field strength at the moment t=0, θ_1 - time constant characteristic for the field decay in the arc column due to heat cumulation in extinction medium.

After differentiation of the expression (26)

$$-\frac{dE}{dt} = -\frac{E_o}{\theta_1} \exp {}^{-t}/\theta_1 \qquad (27)$$

and substitution of (26) and (27) in expression (25) we obtain:

$$E = \frac{f_4(i^{\beta})}{C_4 \frac{1}{\theta_1}} \qquad (28)$$

where C_4 - constant.

Numerical data corresponding to the relation $E = f(i)$ according to expression (24) have been obtained from the diagramme $E \cdot \frac{dl}{dt} = f(i)$ represented in fig.9. The product $E\frac{dl}{dt}$ is represented in this diagramme as a function of the current referred to the double width of the fuse and taking its thickness as parametre. The analysis of measuring results represented by the diagramme allows for rewriting expression (24) in the following form [8]:

$$E = \frac{C_5\left(\frac{i}{2F\ \ln a/a_o}\right)^{\beta}}{dl/dt} \tag{29}$$

where C_5 - proportionality factor, a_o - critical thickness equalling 0.0032 cm, a - fuse thickness in cm, F - width of fuse in cm.

For symmetry purposes of expressions (28) and (29), the current in the relation $E = f(i)$ in expression (28) may also be referred to the dimensions of the fuse:

$$E = \frac{C_6\left(\frac{i}{2F\ \ln a/a_o}\right)^{\beta}}{C_4\ \frac{l}{\theta_1}} \tag{30}$$

Substituting expressions (29) and (30) in expression (23) we obtain:

$$E = \frac{C_7\left(\frac{i}{2F\ \ln a/a_o}\right)^{\beta}}{\frac{dl}{dt} + C_4\ \frac{l}{\theta_1}} \tag{31}$$

In the above considerations it was assumed that the conductivity of the arc column is a function of the current. Fig.8 displays that this conductivity is also a function of time and can be expressed by the equation:

$$G_k = G_o\ \exp^{-t}/\theta_1' \tag{32}$$

where G_k - conductivity of arc column in 1/ohm, G_o - conductivity of arc column at the moment t=0, θ_1' - time constant of the decay of the conductivity of the arc column. The diagramme shows that $\theta' = \theta$.

Thus, taking into account the relation (32) the expression (31) will have the form:

$$E = \frac{C_8 \left(\frac{i}{2F \ \ln \ a/a_o} \right)^{\beta}}{\left(\frac{dl}{dt} + x \right) \exp^{-t/\theta_1}} \qquad (33)$$

where C_8 - proportionality factor equalling $1{,}1 \cdot 10^{-2}$, β - exponent equalling 2 ± 0.2, F - width of fuse in cm, a - thickness in cm, $a_o = 0.0032$ cm, θ_1 - time constant equalling 1.6 to $6.2 \cdot 10^{-3}$ s, $x = C_4 \frac{1}{\theta_1}$; for simplification reasons it was assumed that x is a constant amounting to $x = 111 \pm 1$.

The mentioned numerical values apply to cut outs with band fuses of thickness 0.005 to 0.03 cm. For wire fuses, the value C_8 amounts to $1.7 \cdot 10^{-2}$, and 2F and ln a/a_o should be respectively substituted by terms $\pi \cdot d$ and $z \cdot \ln \ d/d_o$ where d- wire diameter in cm /in the range from 0.006 to 0.06 cm/, z - number of parallel wires, d_o - critical diameter equalling 0.0032 cm.

The expression (33) can be applied only in approximate calculations as it does not take account of the phenomenon of arc hysteresis. This phenomenon can be taken into account by introducing in the expression (33) of supplementary relations resulting from Mayr's report [14]. When these relations are introduced and after simplifications made the expression (33) will have the form [8]:

$$E = \frac{C_8 \left(\frac{i}{2F \ \ln \ a/a_o} \right)^{\beta} \exp^{t/\theta_2}}{\left(\frac{dl}{dt} + x \right) \exp^{-t/\theta_1} + \frac{\int_{t_z}^{t_k} i^2 \exp^{t/\theta_2} dt}{E_{max} \cdot i_{max} \cdot \theta_2}} \qquad (34)$$

where θ_2 - arc time constant according to Mayr, i_{max} - peak-value of limited current, E_{max} - electric field strength corresponding to i_{max}, t_z - arc firing moment, t_k - moment at which the breaking process is ended.

Taking into account the relations (5), (15) and (34) we obtain finally for (3) the expression:

$$U_m \sin(\omega t + \psi) - L \frac{di}{dt} - Ri = n(\triangle U + k i) + n \left[C_p + \int_{t_z}^{t_k} \frac{C_2}{C_v \triangle T + h + h'} \left(\frac{i \ U_B}{S} \right) \right]$$

$$\cdot \frac{C_8 \left(i \frac{1}{2F} \cdot \frac{1}{\ln a/a_0} \right)^{\beta} \exp^{t/\Theta_2}}{\left(\frac{dl}{dt} + x \right) \exp^{-t/\Theta_1} + \frac{1}{E_{max}\, i_{max}\, \Theta_2} \int_{t_z}^{t_k} i^2 \exp^{t/\Theta_2} dt} \qquad (35)$$

An algebraical solution of this equation does not exist. It may only be solved by the iteration method on a digital computer, preparing of course a suitable calculation programme. The arc firing moment can be calculated by means of the method quoted in report [13].

CALCULATION EXAMPLES The fig.11 represents the voltage and current waves calculated by means of expression (35) - dotted line. The continous line displays the same curves from oscillographic records. The calculated and the oscillographically recorded curves concern the same design parametres of the cut-out and the same test conditions. The fuses type H_n, a = 0.02 cm, F = 1 cm, S_z/S=0.5, N=8. The error in the calculation of the fuse length does not exceed ±5%. The particular coordinates of the calculated current and voltage curves and the respective coordinates of actual curves do not differ by more than 10%.

Fig.10 shows four curves A,B,C,D of voltage and current calculated according to expression (35) for the same circuit parametres. The calculations concern fuses typ H_n of design parametres: a=0.02 cm, F=1 cm, S_z/S=0.5 differing only by the number of overloads n.

CONCLUSIONS

a/ The proposed method allows for the calculation of the following electric and design parametres of the cut-out:

1/ the breaking transients and the current flowing in the circuit, the voltage across the cut-out, the power and energy of the arc,

2/ the dimensions of the fuse element: its length, width and thicknes, as well as the number of neckings.

b/ The calculation method allows for the determination of the fuse length required in the given short-circuit conditions and for the correct breaking performance, under preset other design parametres, with an error range of ±10%.

c/ The calculation method allows for the choice of the most advantageous voltage waveshape, for a given type of cut-out, by a suitable shaping of the fuse element.

References

A. Books

1. Baxter H.W.: Electric fuses E. Arnold London 1950

2. Lipski T.: Low voltage cut-outs, PWNT Warszawa 1968

B. Reports, periodicals and other

3. Boehne E.W.: The geometry of arc interruption. Gen. Electr. Rev. 1941, p.207-216.

4. Boehne E.W., Schuck C.L.: Performance criteria for current limiting power fuses. Trans. AIEE 1946, p.1034-1045, 1191-1194.

5. Dołęgowski M.: Spannungsverlauf an der einfachen Lichtbogenunterbrechung in den Sicherungen mit Sandlöschung und Einengungsschmetzstreifen. Switching arc Phenomena SEP - Łódź 1970.

6. Dołęgowski M.:Gechvindigkeit der Verlangerung des Lichtbogens bei den Streifensicherungen mit Sandloschmittel. International Symp. Switching Arc Phenomena Łódź 1973.

7. Dołęgowski M.: Firing voltage tests in cut-outs with sand extingsnishing medium and necked band fuse elements. Elektrotechnika, IEl Warszawa, Biuletyn Informacyjny 1970, z.4, p.1-5.

8. Dołęgowski M.: Calculation of breaking transients of current limiting cut-outs. Doctor's thesis , Instytut Elektrotechniki Warszawa 1976 /under preparation/

9. Gruner-Nielsen B., Holm Larsen J.: Sikrungsovorspaendinger po Lanspaendingssalaeg. Ingeniren 1964, nr 18, s.455.

10. Hibner J.: Resistance gradient method of calculation of the peak value of overvoltages generated by short-circuit current limiting cut-outs. Doctor's thesis, Technical University Gdańsk, 1973.

11. Kroemer H.: Der Lichtbogen an Schmetzleitern in Sand. Arch. f. Elektr. 1942, Nr 8, s.455-470.

12. Lipski T., Zimny P.: Eine Beitrag zur Berechnung des Joulischen Lichtbogen intergrals und der Ausschalterbeit von Strombegrenzeden Schmelzsicherungen. E und M, 1972, Nr 11, s.461-464.

13. Lipski T.: Graphical method of determining the limited current of fuse cut-outs, PE 1963, Nr 3, s.101.

14. Mayr O.: Beitrage zur Theorie des statischen und des dynamischen Lichtbogens Arch. f. Elektr. 1943, Nr 12, s.588-608.

15. Meyer G.J.: Zur Theorie der Aschmelzsicherungen Munchen 1906.

16. Vermij L.: Electrical behaviour of fuse elements. Dissertation T.H. Eindhoven 1969.

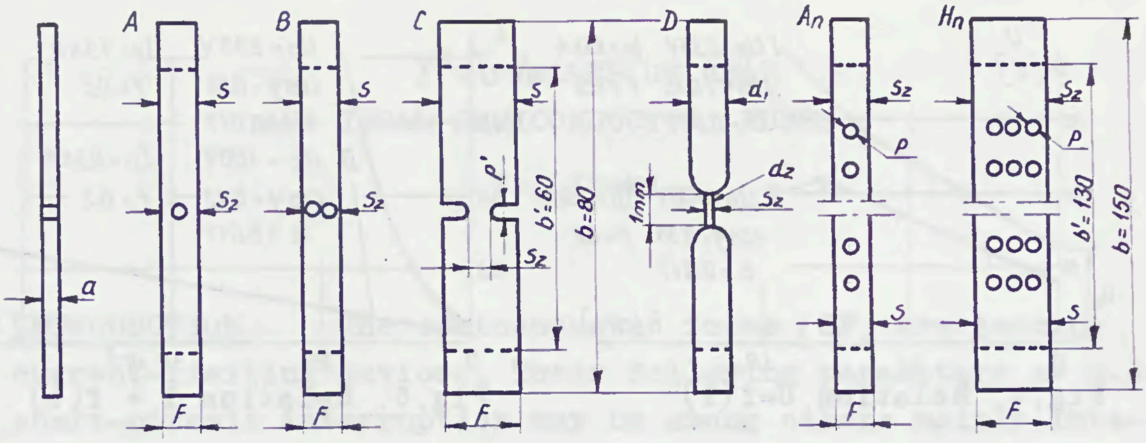

Fig.1. Shapes and dimensions of fuse elements of band type A,B,C, A_n, H_n and of wire type D.

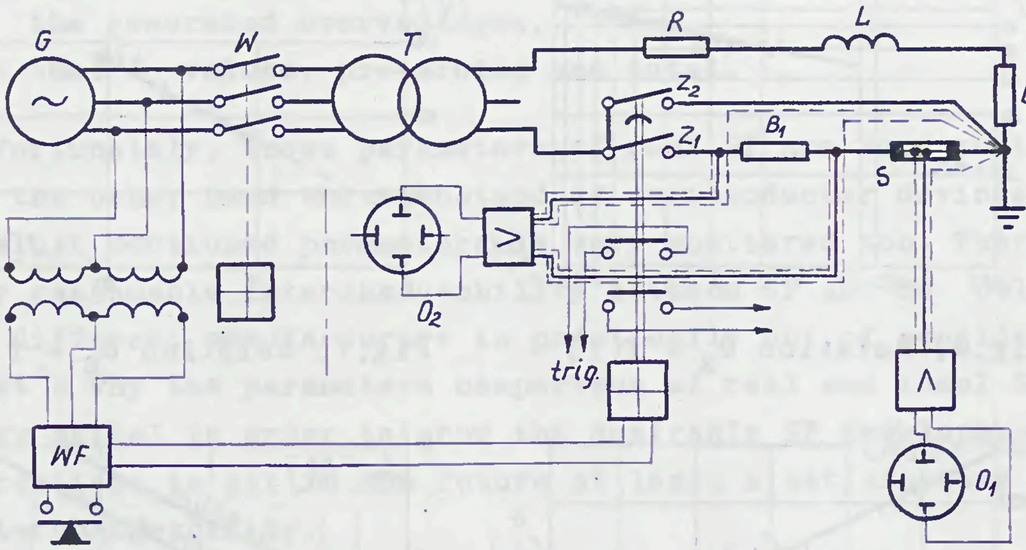

Fig.2. Test circuit for testing cut-outs by the arcing stoppage method. B_1 - tested cut-out, B_2 - auxiliary cut-out.

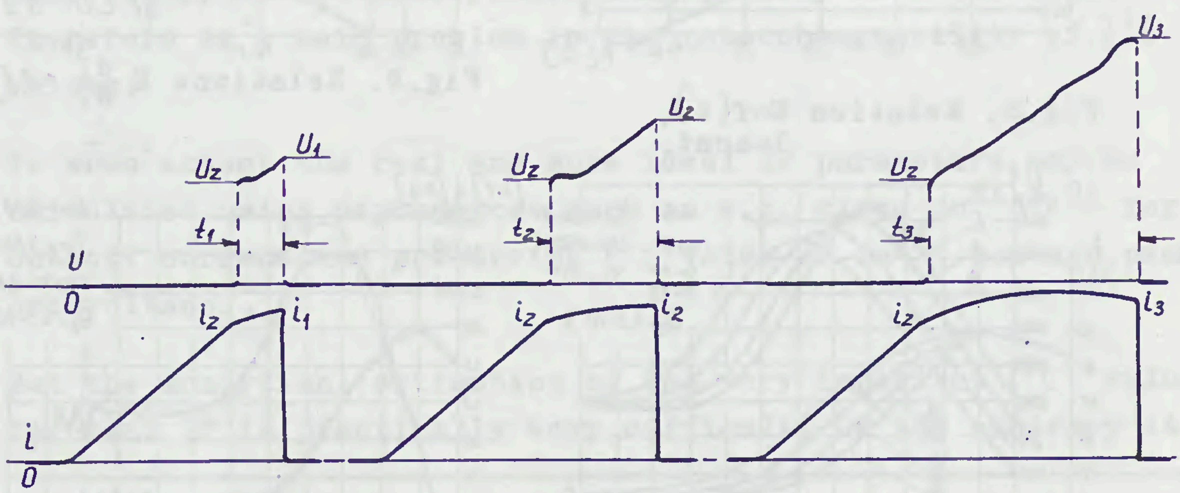

Fig.3. Successive oscillographic records from tests of a series of cut-outs. $U_{1...3}$, $i_{1...3}$ - voltage and current at moment of arcing stoppage.

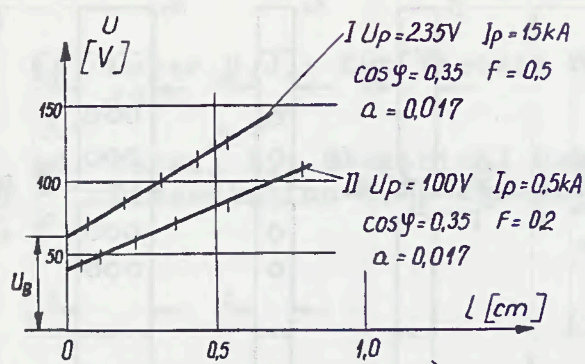

Fig.4. Relation U=f(l)

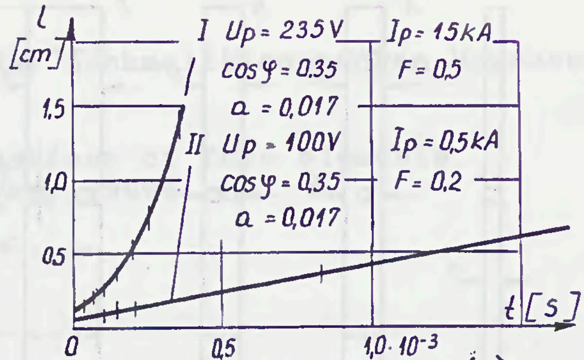

Fig.5. Relation l = f(t)

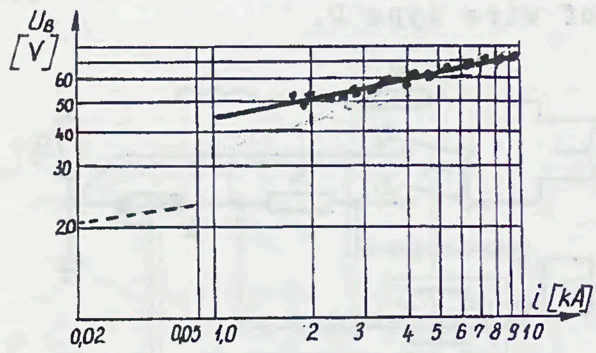

Fig.6. Relation $U_B = f(i)$

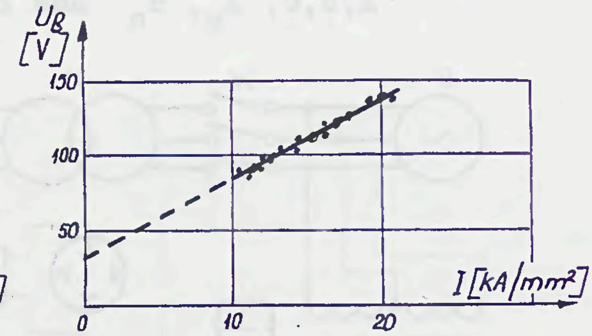

Fig.7. Relation $U_B = f(i/s)$

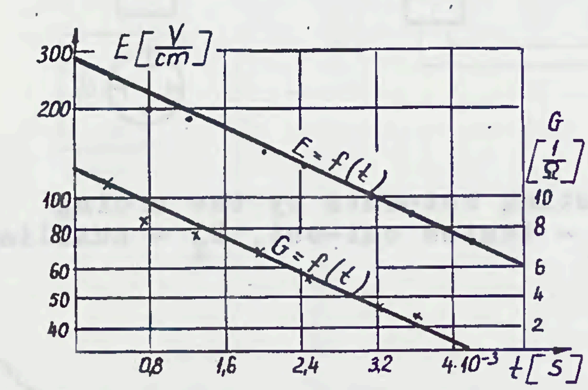

Fig.8. Relation E=f(t), l=cont.

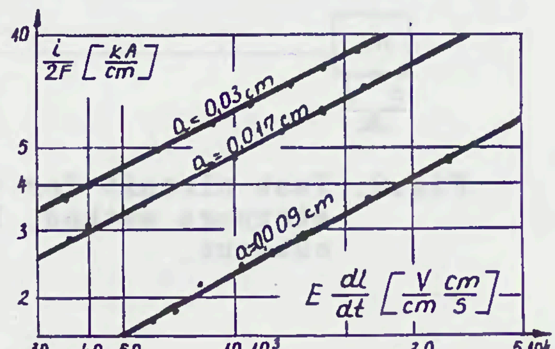

Fig.9. Relations $E\frac{dl}{dt} = f\left(\frac{i}{2F}\right)$

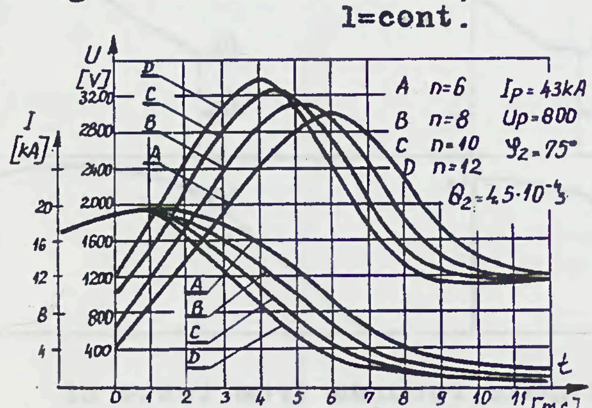

Fig.10. Calculation example of voltage and current transient.

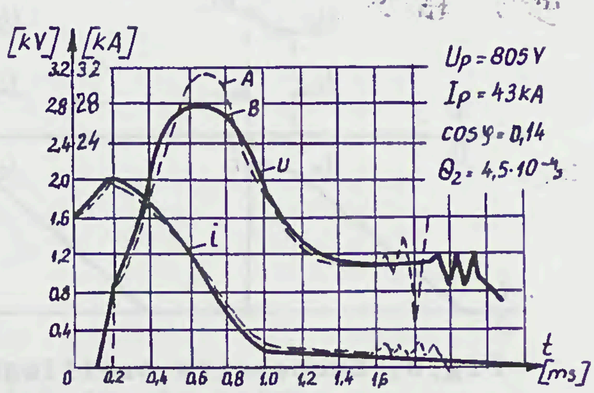

Fig.11. Voltage and current transients. A-calculated B-actual.

I^2t VALUES OF REAL AND IDEAL SEMICONDUCTOR FUSES

T. Lipski

INTRODUCTION   The semiconductor fuses (SF) are genuine current-limiting devices. Their following parameters at a.c. short-circuit interruption may be among others mainly interesting for users:

i the cut-off currents,
ii the generated overvoltages,
iii the I^2t values, pre-arcing and total.

Unfortunately, these parameters of real SF are very scattered. On the other hand the withstand of semiconductor devices (SD) against mentioned parameters is very scattered too. Therefore any reasonable interchangeability between SF and SD delivered by different manufacturers is practically out of consideration. That's why the parameters comparison of real and ideal SF is very actual in order to show the desirable SF development directions to get in the future at least a satisfactory SF interchangeability.

Because the cut-off currents and overvoltages are approx. similar for SF made by several manufacturers, these parameters practically do not limit interchangeability of these fuses. Therefore it's main problem is the interchangeability of I^2t values.

To some extent the real and more ideal SF parameters may be calculated using dependences such as e.g. given in [1,2,3] for cut-off current and pre-arcing I^2t value or in [4] for arc peak overvoltage.

But the analytical estimation of the very important I^2t value for real SF is practically very difficult. On the contrary it

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is very easy for an ideal SF.

That's why the I^2t parameters comparison for ideal SF will be based on calculations and for real SF on the data given by manufacturers information sheets.

WHAT IS AN IDEAL SF? As an ideal SF let understand the one with following features:

1 The shape of the arc voltage e_a is a rectangular one (fig.1).
2 The whole range of different fuse-links rated currents is homogeneous in respect to IEC Specification[5].
3 The changes of the fuse-link rated current is achieved by monotonous change in number of fuse-element stripes.
4 The mutual thermal and arcing influence of the several fuse-element stripes is neglected.
5 The arc burning process in each stripe is this same.
6 The notched parts of the fuse-element are of uniform--section.

THE SHORT-CIRCUIT PARAMETERS OF AN IDEAL SF The worst case is when the instantaneous value of applied voltage is troughout the arcing period as large as possible. For a sinusoidal a.c. voltage this implies that the entire arcing period t_a shall extend equally on both sides of the maximum value of the applied voltage E_m (fig.1).

During the typical short-circuit current interruption by SF the operating time is in order of 1:10 part of one half-period. Than, with a practically nonresistive circuit, the onerous interrupting conditions are with short-circuit making angle abt 90 el.deg. after voltage zero. This angle gives the maximum prospective current rate of rise, maximum value of the cut-off current and maximum magnetic field energy $Li_o^2/2$.

Because of the very short operating time we may assume a maximum value of the applied voltage be constant throughout the whole operating time. Than the mode of SF operation in the worst conditions may be shown by fig.2.

From recent papers[6,7] one may conclude that in some cases for SD protection there are better the I^3t values instead I^2t. Therefore in the following relations we use notation I^mt. The pre-arcing and arcing I^mt values for ideal SF, operating as it is shown in fig.2, are as follows:

$$J_1=\int_0^{t_1} i^m dt=\frac{E_m^m}{L^m}\,\frac{t_1^{m+1}}{m+1} \qquad (1)$$

$$J_2=\int_{t_1}^{t_2} i^m dt=\frac{E_m^m}{L^m}\,\frac{t_1^{m+1}}{m+1}\,\frac{1}{n-1} \qquad (2)$$

and

$$\frac{J_1}{J}=\frac{n-1}{n} \qquad (3)$$

where $m\neq -1$, $J=J_1+J_2$ and $n=e_a/E_m$ - the overvoltage ratio. So we see that the ratio J_1/J is not dependent from the power m.

In any making angle instant other than 90 el.deg. the ratio J_1/J will exceed the values of $n-1/n$. It means, that for given n and J_1 the maximum of J_1 may be calculated from equation (3) only.

The influence of the overvoltage ratio n on I^2t is significant (fig.3). By changing the ratio n from 1 to 2 the ratio J_1/J rise from 0 to 0.5. Only with $n\rightarrow\infty$ we can get $J_1/J\rightarrow 1$. It means, that with extra high overvoltages the arcing I^2t is negligible.

Further, from[4] we know

$$n=\frac{\rho_0 l}{E_m}\sqrt{\frac{i_0}{S}} \qquad (4)$$

where l means the short-circuit length of the fuse-element, i.e. the sum of the length of the fuse-element notched parts, ρ_0 - the disrupted fuse-element resistivity at the moment t_1

(fig.1), S - the cross-section area of the notched element. Under circumstances of an ideal SF for any rated current of a fuse-link I_n with current density $j=const$, we have

$$I_n = Sj$$

and

$$n = \frac{\rho_o l}{E_m}\sqrt{\frac{i_o j}{I_n}}$$

therefore

$$\frac{I_n E_m}{2} = \frac{\rho_o l}{n}\sqrt{\frac{I_n j i_o}{2}} \qquad (5)$$

where $I_n E_m/\sqrt{2}$ we call as the rated power of a SF at the rated applied voltage $E_m/\sqrt{2} = U_n$.

For $m=2$ it is well known that

$$i_o = c_1 I_n^{1/3} \qquad (6)$$

and

$$t_1 = c_2 I_n^{2/3} \qquad (7)$$

These dependences are correct for linear rise of prospective currents only.

Because for $m=2$

$$J = \frac{E_m^2}{L^2}\,\frac{t_1^3}{3}\,\frac{n}{n-1} \qquad (8)$$

than from (5) to (8) it follows

$$\frac{J}{I_n U_n} = \frac{\sqrt{2}}{3}\,\frac{E_m^2}{L^2}\,\frac{1}{\rho_o l\sqrt{j}}\,\frac{n^2}{n-1} = const \qquad (9)$$

for a given circuit and for given homogeneous series of fuse--links. Dependence (9) shows, that the relation total I^2t to rated power of an ideal SF is constant.

Furthermore, the ratio J/P is very interesting too, where P are power losses at the rated current of a SF. The P value may be calculated from equation

$$P=I_n \rho l j \qquad (10)$$

where ρ - the fuse-element material resistivity. Than from (7), (8) and (10) one can get

$$\frac{J}{P}=\frac{1}{3}\frac{E_m^2 I_n}{L}\frac{1}{\rho l j}\frac{n}{n-1}=CI_n \qquad (11)$$

It means that dependence of J/P versus the rated current of an ideal SF is linear.

THE SHORT-CIRCUIT PARAMETERS OF REAL SF In figures 4 to 9 are shown the parameters for real SF manufactured in 1975 by six European firms. It is evident, that these real short--circuit parameters are very scattered, indeed. They are very far to a desirable situation, when for a given SD the SF rated current of any manufacturers product should be the same.

For instance, from fig.4 it is obvious, that the majority of real pre-arcing I^2t are greater than I^2t withstand of manufactured SD. Than, only abt 15 % of examined real SF have convenient total I^2t values suitable for correct coordination with I^2t withstand of 50 % SD with those same rated currents of the SF and SD (fig.5).

By present state of real I^2t withstand of SD the pre-arcing I^2t of SF by very common $n=1.5$ should be not greater than the values indicated by line a (fig.4) or line b. The lower line (a) corresponds to the 99 % correct coordination with SD I^2t withstand and the upper line (b) - to the 50 % correct coordination. It means, that practically all or 50 % of SD will be correctly protected by SF, if their pre-arcing I^2t are not greater as stated correspondingly by line a or by line b.

Fig.6 shows that the real SF J/J_1 ratio is greater than the correspondent ratio for an ideal SF by e.g. $n=1.5$.

The comparison of results given by dependence (9) and fig.7 shows, that the ratio $J/I_n U_n$ of a real SF is not constant. The real ratios are growing with the rated currents and they are very scattered. It seems, that the greatest in-

fluence not satysfying the dependence (9) are coming from:
i the mutual heating of the stripes is homogeneous multi--stripe fuse-elements,
ii the approx. trapezoidal instead rectangular shape of e_a.

The real values of $J/P=f(I_n)$ (fig.8) are very scattered too. The mean line of the real spread zone shows a greater rate of rise than calculated from dependence (11). This difference could find an explication in two reasons mentioned just above and additionally in:
iii the manufacturers tendency to keep the same value of the peak arc overvoltages throughout the whole range of the fuses independing from their rated currents.
It means, that the total length of all notched parts is growing with the rated current.

The next fig.9 shows the tendency to rise the ratio J/V with the rated current, where V - the external volume of the fuse-link excluding contact blades.

<u>CONCLUSIONS</u> The presented comparison of I^2t values of real and ideal SF shows that we are still far away from a well arranged SF.

The desirable situation in this field is to have the I^2t values of a real SF like those for an ideal SF and their pre-arcing I^2t values situated not higher than the line a indicated in fig.4.

Afterwards, the ratio J_1/J should be alike for the ideal SF too, given by relationship (3) for rectangular shape of the arc voltage and for the said value n=e.g.1.5.

The simple analytical solution for J_1/J ratio (relationship 3) is practically the same as the calculation results obtained by authors[6] using the computing calculator.

In order to get interchangeability between SF and SD delivered by different manufacturers it is necessary:
i The SF manufacturers should deliver the SF with pre-arcing

and total I^2t values respectively not lower and not greater then the values specified by standard for given rated currents.

ii The SD manufacturers should deliver the SD with I^2t withstand not lower than the values specified by standard for given rated currents.

To reach this state it is necessary to complete the existing standards with corresponding requirements.

REFERENCES

1. Rauch W.: 'Strombegrenzung bei der Abschaltung von Wechselstrom - Kurzschlüssen durch Sicherung'. ETZ-A. 1958. H.16. S.543-547
2. Lipski T.: 'A graphical method of cut-off current estimation of the fuses' (in polish). Przegląd Elektrotechniczny 1963. No.3. p.101-106
3. Wilkins R., Mc Ewan P.M.: 'A.c. short-circuit performance of notched fuse elements'. Proc.IEE No.3 March 1975 p. 289-292
4. Hibner J.: 'A resistance gradient method for calculation of arc overvoltage peak values generated by current limiting fuses' (in polish). Ph.D. Dissertation. T.U. Gdańsk 1973
5. 'Low-voltage fuses. Part 1: General requirement'. IEC Publication 269-1.1968
6. Ky Hong: 'I^3t of fuses and semiconductors' IEEE Trans. on Ind.Electr. a. Control Instr. No.2. May 1971. p.29
7. Czucha J.: 'The desirable short-circuit parameters of semiconductor fuses' Int.Conf. on Electric Fuses a. their Applications. Liverpool. 7 - 9 April 1976.
8. Vermij L., Raelofs : 'The Joule integral of the protective fuses for semi-conductor devices'. CIRED-Conference. 1975. A.I.M. Liége. Reports No.48

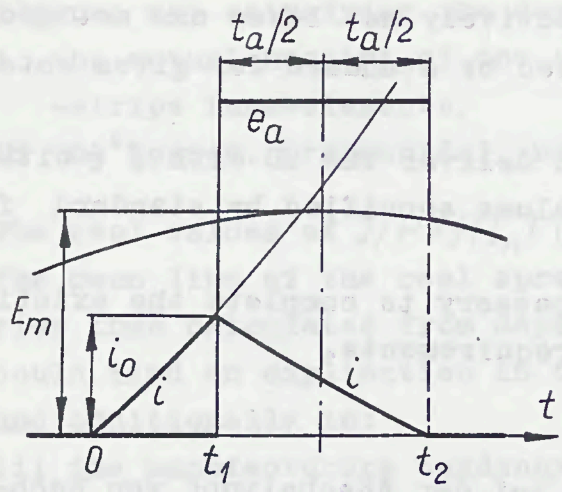

Fig.1 Simplified short--circuit breaking oscillogram of SF

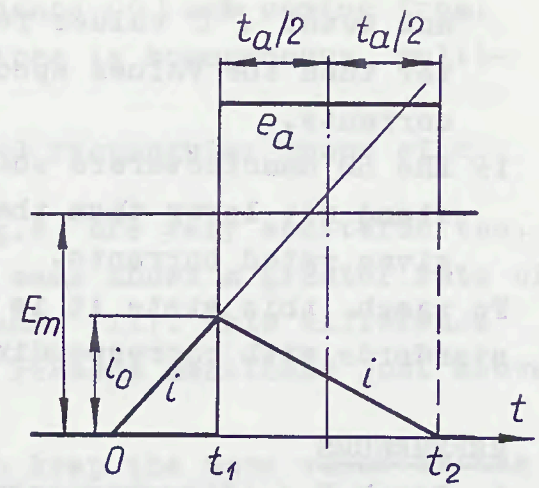

Fig.2 Mode of operation of an ideal SF in the case of worst circuit conditions

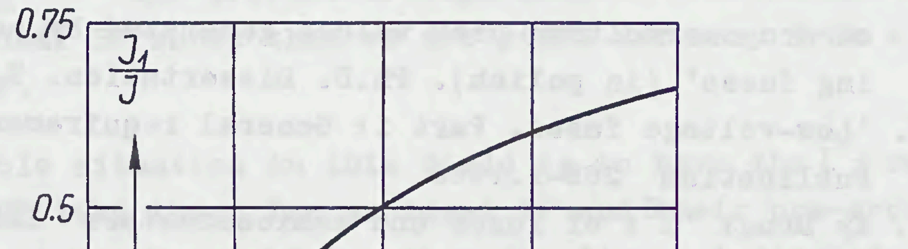

Fig.3 J_1/J ratio versus n of an ideal SF

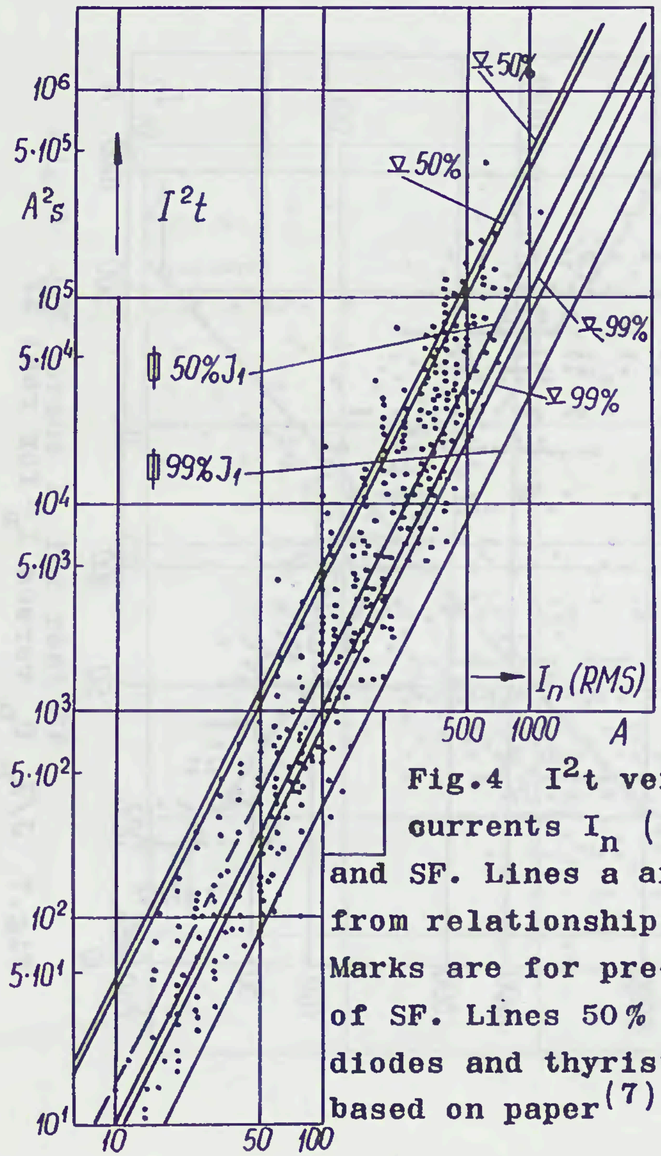

Fig.4 I^2t versus rated currents I_n (in RMS) of SD and SF. Lines a and b calculated from relationship (3) for SF. Marks are for pre-arcing I^2t of SF. Lines 50 % and 99% for diodes and thyristors are based on paper(7)

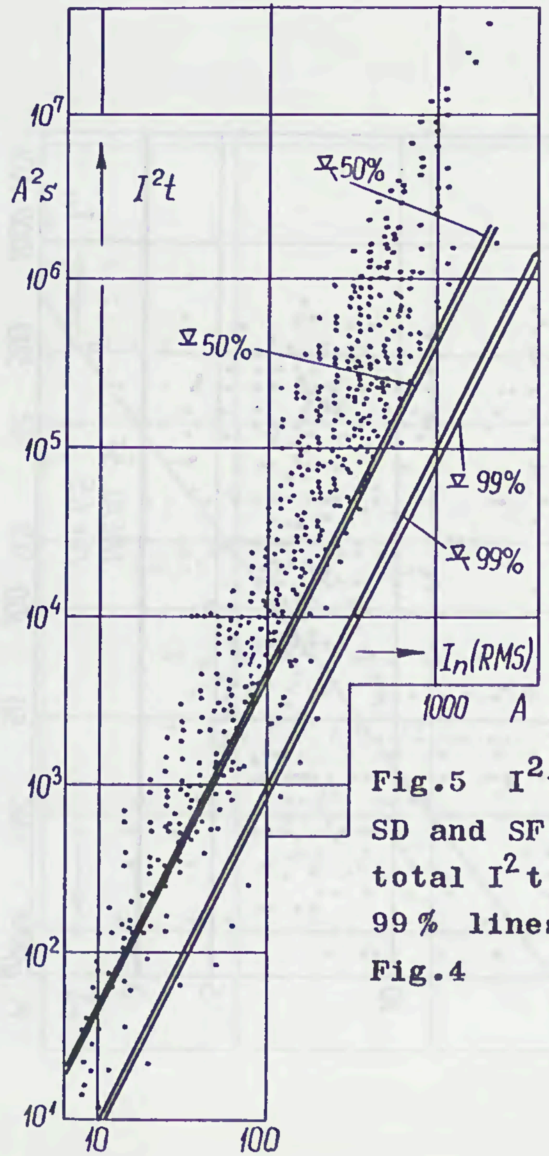

Fig.5 I^2t versus I_n of SD and SF. Marks are for total I^2t of SF. 50 % and 99 % lines are as in Fig.4

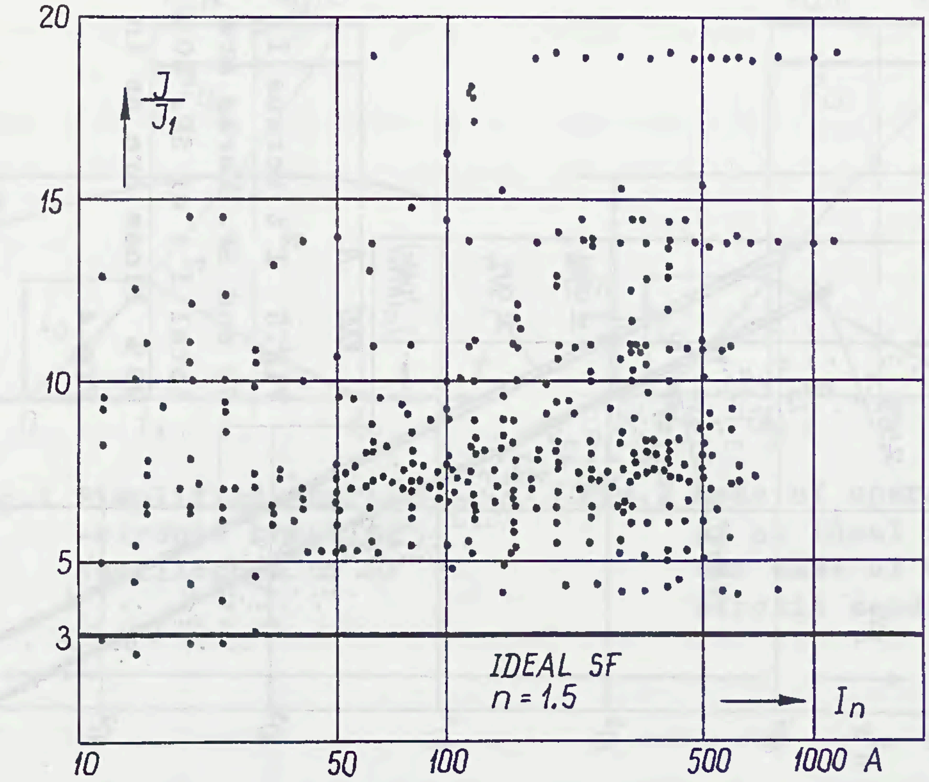

Fig.6 J/J_1 versus I_n for real SF

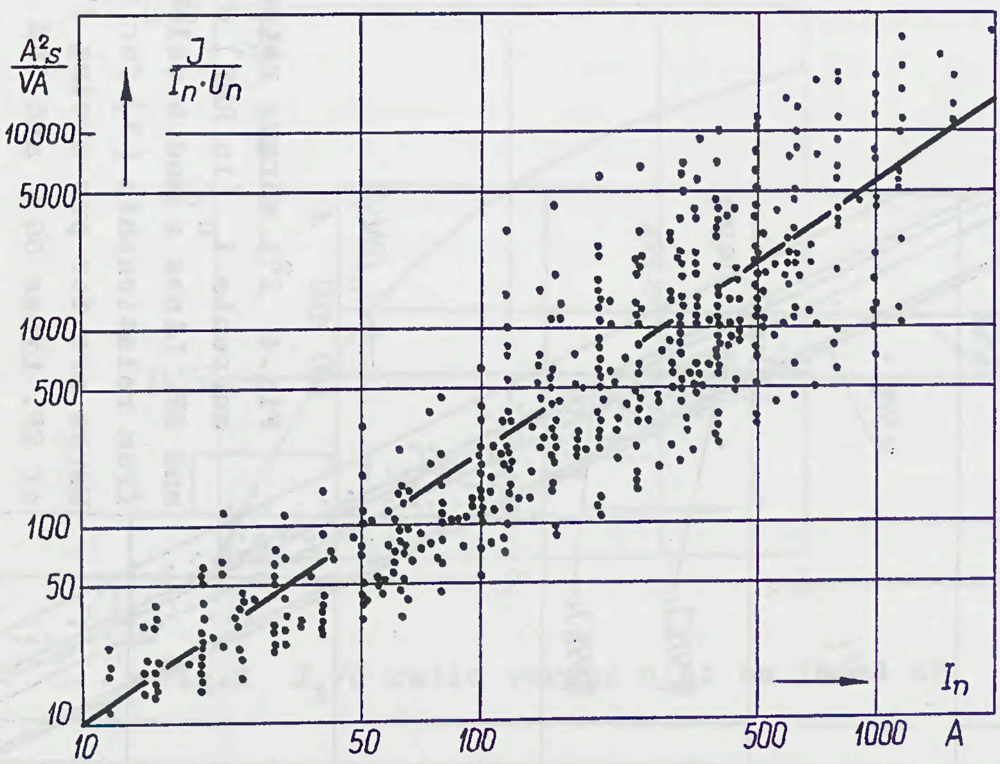

Fig.7 $J/I_n\ U_n$ versus I_n for real SF

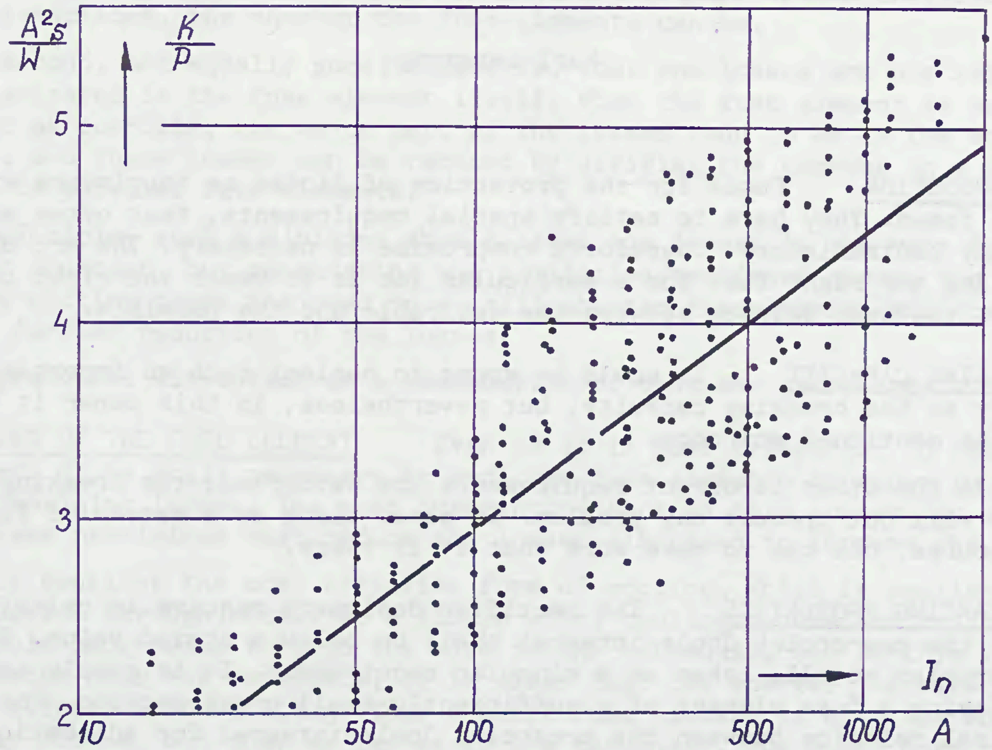

Fig.8 J/P versus I_n for real SF

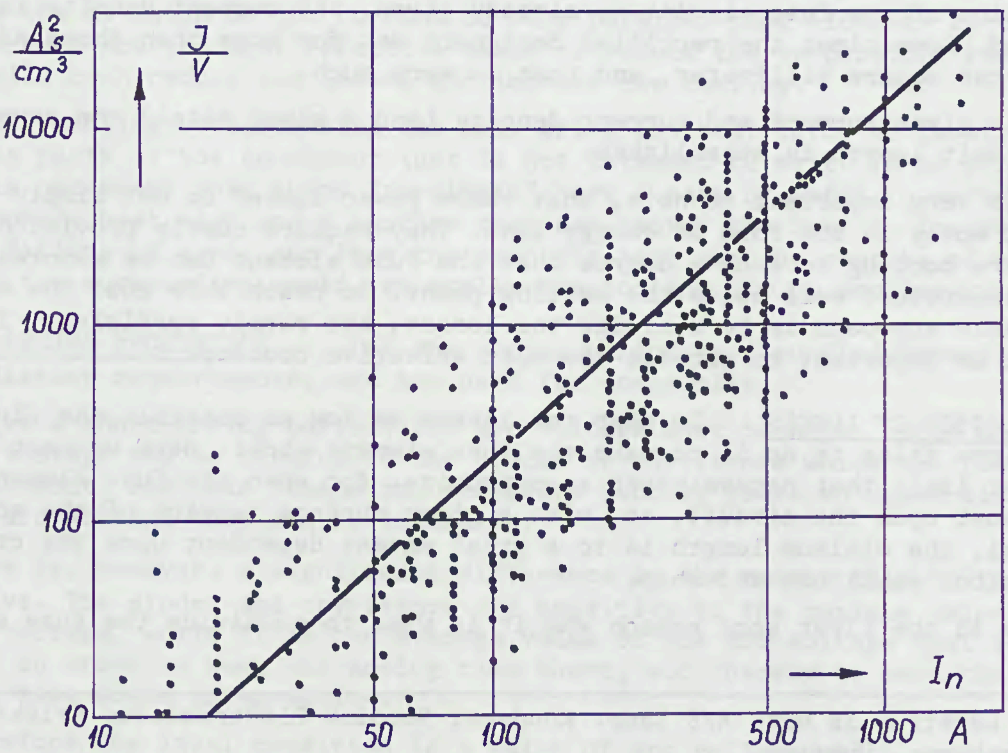

Fig.9 J/V versus I_n for real SF

THE DIMENSIONING OF FUSES FOR DIODES OR THYRISTORS

Karl Lerstrup.

INTRODUCTION Fuses for the protection of diodes or thyristors are not just fuses. They have to satisfy special requirements, that often are mutually contradictory. Therefore a compromise is necessary. The art of selecting the right fuse for a particular job is to reach the right compromise, the best balance between the desirable and the possible.

BREAKING CAPACITY It would be wrong to neglect such an important property as the breaking capacity, but nevertheless, in this paper it shall not be mentioned any more.

If all the other important requirements are satisfied, the breaking capacity will not present any problem. It comes along as a matter of fact, but of course, one has to make sure that it is there.

PRE-ARCING PROPERTIES The rectifier designers require in principle that the pre-arcing Joule-integral shall be below a stated value. This is no problem at all, taken as a singular requirement. It is simply satisfied by having a fuse element of a sufficiently small cross-section. The mathematical relation between the prearcing Joule-integral for adiabatic melting and the cross-section is very simple and most reliable.

The problems only arise because the designers also require that the fuse shall be capable of carrying a certain amount of current, and as the cross-section of the fuse element is already given, the current density is also fixed. Some times the rectifier designers ask for more than thousand amperes per square millimeter, and that is very much.

For a given current and current density (and a given metal) the power loss per unit length is established.

It is very important to note, that these power losses do not simply represent money in the form of energy lost. They require costly provisions to ensure cooling to such a degree that the fuse element can be maintained at a temperature well below the melting point. To reach this goal the most desirable approach is to minimize the losses, but rarely sufficient. It is just as important to provide the most effective cooling.

REDUCTION OF LOSSES To keep the losses as low as possible the first and obvious thing to do is to make the fuse element short. Here we meet the first limit that necessitates a compromise, for when the fuse element melts, it must open the circuit, so, with a given surface tension of the molten metal, the minimum length is to a great extent dependent upon the cross-section, magnitude and shape.

This is the first good reason why it is wise to subdivide the fuse element

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into many small parallel fuse elements, for the smaller the individual cross-sections, the shorter the fuse elements can be.

The second, and equally good, reason is, that the losses are not solely concentrated in the fuse element itself. When the fuse element is made as short as possible, the major part of the losses tend to be in the approaches, and these losses can be reduced by dividing the current on a plurality of parallel fuse elements.

In principle, such a division should leave the losses in the very fuse elements constant, but considering the limitation mentioned above, the smaller cross-section paves the road to a still shorter fuseelement, and thereby to a further reduction of the losses.

The practical limitation is a combination of cost and technology.

COOLING OF THE FUSE ELEMENT   Even if it is most beneficial to reduce the losses, it is still necessary to cool the fuse elements in order to remove the remaining losses. The most interesting fact in this connection is that the same provisions that reduce the losses also tend to improve the cooling.

Let us consider the most effective form of cooling, which is cooling by conduction through metal. In a simple wire, cooling by conduction is only possible lengthwise through the wire to the terminals, and as this is only effective near the terminals, it is clear that the shorter the wire, the more effective the cooling. Thus a short fuse element is also the most effectively cooled, but only as far as to the terminals, the ends. Here the heat will meet exactly the same obstacles as the current, namely the approaches, and therefore we see that again the division on more parallel approaches will reduce the thermal resistance to the passing of the heat.

Thus the division of the current on many parallel fuse elements is the most important and the most effective means to reduce the temperature rise, for it will both reduce the losses and improve the cooling.

Still, cooling by conduction can only bring the heat into the"terminals", those parts of the conductor that is not intended to melt. To be effective, it is necessary that these "terminals" have a mass of metal to serve as a temporary heat sink and a surface that can convey the heat to the surrounding filling of sand, and from the sand the heat must be capable of escaping into the surrounding world, generally the cooling air or cooling water.

THE ARCING PROPERTIES   For the arcing period we also find mutually contradicting requirements, and the need for compromise.

To get a short arcing period, the arc voltage must be high, but a too high arc voltage may be harmful to the diodes or thyristors which the fuses have to protect. For this reason the designers usually place an upper limit on the arc voltage that can be tolerated.

There is, however, a significant difference in the manner this voltage is active. The diodes and thyristors are sensitive to the maximum value of the arc voltage, while it is the average value of the arc voltage that is important in order to keep the arcing time short, and thereby to keep the arcing-time Joule-integral low.

Therefore, the ideal condition is a value of arc voltage which remains as far as possible constant throughout the arcing period, that is, an arc voltage that on the oscillogram shows a rectangular form, and therefore often referred to as a rectangular arc voltage.

THE RECTANGULAR ARC VOLTAGE The arc voltage is composed of the anode drop, the cathode drop and the plasma voltage. Of these the anode and cathode drops are essentially constants, while the plasma is a function of length, pressure, cross-section and cooling.

Under these circumstances, the only way to approach a rectangular arc voltage is to have the constant components as the predominant components, or in other words, to have a minimum of plasma voltage.

This is the same as saying that the arc shall be as short as possible.

THE MULTIPLE ARCS However, the constant value of the short arc leads to a rather low value of arc voltage, and it is rare that this arc voltage of a single arc is sufficient. To get higher values two ways are open. Either several short arcs in series or the acceptance of a longer arc.

Going from one to two short arcs will double the arc voltage, but two fuse elements in series will also double the pre-arcing losses. Such an increase of the losses will be particularly significant for operation under normal load.

If in stead we should create the double arc voltage by means of a longer arc, this would necessitate a much longer fuse element, and very much higher losses. How great the relative increase of the losses will be also depends on how many parallel fuse elements there are, for the more the current is divided, the less will be the influence of the approaches, and the greater the increase because of the lengthening of the fuse element itself. In practice, the same increase of arc voltage will cost a minimum of loss by the use of multiple short arcs.

Still more important, when the number of fuse elements in series is increased, the cooling conditions for the individual fuse elements are not interfered with, but any lengthening of a fuse element will have a detrimental influence on the cooling.

Nevertheless, the most important advantage of the short arc is still the almost rectangular arc voltage. The longer the arc, the greater the difference between the maximum arc voltage and the average arc voltage.

The conclusion of this is, that the best fuse is achieved by producing the necessary arc voltage by means of a sufficient number of arcs i series, but the cheapest fuse to make is the one with the longer fuse elements.

SELECTING THE ARC VOLTAGE It has been mentioned earlier, that the rectifier designer in principle would demand a maximum limit on the pre-arcing Joule-integral. This is a truth with modification, for what is of interest is the total Joule-integral, the pre-arcing plus the arcing Joule-integral.

If for the time being we limit our considerations to the case of an overcurrent of short-circuit magnitude, where the melting of the fuse element is adiabatic, it is true that the higher the arc voltage (average value), the smaller the arcing Joule-integral.

Furthermore, to keep a high value of arc voltage well under control, that is, so that it remains below what the semi-conductors can withstand, it must be done by means of many short arcs, and the many fuse elements in series means losses proportional to the number.

However, as a high value of the average arc voltage results in a low value of the arcing Joule-integral, this will permit an increase of the pre-arcing Joule-integral, for the significant criterion is that the sum remains constant and below the set limit.

An increase of the pre-arcing Joule-integral is the same as a greater cross-section (e.g. more fuse elements in parallel), and that again a lowering of the current density and thereby a reduction of the pre-arcing losses.

THE COMPROMISE Thus we meet another important compromise. A shift to higher arc voltage both increases and decreases the losses, but it does more than that.

The higher arc voltage also permits a shift of the components of the total Joule-integral such that a larger portion falls on the best known part, the prearcing Joule-integral, and consequently the total becomes better known. It is a general rule that with a better known value one can go closer to the limit, and this permits the selection of a still larger cross-section and consequently a further reduction of the losses.

There is also a very important advantage in the fact that the larger cross-section improves the ability to withstand temporary overloads. This ability is further enhanced by the fact that more fuse elements, both in series and in parallel, generally implies a larger fuse body and thereby better cooling.

On the other side of the account it is necessary to admit that all of this leads to a larger fuse which takes up more space in the installation and which will cost more money. Thus the compromise is not limited to the technical problems. It is very much a matter of economics.

THE PROBLEM OF COST The biggest hindrance for the use of the technically best fuse design is simply the cost.

The traditional design has the fuse elements formed by holes and notches in a ribbon of silver, and the effective cooling requires large masses of metal between the fuse elements. When this is combined with the design requirement of many fuse elements in series and many fuse elements in parallel, all of which require extra metal to form heat-sinks and cooling surfaces, then the amount of silver needed becomes considerable.

Silver is expensive, and the price has been rising. It is not unusual that for a good compromise of a semiconductor type fuse, the cost of the silver alone is the greater part of the total cost.

Because of this the search for a substitute for silver has been going on for a long time. Copper has been used with fairly good results for ordinary industrial fuses, but for the fuses for diodes or thyristors copper will fail because of the oxydization of the fuse elements when operated at high temperatures, such as it is generally necessary in this kind of service.

THE ALUMINIUM FUSE ELEMENT No useful substitute for silver was available until it was discovered at the laboratories of LK-NES that there was a way to avoid the well known difficulties associated with the use of aluminium due to its high affinity for oxygen.

When aluminium is used in a fuse of ordinary fuse design a relatively large amount of aluminium will be heated to a temperature where the metal will react chemically with the sand filling to form aluminium oxide and pure silicon, and this chemical reaction is exothermic.

As a result of this exothermic reaction so much extra energy will be released inside the fuse, over and above the energy of the arcing, that the fuse not only will fail to break the current, but it will end up as a red hot molten mass and constitute a danger to the surrounding equipment.

THE ALUMINIUM SEMICONDUCTOR FUSE In order to avoid these difficulties, inherent to the fuse element of aluminium, we have to follow two paths. It is necessary to reduce the amount of aluminium that reaches a high temperature to a minimum and at the same time cool the fuse element in the most effective manner.

It is obvious that these two requirements coincide beautifully with the technical requirements already discussed as advantageous for a fuse for the protection of semiconductor devices.

If we furthermore consider that there is no other type of fuse where the need for the finding of a less expensive metal for the fuse element is more urgent, then it becomes clear that this is the most obvious opportunity to take advantage of this possibility of using the inexpensive aluminium in stead of the expensive silver.

However, theory is of little value if it is not supported by proper technology, and many technological problems were associated with the substitution of aluminium for silver i fuses.

It may be sufficient just to mention that the production of a fuse using aluminium fuse elements requires that thin ribbons of aluminium shall be welded to the heavy sections of metal forming the fuse contacts. Many methods were explored, and several of them led to results that were satisfactory from the point ofview of fuse performance, but exhibiting severe weaknesses from the economic or from practical manufacturing aspects.

To-day fully satisfactory solutions have been found, and the aluminium fuse can be produced in a consistent quality and at a low value of production cost. Because of the low cost of aluminium, the price of these fuses is also lower, and when the large amount of development work has been paid, there will be room for even greater savings for the user.

This method of utilizing aluminium for the fuse elements has been patented in many countries, including the big industrial nations USA and USSR.

CONCLUDING REMARKS It is a most satisfactory result of this development work that it has been possible to produce a fuse using aluminium in stead of silver for the fuse elements, and at the same time replacing copper and brass in the other metal parts of the fuse by aluminium. This represents a significant economic advantage.

It is even more satisfactory to note that this aluminum fuse in many respects will perform as well as the silver fuse, and in some respects even better.

However, in addition to these advantages, it is a case of replacing a rare metal, silver, with an abundant metal, aluminum, and although this to-day may be dismissed as a purely ethical point of view, it may some day be a dire necessity for more than simple economic advantages.

ADVANCES IN THE PROTECTION OF SEMI-CONDUCTORS BY FUSES

J.G. Leach

1. INTRODUCTION The use of semi-conductor rectifiers for power control has become well established and techniques for their protection have developed alongside the devices. The equipment designer has many methods at his disposal which can be combined to give an appropriate level of protection. These include fast acting (semi-conductor) fuses, fast or medium speed circuit breakers, contactors, firing control of thyristors and surge current suppression whereby firing pulses are quickly removed from a thyristor gate. Current limiting by-pass switches (electronic "crow-bar") are also used. In some cases (e.g. rail traction) the use of high impedance supply transformers (10% impedance), mechanically strong busbar systems and "over size" thyristors and diodes can enable equipment to withstand the thermal and magnetic forces long enough for a conventional breaker to operate.

In most protection schemes, fast acting fuses are included as being the most economical solution to device protection in the short times associated with short circuit conditions. This is because a fuse forms an analogue model of the semi-conductor junction. It is capable of responding thermally faster than a junction and also absorbing circuit energy at a very high rate. The fuse also has the advantage of not requiring maintenance, since after operation on a fault, it is replaced by a new fuse.

2. FUSE PROTECTION The information needed for correct fuse application can be divided under three headings.

1) Information to ensure the fuse will protect the semi-conductor under fault conditions.

2) Information to ensure the fuse will satisfactorily carry the current, including any overload, required.

3) Information to ensure that the fuse will not operate when other parts of the protective system are intended to operate.

Advances in the protection of semi-conductors by fuses have taken place in all three areas, partly as a result of actual improvement in fuse performance but also, most significantly, as a result of a greater understanding of fuse behaviour. In the past much of the theoretical work associated with the fuse was done by research bodies unconnected with industry rather than fuse manufacturers, and most practical fuse development was by "trial and error". It is only in

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recent years that manufacturers have realised that a fundamental understanding of the fuse is necessary for its correct application and development, and with the advent of large digital computers, have been able to actually understand the associated phenomena.[1.2.]

2.1. <u>PROTECTION OF THE SEMI-CONDUCTOR DEVICE</u> Methods used for determining whether a device is protected for high fault levels usually depend on the use of I^2t (more strictly $\int i^2 dt$) and/or peak current. A difficulty exists when neither of these is sufficient on its own. This is because the I^2t and peak current withstand of a device depends on the actual current shape and duration, and fuse I^2t and peak let-through varies with fault circuit conditions. Other criteria, for example $I^2\sqrt{t}$, have been proposed,[3] but in general I^2t still remains the most widely used parameter. Some methods of resolving the difficulty are as follows.

2.1.1. <u>Device Withstand</u> Information is usually presented in the following forms:

a) Maximum non-repetitive surge current (peak value of a half sinewave current 50 or 60 Hz) versus number of equal amplitude pulses. The equivalent rms value is then half of the peak.

b) The value of just one pulse is quoted in published information as I_{TSM}. The 10 ms withstand for 50 Hz current is then $\frac{I_{TSM}}{2}^2 \times 0.01$ Amp^2 seconds.

c) For shorter times, the I^2t is normally less than the 10 ms value and may be presented as I^2t versus time. It may also be presented as peak half sine-wave versus time, or the I^2t quoted for one or more fault durations (e.g. 5 ms and 1.5 ms). In all cases the withstand is for a half sinusoidal pulse of the appropriate duration (i.e. a higher frequency is used for testing).

Although the I^2t withstand decreases with time the peak current withstand increases. For example, a particular device may have a non-repetitive single cycle surge withstand of 9000A at 5 ms, gives a I^2t withstand of 200,000 A^2sec., while at 1.5 ms its surge withstand would be 12,700A giving a I^2t withstand of 120,000 A^2sec. I^2t figures are usually quoted for the device junction hot (max. temperature) before fault. Figures may also be given for junction cold (I^2t generally 20% higher) and with zero re-applied voltage (may be 60% higher than with 100% re-applied voltage).

2.1.2. <u>Fuse let-through I^2t</u> There are many circuit parameters which affect I^2t let-through. They have been extensively discussed[4.5.] but will be briefly mentioned here.

i. Supply voltage - this affects only the arcing I^2t and an increase from say 250V to 500V with a 500V rms fuse can give an increase in arcing I^2t of about 150% to 200%.

ii. Fault level - this affects both pre-arcing I^2t and arcing I^2t and in general an increase in fault level decreases pre-arcing I^2t, by reducing time, and increases arcing I^2t. Overall I^2t can thus be increased or decreased depending upon the design of fuse and the supply voltage.

iii. Power factor - the lower the power factor (or higher the $\frac{X}{R}$ of the fault circuit the harder it is for the fuse to clear due to the larger circuit inductance, and hence stored energy. I^2t let-through at 0.1 power factor $(\frac{X}{R} = 10)$ can be as much as 1.8 times that with a power factor of 0.7($\frac{X}{R}$ = 1). With a dc fault, the comparable parameter is circuit L/R (time constant). An increase in L/R will increase arcing. Also, due to the lower rate of rise of current, a greater heat loss will occur during the pre-arcing time. This will increase the pre-arcing I^2t.

iv. Point on wave - the point on the voltage waveform at which the fault occurs, and hence the voltage the fuse sees during arcing, can have a large effect on I^2t let-through. A ratio as high as 5 to 1 worst to best case conditions can result.

v. Frequency - increase of frequency increases rate of rise of fault current and leads to lower pre-arcing times. Inductance will also be less for the same power factor and fault level and a decrease in I^2t results. Decrease in frequency causes a more onerous duty for the fuse, ultimately approaching a dc condition. This is known to require, often considerable, voltage derating for an ac fuse.

vi. Pre-loading - if the fuse elements are already hot, having been carrying current prior to a fault, a considerable reduction in pre-arcing and consequently arcing I^2t can occur (typically greater than 25%).

With such a wide variation in I^2t it is normal for a fuse manufacturer to specify I^2t not in simple tabular form, as with many industrial fuses, but to provide sets of curves, normally one for each fuse rating to give accuracy, of I^2t versus fault level. These are drawn at various supply voltages for the most onerous conditions of power factor (< 0.2) and point on wave, with the fuses cold prior to test. This means that in practice I^2t will never be higher, and will usually be lower, than the published data thus giving a suitable safety factor.

2.1.3. Co-ordination of fuse and thyristor One method of fuse and device co-ordination, based on I^2t, which has successfully been used for several years, is shown in fig. 1. Lines are drawn on I^2t/fault level curves to represent the total operating time of the fuses. As the fault level increases, so the operating time is reduced. Device withstand information can then be plotted directly on the fuse let-through curves and any fuse curve lying below the withstand curve will provide protection. In fig. 1., a thyristor having a withstand of 45,000 A^2s at 5 ms and 36,000 at 1.5 ms is shown plotted on fuse curves for the appropriate supply voltage. The 200A fuse will protect the thyristor up to 100,000A, the maximum breaking capacity, while the 235A fuse will protect with faults of up to 60,000A. If the maximum fault level were below 6000A (about 20 times rated current) the 275A fuse would be suitable. This method therefore gives a suitable fuse, if the fault level is known, or the level to which a fault must be limited (using line inductance for example) in order to use a given fuse.

When this method of co-ordination is used, it is seldom necessary to consider peak current let-through and withstand. If a fuse lets through a near sinusoidal pulse with an I^2t let-through less than the device withstand, it must inherently contain a peak value less than the withstand of the device. At higher values of fault current, the fuse let-through waveform becomes more triangular. Device manufacturers normally allow an increase in peak withstand if the waveform is triangular rather than sinusoidal such that the two waveforms have the same I^2t. For all currents then, if the decrease in device I^2t with reduction of fault duration is taken into account, peak current withstand will also be taken care of.

2.1.4. Arc voltage The maximum voltage produced across a semi-conductor fuse during arcing is normally greater than the maximum peak value of the supply voltage. If semi-conductor devices which are blocking see this voltage, care must be taken that they are of a high enough voltage capability. A fuse will produce a minimum arc voltage on fault, related to the number of its restrictions. This will occur even with a very low supply voltage since di/dt in the circuit inductance will supply the remaining emf. For example, a 700V fuse on 120 volts may produce an arc voltage of 300 volts, while on 65 volts will still produce about 300 volts. Care must be taken to check manufacturers data if a fuse is used at a low voltage relative to its rating. A similar effect occurs if two fuses in series in a three phase bridge both operate. Both cannot be relied upon to operate in all cases, since two arms may feed into one or one fuse may be pre-loaded and operate first. Consequently, an arm fuse is normally rated to cope with full line to line voltage. If only one 600V fuse operates at 480V the arc voltage may be 850V. If two fuses in series operate each fuse at 240V would produce 470V giving a combined arc voltage of 940V.

2.2. CURRENT RATING OF A FUSE Industrial type fuses have a fairly well defined rated current based on a temperature rise limit in a standard test rig and an associated watts loss. There is also a conventional fusing and non-fusing current with, in the U.K., a fusing factor (approximately the ratio between "rated" current and that just required to cause operation of the fuse). The current rating of a semi-conductor fuse is usually much less well defined. Fusing factor can be used - but providing this is not below about 1.2 so preventing "nuisance blowing" on non-harmful overloads, this is not very helpful, since a semi-conductor fuse is basically for short circuit operation rather than overload operation (this will be discussed in more depth in section 2.3.).

Watts loss is also of less importance than with industrial fuses since the heat generated in a thyristor can be 5 or more times that generated in its associated fuse. For the same reason the temperature rise of fuse terminals is of less importance, except where they are limited by associated equipment (for example insulation). Also there may be a necessity for restricting fuse temperature because of the use of low melting point materials (such as solder).

If the basic conditions of minimum fusing factor and maximum cap temperature (if applicable) have been satisfied, the ultimate criterion of rating must surely be that of deterioration. Almost any non-ferrous metal when subjected to cyclic stress will eventually fatigue, and fuse elements are no exception. An element receives two forms of stress; firstly every time the equipment is switched on the element temperature will rise from ambient, this will also occur with long period cyclic loading (e.g. 1 minute on, one minute off). Secondly, semi-conductor fuse elements are of necessity so sensitive that the restriction temperatures follow the square of the current waveform and apply, in the case of 50Hz current, stress one hundred times per second! Experience has shown that providing such temperature excursions are limited, by restricting overall element temperature to certain values, a very long fuse life can result (e.g. 10^5 hours). An obvious criterion is therefore element temperature which, with measuring and computing techniques, can be related to hot to cold resistance ratios. The manufacturers of some ranges of fuses therefore specify this ratio (which requires voltage and current measurement) or use it to set a more easily measurable quantity (e.g. cap temperature).

Because a semiconductor fuse runs relatively hot - a consequence of being such a high speed device - it is very much influenced by its surroundings and attachments. The following sections detail some of these variations, all based on maintaining an upper limit to element temperature to ensure long fuse life.

2.2.1. <u>Ambient Temperature</u> Fig. 2 shows a reduction in current rating necessary if the local air conditions vary. It is important to realise that it is this local micro-climate rather than the ambient temperature (normally defined as that outside the cabinet in which the fuses may be placed) which is of importance. It is advisable to find a fuse's actual current rating by looking at such a curve rather than to place too much emphasis on the "rating" marked on the fuse. This marked rating should often be regarded as little more than a list number for replacement purposes which, sometimes, gives an idea of typical current carrying capability.

2.2.2. <u>Busbar Size</u> The above statements are particularly true now that a standard test rig exists with specified sizes of busbars (IEC 269-4 and BS 88: Part 4 1976). Up to 75% of a fuse's heat loss is from the attached busbars and so these have an effect on fuse rating. Fig. 3 shows this variation. For example, a fuse previously rated on busbars of 1 in. x 0.25 in. (25.4 mm x 6.35 mm.) at 275A has, on the new size bars 1.25 in. x 0.25 in. (31.75 mm. x 6.35 mm.), a rating of 283A (cross sectional ratio 1.24, surface area ratio 1.2 giving an increase to approximately 103%). In practice the fuse may be used on much smaller bars, e.g. 20 mm. x 5 mm. This gives a cross sectional ratio of 0.5 and a surface area ratio of 0.65. From fig. 3 this will reduce the rating to about 93% giving I = .93 x 283 = 263A.

2.2.3. <u>Forced Cooling</u> Cooling air is often used to improve the utilisation of thyristors. The associated fuses can also be cooled and fig. 4 shows an uprating curve for various air flows. The element temperature is maintained constant, and the extra heat loss requires a steeper temperature gradient from element to body and cap. For this reason the fuses appear to be running very cool, but the current must not be further increased if reliability is not to be lost. The current rating of the fuse, to which the uprating is applied, is found from the current rating versus ambient temperature curve using the appropriate temperature of the cooling air. A more recent method of uprating fuses is to attach them to water cooled busbars. One such arrangement is shown in fig. 5. This arrangement enabled an uprating of 40% to be obtained, keeping the element temperature approximately constant. This arrangement protects a 2500A rms thyristor at 480V rms having a 5 ms I^2t withstand of 5.1×10^6 A^2sec. The fuse can carry 2200A rms continuously when supplied with 1 gallon/minute of 25 ^oC cooling water. Water cooling is so efficient that it can provide considerable cooling to the busbars also.

2.2.4. Length of Busbars The testing specified in IEC 269-4 and BS 88-4 calls for fuses to be mounted vertically and to be attached to busbars of 500 mm. length carrying a current density of between $1A/mm^2$ and $1.6A/mm^2$. To the ends of these busbars, as a part of the circuit, are attached further lengths of busbar of at least 1 metre long and of similar cross sectional area. This arrangement is seldom duplicated in practice, and it is of interest to examine the effect of shorter lengths of busbar. The results of one such investigation, carried out using numerical analysis of the fuse and busbar, is shown in fig. 6. In this case a length of busbar l, attached to the fuse and to the heat sink was used. Such a "heat sink" is formed by any part of the equipment with a temperature substantially independant of the heat supplied by the fuse. The 100% curve represents 1 metre of busbar attached to a heat sink at ambient temperature and in effect shows the temperature distribution along it. If a heat sink of a given temperature were attached to the busbar at a point of equal temperature the fuse would be unaffected. If the heat sink were attached to a point of high temperature, the fuse could be uprated, as shown by the other curves. If the heat sink were attached to a part of lower temperature some reduction in rating will be necessary, but this tends to be small. For a busbar length of at least 400 mm., unless the heat sink is very hot, the derating required is negligible. This is because the busbar dissipates most of the fuse heat loss by convection and radiation and a slight temperature rise will dissipate more heat, including heat from the heat sink.

2.2.5. Overload A fuse must also be capable of withstanding acceptable equipment overloads. If this overload persists for a time sufficient for the fuse to reach a substantially steady temperature, the fuse current rating must at least equal the overload current. "Rules of thumb" have been used to determine acceptable cold start and hot start non-repetitive overloads and also regular cyclic overloads. These rules usually relate to the fuse's time/current curve and typical acceptable overload values for the above three conditions are 77%, 67% and 50% of the current which, according to the time/current curve, would give operation at a time equal to the overload duration. Cyclic loading of fuses is very complex and a complete paper on this subject is included in the conference.

2.3. CO-ORDINATION WITH OTHER PARTS OF THE PROTECTION SCHEME A semi-conductor fuse is normally required to operate only with very high fault currents since it is in this region a fuse is so effective. It is normal to use circuit breakers, etc., where the breaking duty is less severe and device protection not so critical. Also on overload the fuse may not be fast enough to protect a thyristor, since it is designed to have a very steep time/current curve to give a high current rating with fast short circuit operation. Unlike most industrial fuses it usually does not include 'm' effect low melting point alloy. This time/current curve provides the information necessary to ensure discrimination with circuit breaker overload trips.

Figure 7 shows a typical time/current curve. It may be shown as a single curve with a tolerance on the current. This is normally ± 10% to allow for manufacturing tolerances, although many manufacturers hold ±5% for most ratings. Alternatively two curves representing the upper and lower limit may be drawn. A possible way of presenting industrial fuse time/current curves, uses the IEC 269 bands whereby the upper limit includes arcing. The two limits then become minimum pre-arcing time and maximum operating time. In both cases virtual time is used (I^2t divided by the square of the rms fault current). Thus any fuse whose upper curve lies below the pre-arcing curve of another will discriminate with it; i.e. it will clear before the larger fuse melts. This is useful for fuse discrimination, but for breaker discrimination only the minimum pre-arcing curve is actually needed. In addition with semi-conductor protection the use of virtual time tends to be confusing since I^2t withstand is always in terms of actual time.

Variation in fault waveform has a most significant effect on time/current curves which is why they are standardised by using symmetrical sinusoidal current. This variation will now be examined.

2.3.1. <u>Asymmetrical Current</u> Fig. 7 also shows the effect of fault current asymmetry on the time current curve, which can be quite significant for times below one second.

2.3.2. <u>Half Wave Rectified Current</u> Fig. 8 shows the effect of half wave rectified current on the time/current curve. Obviously operation cannot occur in even half cycles since no current is present. Any time-varying current in which the current repeatedly approaches zero will have such discontinuities around the current zeros. This is explained in greater depth in ref.1. As the fault current increases, operating time with the half wave rectified current is progressively less than with sinusoidal current. This is due to two factors. Firstly, the larger restriction temperature excursions produce more heat due to resistance change in the restriction. This increases the general temperature rise of the element. Secondly, the increased temperature fluctuation itself causes earlier operation, since the element as a whole does not have to get as hot in order for the restrictions to melt. This situation applies to all rapidly time varying currents and currents with a large form factor will result in shorter operating times for most of the time/current curve.

2.3.3. <u>DC Current</u> Direct currents tend to produce longer pre-arcing times than the equivalent rms sine waves. Figure 9 shows a step increase in current (dc of very short time constant) compared with an ac current of the same rms value. Despite the greater rate of rise of dc current initially, the ac current rapidly produces a greater heat generation (as explained above) and this coupled with notch temperature fluctuation gives much faster operation. Figure 8 shows the effect on a time/current curve of dc currents of various time constants.

If fuse co-ordination with a circuit breaker is required the time/current curve can be used to ensure that the fuse does not operate with the appropriate overload current. It must be remembered that since a circuit breaker may be feeding parallel paths or fuses may be in the arms of a bridge, an appropriate correction factor is needed to compare the fuse and breaker characteristics directly. If the fuse overload current is non-sinusoidal, then, particularly for times of less than 1 second, an appropriate time/current curve is necessary. This is especially the case with dc of long time constant.

An alternative approach, and often the only one which can be used if the fault is very irregular, e.g. 1000A rms for 20 ms followed by 1300A rms, is to use a characteristic of pre-arcing I^2t against pre-arcing time. There is for a given fuse a value of pre-arcing I^2t which is approximately constant and corresponds to the condition in which no heat is lost from the restriction (adiabatic heating). For semi-conductor fuses the time for which this is valid can be very small, e.g. less than 0.3 ms. Heat is lost from the element restrictions to the rest of the element and then to the filler and so the pre-arcing I^2t increases with time (becoming infinite when the fuse carries any current which does not cause eventual melting). The heat loss can be so great that at as little as 5 ms the pre-arcing I^2t can be over twice the minimum. This curve is approximately valid for any fault waveform.

2.3.4. Use of Pre-arcing I^2t/Time Curves for Co-ordination We will first examine the validity of such a curve.

i. Element Thickness. Heat loss from a fuse element to the surrounding filler becomes significant for pre-arcing times over about 15 ms. This causes a variation in characteristic and if a generalised curve for a whole range of fuses is being used the curve opens out into a band. This can be seen in fig. 10 where I^2t is expressed in multiples of minimum (adiabatic) pre-arcing I^2t and an element thickness variation of 4:1 exists.

ii. Current Waveform. Fig. 11 shows three curves (for a single element thickness) produced for sinusoidal current, a half wave rectified current and a dc current of 40 ms time constant. The half wave rectified current gives a lower pre-arcing I^2t at a given pre-arcing time. This is because increase in pre-arcing I^2t is a function of heat loss from the restrictions. The half wave current produces more heat for the same I^2t let-through and so reduces I^2t let-through for the same pre-arcing time. In addition the periods of no current in the waveform result in rapid restriction temperature drop and little heat loss during these off periods. The pre-arcing time is thus lengthened without a corresponding increase in heat loss. The half wave curve lies below the sinusoidal curve for all pre-arcing times over one half cycle.

DC current of over a few milliseconds time constant also results in a lower pre-arcing I^2t than a sine wave. This is because restriction temperatures are less than with a sine wave for most of the time. Fig. 12 shows the notch and element temperature variation for two currents which give operation in approximately the same time. One is a sine wave of 1800A rms, the other a dc current with a final value of 2200A and a time constant of 10 ms. The slow build up of dc current effectively increases the pre-arcing time without a corresponding increase in heat loss.

For co-ordination with a circuit breaker the lower limit of these curves, taking into account manufacturing tolerances is required to ensure discrimination. A tolerance of ±5% on the current of published time/current curves represents approximately ±10% on I^2t of these curves. I^2t against time of a fault can be plotted directly onto fig. 11. One example is shown for a dc inverting bridge fault. The dc breaker clears at 20 ms at which point the I^2t is 45% of the dc curve. The circuit breaker will clear without causing fuse operation, but obviously some margin is necessary if fuse deterioration is not to occur. This margin will now be examined.

Pre-arcing I^2t includes I^2t for the notch to reach melting point, I^2t for state change to occur and then I^2t for vaporisation or break up of the restrictions. Irreversible change will occur to a restriction as soon as any state change occurs. The period up to melting represents approximately 73% of the quoted minimum (adiabatic) pre-arcing I^2t. For pre-arcing times of between about 1 and 10 ms the figure is at least 80% and for times in excess of 20 ms it is over 90%. This is because a greater increase occurs in pre-melting I^2t than in either the melting or pre-vaporising I^2t, due to the times involved. For any waveform then, a curve can be produced which gives the minimum pre-melting I^2t against time for a range of fuses (including manufacturing tolerance). To what percentage of this minimum pre-melting curve a fault may approach depends on the fault waveform, whether the fuse is pre-loaded and the frequency of such faults.

a) DC Faults. If the fault will occur rarely (e.g. less than 10 times in the anticipated life of the fuse) it is reasonable for the fault to approach to within about 80% of this pre-melting I^2t if the fuse is unloaded, 60% if the fuse carries current before the fault. If the overload is at all regular, e.g. 1000 times per year, figures of 60% and 45% respectively are probably more realistic, to ensure fatigue will not cause premature operation.

b) Half-wave Rectified Currents. In this case a considerably greater margin should be left due to the very large restriction temperature excursions, particularly for short pre-arcing times. For occasional faults figures of 65% cold and 45% pre-loaded would seem reasonable and for repeated faults 40% and 30% would be necessary.

c) Sinusoidal Currents. This will lie between the other two conditions. If the time is greater than about 0.5 seconds, notch temperature fluctuations are small, and below around 7 ms the notch temperature rise is steady. Under these circumstances (and this will apply to half wave rectified currents also) occasional faults up to about 75% cold, 50% pre-loaded are acceptable or frequent faults at 60% cold, 45% pre-loaded. For ac faults from one half cycle up to around 0.5 seconds the large notch temperature fluctuations result in figures of 65% cold and 45% pre-loaded for occasional faults. Frequent faults demand a reduction to about 50% cold and 40% pre-loaded.

All the above figures have been obtained from a minimal amount of practical testing and the use of restriction temperature/time curves obtained from numerical analysis of the fuse heat flow. Further work and more operating experience using these figures are necessary, but they are presented as a basis for consideration. Life testing is most time consuming and the use of analytical techniques can be very helpful. For times over a few seconds the normal time/current curve can often be used for co-ordination since transient effects are then small.

Returning to the example, and allowing 10% for manufacturing tolerance and 90% as the ratio of pre-melting to total pre-arcing I^2t, the fault at 20 ms is 56% of the minimum pre-melting I^2t. This would be acceptable for occasional pre-loaded faults or a repeated fault from cold (e.g. switch on failure).

2.3.5. Transient effects at rated current Figure 13 shows the fluctuation of restriction temperature at rated current for a fuse carrying full wave, 180° and 120° conduction currents of the same rms value. It can be seen that the rectified currents give larger notch fluctuations and hence more heat production. Compared with dc current, the three waveforms produced 0.3%, 0.9% and 1.6% more heat respectively. At minimum fusing current, a sinusoidal current produced 0.5% more heat than dc of the same rms value, and the notch temperature was about 40°C hotter with ac, just prior to notch melting.

From this, it can be concluded that although variation in current waveform has a large effect on the short time operation of a fuse, it is very much a secondary effect between rated current and minimum fusing current. It is not until conduction periods become much less than 180° that heat production will increase sufficient to affect the rating of a fuse. Effects such as ambient temperature and busbar size swamp these small differences due to waveform.

3. CONCLUSIONS This paper has attempted to show that the protection of semi-conductors by fuses has developed and that it is now less of an art and more of a science. It is to be hoped that the days of a user putting bigger and bigger fuses into his circuit until his device is destroyed, are over. Today, with better information being produced by both fuse and semi-conductor manufacturers, the situation is much better. There is no room for complacency, however, and the two sides of the industry must continue to co-operate to ensure future developments take place in both products.

4. REFERENCES

1. Leach, J.G., Newbery, P.G. and Wright A. "Analysis of HRC Fuselink Pre-arcing Phenomena by a Finite Difference Method". Proc. IEE Vol. 120 No. 9, September 1973, pages 987 - 993.

2. Beaumont, K.J. and Wright, A. "Analysis of HRC Fuselink Arcing Phenomena". To be published in Proc. IEE.

3. Motto, J.W. Jnr. "Can SCRs and Silicon Diodes be Protected by fuses". June 1969. IEE Fuse Application Group.

4. Pearse, J.N. and Newbery, P.G. "Fast acting fuses for the protection of semi-conductors". IEEE Transactions. June 1970.

5. Jacks, E. "The fundamental behaviour of high-speed fuses for protecting silicon diodes and thyristors". Conference record IEEE International Convention Digest 1968, page 149.

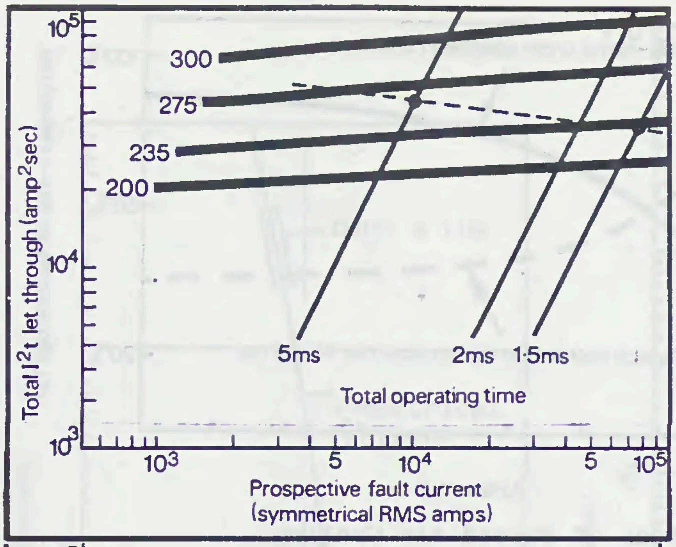

Fig. 1. Fuse Let-through I^2t versus Fault Level.

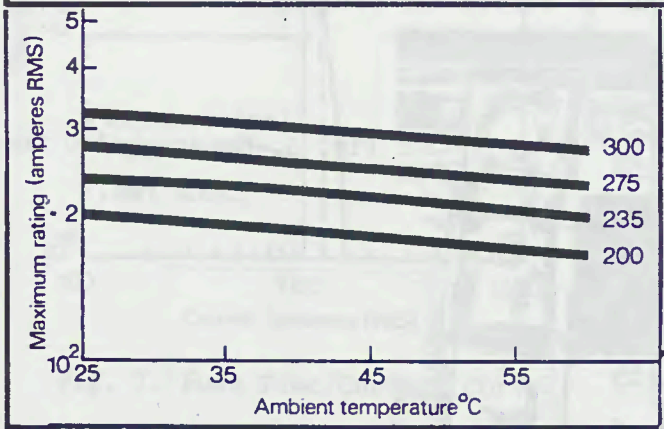

Fig. 2. Maximum Current Rating versus local Ambient Temperature.

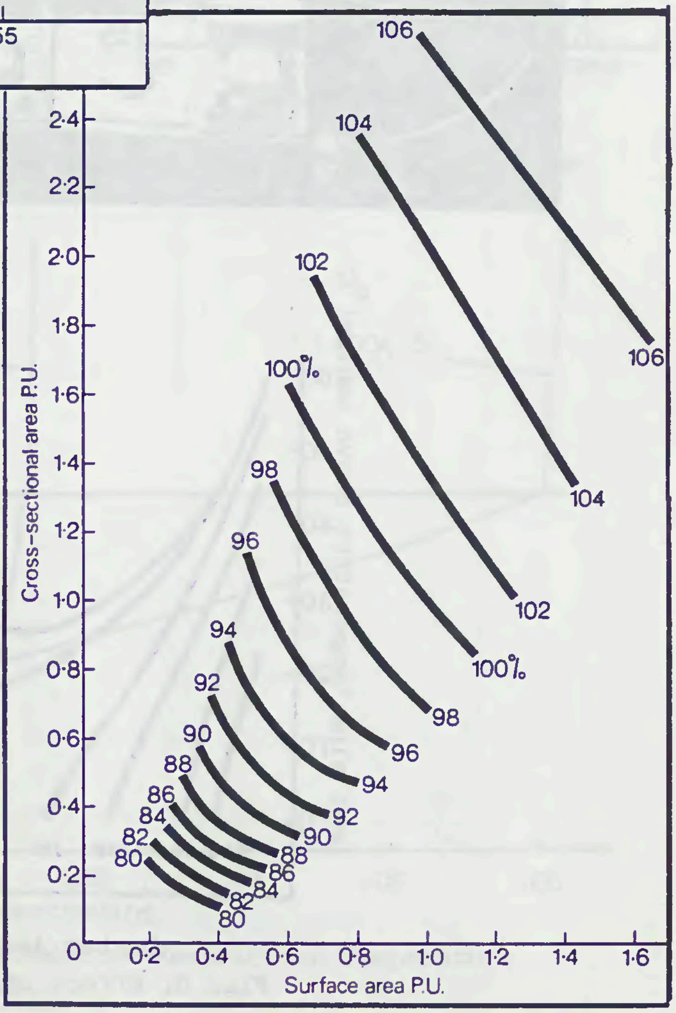

Fig. 3. Variation of Maximum Current Rating with Busbar Size.

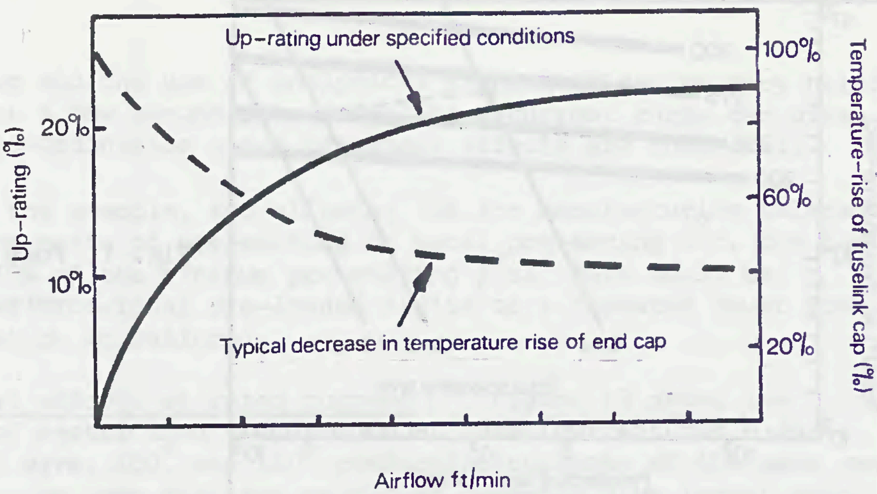

Fig. 4. Effect of Forced Air Cooling.

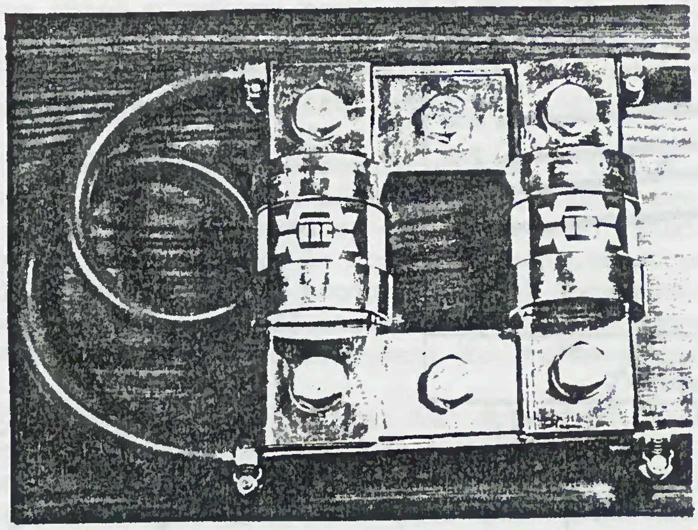

Fig. 5. Water-cooled fuse 2200A rms.

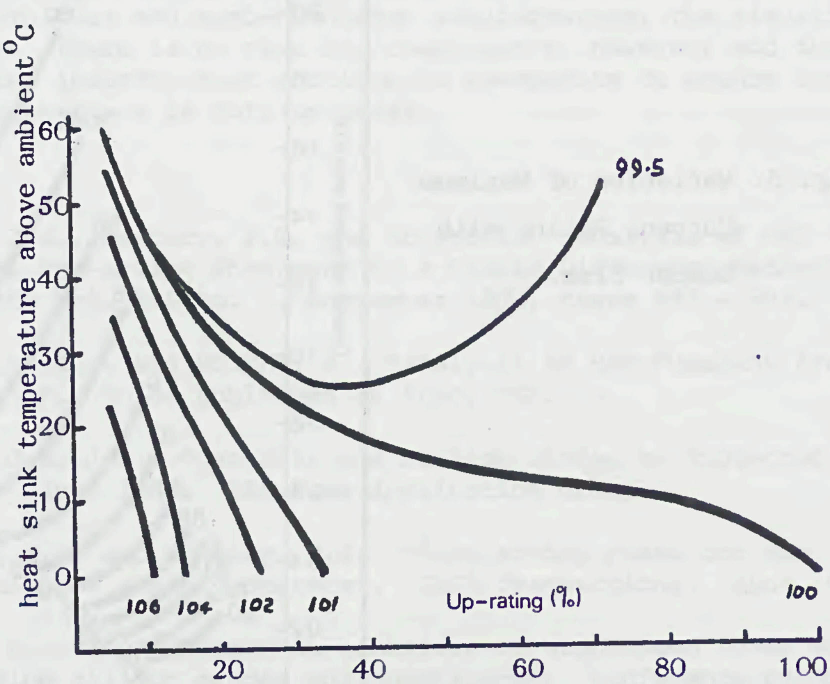

Fig. 6. Effect of Busbar Length on Current Rating.

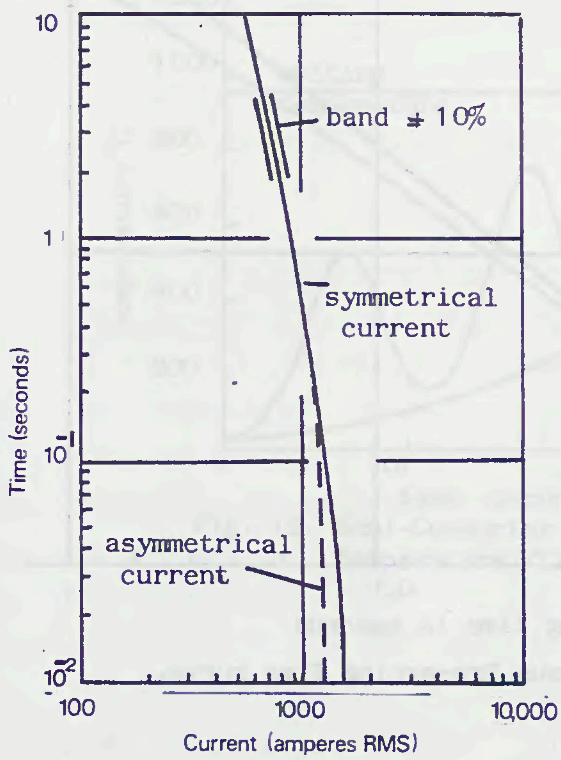

Fig. 7. Fuse Time/Current Curve

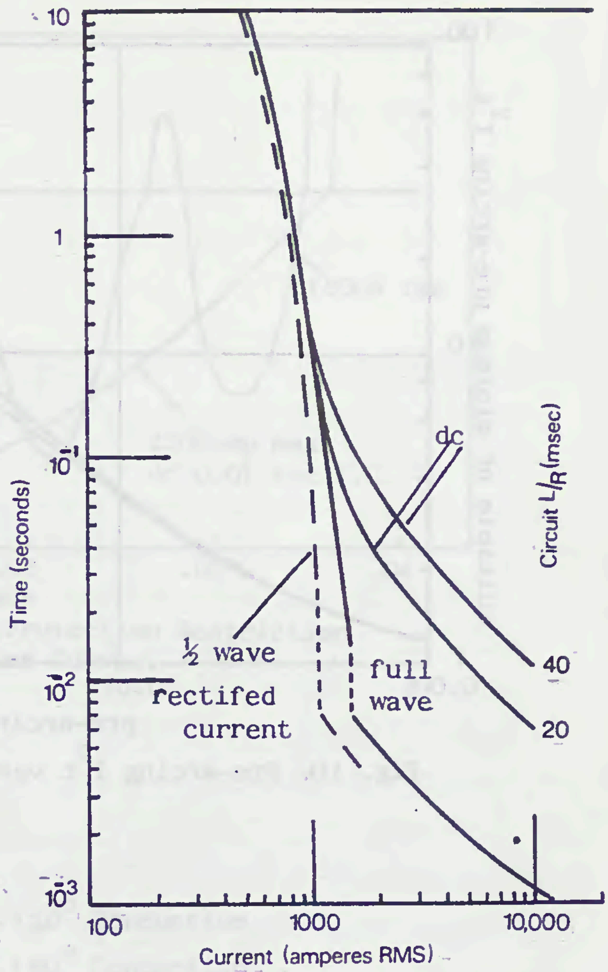

Fig. 8. Effect of Waveform on Fuse Time/Current Curve.

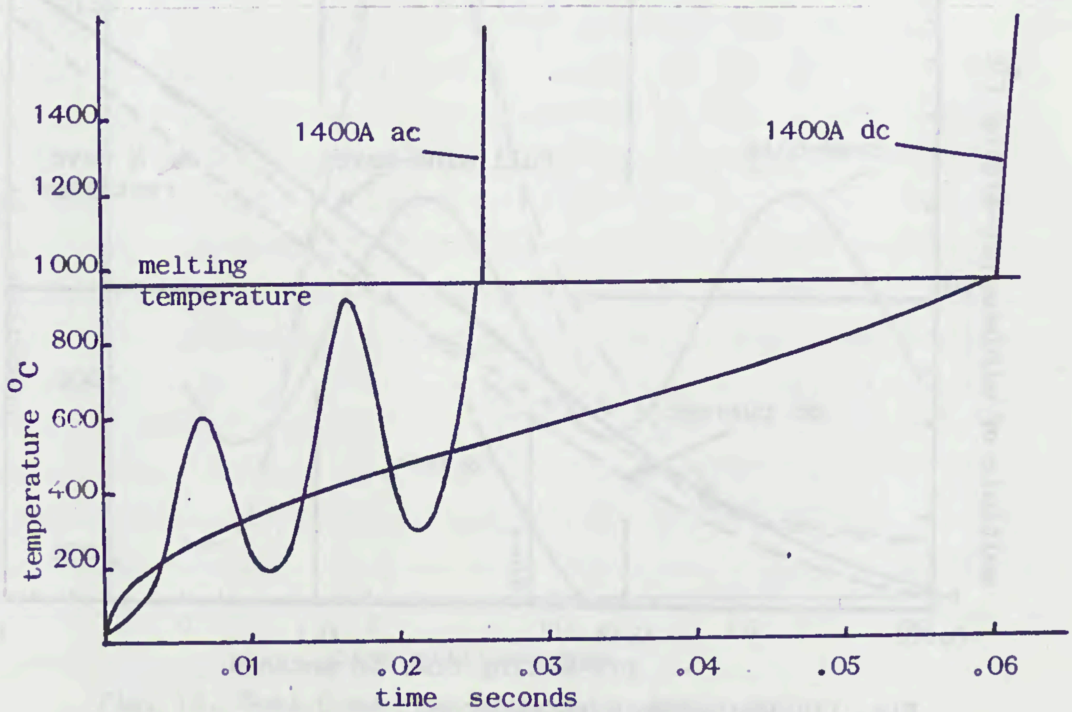

Fig. 9. Semi-Conductor protection Restriction Temperature versus Time Curves.

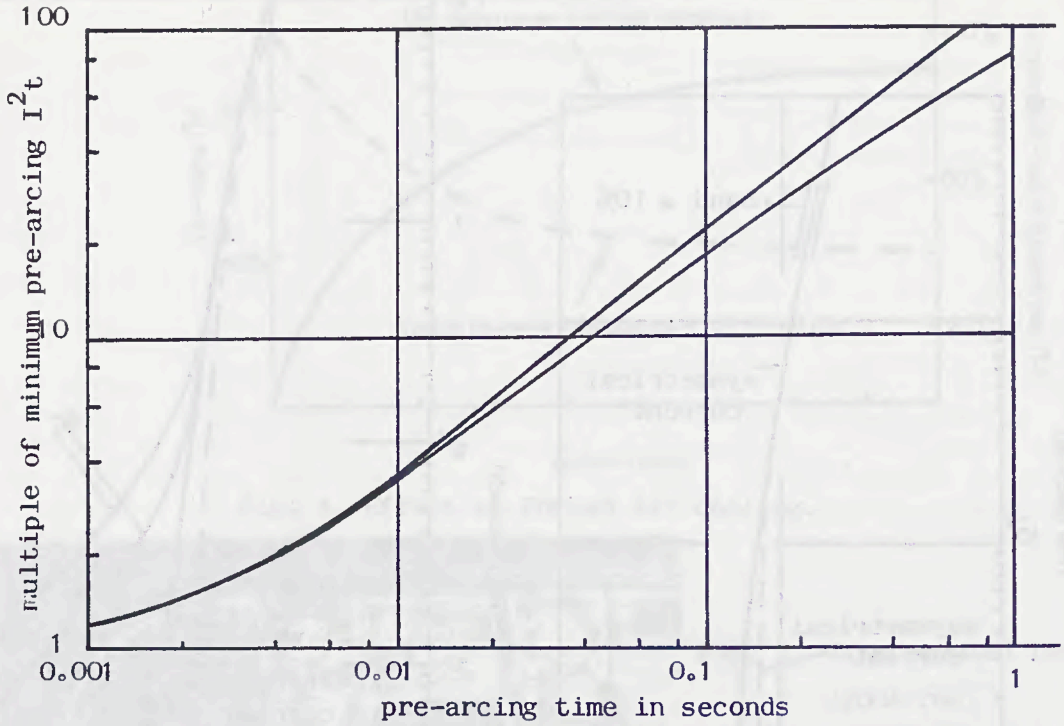

Fig. 10. Pre-arcing I^2t versus Pre-arcing Time curve.

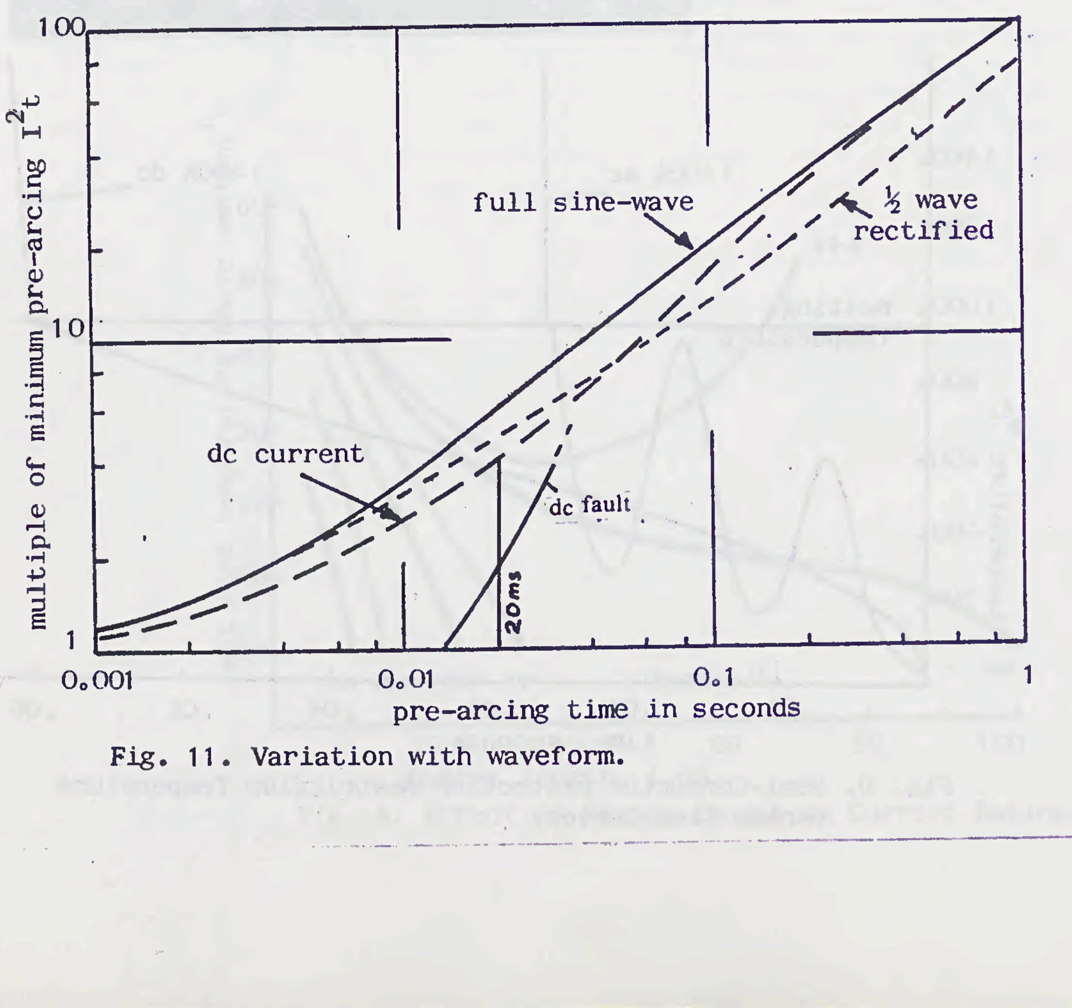

Fig. 11. Variation with waveform.

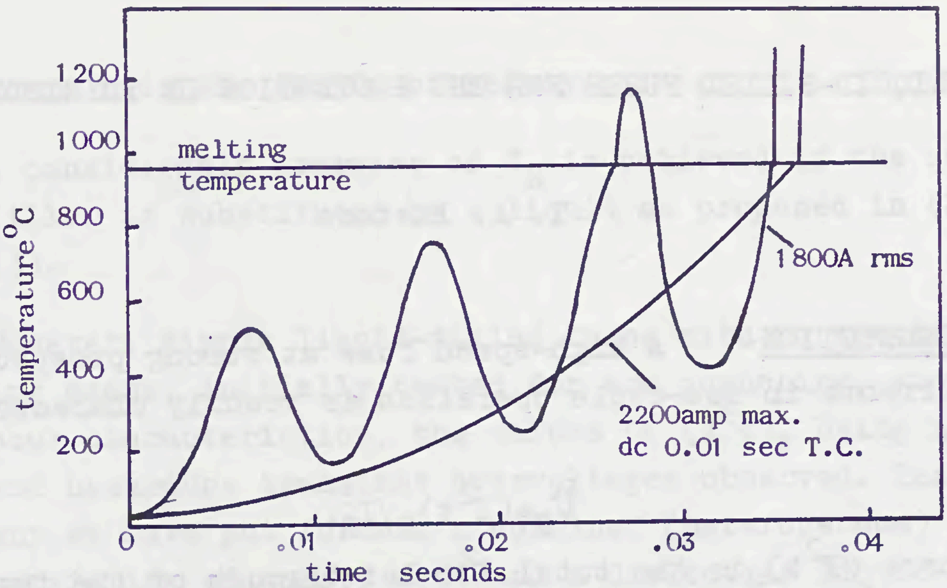

Fig. 12. Semi-Conductor Protection Restriction
Temperature /Time Curves.

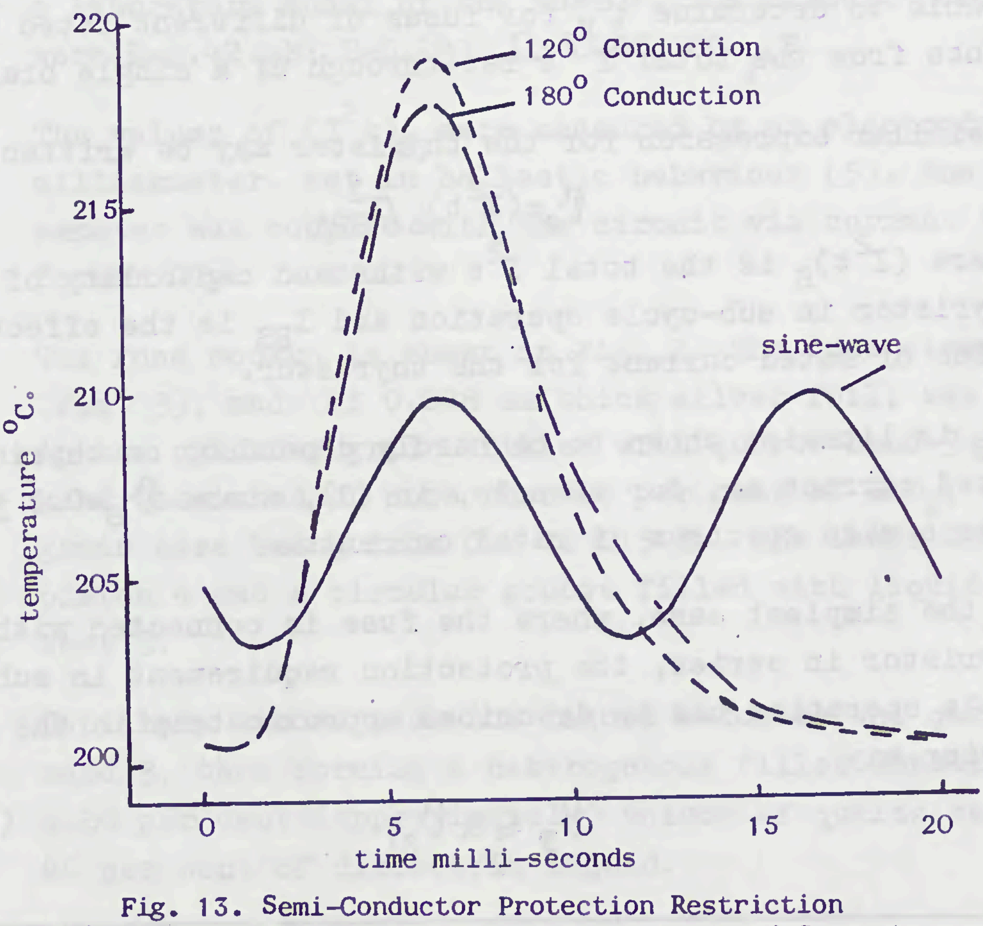

Fig. 13. Semi-Conductor Protection Restriction
Temperature Fluctuations at Rated Current.

LIQUID-FILLED FUSES FOR THE PROTECTION OF THYRISTORS

Y. A. Pastors

INTRODUCTION A high-speed fuse at strong prospective currents in sub-cycle operation is readily characterized by

$$\tau_F=(I^2t)_F/I_R^2, \qquad (^x)$$

where $(I^2t)_F$ is the total I^2t let-through of the fuse-link and I_R is fuse-link's rated current. For fuses of one and the same type, but having various rated currents, τ_F is hardly dependent on rated current. If arc-quenching in the parallel branches of the fuse-link element is assumed to be taking place independently, the above expression is usable to determine τ_F for fuses of different rated currents from the total I^2t let-through of a single branch.

A similar expression for the thyristor may be written as

$$\tau_s=(I^2t)_s/I_{RS}^2,$$

where $(I^2t)_S$ is the total I^2t withstand capability of the thyristor in sub-cycle operation and I_{RS} is the effective value of rated current for the thyristor.

τ_S is likewise shown to be hardly dependent on thyristor's rated current as, for example, in (1), where $\tau_S=0.3 \pm 0.1$ s over a wide spectrum of rated currents.

In the simplest case, where the fuse is connected with the thyristor in series, the protection requirement in sub-cycle operation can be described approximately in the following way

$$\tau_F \leqslant k\,\tau_S, \qquad (xx)$$

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where k is the factor of safety.

A considerable increase of I_R is achieved if the quartz filler is substituted by a liquid as proposed in (2) and (3).

However, simple liquid-filled fuses with no special quenching means, initially tested for arc quenching, showed poor characteristics, the values of $(I^2t)_F$ being high and hazardous transient overvoltages observed. That is why we have put forward a combined (heterogenous) filler, consisting of quartz sand and a dielectric liquid (4).

EXPERIMENTAL SET-UP The experimental set-up is shown schematically in Fig. 1. The capacitor battery C was first charged to a definite voltage of U and then, upon closing the circuit breaker CB, the current was passed through a laboratory model of the fuse F. The circuit parameters were L=2.42 mH; R=0.223 Ω; C=80,000 μF.

The values of $(I^2t)_F$ were measured by an electrodynamic milliammeter, set in ballastic behaviour (5). The milliammeter was coupled with the circuit via current transformer CT.

The fuse mockup is shown in Fig. 2. The fuse element 1 (Fig. 3), made of 0.028 mm thick silver foil, was placed in the cylinder grid 2 filled with quartz sand 3. The sand consisted of more than 98 per cent of SiO_2, the grain size being from 0.2 to 0.5 mm. The lower dielectric piston 4 had a circular groove filled with liquid under test 5.

Capillary forces made the liquid saturate the quartz sand 3, thus forming a heterogenous filler containing a 60 per cent (approximately) volume of quartz sand and 40 per cent of dielectric liquid.

As arc quenching is largely dependent on pressure in the sand, as pointed out in (6), the latter was maintained constant throughout the experiment. To achieve it, prior to testing a pressure of 10 kG/cm^2 was built up in the sand by means of the upper piston 6 and then the piston was fixed by the screw 7. The path of the test current was through piston 6, fuse element 1 and lower contact 8.

EXPERIMENTS AND RESULTS In arc quenching tests, the values of $(I^2t)_F$ obtained for dry quartz sand were compared with those obtained for the combined filler. As shown by the curve (a) in Fig. 4, the values of $(I^2t)_F$ were low, which is due to the fact that the thickness of the fuse element was very small and that a definite pressure existed in the sand. Heterogenuous fillers made up of quartz sand and carbon tetrachloride, as well as of sand and chloroform, are shown by the same curve to be as good arc quenchers as dry quartz sand. Ethylene-glycol-containing fillers were found to possess $(I^2t)_F$ values (curve b), which are 20 to 30 per cent greater than those offered by dry sand.

Overvoltages during arc-quenching in the heterogenous fillers were shown by electron oscillograms to be of the same order as in dry sand.

In the case of chloroform-, as well as thermex-containing fillers, the circuit was found,after the arc was quenched, to be passing considerable current. The fulguritesof these fillers appeared to possess a rather significant conductivity and, therefore, both chloroform and thermex were found to be unsuitable for forming heterogenous fillers.

Tests for rated currents were performed using the same model as in Fig. 2. A fuse element with an active length of l=48 mm and having four incisions was used instead of that shown in Fig. 3, all the other parameters being the same as in Fig. 3.

It is certainly possible for such a fuse element to break a circuit with considerably higher voltages as in the above tests for arc quenching, where a shorter fuse element having one incision was used.

The temperature of casing 9 was set at +25 ±0.5 °C by means of a thermostat.

Fig. 5 illustrates the dependency of fuse element resistance r upon steady current I. Curve (c) represents dry sand; curve (d) - heterogenous filler containing sand+carbon tetrachloride; (e) - heterogenous filler subjected to a high intensity electric field.

The electric field was provided by inserting into the fuse a high-voltage electrode, as described in (4), which was connected with a 4 kV 50 cps AC source. In the case of a heterogenous filler, the resistance r, as shown by curve (d) in Fig. 5, increases slowly, which is attributed to the cooling effect of the liquid.

The increase of r is even more slower under the influence of electric field, since the latter considerably intensifies heat dissipation from the fuse element (curve (e)).

Let us assume the fuse rated current to be of such a value that it elevates the fuse element temperature to a definite mean value of, say, +70 °C. Then the corresponding resistance will be r=21 mΩ in which case for dry sand I_R=10 - 11 A and 16 - 18 A for sand containing carbon tetrachloride, whereas, in the case of electric field, I_R is estimated to be between 21 and 22 A.

It is evident from Eq. (^{x}) that at $(I^2t)_F$ =idem the value of ϑ_F for the heterogenous filler decreased 2 to 3 times as compared with dry sand while the decrease for heterogenous filler was even three- to four-fold when it was under the influence of electric field, the satisfaction of (^{xx}) being thus considerably better.

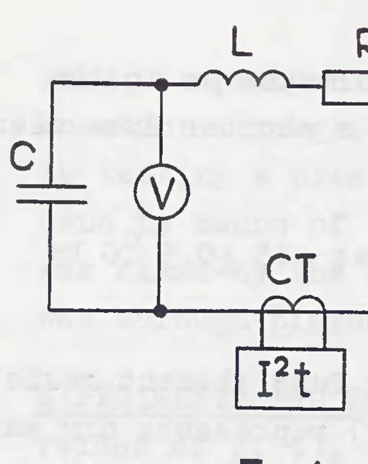

Fig.1

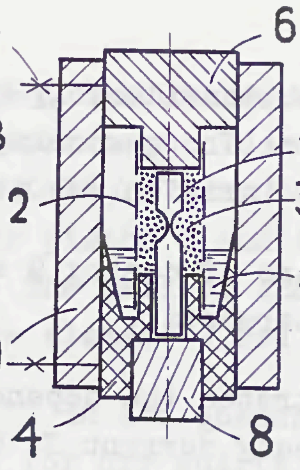

Fig.2

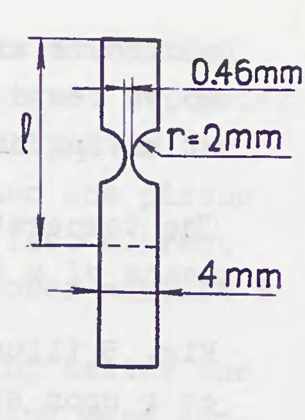

Fig.3

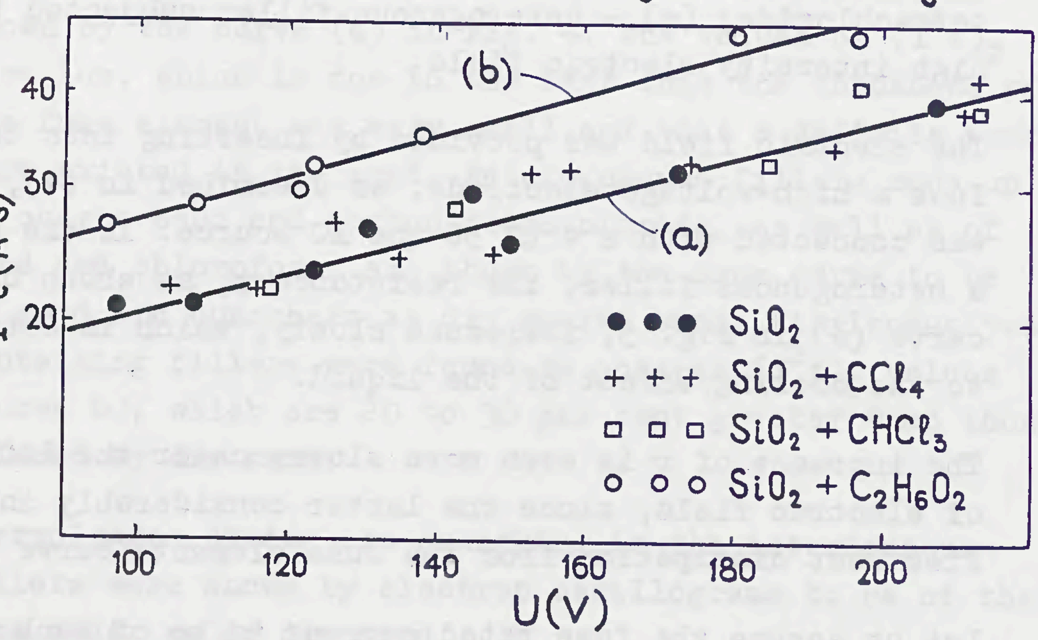

Fig. 4

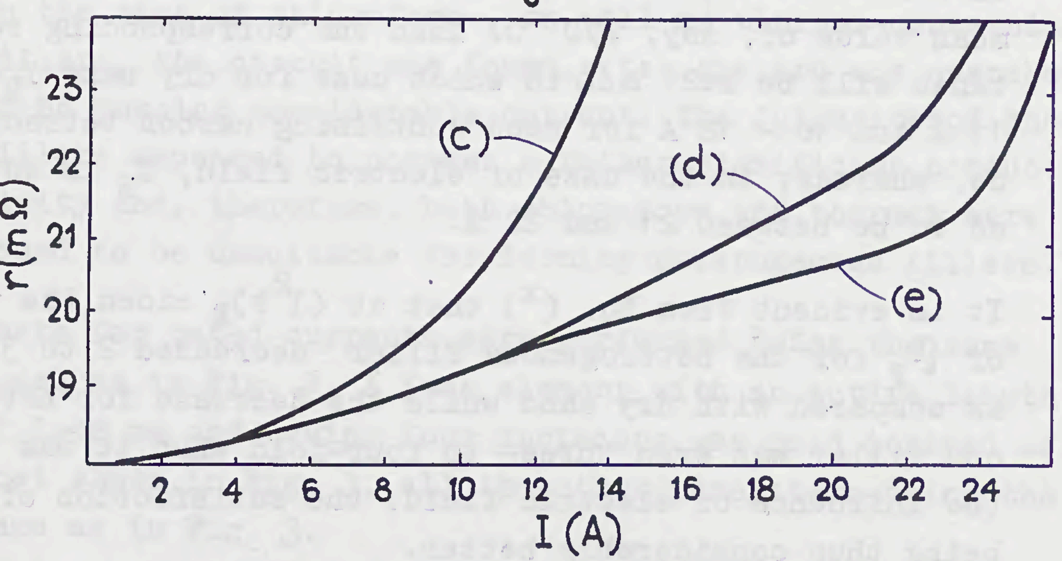

Fig. 5

REFERENCES (1) Westinghouse Brake and Signal Co, Techn. Publ. T/WEC, Issue 2, Jan. 1973.

(2) Hayden J.T., Liquid-Filled fuses for the protection of thyristors, Conf. Pwr. Thyr. Appl., London, 1969, p. 132-139.

(3) Staub Fred W., Corman James C., Walmet Gunnar E., Current limiting fuse, US Patent 3, 710, 295, Jan. 9, 1973.

(4) Pastors Juris A., Litsitis Andrei A., Grislis Viktor Y., Electric circuit-breaking fuse, U.S.Patent, 3,818,409, June 18, 1974.

(5) Pastors Y.A. Joule integral measurements in a fuse - links investigation, Izvestiya AN Latviiskoi SSR ser. Fiz. i Tekn. Nauk 1970, N 3, p. 30-32.

(6) Pastors Y.A. Some characteristics of electric arc extinguishing in compressed quartz sand, Izvestiya AN Latviiskoi SSR ser. Fiz. i Tekn. Nauk, 1969, N 5, p.55-58.

THE DESIRABLE SHORT CIRCUIT PARAMETERS OF SEMICONDUCTOR FUSES

J. Czucha

INTRODUCTION Diodes and thyristors in the following called semiconductor devices SD have short-circuit withstand normally determined in manufacturers sheets* by two parameters: I_{TSM} - non repetitive peak on-state current and I^2t. This paper pointed out, that they do not give a complete determination of the requirements for the selection of semiconductor fuses (SF).

I^2t OR I_{TSM}? I^2t value is defined as follows:

$$I^2t = \int_0^{t_c} i^2 dt$$

where t_c - conductions current duration, i_T - on -state current. Generally that value is determined in data sheets for t_c = 10 ms. In some sheets its value is determined for t_c = 3 ms or 1,5 ms.

On the basis of simple calculation it is possible to demonstrate that manufacturer's I^2t value corresponds to the value calculated for the I_{TSM} declared in another place in data sheets. Well, it may be concluded that that does not give any supplementary information about the short-circuit withstand of examined SD. I^2t value is a simple transform of the already previously know value I_{TSM} only.

DECLARED I_{TSM} AND I_{FSM} Fig.1 shows a summary of manufacturers ratio values $I_{TSM}/I_{T(RMS)}$ versus $I_{T(RMS)}$, where

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* The comments given in this paper are based on data published by ten various European firms in 1974

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$I_{T(RMS)}$ is R.M.S. value of on-state current. From this figure it follows, that the permissible overload currents are very scattered. E.g. the ratios for the same manufacturer SD with nearly the same $I_{T\ RMS}$ (Fig.1, crosses 1A and 1B) differ about 1.5 times one from another. In other case (Fig.1, crosses 2A and 2B) SD, which $I_{T(RMS)}$ values differ abt 3.5 times, have approx. these same value of their non repetitive peak on-state current I_{TSM}. In the case of SD from different manufacturers or with an evidentially different way power losses leading but with the same $I_{T(RMS)}$ the differences are still greater e.g. crosses 3A and 3B and are up to abt 3.5.

I^3t IS BETTER THAN I^2t I_{TSM} and I^2t values given by manufacturer enable the various interpretations of those parameters under working conditions, depending on shape of the overload current curve in SD. Frequently encountered in service shapes are shown in Table I, column 1. In column 2 dependences for $\int_0^{t_c} i^2 dt$ calculations are given. In order to get more distinct further comparison results the I^2t value and I_M for one half-sine wave is treated as a basic one. Than, for this same I^2t but for different curve shapes calculations of I_M value carried out. Results are shown in column 3. Futhermore in column 4 for this same I_M the calculated values of $\int_0^{t_c} i^2 dt$ are given. The results are for this same time t_c.

For typical current shape there are very important values given in line2. E.g. for I^2t = const. the permissible current amplitude is 1.22 times greater than for one half sine--wave amplitude. It means, if $I_M = I_{TSM}$ for half sine-wave one might be overloaded the SD by 1.22 times greater current amplitude.

The short-circuit current time duration is an important factor determining the SD short overcurrent withstand. E.g. from Fig.2 for high data thyristor it may be concluded that I^2t value decreased to abt 0.65 times if t_c changes from 10 ms to 1.5 ms.

The better determining parameter of SD short circuit current withstand instead of I^2t is I^3t. The next part of paper shows that not only for low data thyristors it is true [1].

The curve 1 in Fig.3 represents the permissible value of the I_{TSM} in the shape of a half-sine wave as determined by the manufacturer in the function of the time t_c. The curve 2 shows dependence calculated from the I^2t = const. condition. A great difference between the curves 1 and 2 is clearly visible. Curve 3 represents the calculated dependence as from I^3t = const. condition. In this case there is a much better conformity with the data given by the manufacturer. The numerous other calculations of the I_{TSM} following from the I^3t condition for $t_c \neq 10$ ms show a good conformity of results (+5%, -10%) with the data given by some manufacturers too. Therefore one may be pointed out, that the I^3t parameter gives the more precise coordinate possibility between SD and SF.

CONCLUSIONS The permissible overload currents of SD are very scattered, indeed. That´s why the interchangeability between SD delivered by different manufacturers is impossible now.

The overload current parameters of SD in data sheets are defined for a determined curve shape and overload duration half sine-wave with a time t_c = 10 ms . The shape of the current fault curve in real systems, however, may differ considerably from the declared one. The differences in determining the I_{TSM} and I^2t in dependence upon the shape of the curve may be considerable. Relevant calculations are given in Table I.

The duration of the current fault is different from the declared value 10 ms in many cases. The I^3t = const.parameter gives a better representation of the influence of the fault current amplitude and duration for SD. Correction factors for the relevant calculations with consideration given to the shape of the current curve are compiled in Table I.

REFERENCES

1 Ky Hong, 'I^3t of fuses and semiconductors'. IEEE Transaction on Industrial Electronics and Control Instrumentation, Vol. ICEF 18, No.2, May 1971

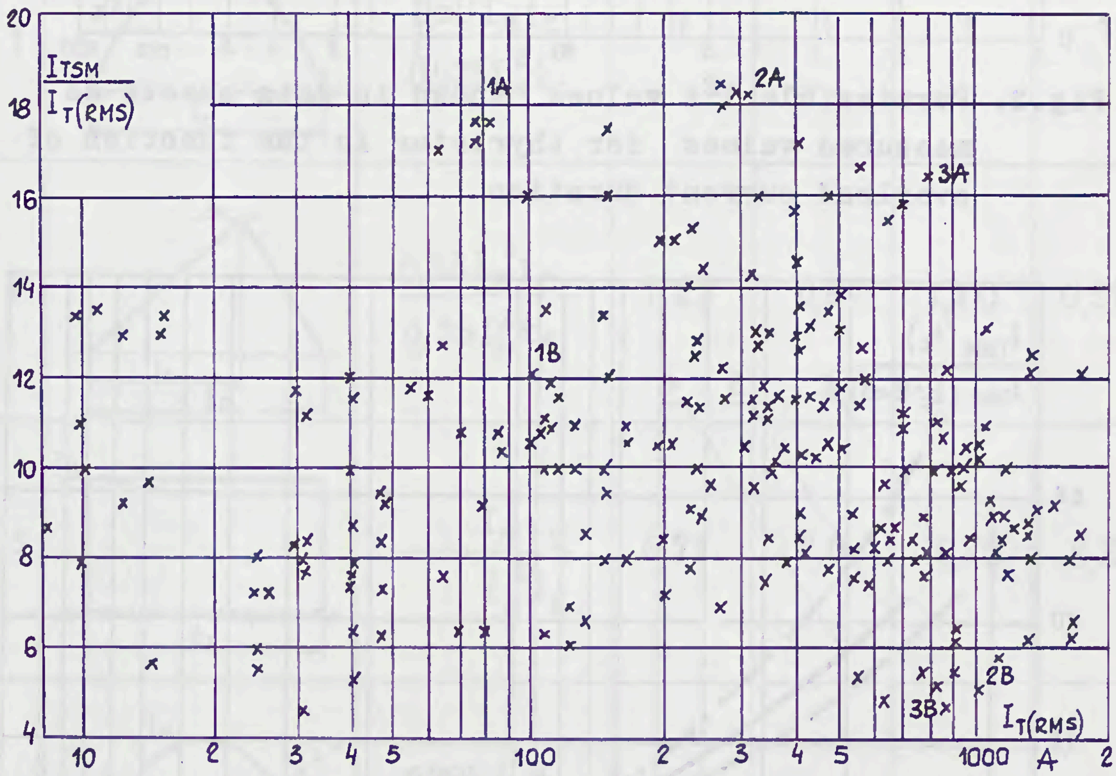


Fig.1. Diode and thyristors relative non-repetitive on-state current values in the function of on-state current absolute values as declared by manufacturers

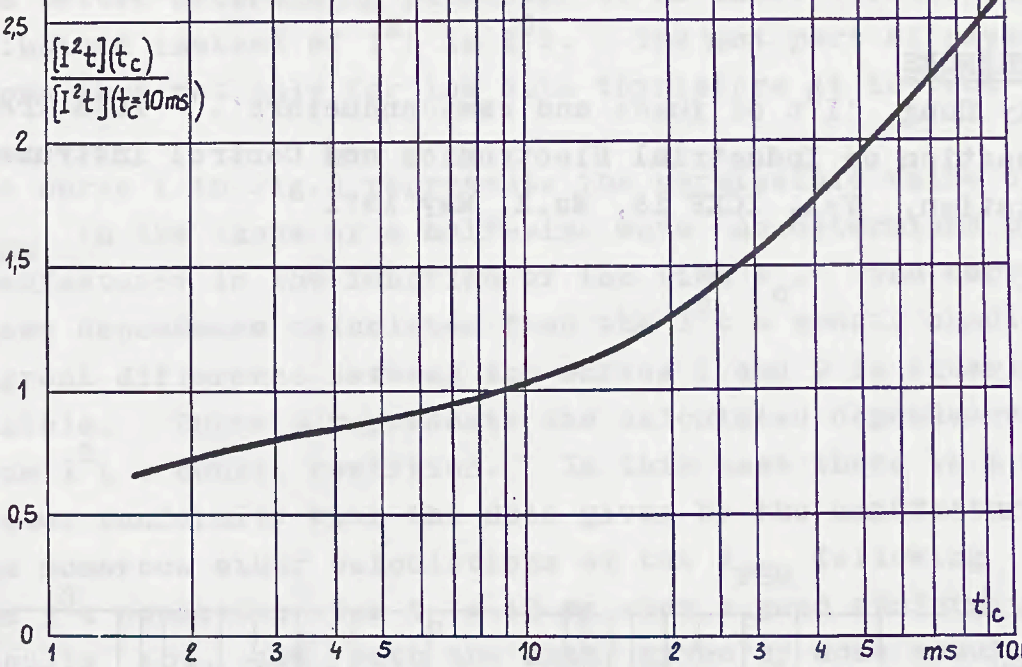


Fig.2. Permissible I^2t values shown in data sheets as measured values for thyristor in the function of overload current duration

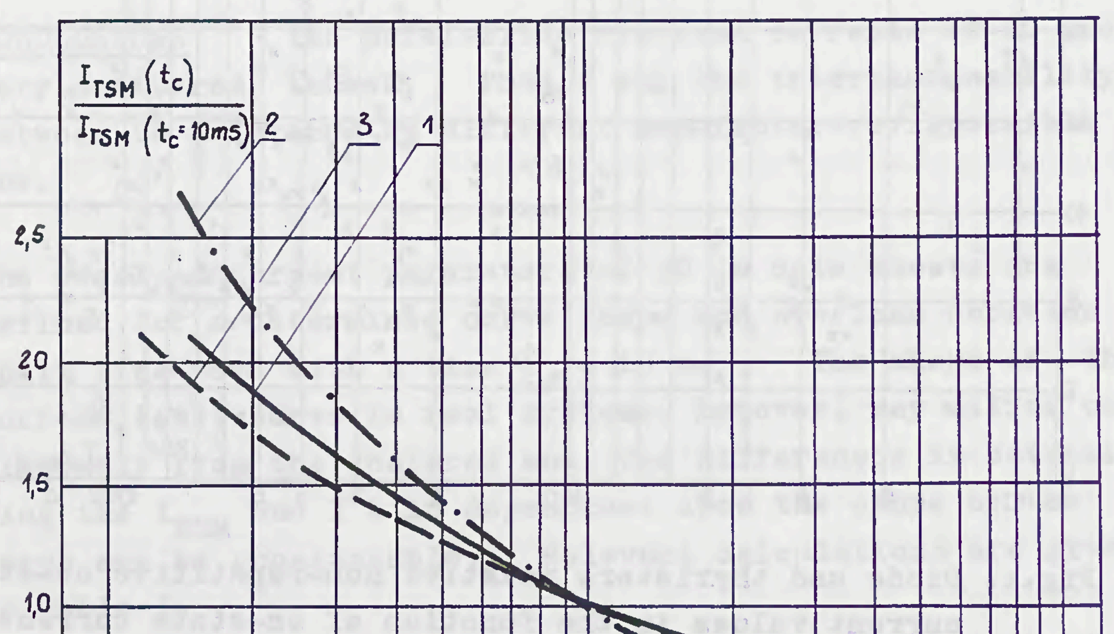
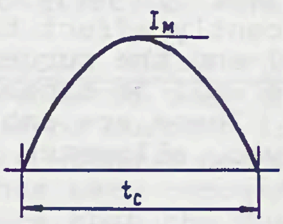
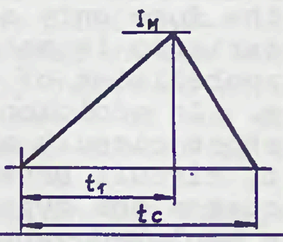
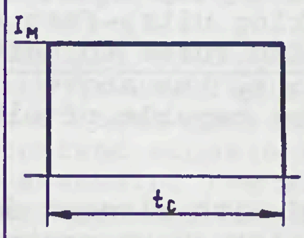
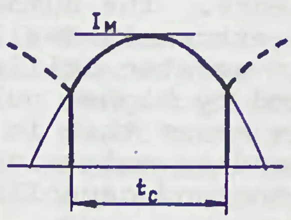
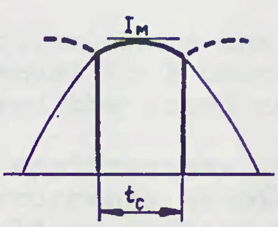


Fig.3. Comparison of non repetitive on-state current permissible values in the function of overload duration - 1 - value determined ny measurement; 2 - calculated from condition I^2t = const.; 3 - calculated from condition I^3t = const.

Table I Relations for determining I^2t and I^3t parameter values for various shapes of the current curve

SHORT-CIRCUIT CURRENT CURVE SHAPS		RELATIONS $I^2t = f(I_M, t_c)$ / $I^3t = f(I_M, t_c)$	RATIO OF I_M FOR $I_M^2t = const$	RATIO OF $\int_0^{t_c} i^2 dt$ FOR $I_M = const$	RATIO OF I_M FOR $I_M^3t = const$	RATIO OF $\int_0^{t_c} i^2 dt$ FOR $I_M = const$
1		2	3	4	5	6
1		$0{,}50 I_M^2 t_c$ / $0{,}425 I_M^2 t_c$	1	1	1	1
2		$0{,}33 I_M^2 t_c$ / $0{,}25 I_M^3 t_c$	1,22	0,67	1,20	0,59
3		$I_M^2 t_c$ / $I_M^3 t_c$	0,71	2,0	0,75	2,35
4		$0{,}704 I_M^2 t_c$ / $0{,}621 I_M^3 t_c$	0,84	1,45	0,88	1,46
5		$0{,}913 I_M^2 t_c$ / $0{,}875 I_M^3 t_c$	0,74	1,83	0,78	2,05

CYCLIC LOADING OF FUSES FOR THE PROTECTION OF SEMI-CONDUCTORS

G. Stevenson

INTRODUCTION In some applications fuses used for the protection of semi-conductors are subjected to overload currents. These over-loads can either be occasional or cyclic and under extreme conditions the thermal excursions caused by the overload may result in undue stress being imposed on the fuse element. This would ultimately cause premature operation of the fuse.

Increasing interest is now being shown in the selection of fast acting fuses for cyclic loading duties. In many applications other factors which significantly affect the choice of type of fuse (ultra fast, fast) and the current rating automatically ensure that the fuse will be capable of withstanding the associated cyclic duty. These are ambient temperature, protection philosophy employed, allowance for mis-sharing between parallel paths etc.

The general U.K. practice for large steel mill drives and similar applications, is to ensure that the fuse only operates when a device fails, and the fuse characteristic is matched against the sum of the total withstand capabilities of all the devices connected in parallel in each arm. In addition it may also be required that in the event of a short circuit at the d.c. terminals or an interconvertor fault, circuit breakers and not fuses operate. The foregoing dictates the type of fuse required and normally fast fuses are employed rather than ultra-fast types. Since, generally speaking ultra-fast acting fuses are more susceptable than fast acting fuses to mechanical fatigue caused by cyclic loading conditions, the above philosophy ensures that the fuses are more capable of withstanding cyclic pulses of current.

It is probable that these factors coupled with element designs that embody a good pulse withstand capability have contributed to the exceptionally good service experience. The number of problems encountered in service has been extremely small. However as the present trend is to obtain greater utilisation of devices, this will in turn be reflected by higher pulsed currents being carried by the fuse. This means that in order to ensure that the past good service record is maintained more attention has to be paid to the pulse withstand capability of the fuse.

G. STEVENSON IS WITH GEC FUSEGEAR LTD.,

SERVICE PROBLEMS In installed equipments the fatigue failure of fuses can present serious problems because of the necessity of replacement, or the fact that as each fuse operates it may remain undetected until the equipment finally ceases to function thereby causing a serious increase of downtime. Hence it can be seen that it is essential that the fuse selected has an adequate pulse withstand ability.

Outside the U.K. the tendency has been to use ultra-fast acting fuses the philosophy being to ensure that the fuse will protect the device under all fault conditions. It may be because of this fact that more withstand problems have been encountered on cyclic loading duties. Arising from this some equipment manufacturers include a pulse test in the fuse specification, which usually takes the form of subjecting the fuse to a specified number of pulses, in order to assess the suitability of the fuse to withstand the pulses in service.

EMPIRICAL RULES FOR OVERLOADS AND CYCLIC LOADS It must be appreciated that the rated current of a fuse is normally that value of current (r.m.s.) which the fuse can carry continuously without deterioration of the fuse elements occurring. It has been recognised that this test does not necessarily ensure that the fuse is capable of being continuously switched at rated current. In the Standard for semi-conductor fuses (IEC 269-4) the new method of determining rated current is based on the fuse being able to withstand the rated current being switched at least 100 times. In practice with the exception of one or two designs, fuses are capable of a much greater number of operations.

Based on the foregoing and also on service experience and knowledge the following empirical rules were determined.

OVERLOADS (OCCASIONAL) The time-current characteristic which is usually published is an operating characteristic, but it does give some indication of the ability of a fuse to withstand occasional overloads. There is no real difficulty in assessing the ability of a fuse to withstand occasional overloads and the following rule has proved to be a very useful method of selection.

> The r.m.s. current for the duration of the overcurrent must not exceed 85% of the time-current characteristic. If the overcurrent is due to a short circuit at the d.c. terminals, it is also necessary, because of assymetry to ensure that the r.m.s. current of the first pulse does not exceed 85% of the time-current characteristic.

In cases where the duration of the overcurrent is greater than or equal to 1 hour, the equivalent r.m.s. current should not exceed the rated current of the fuse.

For applications where the equipment is liable to frequent overcurrents as distinct from cyclic loads the above factor should be reduced to 70%.

OVERLOADS (CYCLIC LOADS) The selection of a fuse for these particular duties can be much more difficult because of the many variations which can occur. The present recommendations are as follows:-

Ensure for the ON time being considered that the current pulse does not exceed 40/50% of the time-current characteristic for the same ON time.

The equivalent continuous r.m.s. current should not exceed the rated current of the fuse.

The factor (40/50%) depends on the type of fuse e.g. fast or ultra-fast and also the element design. However there are some applications (highly repetitive duty cycles) where the above factors are inadequate. It is primarily for these cyclic loading conditions that the above rule requires modification and is the reason for the investigations described later in this paper.

BRIEF HISTORICAL REVIEW OF HIGH SPEED FUSES Generally speaking the faster acting a fuse is the more susceptable it will be to cyclic loading. In order to achieve an ultra-fast operation the reduced sections of the elements are smaller than those of the slower fuses. When subjected to a cyclic current pulse, these smaller reduced sections may be subjected to more stress during the heating and cooling periods, and hence have less ability to withstand cyclic pulses.

The historical development of high speed fuses (naturally cooled) with which the author is familiar is shown in Fig.1. Comparing the 2nd and 3rd generations it can be seen that the difference in current density is not as significant as that between the 1st and 2nd generations. This is because by optimising the design parameters the increase in speed has been achieved not only by smaller element reduced sections, but also by improved element design and by enclosing each element in its own fuse barrel.[1)]

Based on this fact it is apparent that the current densities in the reduced section cannot be further increased without jeopardising other parameters, and in order to obtain maximum utilisation of these ultra-fast fuses a fairly extensive Laboratory test programme was undertaken to investigate their pulse withstand capability.

LABORATORY TESTS In order to reduce the amount of testing time required particular duty cycles were chosen e.g. 5 seconds ON 5 seconds OFF. This cycle being repeated continuously.

Fast and ultra-fast fuses of various current and voltage ratings were connected in series, and then subjected to a particular repetitive duty cycle, the test being continued until all the fuses had operated. Individual fuses being replaced by copper links when they operated.

The tests were then repeated using different values of current during the ON period again until all the fuses had operated.

These results were then used to plot fatigue characteristics for a given duty cycle. A typical curve is shown in Fig.2. The results show, as expected, that the curve is not asymptotic i.e. silver has not fatigue limit.

A BASIS FOR ACCELERATED CYCLIC LOADING TESTS Obviously verification by test at the longer times on the fatigue characteristic is not a practicable proposition, and because of the shape of the curve it is difficult to predict the withstand capability of the fuse with accuracy.

However it can be stated that the test results approximate to a law of the form:-

$I = aN^{-\theta}$ where I = R.M.S. current for the ON period

a = constant for a given fuse current rating.

N = number of cycles

θ = slope of the characteristics (constant)

Taking logs we obtain:-

$\log I = \log a - \theta \log N$

which is of the form $y = mx + c$

hence re-plotting the test results on a log-log scale will in fact produce characteristics as shown in Fig.3.

Therefore for a particularly arduous cyclic duty it is not unreasonable to determine two or more points for relatively short times. Plot the results on a log-log scale and simply draw a best-fit straight line through the test points. Then by extending the straight line predict the number of cycles the fuse will withstand for a particular value of current during the ON time (Fig.4).

The Laboratory tests have shown quite clearly (Fig.5) that the life of a given fuse can be extended considerably by providing some stress relief bends in the element. The shape and number of stress relief bends being important factors in order to achieve the greatest improvement.

PRESENTATION OF THE CYCLIC WITHSTAND CAPABILITY FOR THE EQUIPMENT DESIGNER. There are so many variations which can occur in service that the information must be relatively easy to understand and use.

1) The information must be presented in such a manner that it is not unduly conservative and hence result in uneconomic designs or pose protection problems.

2) It should also be easy for the designer to equate the information to his particular application.

One way of achieving this is to present fuse characteristics as shown in Fig.6.

In order to take full advantage of the information the equipment designer must first decide on what is a reasonable service life for the fuse and then from a knowledge of the duty cycle, determine how many cycles the fuse will experience during its service life. Then using Fig.6 it is a relatively easy matter to determine, as a function of rated current, the highest pulse the fuse can withstand.

CONCLUSIONS The proposed method of conducting an accelerated cyclic load test should be useful for both the fuse manufacturer and the equipment designer. Using Laboratory test results that can be obtained relatively quickly it enables the life expectancy of a fuse to be predicted for a given cyclic pulse duty.

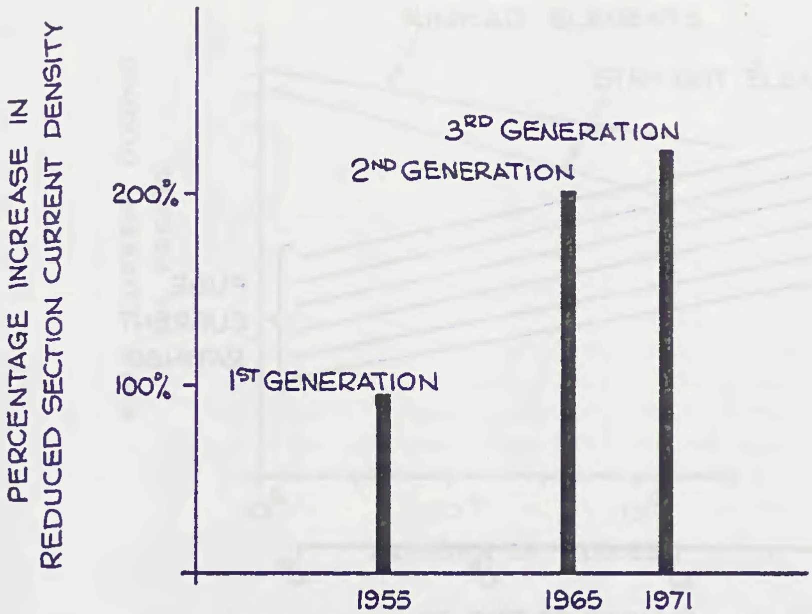
From a knowledge of the element designs for a range of various current ratings, it is possible to construct a family of life characteristics.

A more precise method than the existing empirical rules for selecting fuses to withstand cyclic loading conditions is outlined. Presenting the cyclic withstand characteristics for a range of fuses as shown in Fig.6 allows the equipment designer more scope and flexibility.

Although the withstand characteristics are nominally based on equal ON and OFF times, tests have been conducted with varying OFF times which demonstrate that for practical purposes allowances can be made for these effects.

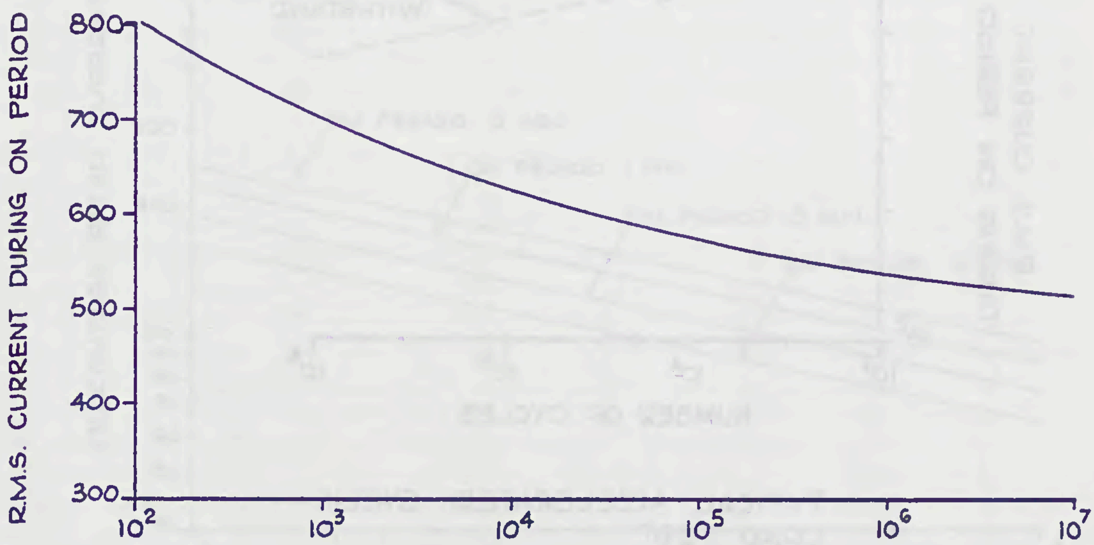
REFERENCES

"The Technological Development of the H.R.C. Fuse" J. Feenan - Liverpool Polytechnic, International Conference on Electric Fuses and their Applications. April 1976.



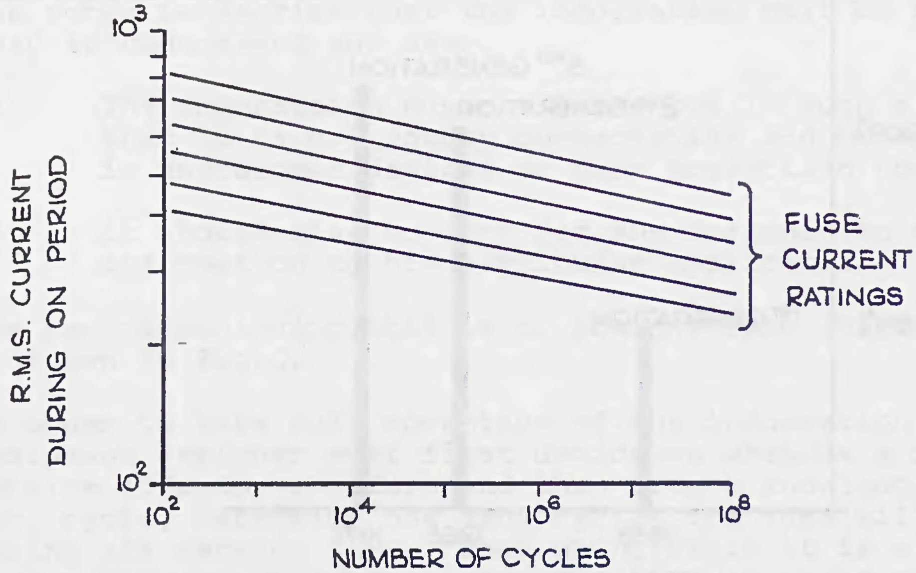
HISTORICAL DEVELOPMENT
OF HIGH SPEED FUSES

FIG. 1



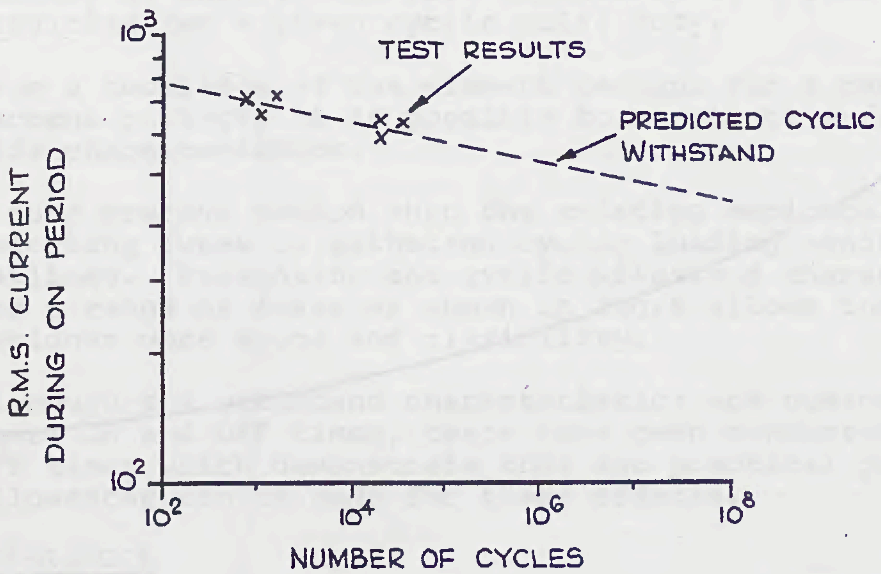
TYPICAL CYCLIC WITHSTAND CHARACTERISTIC
FOR A HIGH SPEED FUSE

FIG. 2



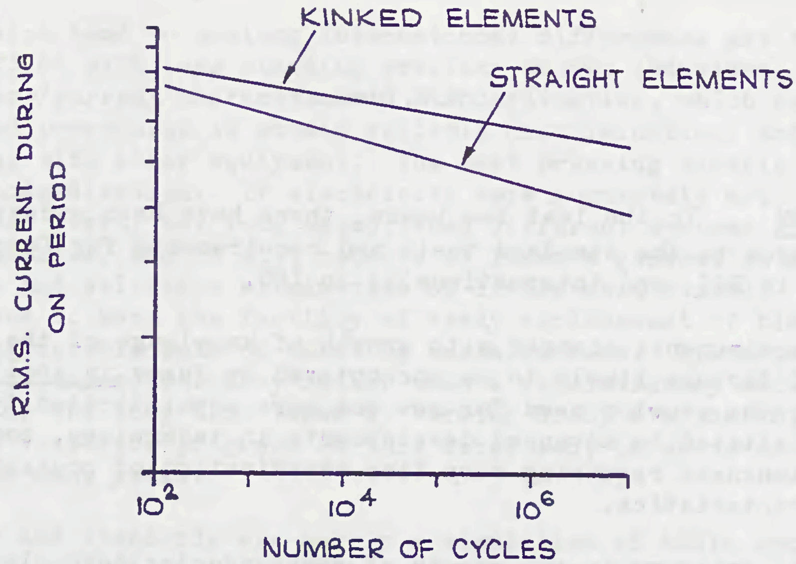
TYPICAL CYCLIC WITHSTAND CHARACTERISTIC FOR A RANGE OF ULTRA FAST ACTING FUSES

FIG. 3



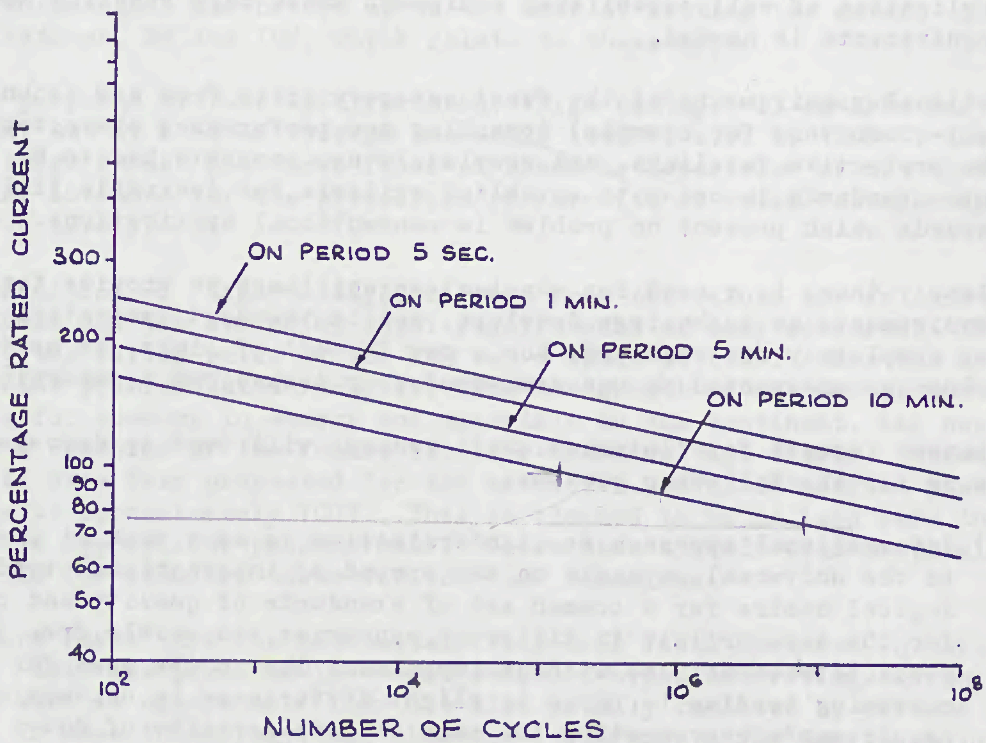
TYPICAL ACCELERATED CYCLIC LOAD TEST

FIG. 4



COMPARISON BETWEEN KINKED AND STRAIGHT ELEMENTS IN A GIVEN FUSE.

FIG. 5



PRESENTATION OF CYCLIC WITHSTAND CHARACTERISTICS

FIG. 6

FUSE TESTS AND STANDARDS

H.W.Turner

INTRODUCTION In the last few years, there have been widespread fundamental changes to the standard tests and requirements for fuselinks, both nationally in BSI, and internationally in IEC.

National requirements changed with growth of knowledge of the relative severity of factors likely to be encountered by fuses in application, and also due to the growing need for new and more sophisticated types of fuselink, necessitated by advanced developments in technology, combined with cost-consciousness requiring very fine coordination of protection and damage characteristics.

In the first category is the growth of semiconductor technology and in the second the new technology of cable rating.

Fuselinks which had proved their worth in trouble-free operation in service over many years are able to meet new tests of greater severity where these represent some newly discovered severity in actual service, because the fuses will have been exposed to that service already in large numbers without problem. There is great temptation to economise on protection, however, which could deteriorate into inherently unsafe practice. Thus additional testing to eliminate danger in new developments, and to give data for application of well established equipment under more exacting modern requirements is needed.

National requirements of the first category arise from new technology (of semi-conductors for example) demanding new performance characteristics for the protective fuselinks, and completely new concepts had to be incorporated into standards in order to establish criteria for desirable limitation of hazards which present no problem in conventional applications.

Clearly there is a need for constant surveillance to provide for such new requirements as technology develops, and in the next generation we may yet see completely new standards for a new 'breed' of links, to meet a technology as unexpected as was semi-conductor technology a generation ago.

Changes imposed for 'International' reasons will tend to decrease in future years for the following reasons:-

1) International approach to standardisation is at a peak at present due to the universal emphasis on the spread of international trade, and the logical desire for a common set of standards of quality and performance for the same article in different countries, to enable free flow of goods between nations without impediment due to the need for time-consuming testing to prove to slight differences in conventional requirements representing the same extreme severity of duty.

2) Eventually, the philosophy of testing can become the same in all countries, except for specified special test to cover extreme applications (e.g. in tropical or arctic conditions). National Standards bodies will follow the decisions made in International meetings, merely translating

the requirements to meet local needs with as few variations in testing procedure as is possible.

Factors which tend to prolong International differences are those which would conflict with long standing practice in the individual countries, such as time/current characteristic standardisation, which related to established procedures to obtain reliable discrimination, and problems of interfacing with other equipment. The most pressing example is dimensional standardisation. If electricity were completely new, this would be standardised first, but long established different systems exist in different countries, and it will require at least a generation (making no new dimensions and selective elimination of little used sizes). There is the primary need to have the facility of ready replacement of blown fuselinks in the considerable bulk of existing installations. Dimensional realignment is thus an evolutionary rather than a revolutionary activity, and accounts for the long time taken by Working Group 8 of SC32B, which makes steady but very slow progress in this direction, in spite of considerable effort over many years.

Fuse tests and standards are merely a simulation of their application, and in this paper we will classify the various types of fuselink available and indicate how tests and standards reflect the uses to which they are put.

MAIN CLASSIFICATION OF FUSELINKS It is convenient to classify fuselinks according to the three main subcommittees of IEC technical committee TC32:

High voltage fuses	(IEC SC32A)
Low voltage fuses	(IEC SC32B)
Miniature fuses	(IEC SC32C)

Fig. 1 summarises the main categories and their separate types, advantages and disadvantages, and brings up to the date of writing the detail of the specifications, BS and IEC, which relate to these types.

For the purposes of fuse specification, "High voltage" is an arbitrary division, set at a rated voltage exceeding 1000 V. a.c. or 1500 V. d.c. "Low voltage fuses" are those fuses of breaking capacities of not less than 2kA, intended for the protection of circuits of rated voltages up to the above levels.

This definition of "High voltage" differs from the values set in safety regulations and the differing legal requirements of many countries. For example, the wiring rules of the IEE set a limit at 650V. This was not a significant problem until recently, when the growth of the use of 660V circuits for economy in energy and materials on the continent, has necessitated a re-think of the future level of these voltage limits. Strong arguments have been presented for the extensive use of industrial power supplies at approximately 700V. This is claimed to be no less safe than 415V (with appropriate precautions). There have already been proposals before IEC for standard tests for the 660V fuselinks.

"Miniature Fuses" are the most extensively used fuses included in this survey. They are produced in a vast range of types and ratings (from 32mA) and are used in apparatus. They are also usually replaced by persons untrained in fuse technology, and thus the requirements for the fuseholders alone are so extensive that they merit a completely separate IEC publication (IEC Publication 257 (1968)) at present under revision to take account of new problems arising from the recent extension in the current ratings of the fuselinks in the corresponding IEC Miniature Fuse specification (IEC Publication 127 (1974)).

COMMON ASPECTS OF STANDARDS Nearly all fuses contain fusible metal elements which open the circuit in which they are inserted, by fusion, when the current has exceeded a given value (the minimum fusing current) for a sufficient time. The fuse comprises all parts that form the complete switching device.

The only type of fuse considered by these committees that does not fit this description is the so-called 'thermal fuse', dealt with by IEC 32C, and briefly described later in this paper.

Consequently it is possible to use a common set of definitions for most fuse components and general terms, and the reader is referred to section 2 of any of the IEC recommendations referred to in Fig. 1, or to IEC Publication 291 (1969) Fuse Definitions.

All the types have standards which have the object of establishing the characteristics of the fuses or their parts in such a way that accurate replacement is facilitated. Characteristics are presented with reference to rated values, insulation, temperature rise in normal service, power loss, time/current characteristics, and effectiveness in clearing short circuits, in all the standards.

In the detail of the specifications however, the difference in requirements and capabilities of the various types become apparent, and this is best illustrated by considering some of the more important clauses of each specification in turn.

BREAKING CAPACITY TESTS These vary most of all between the various specifications, because differences in supply voltage and circuit severity appear across the fuse terminals only when the element has melted, the potential difference before that time being the same at all supply voltages, and equal to the product of current and fuse resistance.

As an illustration tables for the most general types are given for high voltage fuses in Table 1, and for low voltage fuses in Table 2.

There are other special breaking capacity tests for expulsion fuses, domestic fuses, miniature fuses, semi-conductor fuses etc., but the tables illustrate the general principles applied to all breaking capacity tests.

Important regions included in such tables are maximum breaking capacity (test duty 1 in Tables 1 and 2), tests at maximum arc energy (test 2) and tests at small overcurrent (test 3 in Table 1; tests 3, 4, and 5 for l.v. fuses in Table 2). In every case the maximum breaking capacity is tested at the most severe repeatable condition. This test is set at a given making angle (30° ± 5°) for miniature fuses only, because so many fuses are tested, and repeatability is impostant. For h.v. and l.v. fuses however, where fewer fuses are tested, the more difficult arcing angle is specified

TIME/CURRENT CHARACTERISTICS AND I^2T Time/current data are required for every fuse, but the degree of specification and the tests required to obtain them are different.

The h.v. fuse specification requires the manufacturer to provide them, but does not specify how they are to be obtained, the test conditions, or what the method should be.

The l.v. fuse specifications require 'time/current zones' to be verified, where the lowest curve is the minimum pre-arcing time (i.e. the minimum time/current characteristic in normal parlance). The upper limiting curve is the total operating characteristic (i.e. includes the arcing period). Detailed specifications do not exist for the test methods for obtaining these curves (i.e. circuit conditions, voltage, etc.) except a vague statement that they can be verified from the breaking tests. Study of Table 2 shows that this would not define a full time/current curve.

Test rigs also produce somewhat different shapes of characteristic, compared with the variety of fuseholders.

The sensitivity of semi-conductor fuses to point-on-wave requires a symmetrical closing angle.

The miniature fuses specification is much more clearly defined. The test points are pre-arcing values only, and are to be determined with d.c. at constant current. Actual pre-arcing times on a.c. may be considerably different from those checked in the standard test. This is due to low thermal inertia of the element, and Peltier and similar effects.

CONVENTIONAL TESTS Tests in standards are conventional tests, i.e. tests made in a repeatable manner, which simulate practical conditions. Other tests (notably the many different temperature rise tests) could be quoted as examples of the danger of reading too much precision into conventional test results.

However, such conventional test conditions are essential, in order that tests in different test stations are comparable, and that like products can be compared with each other, for standardisation purposes.

Knowing the effect of location of the fuse and circuit severity on the direction of deviation, the user can make his own allowances for special conditions of his installation.

HIGH VOLTAGE FUSES Tests and standards are now separately specified for the two main types. These are non-current limiting fuses and current-limiting fuses.

The non-current limiting fuse, or 'expulsion fuse', behaves differently during its arcing operation to most of the other types. There is more than one version of this type of fuse, widely used internationally. The least expensive is an easily rewired version, popular in remote districts, where economy is needed, and covered by BS 2692, 1956. A more sophisticated version is available in the USA in a number of types. This second type is more closely covered by IEC Publication 282 - 2. During the operation of these fuses the extinction of the arc is within a tube of gas-evolving material, and there is often a display of flame and noise, which would usually only be acceptable outdoors. In IEC 282 - 2, Class I has better insulation level or dielectric properties than Class II, a higher breaking capacity and higher maximum rated currents. Class II has replaceable fuse-links. Class I is recommended for the protection of large transformer banks, voltage transformers and important power factor correction banks, whereas Class II is applicable to protection of small transformers, smaller power factor correction banks, or for sectionnalising the circuit on outdoor open wire power distribution systems.

These differences are reflected in two different sets of complicated breaking capacity tests.

The current-limiting fuse is covered by IEC 282 - 1 (1974), which is very closely parallelled by BS 2692 (1975).

There are three levels of breaking capacity, identified above, and shown in Table I. With a powder filled fuse it is more reliable to predict a region of maximum arc energy at reduced prospective current where the instantaneous current at the instant of arcing is between 0.85 to 1.06 times the rms value of the test current. (Making at an angle of 0° -20° after voltage zero).

The most controversial feature of the breaking capacity tests of IEC 282 - 1 is the specification of a test voltage below rated voltage for breaking capacity tests 1 and 2. The test voltage is reduced to 87% of rated voltage, on the argument, that in three-phase systems they will not be subjected to the highest line-to-line voltage, because two fuses in series would share this voltage. This is a principle that is still strongly challenged from several quarters.

On single-phase use, fuselinks with a voltage rating equal to 115% of the highest single-phase circuit voltage have to be employed.

The problem of a double earth fault on a three-phase unearthed system with a fault on the supply side of the fuse simultaneously with a fault on the load side, is clearly not covered.

Test duty three is expensive and time consuming, but is necessary, because many h.v. fuselink designs are back-up fuses. This helps the user to ensure that the circuit protected by the fuse is interrupted by some other associated device at currents between rated current and minimum breaking current. This test must be performed at full rated voltage, and a fuse is not considered to be 'general purpose' unless the time, corresponding to minimum breaking current is at least one hour.

As with low voltage fuses, attempts are still being made, to standardise dimensions. The same problems exist as in the l.v. case, and the solution emerging is similar.

Time/current characteristic standardisation is also proceeding, but with some difficulty. Unlike low voltage fuses, where common standards for time/current characteristics are now established world-wide for fuselinks of rated currents above 100A, it has been found necessary for h.v. fuses to have different characteristics, particularly in the centre of the time/current range.

For motor protection, where the 'take-over' of other switching devices is involved, a vertical (almost constant current) time/current characteristic is preferred.

For transformer protection a 45° slope is needed (i.e. practically constant I^2t).

<u>Low Voltage Fuses</u> One general type cannot be used for all applications because of the conflicting requirements of protection in different realms

of application - e.g. industrial, domestic and similar purposes, semi-conductor protection. This is recognised in IEC 269 by the existance of 4 separate publications, IEC 269 - 1 which sets out the general tests and requirements necessary for all low voltage fuses, and IEC 269 - 2, 269 - 3, and 269 - 4 which are specialist parts dealing respectively with Industrial fuses, domestic fuses and semi-conductor protection fuses.

Some countries combine Industrial fuselinks of the equivalent to the British BS 88 type with domestic fuselinks for the protection of conductors at the supply point. This clearly has difficulties of compromise, which are evident in the break in the continuity of the shape of the fuselinks in GI characteristics of IEC 269 - 2 at 100A.

Comparatively, the GII (British type) characteristic has a smooth transition, largely because of the existance of the specialised industrial fuselinks to BS 88 and the separate tests in BS 1361 to meet special 'domestic' requirements.

IEC 269 - 3 also covers the tests for the type of fuselink used in plugs in the UK, (the BS 1362 fuselink). The significant difference in the tests for this fuselink is the absence of the low power factor in the Test duty 2 test, since such a highly inductive low level of short circuit is not met in domestic situations when connected by a flexible lead in a plug or spur box.

Mention has been made elsewhere of the difficulties of dimensional standardisation, and to reduce the proliferation, a supplement to 269 - 3, 269 - 3A (1974), has been issued which requests all countries to keep to existing nationally standardised systems until it becomes possible in the distant future to introduce a world wide acceptable unified system.

Low voltage back-up fuses of the type aM are included in IEC 269 - 2 for industrial use. These should not be confused with the general purpose fuse element in a small size barrel used for a similar type of purpose in the UK and referred to as a 'motor-rated' fuselink.

MINIATURE FUSES These are covered by IEC publication 127 (1974) and BS 4265 in fuse holders to IEC publication 257 (1968). Since these fuselinks are well down the chain of protection backed up by low voltage fuses, and mcb's at the end of the flexible cable connection, the prospective short circuit current is quite low. Maximum breaking capacity tested is set by IEC to be 2 kA at 250V a.c. (although some designs are capable of much higher breaking capacities - power factor minimum 0.7).

International standardisation is needed for these fuses more than for other types, because equipment fitted with miniature fuselinks crosses frontiers in multi-million quantities annually, and such equipment needs replacement fuselinks locally in its new home.

The fuselinks are also available in glass (transparent) barrels unfilled, and the maximum breaking capacity then tested is 35A or $10I_n$ (whichever is the greater), at unity power factor and 250V a.c.

The latter fuselinks should not be placed in circuit locations where the prospective current is greater. This has caused some controversy in recent years when the current ratings exceeding 2A were introduced in the 5mm x 20mm size.

Since only two sets of dimensions are specified, the marking clauses of these fuses are important, for all types in a given barrel size are physically interchangeable but electrically non inter-changeable. These fuselinks are tested in greater numbers than any other type of fuselink, and the manufacturer is required to supply 48 fuselinks of every rating when submitting samples for type testing (4 extra are required for time delay fuselinks which additionally are tested for one hour at 70°C carrying a multiple of the rated current).

Time/Current Characteristics of Miniature Fuses A way out of this problem is at present being considered by a special working group (WG4) of IEC 32C.

This working group is seeking to divide the operating range into up to 5 bands of time/current and to classify fuses as FF (very quick acting) F (quick acting) M (medium time lag) T (time lag) and TT (long time lag) according to which of these bands they 'fit'.

With small fuse ratings the element is often scarcely visible to the naked eye, and precision, particularly in a complicated construction, is not necessarily as great as that attainable with elements of much bigger dimensions.

In addition there are considerable differences in the philosophy of rating etc. in different countries, with an identical fuselink being assigned a higher current rating in USA, for example, than in Europe.

When agreement is reached on this fundamental issue, there will be a considerable step forward in the value of the fuselinks tested to these standards, world wide.

Thermal Fuses These devices are not fuses in the strict sense of the IEC definition, because they are not designed to be fused by the action of the current passing through them (although they may do so in exceptional overload conditions) but operate when they reach a critical temperature, due to fusion of some component of the thermal fuse by the surrounding heat. They can consist of tiny switches held close by a pellet of low fusing material, conductors of low fusing metal or other such constructions. In IEC these are being considered by a special working group (No. 2) for a specification for tests of thermal fuses for use in applications where temperatures of a dangerous or hazardous value have been caused by some defect within apparatus.

Capacitor Protection This is not a great problem with h.v. fuses, but problems of application do arise with h.v. fuses, and a special working group of SC32A (WG4) has evolved special tests for this purpose which are nearing the issue of standard recommendations.

Semi Enclosed Fuses These rewirable fuses for l.v. are still very extensively utilised in the UK, and appear to be quite adequate for any circuit where the prospective short circuit current is low and the power factor not too low. They are cheap and easy to renew and do not appear to be unsatisfactory except when misused e.g. by over-wiring or placing in locations where the short circuit level exceeds this breaking capacity comparatively speaking, they are relative to the high breaking capacity low voltage fuse, as the expulsion fuse is relative to the h.v. current limiting fuse, and equally well can expect application in the UK for some considerable time yet, although specifically excluded from IEC 249 - 1 and

BS 88 (1975). However, a British Standard BS exists which gives a comprehensive series of tests for these fuses, and strict adherence to its requirements ensures that the above remarks on adequacy remain true in modern applications.

It should be remembered, as with expulsion fuses, that these are a coarser and more variable form of protection than the sand filled cartridge fuse and suitable allowance made in their use.

Concluding Remarks The tests required in the standards of testing become more and more complicated and extensive with time, largely because of the final control required for close economical protection demanded increasingly today on the one hand, and the demands made by technology on the other. The lesson can be learned from the use of some standards however that if the testing becomes too expensive, the standard could drop out of use with disadvantage to user and manufacturer alike, and thus the standards engineer must set tests which are both searching, well matched to the application, and inexpensive to perform. Although it is impossible to meet all these contradicting criteria, an optimum choice between them has to be made.

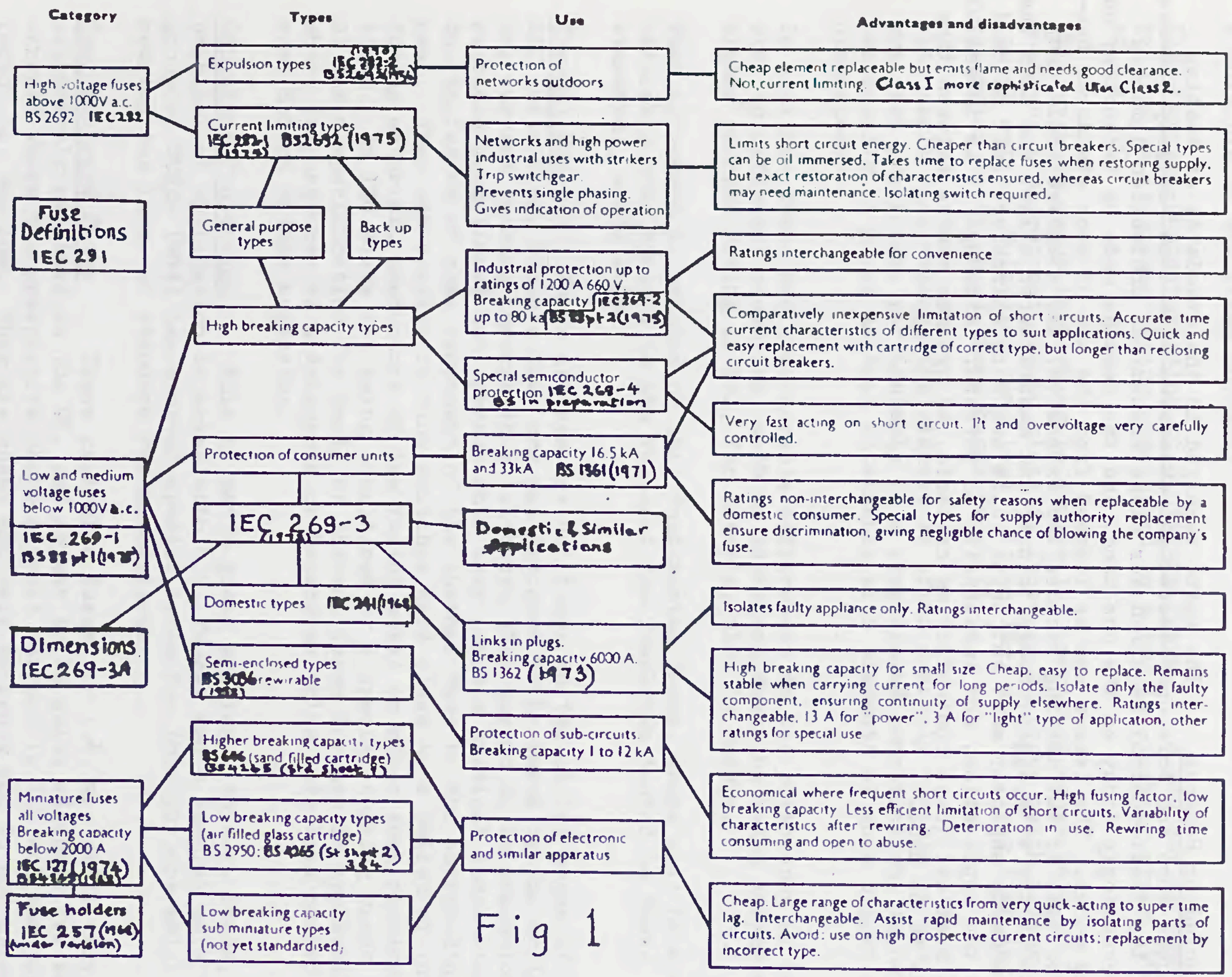

Category
Types
Use
Advantages and disadvantages
High voltage fuses above 1000V a.c. BS 2692 IEC282
Fuse Definitions IEC 291
Low and medium voltage fuses below 1000V a.c.
IEC 269-1 BS88 pt1(1975)
Dimensions IEC269-3A
Miniature fuses all voltages Breaking capacity below 2000 A IEC 127(1974)
Fuse holders IEC 257(1968) (under revision)
Expulsion types IEC282-2 (1970) BS2692(1956)
Current limiting types IEC 282-1 (1974) BS2692 (1975)
General purpose types
Back up types
High breaking capacity types
Protection of consumer units
IEC 269-3 (1973)
Domestic types IEC241(1968)
Semi-enclosed types BS3036 rewirable (1958)
Higher breaking capacity types BS646 (sand filled cartridge) BS4265 (Std Sheet 1)
Low breaking capacity types (air filled glass cartridge) BS 2950: BS4265 (St sheet 2) 3&4
Low breaking capacity sub miniature types (not yet standardised)
Protection of networks outdoors
Networks and high power industrial uses with strikers
Trip switchgear.
Prevents single phasing.
Gives indication of operation
Industrial protection up to ratings of 1200 A 660 V. Breaking capacity up to 80 kA IEC269-2 BS88 pt2(1975)
Special semiconductor protection IEC 269-4 BS in preparation
Breaking capacity 16.5 kA and 33kA BS 1361(1971)
Domestic & Similar Applications
Links in plugs. Breaking capacity 6000 A. BS 1362 (1973)
Protection of sub-circuits. Breaking capacity 1 to 12 kA
Protection of electronic and similar apparatus
Cheap element replaceable but emits flame and needs good clearance. Not current limiting. Class I more sophisticated than Class 2.
Limits short circuit energy. Cheaper than circuit breakers. Special types can be oil immersed. Takes time to replace fuses when restoring supply, but exact restoration of characteristics ensured, whereas circuit breakers may need maintenance. Isolating switch required.
Ratings interchangeable for convenience
Comparatively inexpensive limitation of short circuits. Accurate time current characteristics of different types to suit applications. Quick and easy replacement with cartridge of correct type, but longer than reclosing circuit breakers.
Very fast acting on short circuit. I²t and overvoltage very carefully controlled.
Ratings non-interchangeable for safety reasons when replaceable by a domestic consumer. Special types for supply authority replacement ensure discrimination, giving negligible chance of blowing the company's fuse.
Isolates faulty appliance only. Ratings interchangeable.
High breaking capacity for small size. Cheap, easy to replace. Remains stable when carrying current for long periods. Isolate only the faulty component, ensuring continuity of supply elsewhere. Ratings interchangeable, 13 A for "power", 3 A for "light" type of application, other ratings for special use
Economical where frequent short circuits occur. High fusing factor, low breaking capacity. Less efficient limitation of short circuits. Variability of characteristics after rewiring. Deterioration in use. Rewiring time consuming and open to abuse.
Cheap. Large range of characteristics from very quick-acting to super time lag. Interchangeable. Assist rapid maintenance by isolating parts of circuits. Avoid: use on high prospective current circuits; replacement by incorrect type.

Fig 1

TABLE I

Parameters	Test duties		
	1	2	3
Power-frequency recovery voltage	(0.87 × rated voltage) $^{+5}_{0}$ %		Rated voltage $^{+5}_{0}$ %
Prospective TRV characteristics	See Sub-clause 13.1.2		Not specified
Power factor	Not higher than 0.15 See 1 below		0.4 to 0.6
Prospective current (r.m.s. value of the a.c. component)	I_1 $^{+5}_{0}$ %	I_2	I_3 $^{0}_{-10}$ % See 2 below
Instantaneous current at initiation of arcing	Not applicable	From 0.85 I_2 to 1.06 I_2	Not applicable
Making angle	Not before voltage zero	From 0° to 20° after voltage zero	Random timing
Initiation of arcing after voltage zero	*For one test:* From 40° to 65° *For two tests:* From 65° to 90° See 3 below	Not applicable	Not applicable
Maintained voltage after breaking (See 4 and 5 below)	Not less than 15 s	Not less than 60 s	
Number of tests	3	3	2

1. To answer this specification, the circuit should not be adjusted with resistors to obtain any specified value within the tolerance.
2. When testing station limitations prevent the maintenance of constant current, the tolerance on the current can be exceeded in either direction during not more than 20% of the total melting time, provided that the current at the initiation of arcing is within the tolerance specified for test duty 3.
3. Since the operating conditions can produce a wide variety of stresses on the fuse and as the breaking tests are intended in principle to produce the most severe conditions mainly as regards the arc energy and the thermal and mechanical stresses for this value of current, it is recognized that these conditions will be practically obtained at least once, when making the three tests indicated.
4. For fuses which are subject in service to the recovery voltage for a time less than 1 s, the maintained voltage period after operation will be 1 s.
5. The initial value of the power-frequency recovery voltage shall be equal to the specified value, but when testing limitations prevent the maintenance of constant voltage, the maintained voltage may drop to 15% below the specified value.

TABLE II

Values for breaking capacity tests for a.c.

		Test according to Sub-clause 8.5.5.1				
		No. 1	No. 2	No. 3	No. 4	No. 5
Power-frequency recovery voltage		110% of the rated voltage $^{+5\%}_{-0\%}$ *				
Prospective test current	For general purpose fuse-links	I_1	I_2	$I_3 = 3.2\ I_f$	$I_4 = 2.0\ I_f$	$I_5 = 1.25\ I_f$
	For back-up fuse-links	I_1	I_2	$I_3 = 2.5\ k_2\ I_n$	$I_4 = 1.6\ k_2\ I_n$	$I_5 = k_2\ I_n$
Tolerance on current		+ 10% − 0%	Not applicable	± 20%	+ 20% − 0%	
Power factor		0.2 - 0.3 for prospective test currents up to 20 kA 0.1 - 0.2 for prospective test currents above 20 kA	Same value as for test No. 1	0.3 - 0.5		
Making angle after voltage zero		Not applicable	$0\ ^{+20°}_{-0°}$	Not specified		
Initiation of arcing after voltage zero		For one test: 40°- 65° For two tests: 65°- 90°	Not applicable	Not applicable		

* This tolerance may be exceeded with the manufacturer's consent.

I_1: current which is used in the designation of the rated breaking capacity (see Sub-clause 5.7).

I_2: current which shall be chosen in such a manner that the test is made under conditions which approximate those giving maximum arc energy.

Note. — This condition may be deemed to be satisfied if the current at the beginning of arcing (instantaneous value) has reached a value between 0.60 $\sqrt{2}$ and 0.75 $\sqrt{2}$ times the prospective current (r.m.s. value of the a.c. component).

As a guide for practical application, the value of current I_2 may be found between three and four times the current which corresponds to a pre-arcing time of 0.01 s on the time/current characteristic.

I_3, I_4, I_5: the tests made with these test currents are deemed to verify that the fuse is able to operate satisfactorily in the range of small over-currents.

I_f: conventional fusing current (see Sub-clause 5.6.2) for the conventional time indicated in Sub-clause 8.4.3.3, Table VII.

k_2: see Figure 1, page 72.

OPTIMUM CONDITIONS FOR TESTING ELECTRICAL FUSES AT MAXIMUM PREARCING ENERGY

C.B.Wheeler

INTRODUCTION The occurrence of a serious fault in an electrical circuit energised by a power supply leads to the rapid accumulation of magnetic energy in the residual circuit inductance. If the supply is protected by a conventional fuse then this energy increases until such time that Ohmic heating in the solid fuse link is sufficient to cause melting. The link material subsequently constricts under the electromagnetic forces to form one or more arcs and the associated large increase in circuit resistance causes the fault current to fall rapidly to zero. The magnetic energy accumulated in the fault circuit before the fuse link disrupts is called the prearcing energy and it is subsequently dissipated in the circuit resistance as the current falls to zero during fuse disruption. For severe faults in a circuit protected by a quick-acting fuse the major resistance during this current cut-off phase is that associated with the disrupted fuse itself. However the current cut-off phase can be of sufficient duration for appreciable energy to be fed directly into the disrupted fuse from the power supply. Consequently the prearcing energy is usually the minimum energy that is dissipated in a fuse during the process of clearing a fault circuit. The duration of the cut-off phase is controlled by the magnitude of the fuse arc burning voltage in relation to the supply voltage. If this arc voltage is much greater than the opposing supply voltage then the current fall is very rapid and the total arc energy is equal to the prearcing energy. On the other hand if the arc voltage is equal to or less than the supply voltage, as for a fuse of insufficient voltage rating, then the current could rise after the prearcing phase, possibly leading to continuous arcing and failure to clear the circuit. The arc voltage is primarily determined by the fuse construction but is also considerably influenced by the circuit parameters during the cut-off phase. An increase in the length of the fuse link will increase the total arc voltage as will also its containment in a cartridge filled with a material that is efficient in arc quenching. The various functions performed by the filler material in the extinction process are discussed in a recent paper by Turner and Turner (1973). Baxter (1958) has measured the electrical

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energy dissipated in fuses undergoing short-circuit tests and has shown conclusively that the prearcing energy is approached as the length of the fuse link is increased for a given filler material and supply voltage.

The ability of a fuse to clear a fault circuit without the cartridge exploding or splitting is primarily determined by the energy dissipated within it. Each category of fuse manufactured is put through a short-circuit test to verify that it will safely contain the maximum energy likely to be encountered in the circuit it is intended to protect. Such testing is an iterative and therefore a costly procedure unless the test circuit parameters can be optimised beforehand so as to dissipate maximum energy within the fuse under test. The calculations here determine the fault circuit parameters required to maximise the prearcing energy and are therefore directly applicable to the testing of fuses exhibiting rapid cut-off. They also serve as convenient initial conditions for testing fuses for which the arc voltage is not significantly greater than the supply voltage. For D.C. power supplies Wheeler (1972) has located a maximum in the prearcing energy for a given fuse in a fault circuit of specified time constant and his analysis enables the optimum fault current and prearcing time to be evaluated. Consideration of A.C. power supplies introduces another variable into the fault circuit, namely the phase in the supply voltage cycle when the fault is applied, referred to as the closing angle. Boehne (1946) and Toniolo and Cantarella (1969) have studied the prearcing phase in circuits of power factor of 0 and 0.2 respectively. Their results enable the prearcing energy for a given fuse to be evaluated as a function of closing angle and fault current, however the possibility of a maximum is not considered. Wheeler (1973) has evaluated the maximum energy and associated cut-off currents for fault circuits of various power factors, all at zero closing angle. He points out that, for a given power factor, an overall maximum energy must exist for some optimum closing angle. Recently Wilkins and McEwan (1975a) evaluated this overall energy maximum and the associated optimum fault currents for circuits of selected power factors less than 0.5. This paper determines the overall maximum prearcing energy for all power factors together with the optimum values of fault current, closing angle, prearcing time and cut-off current. These parameters are conveniently expressed in units that enable application to any supply circuit and almost any fuse.

FAULT CURRENT WAVEFORM The fault circuit is characterised by its inductance L, and resistance R, however for fuse applications it is standard procedure to define the circuit by one parameter, namely by the time constant $\tau = L/R$ for the D.C. case and by the power factor $\cos\alpha = R/(R^2+\omega^2L^2)^{1/2}$ for the A.C. case, where ω is the angular frequency of the supply. During the prearcing phase the fuse link is transformed from the solid to the liquid state, necessitating an increase in fuse resistance. The change in total circuit resistance resulting from this process is usually very small and in the following analysis it is assumed that the parameters R and L do not vary during this phase. The fault current is characterised by the prospective current I_o, which is the amplitude of the current that would flow in the steady-state if the fuse link were replaced by a perfect short-circuit. If V denotes the D.C. supply voltage or the amplitude of the A.C. supply voltage then

$$\text{D.C.} \quad I_o = V/R, \qquad \text{A.C.} \quad I_o = V/(R^2+\omega^2L^2)^{1/2} \tag{1}$$

The time dependence of the fault current $I(t)$ can then be expressed in terms of I_o as follows

$$\text{D.C.} \quad I(t)/I_o = 1 - \exp(-t/\tau), \qquad \text{A.C.} \quad I(t)/I_o = \sin(\omega t+\beta-\alpha) - \sin(\beta-\alpha)\exp(-\omega t \cot\alpha), \tag{2}$$

where β is the phase angle in the supply voltage cycle when the fault occurs and time is measured from the occurrence of this fault. Figure 1 shows the current waveforms for power factors of 0.9 and 0.1 with closing angles β varying between 0° and 180°. For the particular case of $\beta=\alpha$ equation (2) shows that the transient term is zero and the peak fault current therefore equal to the prospective current. This is termed the case of symmetrical current and the closing angles $\beta=\pi/6$ for $\cos\alpha = 0.9$ and $\beta=\pi/2$ for $\cos\alpha = 0.1$ in Figure 1 are quite close to this situation. In general the approach to the steady-state is rapid for large power factors and slow for small power factors as required by equation (2) since the transient term becomes negligible for times such that $\omega t \gg \tan\alpha$. Also, for small power factors, the peak fault current in its initial stages can exceed the prospective current by up to a factor of two.

PREARCING TIME The fault current waveform is maintained until such time the sufficient Joule heating has taken place in the fuse link to disrupt it. If the heating takes place on a time scale that is much shorter than that required for significant heat loss from the link then the total Joule energy input up to the time of disruption can be equated to the thermal capacity of the link at its state of disruption.

$$\int_0^{t_p} J^2(t)\,dt = K. \tag{3}$$

$J(t)$ is the current density, t_p is the prearcing time and K a parameter that depends only on the physical properties of the link metal. Uniform current density is assumed, implying that the time-scale of the process is sufficiently long for skin effects to be negligible. In almost all applications of quick-acting fuses to conventional power systems the prearcing time falls within the upper and lower limits imposed by the above considerations. Morgan (1971) has given a very thorough account of the calculation of K for various metals following the technique proposed by Gibson (1941). Measurements of prearcing time for copper fuse links in power circuits by Baxter (1950) and Wheeler (1972) show that about 30% of the link metal must be transformed to the liquid state before current cut-off occurs. This condition requires the value $K = 9.5 \times 10^8\ A^2s\ cm^{-4}$ for copper and $K = 6.1 \times 10^8\ A^2s\ cm^{-4}$ for silver. If the link is of uniform cross-sectional area a then $J(t) = I(t)/a$

and equation (3) can be written in the following form

$$\text{D.C.}\quad I_o^2 = K\alpha^2/\tau \Big/ \int_0^{t_p/\tau} [I(t)/I_o]^2 \, d(t/\tau),$$

$$\text{A.C.}\quad I_o^2 = K\alpha^2\omega \Big/ \int_0^{\omega t_p} [I(t)/I_o]^2 \, d(\omega t). \tag{4}$$

Reference to equation (2) shows that, for a given fault circuit, the integrals here are only a function of t_p, τ or of t_p, α, β; implying that equation (4) is essentially a relation between prearcing time and prospective current. There is one type of fuse link, the notched link, that cannot be treated in this simple manner. For such a link the length of the constricted portion may not be sufficiently great for the neglect of longitudinal heat losses during the prearcing phase. This problem has recently been treated by Wilkins and McEwan (1975b).

<u>PREARCING ENERGY</u> The prearcing energy is the circuit inductive energy at the commencement of link disruption,

$$W = \tfrac{1}{2} L I^2(t_p). \tag{5}$$

If the inductance is expressed in terms of the circuit time constant or power factor then equations (1), (4) and (5) can be combined to give

$$\text{D.C.}\quad W/(V^2K\alpha^2\tau)^{1/2} = [I(t_p)/I_o]^2 \Big/ 2\left[\int_0^{t_p/\tau} [I(t)/I_o]^2 \, d(t/\tau)\right]^{1/2},$$

$$\text{A.C.}\quad W/(V^2K\alpha^2/\omega)^{1/2} = [I(t_p)/I_o]^2 \sin\alpha \Big/ 2\left[\int_0^{\omega t_p} [I(t)/I_o]^2 \, d(\omega t)\right]^{1/2}. \tag{6}$$

Reference to equation (2) shows that the right-hand-side of this equation is a function only of t_p and τ or of t_p, α and β. This means that the energy can be expressed either as a function of the prearcing time, or of the cut-off current using equation (2), or of the prospective current from equation (4). Figure 2 shows the D.C. prearcing energy expressed as a function of these three variables. The maximum energy and its optimum coordinates are

$$W = 0{\cdot}488(V^2K\alpha^2\tau)^{1/2}, \qquad t_p = 0{\cdot}943\tau,$$

$$I = 0{\cdot}611\, I_o, \qquad I_o = 2{\cdot}62\,(K\alpha^2/\tau)^{1/2}.$$

This maximum and the optimum current cut-off ratio have previously been evaluated by Wheeler (1972). Figures 3 and 4 show the A.C. prearcing energy expressed as a function of current cut-off ratio for the current waveforms depicted in Figure 1. Only the first current loops are presented and it is apparent that there is an overall maximum energy for a closing angle near $\beta=\pi/3$ for $\cos\alpha = 0{\cdot}9$ and in the vicinity of $\beta=0$ for $\cos\alpha = 0{\cdot}1$. These energies have been evaluated for all power factors by maximising equation (6) with respect to ωt and β simultaneously. Figure 5 shows the energy maxima together with the optimum closing angles and Figure 6 shows the optimum prearcing times together with the current cut-off ratios. The sum of the closing angle and the prearcing time is termed the arcing angle, which is simply the phase in the supply voltage waveform when cut-off begins. This angle is shown in Figure 7 together with the optimum prospective currents.

DISCUSSION The manner in which the supply voltage V and the fuse parameter Ka^2 enter into these calculations is interesting. Figures 2,5,6 and 7 show that V enters only into the prearcing energy whereas Ka^2 enters only into the energy and the prospective current. The remaining optimised parameters, namely the prearcing time ratio (t_p/τ or ωt_p), the closing angle and the current cut-off ratio, have values that are either fixed for the D.C. case or are functions only of power factor for the A.C. case. For given values of V and Ka^2 the important parameters for carrying out an A.C. short-circuit fuse test are the optimum closing angle of Figure 5 and the optimum prospective current of Figure 7. The prospective current varies smoothly between $0{\cdot}688(Ka^2\omega)^{1/2}$ for $\cos\alpha = 0$ and infinity for $\cos\alpha = 1$. However the closing angle shows an abrupt behaviour around $\cos\alpha = 0{\cdot}4$ where it departs from a constant value of zero and subsequently reaches $\pi/2$ at $\cos\alpha = 1$. The optimum prearcing time in Figure 6 exhibits a similar, less pronounced behaviour around $\cos\alpha = 0{\cdot}4$ but there is no analogous behaviour in the arcing angle of Figure 7 that is formed by summing these two quantities. This optimum arcing angle varies between $\pi/2$ and $2{\cdot}44$ radian, indicative of cut-off between circuit voltage maximum and 64% of this maximum on the falling voltage characteristic.

It must be emphasised that the prearcing energy only represents the total fuse energy dissipation if the supply voltage is very much less than the arc burning voltage. Under such conditions fuse testing need only be carried out in a D.C. circuit since the A.C. performance can then be assessed from the figures presented here.

REFERENCES

Baxter, H.W. 1950 Electrical Fuses, (London: Arnold).

Baxter, H.W. 1958 Electrical Times, 3rd July, 3-7.

Boehne, E W. 1946 AIEE Trans., 65, 1034-1045.

Gibson, J.W. 1941 J.IEE., 88, 2-24.

Morgan, V.T. 1971 Proc.IEE., 118, 555-570.

Toniolo, S.B. and Cantarella, G. 1969 IEEE Trans., PAS -88, 94-99.

Turner, H.W. and Turner, C. 1973 2nd International Symposium on Switching Arc Phenomena, 253-256. (Lodz, Poland).

Wheeler, C.B. 1972 J.Phys.D., 5, 133-140.

Wheeler, C.B. 1973 J.Phys.D., 6, 145-152.

Wilkins, R. and McEwan, P.M. 1975a, Proc. IEE, 122,285-288.

Wilkins, R and McEwan, P.M. 1975b, Proc. IEE, 122,289-292.

FIGURE CAPTIONS Figure 1. Current waveforms for power factors of 0.1, 0.9 and for various closing angles β (radian) within the voltage cycle.

Figure 2. Prearcing energy W for a D.C. circuit of time constant τ as a function of cut-off current I, prearcing time t_p and prospective current I_o.

Figure 3. Prearcing energy W for a circuit of power factor 0.9 and prospective current I_o as a function of cut-off current I and for various closing angles β (radian).

Figure 4. Prearcing energy W for a circuit of power factor 0.1 and prospective current I_o as a function of cut-off current I and for various closing angles β (radian).

Figure 5. Maximum prearcing energy W and optimum closing angle β (radian) as a function of circuit power factor $\cos\alpha$.

Figure 6. Optimum prearcing time t_p (ωt_p in radian) and optimum cut-off current I as a function of circuit power factor $\cos\alpha$.

Figure 7. Optimum prospective current I_o and optimum arcing angle $\omega t_p + \beta$ (radian) as a function of power factor $\cos\alpha$.

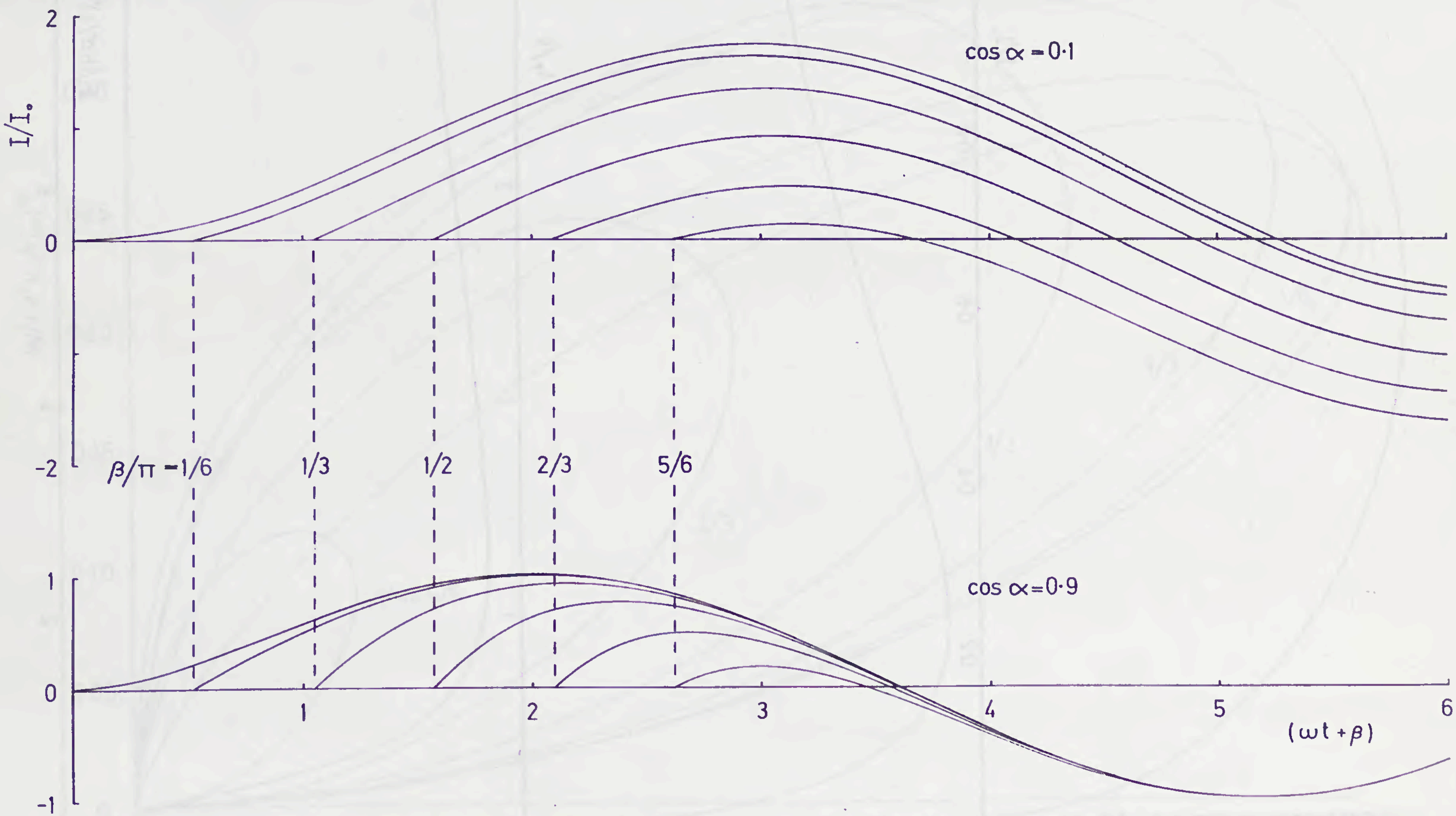


Figure 1.

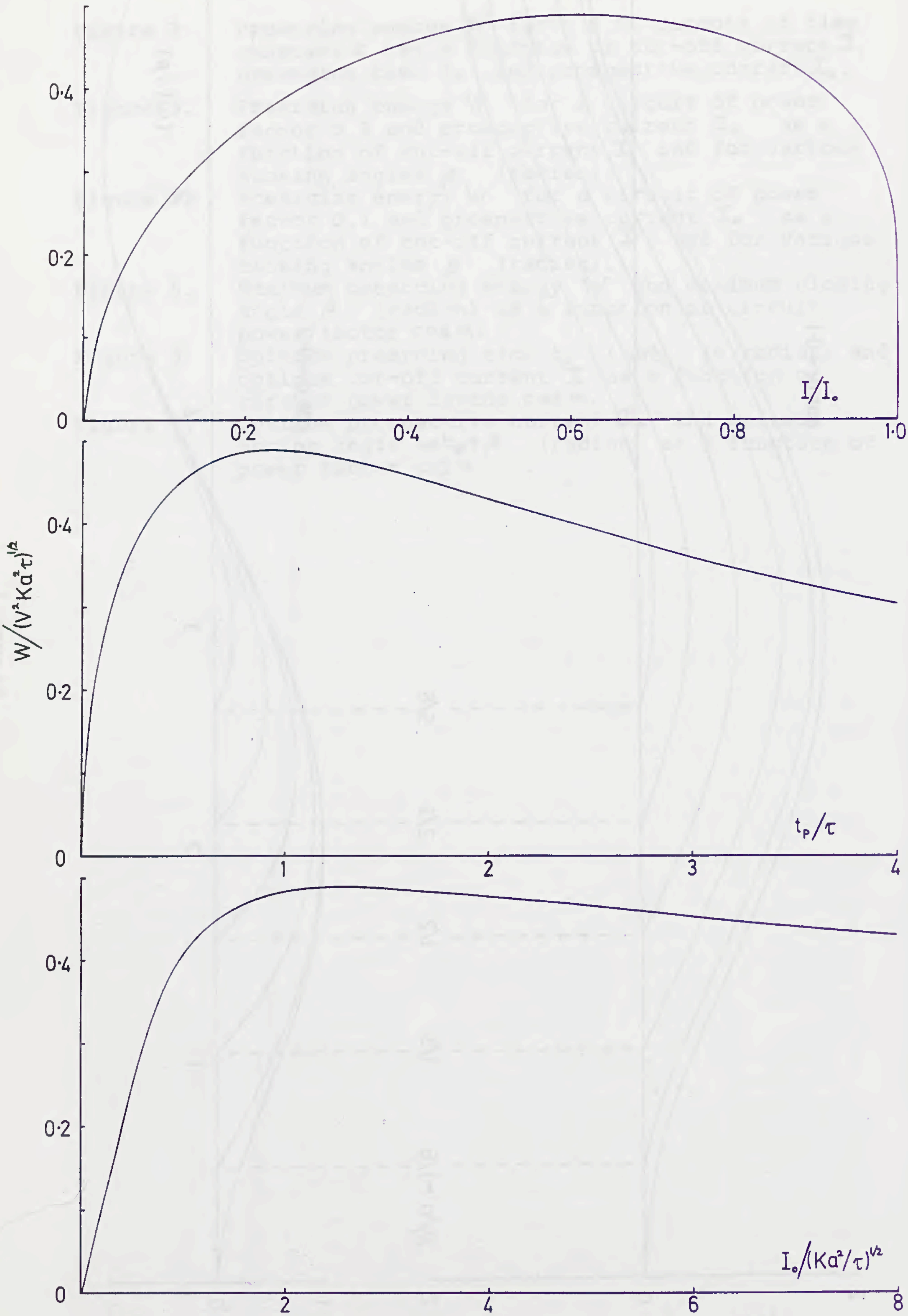

0·4
0·2
0
0·2
0·4
0·6
0·8
1·0
I/I₀
W/(V²Ka²τ)^½
0·4
0·2
0
1
2
3
4
t_p/τ
0·4
0·2
0
2
4
6
8
I₀/(Ka²/τ)^½

Figure 2

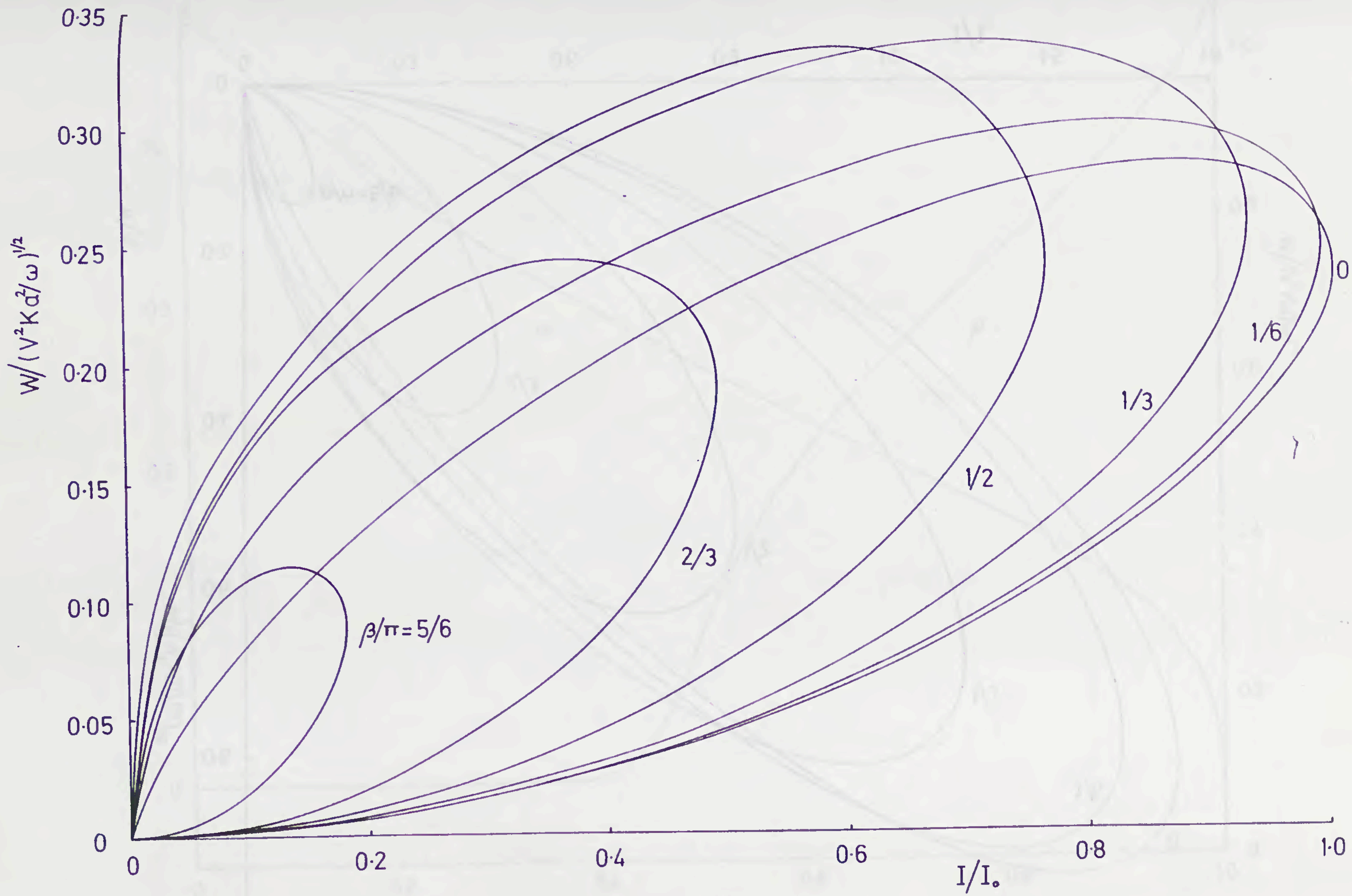

0·35
0·30
0·25
0·20
0·15
0·10
0·05
0
W/(V²Ka²/ω)^1/2
0
0·2
0·4
0·6
0·8
1·0
I/I₀
β/π = 5/6
2/3
1/2
1/3
1/6
0

Figure 3.

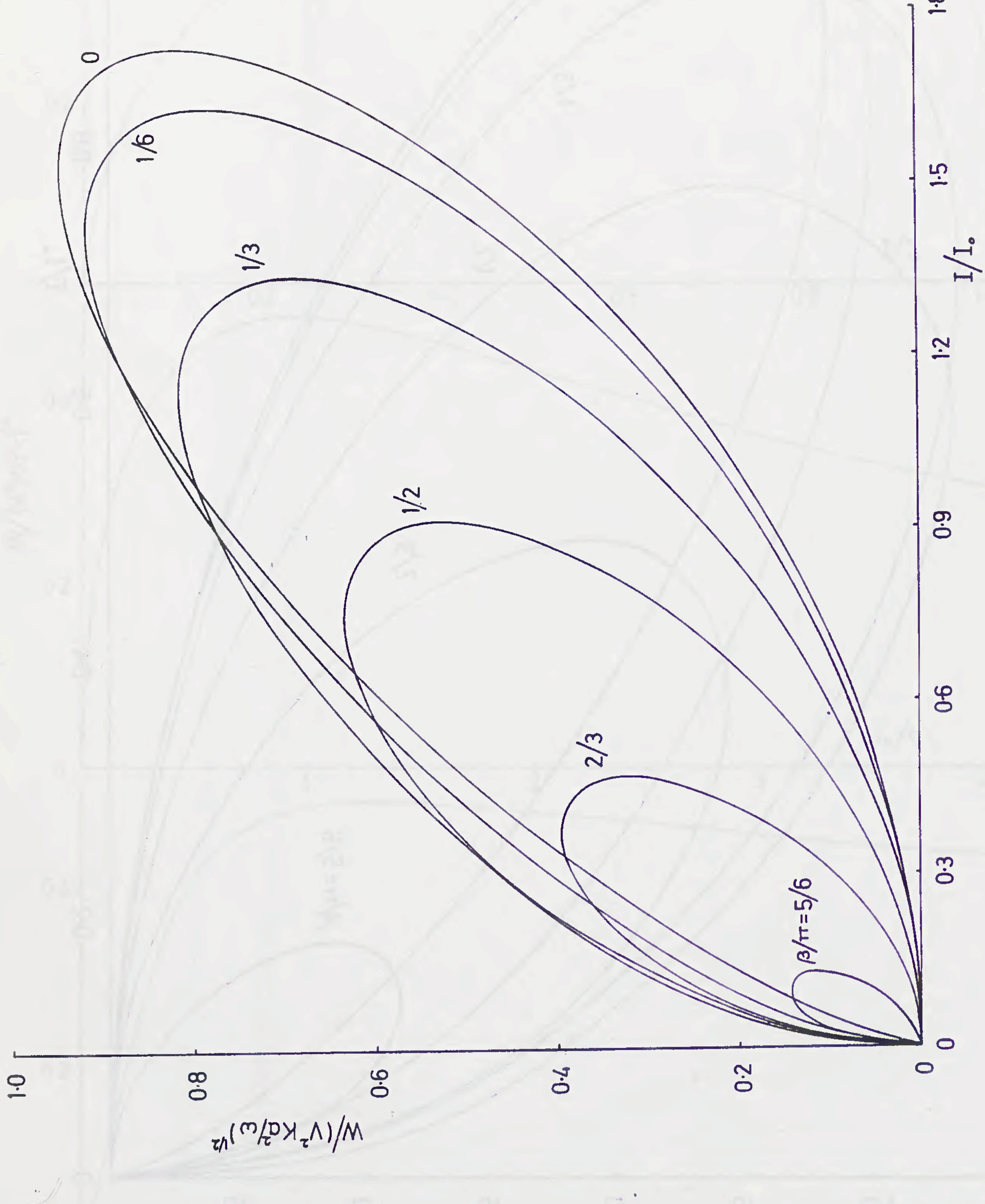


Figure 4.

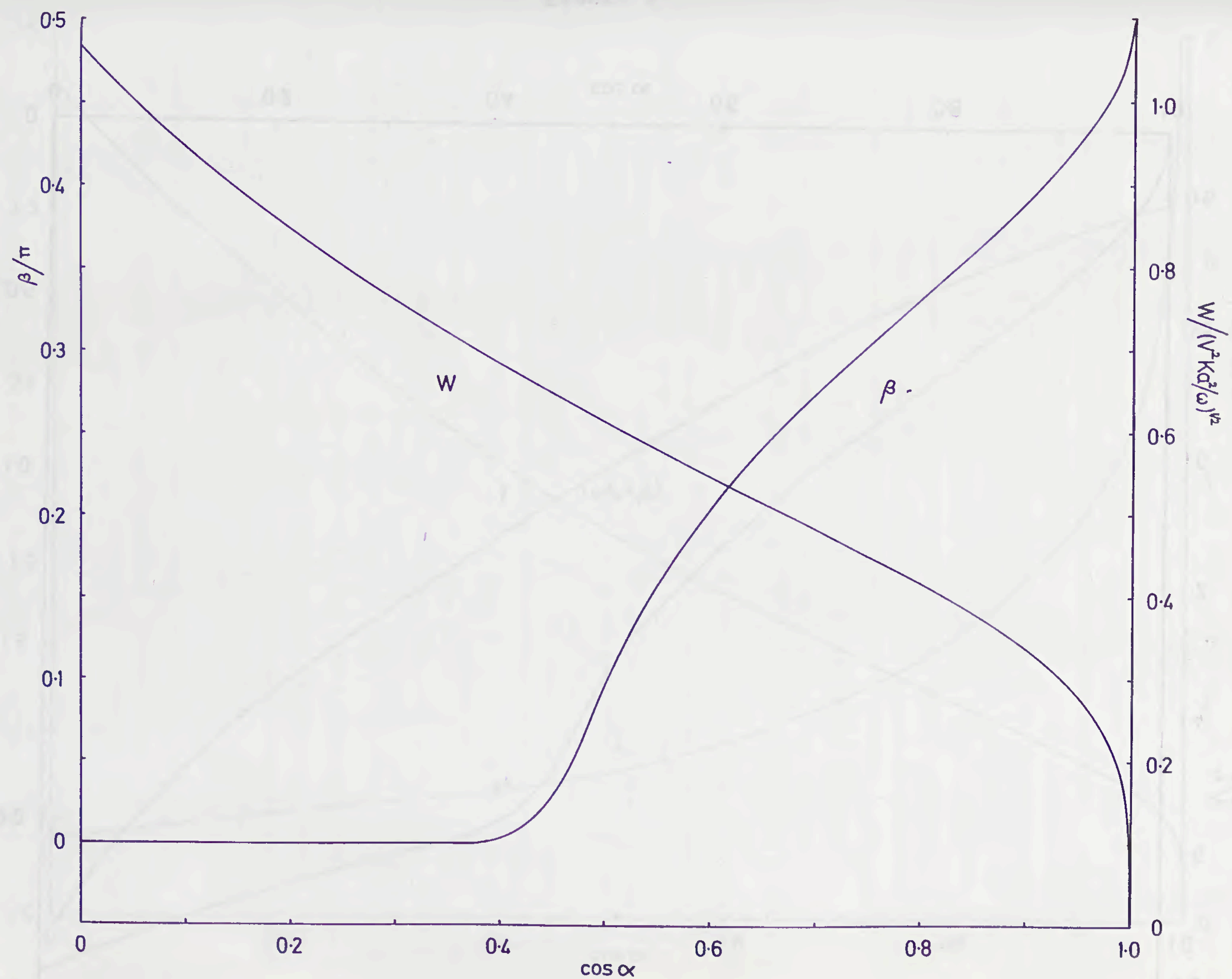


Figure 5.

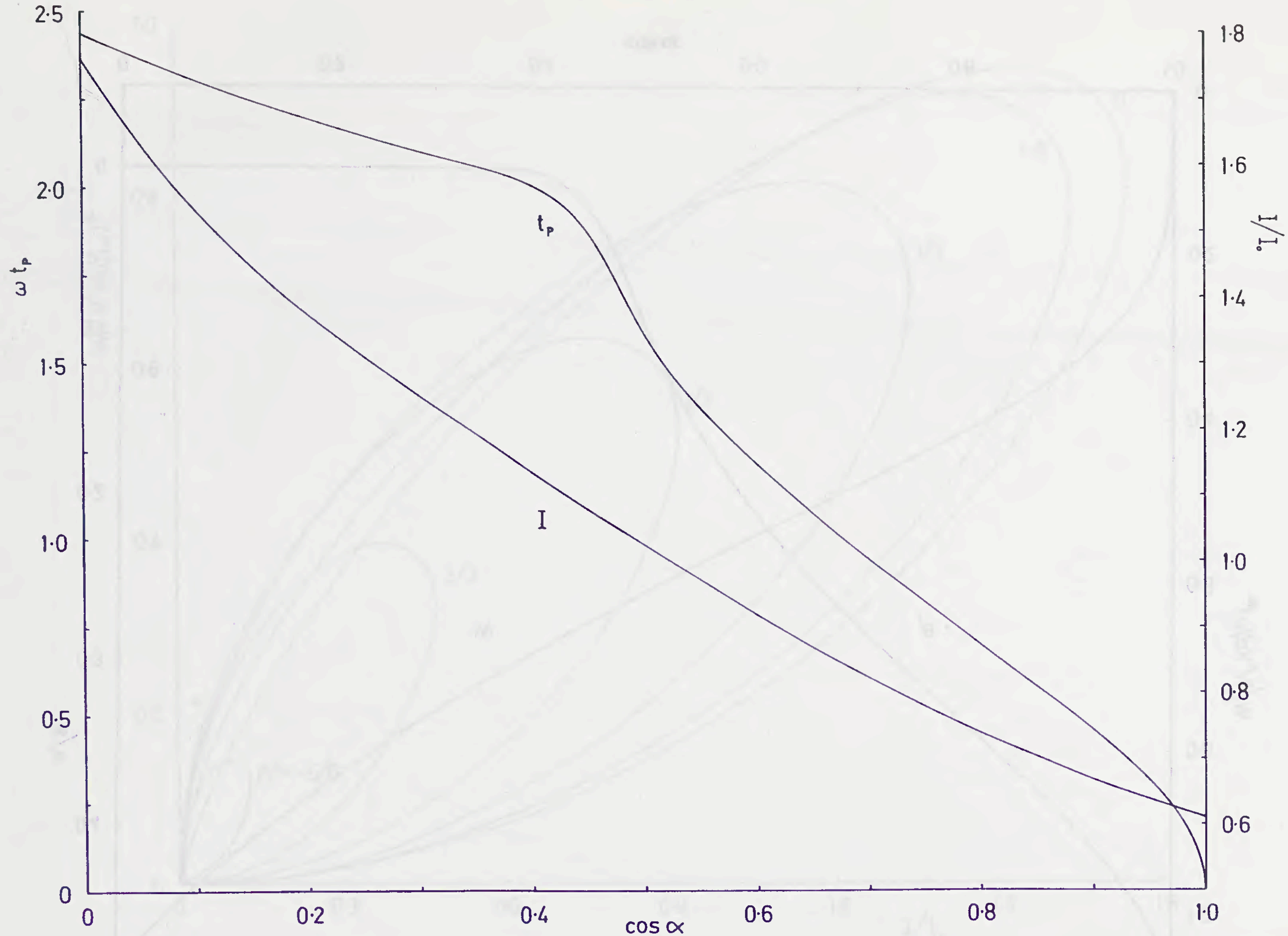
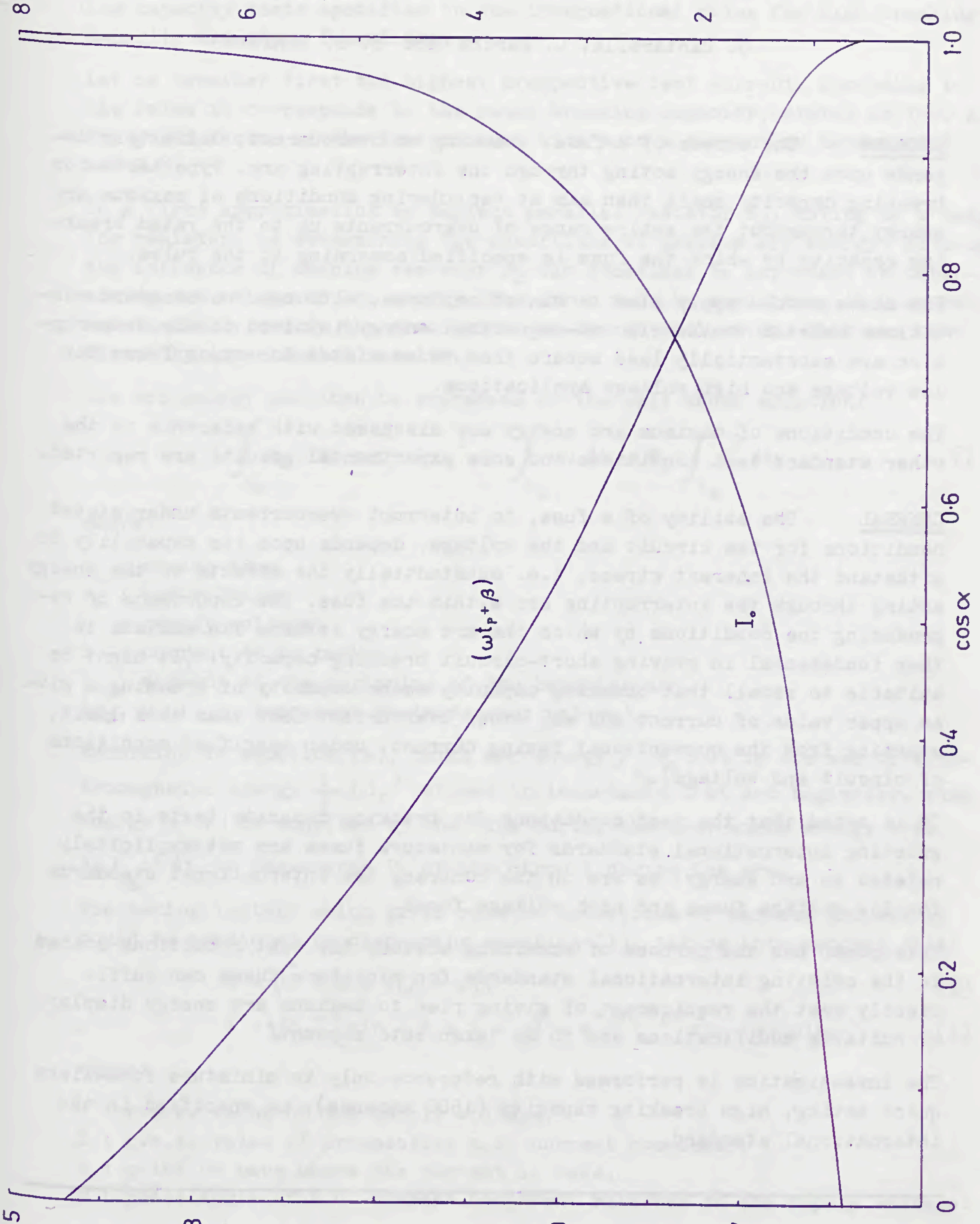

2·5
2·0
1·5
1·0
0·5
0
ωt_p
t_p
I
1·8
1·6
1·4
1·2
1·0
0·8
0·6
I/I₀
0
0·2
0·4
0·6
0·8
1·0
cos α

Figure 6.



I₀/(Ka²ω)^1/2
8
6
4
2
0
(ωt_p+β)
2·5
2·3
2·1
1·9
1·7
1·5
cos α
0
0·2
0·4
0·6
0·8
1·0
I₀
(ωt_p+β)

Figure 7

BREAKING CAPACITY TESTS FOR MINIATURE FUSES

G. Cantarella, G. Farina and S. B. Toniolo

SUMMARY The stress of a fuse, breaking an overcurrent, definitely depends upon the energy acting through the interrupting arc. Type tests for breaking capacity shall then aim at reproducing conditions of maximum arc energy throughout the entire range of overcurrents up to the rated breaking capacity by which the fuse is specified according to the rules.

The above should apply also to miniature fuses, although the standard conditions related to the electro-magnetical energy involved in the interruption are substantially less severe than those stated for major fuses for low voltage and high voltage applications.

The conditions of maximum arc energy are discussed with reference to the other standard test conditions and some experimental results are reported.

GENERAL The ability of a fuse, to interrupt overcurrents under stated conditions for the circuit and the voltage, depends upon its capability to withstand the inherent stress, i.e. substantially the effects of the energy acting through the interrupting arc within the fuse. The importance of reproducing the conditions by which the arc energy attains its maximum is then fundamental in proving short-circuit breaking capacity. (It might be suitable to recall that breaking capacity means capacity of breaking a given upper value of current and any other overcurrent less than this limit, starting from the conventional fusing current, under specified conditions of circuit and voltage).

It is noted that the test conditions for breaking capacity tests in the existing international standards for miniature fuses are not explicitely related to arc energy, as are on the contrary the international standards for low voltage fuses and high voltage fuses.

This paper has the purpose of examining whether the test conditions stated in the existing international standards for miniature fuses can sufficiently meet the requirement of giving rise to maximum arc energy display, or suitable modifications are to be taken into account.

The investigation is performed with reference only to miniature fuse-links quick acting, high breaking capacity (1500 amperes), as specified in the international standard.

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CONDITIONS OF MAXIMUM ARC ENERGY DEPENDING ON THE MAKING INSTANT FOR A GIVEN CURRENT TO BE INTERRUPTED Figure 1 shows the circuit for breaking capacity tests specified in the international rules for high breaking capacity miniature fuse-links.

Let us consider first the highest prospective test current. According to the rules it corresponds to the rated breaking capacity, stated in 1500 A. The power factor of the test circuit with such a current is between 0.7 and 0.8.

In a first approximation we neglect parallel resistor R_2, acting as a damping resistor, in determining the conditions of maximum arc energy. Although the influence of damping resistor R_2 can sometimes be important in determining the values of arc energy, the error made by neglecting it does not substantially modify the conclusions of the investigation. This was confirmed by experimental results.

The arc energy can then be expressed by the well known equation:

$$\int_{t_a} v_a\, i\, dt = \frac{1}{2} L i_o^2 + \int_{t_a} v\, i\, dt - R_1 \int_{t_a} i^2\, dt, \qquad (1)$$

where:

t_a : arcing time,
v_a : arc voltage,
v : supply voltage,
i : current to be broken,
i_o : current at the beginning of the breaking arc,
(v_a, v, i, i_o represent instantaneous values).

According to equation (1), total arc energy $\int_{t_a} v_a\, i\, dt$ is the sum of electromagnetic energy $\frac{1}{2} L i_o^2$ stored in inductance L at arc beginning, plus energy $\int_{t_a} v\, i\, dt$ supplied by the line during the arc, minus energy loss $R_1 \int_{t_a} i^2\, dt$ in resistance R_1 of the circuit during the arc.

The making instant which gives rise to conditions of maximum arc energy could be predicted by discussing equation (1), taking into account that:

$$v = \sqrt{2}\, V \sin(\omega t + \psi), \qquad (2)$$

$$i = \sqrt{2}\, I \left[\sin(\omega t + \psi - \varphi) - e^{-\omega t/\mathrm{tg}\varphi} \sin(\psi - \varphi)\right], \qquad (3)$$

where:

V : r.m.s. value of the supply voltage,
I : r.m.s. value of prospective a.c. current component,
ψ : point on wave where the current is made,
φ : phase angle of a.c. current component referred to the supply voltage.

The examination of equation (1) may become easier if some experimental results are taken into consideration.

A.c. tests were carried out in accordance with IEC rules as regards test circuit and voltage conditions. The making instants were distributed in the angular range $0 \div \pi$. By electronic computer the following quantities were determined in each test of each fuse-link:

- arc energy,
- pre-arcing and total joule integrals,
- peak value of test current,
- pre-arcing time,
- total operating time,
- making instant,
- diagrams of the breaking current and of the voltage across the fuse-link.

Figure 2 shows, as an example, typical behaviours of the breaking current and of the voltage across the fuse-link plotted in a test made at prospective current of 1500 A on a fuse-link rated 6.3 A.

In table 1 some values are reported, determined by tests carried out at 1500 A on quick acting, high breaking capacity, 5 mm x 20 mm, non transparent miniature fuse-link specified by rated currents of 500 mA and 6.3 A and rated voltage of 250 V.

Table 1

Fuse-link rated current amperes	Pre-arcing time milliseconds	$\int_{t_a} v_a\, i\, dt$ joules	$\frac{1}{2} L\, i_o^2$ joules	$\int_{t_a} v\, i\, dt$ joules	$R_1 \int_{t_a} i^2 dt$ joules
0.5 6.3	0.13 0.6	1.4 50	0.55 45	0.9 14	0.03 1.2

Values shown in table 1 correspond to making instants which approximate those giving rise to maximum arc energy. Obviously, energy values of table 1 do not satisfy equation (1), written by neglecting damping resistor R_2. However table 1 shows that the energy loss value $R_1 \int_{t_a} i^2 dt$ is negligible in comparison with the values of electromagnetic energy $\frac{1}{2} L\, i_o^2$ and of energy $\int_{t_a} v\, i\, dt$ supplied by the line during the arc.

A consequence is that the making instant which gives rise to maximum arc energy shall practically correspond to the making instant which leads to the maximum value the energy components $\frac{1}{2} L\, i_o^2$ and $\int_{t_a} v\, i\, dt$.

Let us consider first electromagnetic energy $\frac{1}{2} L\, i_o^2$. The prospective current of 1500 A is very high in comparison with the rated currents of miniature fuse links, which are all in the range 50 mA $\div$ 6.3 A. Therefore heating of fuse-link up to melting can be deemed to be adiabatic. Hence, pre-arcing joule integral $\int_{t_{pa}} i^2\, dt$ required for melting the fuse element at such a prospective current can be considered to be a constant, irrespective of the making instant.

On this basis, instantaneous value i_o, reached by the current to be broken at arc beginning, as a function of the making instant, can be calculated.

This was done and figures 3 (a) and (b) show the diagrams determined for fuse-links of 500 mA and 6.3 A rated currents.

Figures 4 (a) and (b) show similar diagrams, concerning experimental results of tests carried out on the same fuse-links.

In figures 3 and 4 it can be seen that current i_o at arc beginning is maximum for making instants ψ near to 90°. As a consequence, the electromagnetic energy $\frac{1}{2} L i_o^2$ attains its maximum value for a making instant close to 90°.

As regards energy supplied by the line during the arcing time, $\int_{t_a} v\, i\, dt$, the necessary condition for obtaining its maximum value is that both the current and the supply voltage are near their highest possible values during the arcing time. Voltage instantaneous values satisfy this condition around sinusoidal wave peak (ψ around 90°), current instantaneous values are higher, the higher the values of current at arc beginning. Therefore also maximum value of energy portion $\int_{t_a} v\, i\, dt$ is attainable for making instants near to 90°.

According to equation (1), then, maximum value of total arc energy shall correspond to a making instant near to 90°. This making instant is rather different from that stated in IEC rules.

Experimental results confirm the above considerations. Figure 5 (a) and (b) show, as an example, diagrams of total arc energy for miniature fuse-links of 500 mA and 6.3 A rated currents.

There are cases, however, in which the breaking current has a behaviour like that shown in figure 6. In these cases further tests shall be made with making instants duly anticipated, if necessary up to 0°, in order to allow maximum arcing time, hence maximum arc energy, to be attained.

CONDITIONS OF MAXIMUM ARC ENERGY DEPENDING ON THE INTENSITY OF THE PROSPECTIVE TEST CURRENT IEC rules require breaking tests also at prospective currents of approximately 5, 10, 50 and 250 times rated current, but not exceeding the rated breaking capacity. For these currents, the inductance in the circuit, according to the rules, is kept constant and the current is adjusted by changing the series resistance. Among them, those values of current are to be considered within the scope of this paper, for which heating of fuse-element up to melting can be deemed to be adiabatic.

Relatively smaller overcurrents can also give rise to difficult breaking conditions, but they are out of this scope.

Let us consider, then, prospective test currents for which adiabatic heating of fuse-elements is ensured. Since inductance L is kept constant, the portion of energy $\frac{1}{2} L i_o^2$ has its maximum value in correspondence of the highest prospective test current; i.e. at 1500 A. In fact, the current i_o at the beginning of the breaking arc is larger the larger the prospective test current.

Since test currents shall be adjusted by changing series resistance R_1, the energy loss $R_1 \int_{t_a} i^2\, dt$ has its minimum value at 1500 A. In fact, for adiabatic conditions, pre-arcing and maximum total joule integrals can be deemed to be constant, irrespective of the values of current to be broken. Maximum arcing joule integral, $\int_{t_a} i^2\,dt$, which is the difference between maximum total and pre-arcing joule integrals, is also constant, while R_1 is larger the smaller the prospective current.

As regards the portion of energy $\int_{t_a} v\,i\,dt$, it is rather uneasy to theoretically deduce the value of prospective current leading to its maximum value. This would imply some assumptions on the behaviour of the arc voltage, as a consequence of the action peculiar of the fuse-link.

Account taken, however, of the above considerations about the portions of energy $\frac{1}{2} L\, i_o^2$ and $R_1 \int_{t_a} i^2\,dt$, the hypothesis that total arc energy has its maximum value in correspondence of 1500 A is far from being unacceptable. The hypothesis should be checked by a sufficiently large number of appropriate tests.

Experimental results of tests carried out on two types of miniature fuse-links rated 500 mA and 6.3 A and on one type of fuse link rated 1 A confirm that.

CONCLUSIONS Experimental results and theoretical considerations show that the making instant giving rise to maximum arc energy for miniature fuse-links tested at the prospective current corresponding to their rated breaking capacity (1500 A) is about 80° - 90°.

Within the limits of the above reported test results, tests at lower overcurrents, for which heating of the fuse-element can nevertheless be deemed to remain adiabatic, like 50 and 250 times the rated current, might be omitted. This conclusion could be a general one, should sufficiently extended test results confirm that for all design of miniature fuse-links maximum arc energy corresponds to the current of standard rated breaking capacity.

REFERENCES

[1] - Cantarella, G.: "L'interruzione di corrente alternata mediante fusibili - L'energia trasformata nell'arco" L'Elettrotecnica, n. 4, Vol. XLVII, 1960.

[2] - Toniolo, S.B. and Cantarella, G.: "Conditions of maximum arc energy in operation of current-limiting fuses" IEEE Trans., 1969, PAS-88, pp. 94-99.

[3] - Cantarella, G. and Farina, G.: "Sulla determinazione delle caratteristiche operative dei fusibili" L'Elettrotecnica, n. 11, Vol. LX, 1973, pp. 1089-1096.

[4] - Wilkins, R.: "Generalised short-circuit characteristics for h.r.c. fuses" Proc. IEE, Vol. 122, No. 11, November 1975, pp. 1289-1294.

[5] - Farina, G.: "Computer data acquisition and processing in short-circuit laboratories" Acta IMEKO 1973, Vol. I, pp. 607-618.

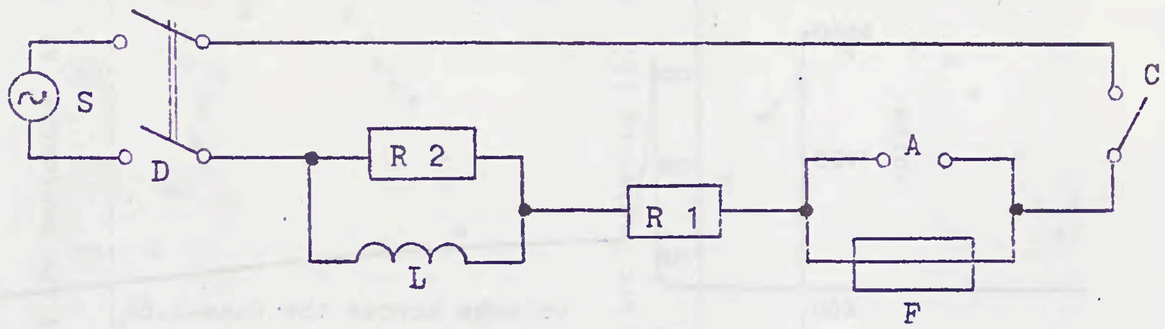

Fig. 1

Circuit for breaking-capacity tests for high-breaking capacity fuse-links

A Removable link used for calibration,

C Contactor that makes the circuit,

D Circuit-breaker to protect the source of supply,

F Fuse under test,

S Source of supply, impedance less than 10% of the total impedance of the circuit,

L Air-cored inductance of 0.30 mH ± 3% to adjust the power factor 07 + 08,

R_1 Series resistor, adjusted to obtain correct prospective current,

R_2 Parallel resistor of 40 ohms ± 10%, acting as a damping resistor.

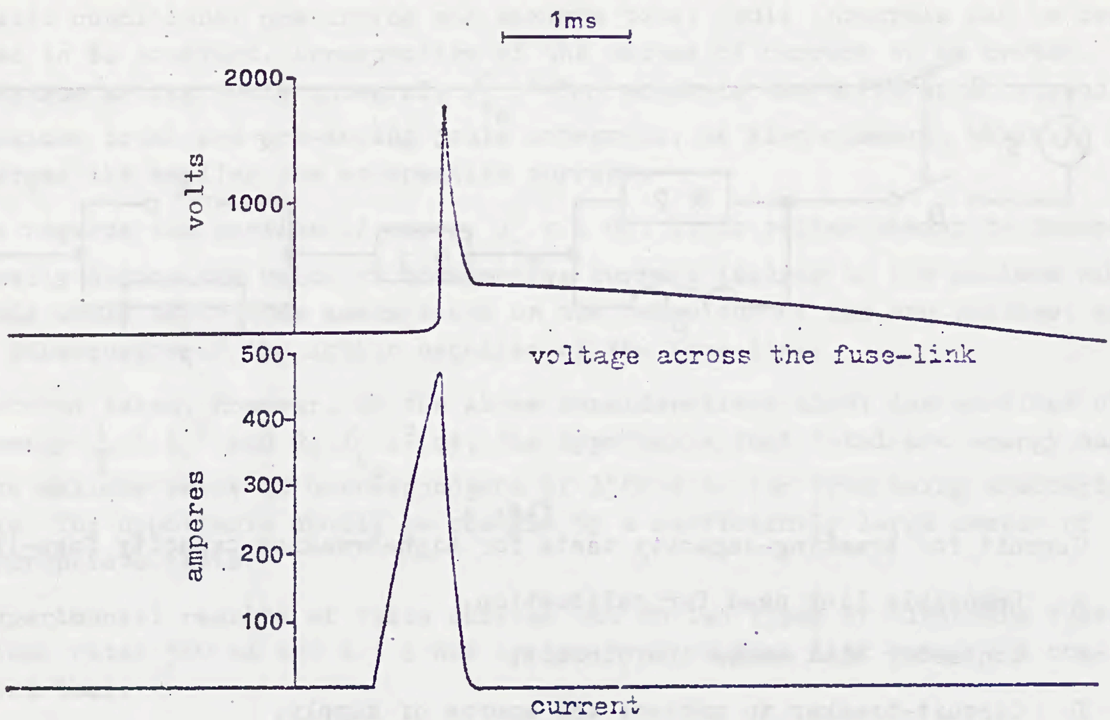

Fig. 2

Typical behaviours of breaking current and voltage across a miniature fuse-link.

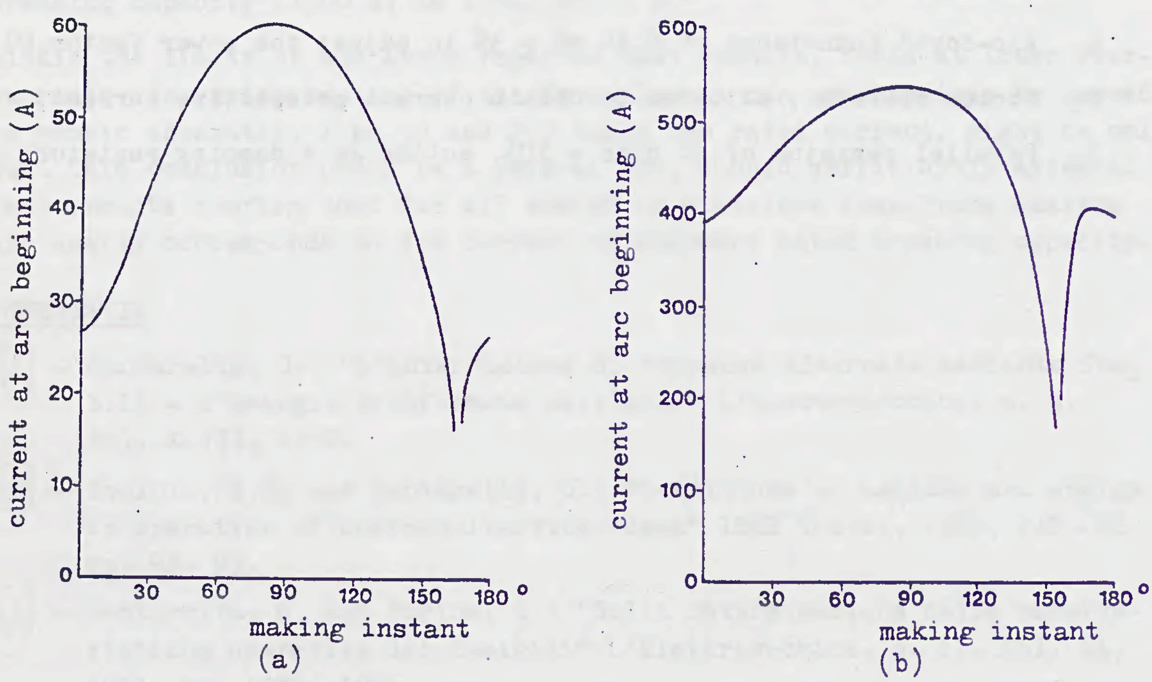

Fig. 3

Instantaneous value of the current at arc beginning,
as a function of the making instant:

(a) on fuse-links rated 500 mA

(b) on fuse-links rated 6.3 A

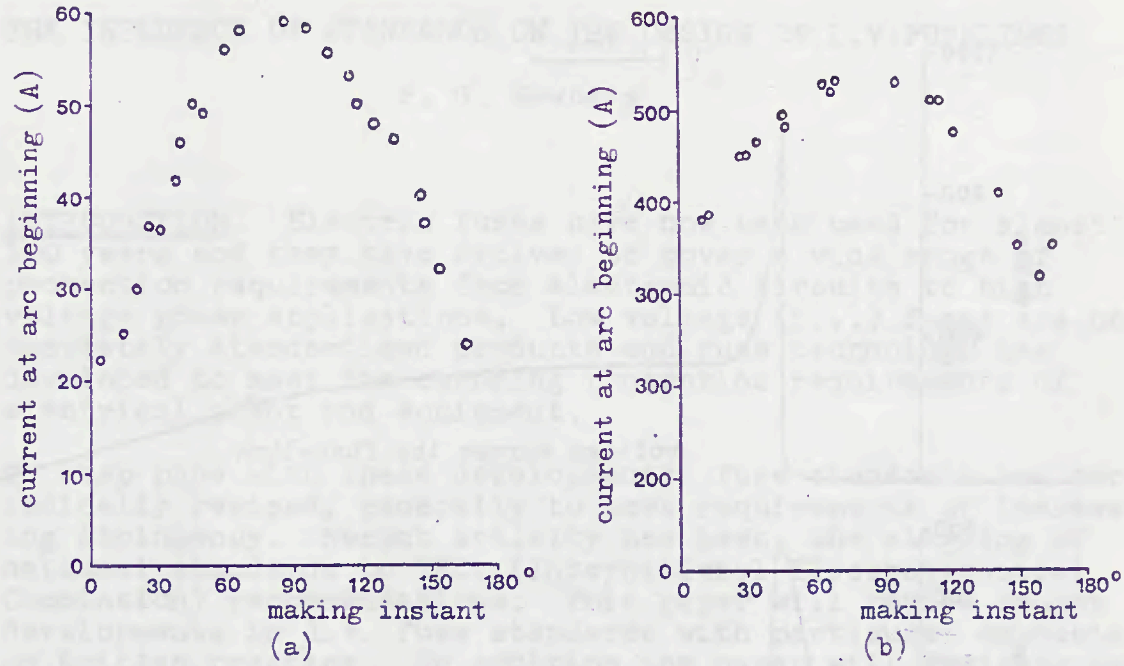

Fig. 4

Current peak as a function of the making instant, recorded in tests carried out:
(a) on fuse-links rated 500 mA
(b) on fuse-links rated 6.3 A

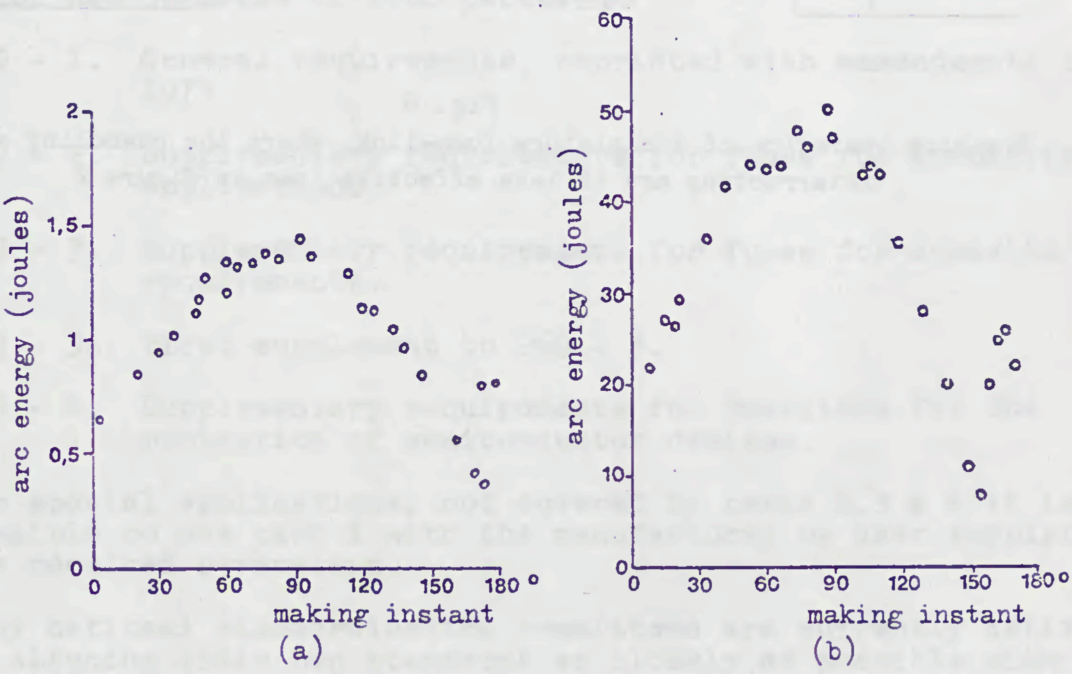

Fig. 5

Arc energy as a function of the making instant, determined in tests carried out:
(a) on fuse-links rated 500 mA
(b) on fuse-links rated 6.3 A

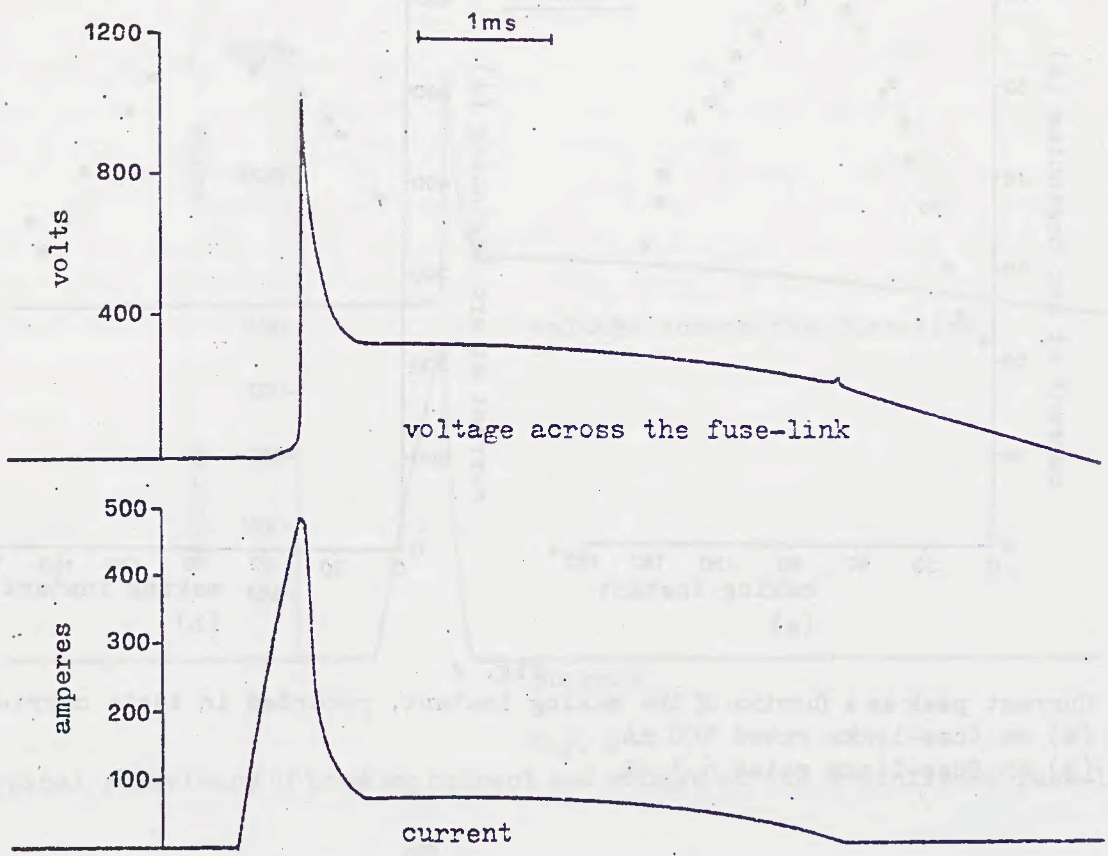

Fig. 6
Breaking operation of a miniature fuse-link, where the quenching of the interrupting arc is less effective than in figure 2

THE INFLUENCE OF STANDARDS ON THE DESIGN OF L.V.FUSELINKS

P. G. Newbery

INTRODUCTION. Electric fuses have now been used for almost 100 years and they have evolved to cover a wide range of protection requirements from electronic circuits to high voltage power applications. Low voltage (l.v.) fuses are not completely standardised products and fuse technology has developed to meet the changing protection requirements of electrical plant and equipment.

To keep pace with these developments fuse standards are periodically revised, generally to meet requirements of increasing stringency. Recent activity has been the aligning of national standards to IEC.,(International Electrotechnical Commission) recommendations. This paper will review recent developments in l.v. fuse standards with particular emphasis on British practice. In addition the paper will indicate how modern analytical methods can assist the designer in meeting these new requirements.

LOW VOLTAGE FUSE STANDARDS. The IEC. recommendation for low voltage fuses are given in the 269 series of publications. These now comprise of four parts:

269 - 1. General requirements, reprinted with ammendments in 1973

269 - 2. Supplementary requirements for fuses for industrial applications.

269 - 3. Supplementary requirements for fuses for domestic requirements.

269 - 3A. First supplement to 269 - 3.

269 - 4. Supplementary requirements for Fuselinks for the protection of semiconductor devices.

For special applications, not covered by parts 2,3 & 4 it is possible to use part 1 with the manufacturer or user supplying the required parameters.

Many national standardisation committees are currently active in aligning their own standards as closely as possible with the above IEC. recommendations. In 1975 the British Standard on l.v.fuses, BS 88,was revised with this objective. The new format of IEC 269 and BS 88 : 1975 are distinctly different from the 1967 edition of BS 88 in which part 1 dealt with fuse-links and part 2 with fuse carriers and bases.

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GENERAL REQUIREMENTS. The alignment of BS 88 part 1 with IEC 269 - 1 has introduced several new concepts and test requirements. Salient aspects are:

General purpose fuselinks: These are defined as current limiting fuselinks capable of breaking under specified conditions all currents which cause melting of the fuse-element up to its rated breaking capacity. The majority of British industrial and domestic fuselinks fall into this category.

Back-up Fuselinks: These are defined as " A current limiting fuselink capable of breaking under specified conditions all currents between the lowest current indicated on its time/current characteristic and its rated breaking capacity". It has never been British practice to use such fuselinks in the protection of industrial and domestic applications and their inclusion does not recommend their use in such applications. The need for their introduction in addition to IEC practice is for semiconductor fuselinks which by definition are a form of back-up fuselink.

Reynard series of current ratings: To align with general IEC. practice for electrical equipment the R10 Reynard series is used. The preferred current rating for fuselinks are:
2 - 4 - 6 - 8 - 10 - 12 - 16 - 20 - 25 - 32 - 40 - 50 - 63 - 80 - 100 - 125 - 160 - 200 - 250 - 315 - 400 - 500 - 630 - 800 - 1,000 - 1,250

Power dissipation and power acceptance: Interchangeability of fuselinks in carriers and bases is assessed by the power dissipation values of fuselinks and power acceptance levels for carriers and bases. The power acceptance levels of carriers and bases are determined from temperature rise limits for materials and component parts. In IEC.269-1 these temperature rise limits are"under reconsideration". BS 88 : 1975 has aligned these requirements with IEC 408, Low-voltage air-break switches, air-break disconnectors, air-break switch-disconnectors and fuse-combination units, and IEC 157, Low-voltage switchgear and controlgear. Temperature rise limits for tin plated contacts have also been clarified.

Time current zones: All manufacturers' time/current characteristics must lie within zones which are specified in the additional supplementary parts. These zones have the minimum pre-arcing time and maximum total operating time as their limiting values. The zones therefore assist in ensuring descrimination particularly when different makes are interchanged.

Conventional current tests: For general purpose fuselinks the long time extremities of the time/current zones are verified by conventional fusing current, I_f, and conventional non-fusing current, I_{nf}, tests; these currents are defined as:
Conventional fusing current: A value of current specified as that which causes operation of the fuselink within a specified time (conventional time).
Conventional non-fusing current: A value of current specified as that which the fuselink is capable of carrying for a

specified time (conventional time).
The conventional time is related to the thermal time constant of the fuse and the test arrangement, and is 1, 2, 3 or 4 hours depending on the current rating of the fuselink.

Breaking capacity tests: A total of nine tests are required at five settings, I_1, I_2, I_3, I_4 and I_5 which can be briefly explained as:-
I_1 :- maximum breaking capacity, 3 tests.
I_2 : maximum arc energy conditions, 3 tests.
I_3, I_4, I_5 :- overcurrent tests at full voltage from approximately 2 to 5 times rated current, one test at each setting

Overload tests: These are introduced to give an indication of the ability of a fuselink to withstand a repetitive overload. For a general purpose fuselink three fuselinks are subjected to 50 pulses of current. The test current is 0.8 times the minimum time/current characteristic for a pre-arcing time of 5s. The duration of each pulse is 5s and the interval between pulses 20% of the conventional time. The fuselinks when cooled to ambient temperature are subjected to the overload current and the pre-arcing time must lie within the manufacturers time/current zone.

The ammendments to IEC 269-1 published in 1973 included the above overload test and also the addition of d.c. tests. The assimilation of these ammendments by the designer has raised a few problems which are indicated below:-

The overload test may penalise some designs. For example take a fuselink, A, which has a higher operating current at five seconds than a fuselink, B, of the same current rating. If the slope of the time current characteristic of A around 5 seconds is less than B then the test would be more onerous on design A than B despite its greater surge capacity. Perhaps the test should be based on a percentage of the operating time rather than a percentage of the operating current.

The test requirements in IEC 269-1 for d.c. operation include low overcurrent tests I_3, I_4 and I_5 with typical time constants of 50, 30 and 20 m.s respectively. In the previous national standard such tests have been conducted in circuits with much lower time constants and practically inductance free. These additional requirements pose considerable problems for the fuse designer to maintain previous levels of voltage ratings in a given size of fuselink.

It is also posing problems for nationally recognised testing stations in providing suitable test equipment. This particularly applies to high current ratings and extends to a.c. testing despite the use of the "two part" method. This method can be employed if the testing arrangement does not permit the test current to be maintained at the full voltage for the time required. The fuselink may be pre-heated at reduced voltage and switched over to the test circuit before the arc is initiated.

INDUSTRIAL APPLICATIONS. IEC 269-1 and 269-2 form the basic requirements for industrial applications. A supplementary IEC report has recently been compiled which lists dimensions, associated power losses and test arrangements of commonly used fuse systems of those countries actively participating in IEC recommendations. National standards generally list the preferred dimensions used in that country.

IEC 269-2 lays down limiting parameters within which individual manufacturers characteristics must lie. In particular a minimum rated breaking capacity of 50kA, time current zones, and conventional currents are specified.
These zones use the concept of virtual time which is not common British practice for industrial applications. The virtual time is related to the I^2t and is the I^2t divided by the square of the r.m.s. prospective breaking current. The zones quoted are for virtual times greater than 4 milli seconds(ms) and in IEC 269-2 they are standardised for a maximum rated voltage of 500 volts. In BS 88:1975 they are standardised for a maximum rated voltage of 415 volts. In IEC it was found to be possible to standardise these zones for current ratings of 100 amps and above. However for current ratings below 100 amps it was found necessary to introduce a gI and gII series of zones. The gII zones below 100 amps are more suitable for countries which use such fuselinks for the low overcurrent protection of p.v.c. cables. The gI zones below 100 amps generally have higher values of fusing currents and time/current characteristics which are more compatible with circuit breakers used on minor circuits.

Both gI and gII zones ensure discrimination of all manufacturers characteristics on a 2:1 basis of current ratings for virtual operating times of greater than 4 milli seconds(ms). The virtual operating time of 4 milli seconds(ms) approximates to breaking capacity test I_2. It is common British practice to quote I^2t characteristics under these conditions for a means of assessing discrimination. The limiting I^2t characteristic derived at a virtual time of 4 milli seconds(ms) for gII zones which reflect British practice are shown in Table 1.

In the revised British Standard additional national requirements have been added. These include:-

The provision of an earthed wire screen in the breaking capacity test arrangement. This confirms the suitability of the use of fuselinks in metal enclosures.

A fusing current not exceeding 1.5 I_N(I_N = rated current)at 4 hours. This provides compliance with national wiring regulations for close excess current protection to p.v.c. cables.

A tolerance of ± 10% on current of the individual mean time current characteristic. This condition must apply for each current rating in addition to the requirement of lying within the time/current zone.

The recognition of motor circuit protection fuselinks. In motor circuits, fuselinks provide short circuit protection, the current rating chosen is usually determined by the motor starting current rather than the normal running current. It is therefore possible to design fuselinks with similar characteristics to standardised fuselinks but in physically smaller packages. Such motor circuit fuselinks facilitate a reduction in equipment dimensions to give overall economy. They are a general purpose fuselink and are tested to the full breaking capacity tests.

TABLE 1. I^2t VALUES DERIVED FROM gII TIME/CURRENT ZONES

CURRENT RATING AMPS.	MINIMUM PRE-ARCING I^2t Amp^2- sec.	MAXIMUM TOTAL I^2t Amp^2- sec
2	.34	1.6
4	1.6	10
6	3.6	78
8	10	140
10	10	210
12	78	360
16	140	640
20	210	1,000
25	360	2,000
32	640	3,200
40	1,000	6,700
50	2,000	19,000
63	3,200	36,000
80	6,700	46,000
100	19,000	84,000
125	36,000	144,000
160	46,000	225,000
200	84,000	400,000
250	144,000	580,000
315	225,000	1,000,000
400	400,000	1,600,000
500	580,000	2,700,000
630	1,000,000	7,000,000
800	1,600,000	12,000,000
1000	2,700,000	20,000,000

DOMESTIC APPLICATIONS. IEC 269-1 and 269-3 combine to form the domestic requirements and include additional safety requirements but lower breaking capacity requirements than industrial applications.The time current zones are however the same as for industrial applications.It has been the task of the IEC for several years to formulate some recommendations for "world wide" dimensional standardisation of domestic fuses. This has been fraught with insurmountable technical and commercial difficulties. Since no immediate solution is possible IEC 269-3A has been issued which states:-

"The IEC, whilst awaiting a world-wide acceptable system, earnestly requests all National Committees not to take any unilateral action regarding dimensions of low-voltage fuses which might prejudice the introduction of such a world-wide system."

The associated British standards will therefore be retained in their present form. These are:

BS 1361:1971 Cartridge fuses for a.c. circuits in domestic and similar applications.

BS 1362:1973 General purpose fuselinks for domestic and similar purposes(primarily for use in plugs)

It is hoped that in the near future IEC will formulate a report stating the major fuse systems used by the countries participating in IEC. This will help to minimise the number of systems used which may particularly help developing countries.

SEMICONDUCTOR APPLICATIONS. Semiconductor devices are becoming more popular in the fields of power rectification and conversion. The development of power semiconductors has been dramatic and fuse technology has kept pace with these developments and is well documented (1.2.). The speed of operation of fuses under short circuit conditions cannot be equalled by other protective devices and consequently specially developed "semiconductor fuses" are the most economical means of providing device protection and isolation in the very short time protection region associated with high fault currents.

Although the development of semiconductor fuses is still fluid and application requirements perhaps the most complex of any fuse requirements, IEC 269-4 was issued in 1974. This standardises the a.c. test proceedures and has no limitation on voltage rating.

One of the important parameters of semiconductor fuses in assessing semiconductor device protection is the I^2t letthrough under short circuit conditions. Since the I^2t letthrough under these conditions is dependent on the circuit voltage special tests in addition to breaking capacity are required. These are made at the normal rated voltage of the fuse. It must be remembered that breaking capacity tests are made at 110% of the rated voltage to take account of maximum system voltage that could occur.

These special tests are also used for verification of cut-off and arc voltage characteristics. They are made under low power factor conditions generally between 0.1 and 0.2. The I^2t cut-off and arc voltage characteristics will therefore be more precisely defined in the future.

In general terms semiconductor fuselinks are used for short circuit protection and they can be defined as a back-up fuselink. This is recognised in the test requirements where tests I_3, I_4 and I_5 are replaced by test I_{2a} which relates to the minimum breaking current of the fuselink at a time of 30 seconds. Semiconductor fuselinks, particularly for lower voltages can be designed as general purpose fuselinks in which case they must fulfil the requirements of I_3, I_4 and I_5.

Problems are sometimes encountered with high relative levels of continuous currents. pulsed currents and overloads. A semiconductor fuselink is a thermally sensitive device and its current carrying ability is influenced by its attachments and microclimate. IEC 269-4 has standardisded a test arrangement for thermal tests. This test arrangement is used for power loss and temperature rise tests, the limiting values being assigned by the manufacturer.

A cyclic test is also introduced for verification of rated current. A fuselink is subjected to 100 test cycles, each consisting of an "on" period of 0.1 time the conventional time at rated current and an "off" period of the same duration. After the test the fuse shall not have changed its characteristics. For practical reasons this test is limited to 100 cycles and consequently for service conditions further allowances may have to be made. The reliability of a semiconductor fuselink in service is greatly enhanced if it is operated at a lower level than its maximum limiting current rating and consequently manufacturers may wish to assign a liberal current rating. The current rating of a semiconductor fuselink thus remains as a means of indentification which gives a good indication of the maximum current rating which can be assigned in the specified test arrangement.

The problem of the withstand of fuselinks to intermittant or cyclic overloads is a complex problem and the subject of a complete paper in this conference. Reference to individual fuselink manufacturers is recommended for detailed information. Recent activity in IEC has resulted in the formulation of an overload curve which may assist in providing general application rules.

The application problems of semiconductor fuselinks are recognised by IEC and a working group have recently formulated an explanatory guide to IEC 269-4. This explains the basis of the test requirements and how service conditions affect the performance of semiconductor fuselinks. Future work will include test requirements for d.c. operation.

BS 88 part 4 is in the course of preparation and aligns extremely closely with IEC 269-4 but includes dimensions of commonly used fuselinks.

PREFERRED CHARACTERISTICS. National tests and standards only lay down the limiting parameters of general requirements and these limitations inherently become wider when dealing with IEC recommendations. In addition to these limiting requirements there are strong technical and commercial pressures which the designer faces to give optimum characteristics. Taking the general purpose industrial fuselink as an example the following desirable features are required to cover a wide range of applications:-

Low power loss.

Long term fusing characteristics suitable for the protection of p.v.c. cables.

Good withstand to motor starting surges and normal circuit surges

High maximum breaking capacity, 80 or 100kA r.m.s symmetrical are common.

High a.c. and d.c. voltage ratings.

Low total I^2t let-through

Low cut-off characteristics.

Low ratio of total to pre-arcing I^2t for good discrimination.

Most of the above requirements are conflicting and a compromise design has to be sought, In addition the designer is faced with an overiding economic restriction. This again presents problems since for well engineered products additional performance is related to additional cost, including development costs.

FUNDAMENTAL ANALYSIS. The quantity and cost of development and certification testing tends to preclude a completely practical approach to fuselink development. There is consequently a need for analytical methods to predict fuse performance and thus assist the designer. Analytical methods can show trends in performance more readily than experimental techniques. This can be attributed to inherent measurement problems that exist with many fuse phenomena and the masking effect of manufacuring tolerances.

Fuselink operation can be segregated into two basic processes pre-arcing, or melting, and arcing. Considerable advances have been made into their analysis in the past few years and a fundamental approach to each process is described below:-

The pre-arcing process is perhaps the more predictable but does present a complex three dimensional heat transfer problem. The advent of high storage capacity computers has led to the logical solution of this problem by finite difference methods. Sponsored research(3.)at Nottingham University and independant studies(4.)Liverpool Polytechnic have both sucessfully employed this technique which gives a completely generalised analysis.

This method of analysis can be developed to investigate all major aspects of fuselink pre-arcing performance and can provide fuller information to fuse design and application engineers.

An example of this method is to examine the effects of nonsinusoidal currents such as pulsed cyclic or asymmetric. This is especially important for semiconductor fuselinks and is dealt with in more detail in the paper by J. G. Leach.

Attempts which have been made to analyse the complex arcing phenomena generally relate to the assumption that an independent and predictable voltage is generated by the arc. By the principle of superposition, if the arc voltage is known then the current time relationships of the fuse characteristics can be developed. An analysis of relevant oscillograms will show that the arc voltage is not independantly predictable and varies considerably over a wide range of circuit conditions. Such empirical relationships of fuse voltage during arcing do not deal with the underlying phenomenaand are not of much assistance in explaining behaviour or improving designs. It must however be recognised that the mechanism is very complex and the situation is made more difficult since it is almost impossible to take measurements of parameters such as arc temperature and pressure.

Recent investigation of sponsored research at Nottingham University have developed a model which is considered superior to earlier methods. A more fundamental approach has been made by taking an energy balance over finite time intervals and therefore a generalised solution can be obtained. A paper on the model has been accepted for the Proceeding of the Institution of Electrical Engineers and will be published shortly.

The model can be used to study ways in which parameters such as temperature and pressure within a fuse arc varies during the arcing period. The model enables a better understanding of the arcing phenomena and hence it can be examined and dealt with more scientifically than at present.

<u>CONCLUSION</u>. As electrical systems have developed the type test requirements in standards for fuses have increased in severity and number. Modern standards are a compromise between the ideal and the practically attainable with existing technology. Consequently such standards have a direct influence on the design of the product. Fuse technology has however developed to meet the need of the protection of electrical plant and systems and from the papers presented in this conference it can be seen that there will be a continual demand for fuses.

REFERENCES.

1. PEARCE, J.N. and NEWBERY, P.G. : Fast acting fuses for the protection of semiconductors. IEEE Trans. IECI 17, 1970.

2. LEACH, J.G. and NEWBERY, P.G. : Advances in development and application of semiconductor fuselinks. IEE Conference Publication 123, Pages 1-6, December 1974

3. LEACH, L.G. NEWBERY P.G. and WRIGHT, A. : Analysis of HRC Fuselink pre-arcing phenomena by a finite difference method. Proc. IEE Vol. 120 No.9, September 1973, pages 987-993.

4. WILKINS, R. and McEWAN, P.M. : A.C. short circuit performance of notched fuse elements. Proc. IEE Vol. 122 No. 3, March 1975.

THE STANDARDISATION OF H.V. CURRENT-LIMITING FUSES

J.W.Gibson

1. BASIC RATINGS AND TESTS.. The fundamental matters to be specified are:

1.1. Ratings.

Rated Voltage. Since the fuse is essentially a single-phase device, and since a 3-phase fault frequently results in the operation of only two fuses, the rated voltage, whether for single-phase or 3-phase service, is based on line-to-line voltage.

Rated Current. A current assigned to a fuse which it can carry continuously without exceeding specified temperature rises.

Rated Breaking Current. The value of breaking capacity specified for a fuse. It is related to specified conditions, the basic one being that of rated voltage.

1.2. Tests.

Temperature Rise Tests. Rated current is passed until steady conditions are reached. The temperature rise of the various components must not exceed specified values. It is implicit that the fuse suffers no deterioration with this current for an indefinite time, but this is usually not specified, since it is difficult to check the onset of deterioration by test.

Breaking Tests. Rated breaking current is applied to the fuse at a voltage equal, or approximately equal, to the rated voltage. Since 3-phase tests are difficult to specify, to control and to interpret, single-phase tests are nearly always laid down.

2. BS 2692:1956 (REFERENCE 1). This related to both current-limiting and non-current-limiting fuses. At the time it was advanced in recognising that, for current-limiting fuses, there are three fairly well defined zones of prospective current at which the fuse is highly stressed, and that consequently the breaking tests should comprise three test duties at the following currents:

(a) Rated breaking current.

(b) The current ("critical current") producing maximum arc energy. Arc energy is one of the principal factors governing performance.

(c) A small overcurrent. Here, the mode of operation is different from that at heavy currents. Partly because the arc energy is not evenly distributed along the fuse elements, and between the elements, a fuse can fail with a lower value of arc energy than that which it can satisfactorily accept on test duty 2. The current for this test was established, largely

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for ease of testing, as the current which produced fusion in not less than 0.8s. Although this current is usually several times greater than the rated current, the test proved satisfactory for the most usual use of fuses in the U.K., viz, for incorporation in a switch-fuse combination in which automatic opening of the switch by the fuse strikers relieves the fuses of having to break very small currents.

The standard also recognised that in test duties 1 and 2, the most severe condition is when arcing commences when the circuit EMF is high, and still rising.

3. IEC 282-1 (REFERENCE 2). A commentary on some of the main requirements is given below. The figures in parenthesis refer to clause numbers in 282-1.

3.1. Rated Voltage. This is taken, in line with general IEC practice, as the system highest voltage and groups together a number of mean voltages differing by as much as 10%. This has caused some difficulty in relation to breaking performance since, unlike most other switching devices, the current-limiting fuse is voltage-sensitive rather than current-sensitive.

3.2. Rated Current and Temperature Rise Tests. Rated current of air fuses is based on temperature rise tests in free air. The conductor sizes are specified (Table III) since these have an effect (though less than with low-voltage fuses) on temperature rise on account of a) heat conducted along the conductor from the fuse and b) heat generated in the conductor itself. On the other hand, the fuse base, which also can have an appreciable effect on temperature rise, is merely required to be "as specified by the manufacturer of the fuse link being tested" (12.1.1).

It is not considered necessary to specify the temperature rise of the barrel; in practice, this is almost always higher than that of the contacts and terminals.

The temperature rise of air fuses is higher when they are in an enclosure, but this is regarded as a matter of application and is covered in the Application Guide (22.2).

3.3. Dielectric Tests and Requirements (11, 18.6). The test methods and values are generally the same as for other high voltage equipment. Also, as for other equipment, a second series of figures with reduced insulation level is being added for use under specified conditions where lightning and switching overvoltage are likely not to be severe.

The requirements refer in principle only to fuse bases (fuse mounts) and no tests on blown fuse links are specified. The voltage withstand of a blown fuse-link is reduced if (as by the fault being a light one) large parts of the elements are unmelted. Consequently all that is specified (7.2.3f) is that the blown fuse must withstand system voltage. Thus a blown fuse is not to be treated as having the same dielectric strength as other equipment.

3.4. General Purpose and Back-up Fuses Many fuses have no definite upper limit to the current which they can break, but do have a definite lower limit. While various national specifications had specified minimum breaking current as a ratio to rated current or (as in BS 2692:1956) in terms of time, IEC makes a clear distinction (7.1) between general purpose fuses able to break any current from rated breaking current down to minimum fusing current, and back-up fuses which require another device in series to break small overcurrents or are for use where small overcurrents are unlikely. No values of minimum breaking current are specified for the latter.

3.5. Breaking Tests (13).

General. All tests are single-phase and three test duties are laid down, corresponding to those in BS 2692:1956.

The test voltage (subject to a positive tolerance) for test duties 1 and 2 is specified (Table IV) as 87% of rated (i.e. system highest) voltage, based on the concept that under 3-phase fault conditions, the fuses to some extent assist each other. With low fault currents, it is unlikely that two or three fuses will operate simultaneously and consequently the voltage for test duty 3 is specified as 100% of rated voltage.

For test duties 1 and 2, power factors up to 0.15 are permitted implying that in service the fault power factor should not be less than 0.15.

The peak switching voltage limits (Table IX), approximately 3.2 times the numerical value of the fuse rated voltage, were based on a balance between what values could reasonably be expected from fuses, and the dielectric strength of systems bearing in mind that the duration of the arc voltage of a fuse is intermediate between the voltage durations of an impulse test and a power frequency test. Also taken into account was the possibility of damage to surge diverters caused by overvoltages developed during fuse operation.

The concept of homogeneous series (13.3) is introduced whereby it is not necessary to test all current-ratings in a series.

Nothing is specified (22.4) regarding the following faults on 3-phase unearthed systems:

a) A double earth fault with one fault on the supply side and one on the load side, but this can reasonably be regarded as indicating tests at 100% of rated voltage rather than 87%.

b) A single earth fault, giving rise on an unearthed cable system to a current at leading power factor liable to fall in the small overcurrent range of fuses protecting transformers. However, it has been found that fuses with general purpose, or nearly general purpose, performance operate satisfactorily under these conditions.

Test Duty 1. The making angle is specified as not before voltage zero, since the existence of a minor loop of current reduces the current, and so the stored inductive energy, at the instant of arc initiation. There is also a practical matter of testing; closing before voltage zero is undesirable since pre-arcing in the making switch is liable to result in an indeterminate making instant.

Arc initiation is specified in two ranges, from 40° to 65° and from 65° to 90° after voltage zero. The earlier range tends to produce higher arc energy, but this is not of major importance, since test duty 2 is designed to produce maximum arc energy; hence only one of the three tests of the test duty is made in this range. Later arcing tends to produce higher arc voltages. Since, particularly for fuses having fuse-elements with shallow recesses, the highest arc voltage may occur in test duty 1, tests with late arcing are more important. Also (though for most high-voltage fuses this is not significant) higher mechanical pressure on the cartridge walls is produced. For these reasons, two of the three tests are made with late arcing.

Test Duty 2. The tests are made with almost maximum asymmetry of the prospective current. BS 2692:1956 specified arcing angle and cut-off current. IEC obtains a similar result by specifying making angle and current at initiation of arcing ("melting current"), which together ensure that arcing commences on a rising part of the voltage wave. Specifying melting current rather than cut-off current gives more accurate coverage of two types of fuse element, a) those with long constrictions where arc initiation causes the current to start to fall immediately and b) those with short (and deep) constrictions where the initial arc voltage is small and the current therefore continues to increase for a short time.

Test Duty 3. General purpose fuses are tested at a current causing fusion in not less than 1 hour and back-up fuses are tested at a declared minimum breaking current. Although tests without added resistance are easier and cheaper to perform (particularly with long fusing times), the power factor is specified as 0.4 to 0.6 both because this is considered to be representative of practical conditions and because such values usually result in just detectably more severe conditions than a low power factor.

As an alternative to a normal test, a 2-part method (13.2.2.1) is permitted. The dead period is specified as not more than 0.2s, although in fact much longer periods give very similar results. In practice, changeover is usually effected by the operation of a relay which responds to the melting of the first one or more fuse elements, by monitoring either the fall in current in the low voltage circuit or the rise in voltage across the fuse. It is preferable for the changeover to occur before the fuse is completely melted.

These tests are liable to be very burdensome when the time is of the order of 1 hour. A direct test, because of the resistance which must be used to obtain the specified power factor, is expensive in energy, or the testing station may not have resistors of sufficient dissipation. The 2-part test requires the monitoring equipment to be very accurately set.

In either case it is highly desirable for automatic means to be provided to increase the speed of travel of the recording material of the oscillograph at the instant of switchover or of melting of the fuse-link.

TRV for Tests (13.1.2). The reasons for the choice of values are explained in 282-1 itself, in Appendix B.

Tests of Homogeneous Series (13.3, 13.4 and in Amendment No.1, 13.5). Breaking tests of certain current ratings of a fuse-link of particular dimensions, rated voltage, rated breaking current and rated frequency (13.3) permit the omission of tests of other current-ratings subject to compliance with the very complete set of rules governing a homogeneous series.

This permission is based on the following principles; a) in test duties 1 and 2 where the current during operation and the breaking duty are shared equally between the fuse elements, reduction in the number (n) and /or cross-section (s) of the individual fuse elements facilitates breaking the current, but may increase the arc voltage; b) In test duty 3, where the current during operation is not shared equally between the elements, account is taken of the facts that reduction of the total quantity of metal in the elements does not inherently reduce the duty on the fuse and that the minimum breaking current increases either in direct proportion to the cross-section of individual elements or slightly faster.

As a result of a) above, it is required to make tests to test duties 1 and 2 only on the highest and lowest current ratings of a homogeneous series. An exception to this requirement is for test duty 2 on a series of fuse-links where only "n" is changed, individual elements being identical; here the lowest current rating need not be tested. The reason for this is that the prospective current for test duty 2 is directly proportional to the number of elements, so that the prospective current and thus the actual current, per element is the same and accordingly it is justifiable to assume that the arc voltage is the same.

For test duty 3, the two cases of constant "n" and varying "s" on the one hand and constant "s" and varying "n" on the other, must be considered separately.

For constant "n" and varying "s", only the highest current-rating C is tested. The minimum breaking current of the other fuse-links is then determined (see Fig.1, based on Fig.10 of IEC) by drawing a horizontal line from the intersection of the vertical line representing the test current $I_{3}C$ for fuse C, with the time/current characteristic for fuse C. The minimum breaking currents for the other fuse links are then considered to be those indicated by the intersection with the other curves B and A. This assumption is conservative, since it is inherent that the ratio of the currents indicated by the intersections is closer to unity than the ratio of the value of "s"; the actual values of minimum breaking current, based on their being proportional to "s", are indicated by the dotted line.

For constant "s" and varying "n", both the highest and lowest current-ratings are tested. If both ratings are shown to have the same minimum breaking current (see Fig.2, based on Fig.11 of IEC), the intermediate ratings are deemed to have that minimum breaking current, as shown by the vertical line. If the minimum breaking current of E is greater than that of A, the minimum breaking currents of intermediate ratings are considered to be those indicated by the intersection of the inclined straight line with the other curves B,C and D. This assumption also is likely to be conservative. Although minimum breaking current may in general remain the same, a condition may be reached with increasing "n" where the reduction in spacing between the elements impairs performance. Thus the true curve is likely to be concave to the right, as indicated by the dotted line.

In an actual range of fuse links within a particular barrel, it is likely that both "n" and "s" are varied. In this event, tests to test duty 3 are required not only of the highest and lowest current-ratings; tests are also required with diminishing current-ratings for any current-rating at which "n" is reduced.

In addition to all the above, which is confined to fuse links of a single barrel size, the principle is extended, subject to compliance with similar rules, to barrels of different lengths with either the same (13.5) or different (13.4) rated voltages, but the resulting restrictions on design are such that it appears unlikely that much use will be made of these provisions.

It may often be considered acceptable to omit some of the specified tests of fuses of the lower current-ratings. For example, with modern designs, the switching voltage, while varying considerably with circuit voltage, varies very little with current-density in the elements and is, in fact, approximately the same on test duties 1 and 2. Thus if the switching voltages on test duties 1 and 2 of the fuse of highest current-rating are considerably lower than the permitted maximum, it can usually be said with a high degree of certainty that the permitted value will not be reached with any other fuse in the homogeneous series.

<u>Notes to Clause 13.1.1.</u> Note 2a)is of little use since in practice test duty 1 is not made with symmetrical fault initiation, because this would result in arcing on a falling circuit voltage.

In note 2b)the preference for the second alternative arises because with many designs heating of the element is not adiabatic even at very short times, so that it is preferable to base recommendation on a virtual pre-arcing time closely approximating to that of a test to duty 2.

Note 2 was provided for the guidance of the testing station, but in practice the current I_2 is usually determined by the manufacturer from a simple calculation based on the element dimensions, supplemented by his knowledge of the extent of the deviation, if any, from adiabatic conditions of heating.

With increasing current-rating, the current to satisfy the conditions of test duty 2 increases, and could finally exceed the rated breaking current. Notes 3 and 5 (which should be read together) begin to be applicable with approximately the same increase of current-rating, while note 4 applies only to a considerable further increase. Under the conditions of notes 3 and 4, the TRV will be as normally laid down for test duty 2.

Distortion of Recovery Voltage (13.1.2) Distortion which may change the test severity, usually in a downward direction, is particularly likely to occur in test duty 2. If, as is usual, the making switch is in the transformer primary circuit, closing the circuit near to a voltage zero can saturate the transformer, particularly if it is residually magnetised in the unfavourable direction from the previous test. The resulting large and peaky magnetising current, in passing through the reactor, which is set for a high reactance in this test duty, gives rise to a voltage drop which both reduces and distorts the recovery voltage.

3.6. Oil-Tightness Tests (15) These are as in BS 2692:1956.

3.7. Striker Tests (16,18.12) The standard covers strikers operated by an explosive (as in British practice) or by a spring (as used in some other countries). It states that the characteristics may be verified by the force/travel characteristics of the driving spring or by a pendulum. The freely-hanging pendulum in being struck by the striker measures the useful energy in joules to ensure practical interchangeability between strikers of the same or the other type, but it should be noted that for spring strikers the two permitted methods do not give the same result.

Existing practice is covered by three varieties having different values of energy output and travel. For the future, two types only are laid down.

3.8. Special Tests (as opposed to Type Tests)

Thermal Shock Tests for Outdoor Fuses (17.1.1) The fuse, previously heated by current, is sprayed with artificial rain. The purpose is to simulate tropical conditions, under which the barrel might be cracked if the fuse is subjected to intense solar radiation, followed by heavy rain.

Power Dissipation Tests (17.1.2) Tests at 50% and 100% of rated current are specified. The tests are made in free air and are continued until steady conditions are reached. Dissipation is expressed in watts. The purpose is to give guidance concerning the de-rating necessary when fuses are in an enclosure.

4. BS 2692:PART 1:1975 (REFERENCE 3) This substantially agrees with IEC 282-1 (2nd Edition). The principal deviations are:

(a) The tolerances on power factor for test duties 1 and 2 are tightened. A similar change is likely to be made in 282-1.

(b) The switching voltage is permitted to exceed the IEC values for a time not more than 200 microseconds, provided that the higher values which were permitted by BS 2692:1956 are not exceeded.

(c) For outdoor fuses, a weatherproofness test is combined with the thermal shock test.

(d) Preferred dimensions of fuse-links widely used in the U.K. and previously given in BS 2692:1956, are included.

(e) For fuse-links in oil, the temperature rise greatly depends on the dissipating surface of the oil container. A test tank for oiltight fuse-links of British dimensions is therefore specified. It has a dissipating surface (allowing for the fact that the test is of a single fuse link) representative of that of typical switch-fuses. Since fuse-links of the two standardised dimensions are designed to be used in the same equipment, the same test tank is used for both. For air fuse links, the temperature rise is less dependant on the mounting arrangements, but nevertheless it was considered desirable also to specify test rigs for such fuse links of British dimensions.

(f) While IEC specifies only the mechanical requirements for testing of strikers, the BS specifies also the electrical requirements, so allowing strikers to be tested independently of the complete fuse link. This has the particular advantage of eliminating unnecessary high power testing.

(g) Various explanatory appendices are included.

5. MATTERS BEING CONSIDERED FOR FUTURE STANDARDISATION BY IEC

5.1. Dimensions of fuse-links. As a first step, a report is being prepared giving dimensions of widely used existing standardised types. It is hoped that this will prevent the proliferation of unnecessary new dimensions.

It is suggested that in any future standardisation, the following considerations should be taken into account:

(a) Since high voltage fuse links are handled by qualified persons, it would be unnecessarily restrictive to provide non-interchangeability between fuse links of different rated voltage rated current, rated breaking current and rated minimum breaking current.

(b) Although any particular physical size might nominally or loosely be related to a particular rated voltage, it should not be restricted to that voltage. Thus the manufacturer could provide both a lower rated voltage, often with an increase of the maximum rated current and a higher rated voltage with decrease of the maximum rated current. This useful flexibility is available, and is compatible with economic design, because of the ability to change the helix angle of the fuse elements on the core.

(c) In order to avoid restricting progress, current ratings should not be specified.

(d) It would be desirable to specify that when the required current rating cannot be obtained in the physical size corresponding to a "nominal" voltage, then a size corresponding to a higher "nominal" voltage should be used.

(e) In general, and within the ranges usually used, a fairly long fuse link of fairly small diameter is more economic than one of reduced length and increased diameter with the same rated voltage and maximum rated current.

(f) If there are to be alternative tags or other end fittings, the barrel should remain unchanged, to reduce development, testing and manufacturing costs.

(g) Parallelling of fuse links is assisted by the use of tags of the offset type.

(h) In principle, the dimensions to be specified should be the fixing dimensions, suitably toleranced, and the maximum barrel diameter and maximum length.

It is proposed that a new world-wide system should have dimensions based on Renard numbers, but little progress has yet been made. Indeed, the desirability of such a system is widely questioned on the grounds that no improvements to performance would result and that the resulting economies, as of large scale production, would not be sufficient to justify expensive changes to the design of switchgear.

5.2. Time/current characteristics There are two schools of thought in this matter.

One would prefer to follow the practice for such fuses as domestic, where the standardisation is made as rigid as possible by the specification of time/current zones based on the best possible compromise between existing products; this provides electrical interchangeability between fuse links and is clearly of benefit to the domestic user.

The other (to which the author subscribes) would wish to take account of the following:

a) High voltage equipment is of sufficient importance to justify individual study of particular requirements.

b) As explained in a paper by W.R.Crooks at this conference, different applications (transformers and capacitors on the one hand and motors on the other) are preferably met by fuses having time/current curves of different shapes.

c) Even while making allowance for the existence of two classes of application by specifying them separately, it would be desirable to do this in such a way as to permit and encourage future improvements. As an example, consider fuses for motor circuits. The requirements are that the fuse must not be melted by the motor starting current, but must operate as quickly as possible for an electrical fault. Thus it would be desirable to fix a lower limit, but no upper limit, to the current at a time equal to typical motor starting times. Similarly, there should be an upper limit, but no lower limit, to the current corresponding to a specified very short time.

5.3. Fuses for High-voltage Motor Circuits. Consideration is being given to:

a) Pulsing tests to verify the ability of a fuse repeatedly to carry the starting current of direct-started motors, under which conditions the fuse is typically carrying twice its full load current.

b) Correlation of the characteristics of the fuse with those of other components of the circuit.

5.4. Co-ordination of Temperature-rise Requirements of High-voltage Switchgear and High-voltage Fuses

6. IEC WORK ON CAPACITOR FUSES The IEC is now breaking new ground by preparing a standard to cover the very special requirements of high voltage fuses for the external protection of shunt power power capacitors. It will cover both current-limiting and expulsion fuses. In addition to unit fuses for the usual parallel or series/parallel connection of units, line fuses for overall protection of capacitors are being included. The standard is being based on the assumption that the capacitors are switched by a restrike-free switching device.

6.1. Summary of Service Requirements. In the event of failure of a unit, its fuse may be operated either by the high frequency discharge from the units in parallel or by the power-frequency follow current which (dependent on the connections of the bank) may be inductive or capacitive. The ability of a fuse to withstand the discharge without bursting is verified by breaking discharge tests and its ability to break capacitive follow current is verified by capacitive breaking current tests. The ability of the fuse of a healthy unit to withstand transient high frequency currents is verified by endurance discharge tests.

Notes on these tests are given below.

6.2. Summary of Tests

Breaking Discharge Tests A capacitor having a capacitance to give the required stored energy, expressed in kJ, is discharged into the fuse. The voltage of the test for current-limiting fuses is, in principle, double the normal peak of the power frequency service voltage to take account of the fact that in service a capacitor failure may occur at the instant of switching in, when the overswing charges the capacitor to approximately double voltage. The frequency and decrement of discharge are set to values representative of service conditions. The frequency is directly proportional to rated voltage, also as being representative of practical conditions.

Capacitive Current Breaking Tests. Two test duties are specified. Test duty A (see Fig.3) covers the rated capacitive breaking current. The closing of switch S simulates the complete failure of a unit. C_T represents the capacitance in series in an actual bank and which determines the fault current, while C_p represents the capacitance of the healthy units in parallel with the failed unit and its value is so specified as to be representative of typical banks. It is stipulated that the switch is closed near to a voltage zero, since otherwise the fuse is liable to be blown by the discharge current from C_p.

Test Duty B (see Fig.4) is performed at a current causing melting in 300s and is designed to simulate progressive failure of series elements within a unit. C_T here represents the healthy elements in the unit, while C_p represents the healthy units in parallel with the faulty one and its value is specified at the same value as for test duty A.

The progressive failure of the unit is simulated by the opening of switch S.

Endurance Discharge Tests. Two test duties, which may be at low voltage, are specified. The results are expressed in terms of I^2t.

Test duty A consists of 5 discharges. This test simulates the discharge current passed by one healthy unit into a failed one, and consequently is made at the same frequency as the breaking discharge test.

Test duty B consists of 100 discharges at a frequency independent of rated voltage and representative of values in the higher range of frequency of normal switching inrush currents.

7. REFERENCES.

1. British Standard 2692:1956 - Fuses for Alternating Current Circuits above 660 volts.

2. IEC Publication (Second Edition, 1974) and Amendment No.1 (September 1975) - High-voltage Fuses, Part 1: Current-limiting Fuses.

3. British Standard 2692:Part 1:1975 - Fuses for Voltages exceeding 1000V a.c. Part 1. Current-limiting Fuses.

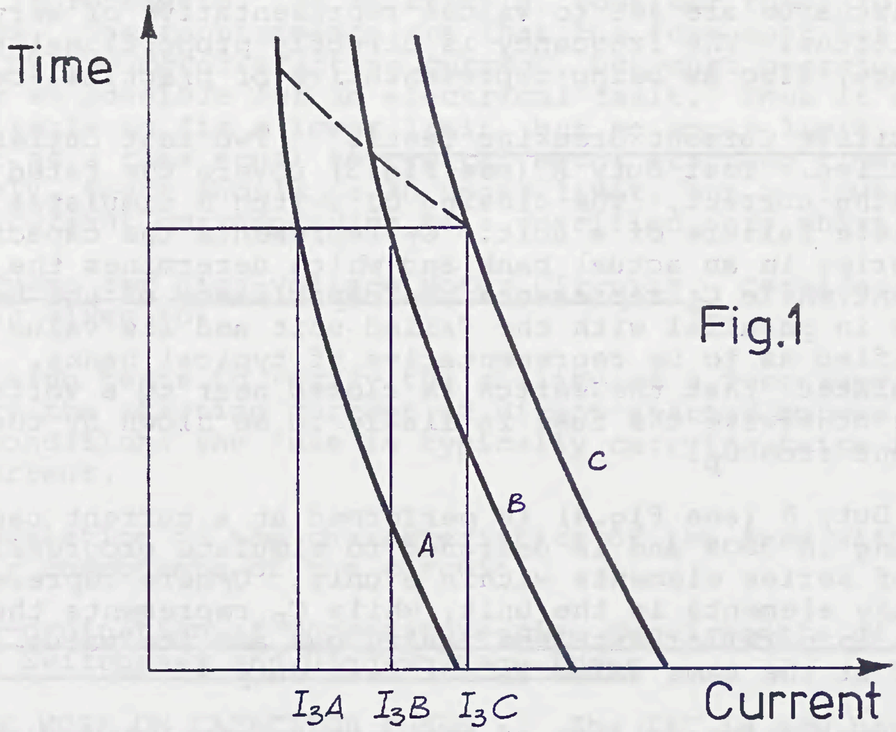
Time
Current
A
B
C
I_3A I_3B I_3C

Fig.1

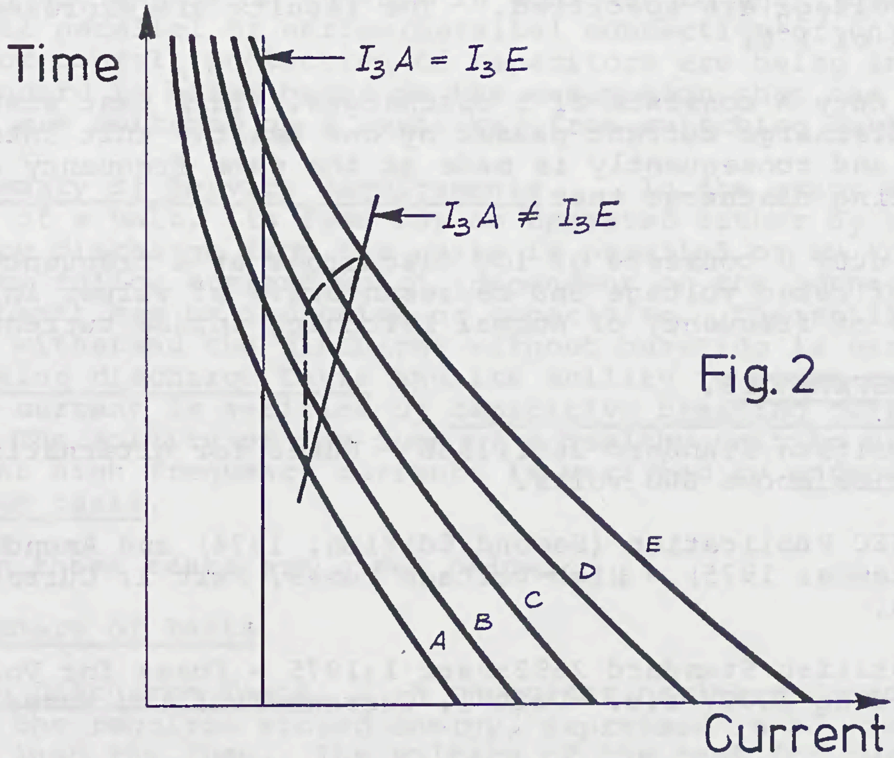
Time
Current
$I_3A = I_3E$
$I_3A \neq I_3E$
A
B
C
D
E

Fig. 2

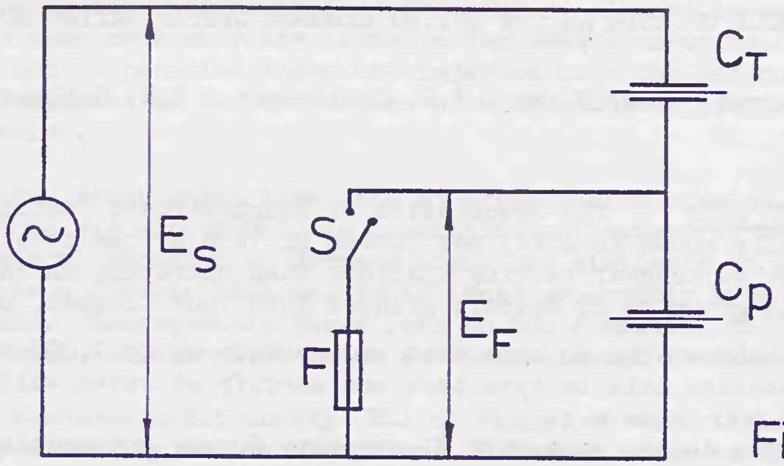

Fig. 3

E_S Source voltage.

E_F Recovery voltage.

C_T Capacitance to produce the desired test current.

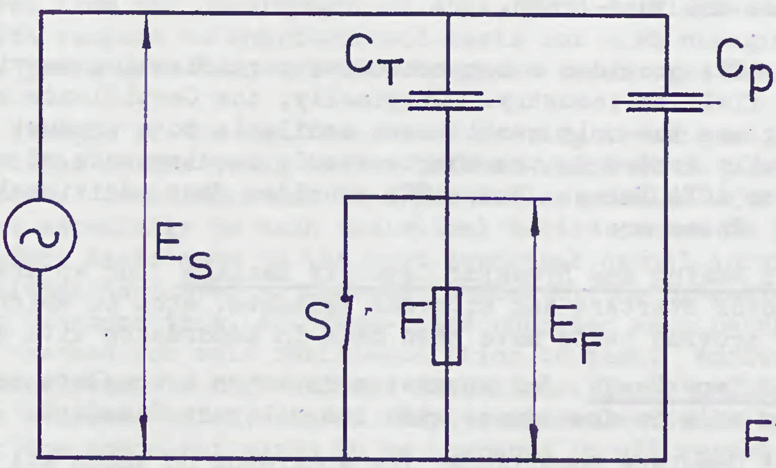

Fig. 4

THE ROLE OF ASTA AS THE UNITED KINGDOM CERTIFICATION BODY

J.G.P. Anderson R.E. Blake B.S. Challenger R.H. Galland D.G. Mee

DEVELOPMENT OF ASTA The Association of Short-Circuit Testing Authorities (internationally known as ASTA) was formed in 1938 by the co-operation of the four major switchgear testing stations then operating in the U.K. Since then, ASTA has grown to 22 Members grouped into four Classes, namely

Class 1	Members able to type test and certify up to 1,000 volts a.c.
Class 11	Members able to type test and certify at rated voltages above 1,000 volts a.c.
Class 111	Open to the statutory Electricity Supply Authorities in the U.K.
Class 1V	Open to other corporate bodies operating short-circuit and/or type testing stations and electricity generation, transmission and distribution authorities and such other users of equipment as the ASTA Council may admit into membership.

The entry of the U.K. into the European Economic Community and the issue by the EEC Commission in 1973 of the Low Voltage Directive has presented ASTA with new responsibilities. In order to implement the requirements of the Low Voltage Directive, H.M. Government has nominated four authorised certification and approvals bodies, one of which is ASTA with particular responsibilities for low voltage switchgear and controlgear generally. Of some relevance to this Conference is that part of the scope of ASTA nomination embracing fuses and fuse-links.

FUNCTIONS ASTA provides a comprehensive certification service within its allocated field to industry. Originally, the Certificate of Short-Circuit Rating was the only certificate available to a product which had been successfully tested to the short-circuit requirements of a relevant Standard and/or ASTA Rules. Now, ASTA provides four additional kinds of certificates. These are:

Certificate of Making and Breaking Capacity Ratings for apparatus such as contactors, motor starters and airbreak switches, etc. on which a successful series of proving tests have been made in accordance with a Standard.

Certificate of Type Tests for apparatus on which a complete series of type tests has been made in accordance with its relevant Standard.

Certificate of Complete Compliance for apparatus on which all the specified inspections, checks and type tests have been successfully completed for the appropriate Standard.

Certificate of Supplementary Tests for apparatus on which successful tests have been made supplementary to those for one of the above Certificates.

The Authors are members of the ASTA Technical Committee.

Members of ASTA operate approved and accredited testing and inspection facilities not only under conditions of confidentiality but also functioning in accordance with harmonised procedures. Agreed interpretations of Standards when necessary are issued under ASTA Instruction to Testing Stations and in parallel these are injected into the various standards making committees in the activities of which ASTA maintains an active participation.

In 1961, the first major link with an organisation outside the U.K. took place. This was with PEHLA, an association of owners of testing stations in the Federal Republic of Germany organised similarly to ASTA. Several years later a further link was established separately with KEMA of the Netherlands. Subsequently these lead to the formation in 1969 of an international collaboration known as Short-Circuit Testing Liaison (STL).

Now, STL embraces additionally CESI of Italy, an association of the national supply authority and manufacturers in France known as ESEF and a similar organisation within Scandinavia called SATS. The recently formed STL of U.S.A. is at present associated in the collaboration. Members of STL are agreed to the uniform interpretation of IEC Standards applicable to the high voltage sector and for which harmonisation is achieved by means of STL Guides to the interpretation of various IEC documents. Other objectives include the uniform presentation of test results and Certificate front sheets, the harmonisation of measuring techniques with minimum limits of accuracies acceptable and the methods employed in performing the type tests specified.

TESTING TECHNIQUES Over the years testing and certification techniques have been developed to enable uniform interpretations and consistent testing conditions in all the laboratories coming within the aegis of ASTA. As may be inferred from the development of ASTA, such developments have occurred mainly with respect to short-circuit tests but with changing circumstances in recent years have been extended to cover other type tests.

One such example of the unification of testing techniques is the verification that the device being tested is that which it is claimed to be by the manufacturer. Identification is a particular problem with cartridge-type fuse-links especially as each individual device cannot be inspected thoroughly before test; some of the most important detail information is, of course, either destroyed or changed in form by the operation of the fuse-link. To overcome this, all fuse-links supplied as a batch by a manufacturer are checked for cold resistance prior to test. Additionally, particularly in relation to high voltage fuse-links, X-ray records may be taken. From this complete batch, random samples are selected to be carefully taken apart for the component parts to be compared in all respects with the detail design data supplied by the manufacturer. Having established that the drawings truly represent the samples being tested, the design data together with the resistance figures and X-ray records are lodged with the testing laboratory.

Perhaps the single most important technique, however, which has been evolved is the prescribing of the accuracy of electrical measurements taken during testing. No British or European Standard lays down the accuracy to which electrical measurements shall be made other than a broad statement which appears in one or two documents that an accuracy of ±5% should be achieved. Building from this statement, ASTA has established comprehensive guidance to testing laboratories laying down the limits of uncertainty for all devices used for the purpose of measurement.

Fundamentally, all parts of the measurement chain contributes to the overall uncertainty of the system. Thus, the characteristics of the signal sensor or transducer, means of transmission, signal processor, recording and finally the quality of the analysis of the recording all have a part to play in establishing the overall accuracy to be achieved.

The word "accuracy" when applied to measurements associated with high speed electrical phenomena does not mean very much unless qualified in relation to the parameter being measured. For example, a specific measurement taken of, say, cut-off current of a fuse-link using oscillographic recording equipment (which is the most common form of recording in current use) entails the knowledge of the frequency performance of the transducer and the frequency response, linearity alignment and sensitivity together with the accuracy and linearity of the time base or time marker of the oscillographic equipment. Such facets involve the historical knowledge of the equipment in use and consequently recommended calibration intervals for the various types of equipment in use at the present time are laid down.

NEW REQUIREMENTS . With the advent of new Standards and the updating of existing Standards, requirements are now being specified that present increased difficulties to test plants which were originally designed to carry out only short-circuit tests.

Some years ago, the existing ASTA Testing Stations were augmented with additional laboratory facilities to enable complete type test certification to be offered to manufacturers of a wide range of electrical equipment. Since modern application requirements for fuse protection demand more accurate specifying of their performance characteristics, recently revised Standards reflect such requirements and now tests are included which are beyond the normal facilities currently available.

An example of one problem at present occupying the attention of fuse manufacturers and testing stations is the testing of both high and low voltage fuses at low values of overcurrent at rated voltage. Such tests raise problems in that the total operating time of the fuse can be of the order of some thousands of seconds and particularly as the tests are required to performed at power factors about 0.5 difficulties of power generation and energy dissipation become considerable.

Overcurrent tests at rated voltage or more have traditionally been undertaken at short-circuit testing laboratories but these, although capable of providing the very high values of output energy required, are without exception only short time rated both as regards to generator output and energy dissipation. This means that, except for the lower current ratings of fuse-links, other means of achieving the test requirement must be adopted. In view of these considerations, both IEC and British Standards permit such tests to be performed on a two part basis where the fuse is preheated at the required test current at low voltage for the major period of the test, the circuit being changed over to another source capable of supplying the required test current at full test voltage shortly before the fuse starts to arc. The principal difficulty in performing such a test is the determination of the instant suitable for the change-over such that the current at full test voltage may be reliably determined but yet not so far in advance of the start of arcing that the time rating of the source of supply is likely to be exceeded.

Thus, different or improved or even more sophisticated testing facilities are often required to satisfy the demands of new specifications. Both processes are continuous.

With certification for complete compliance, most searching and detailed work in relation to procedural requirements is being undertaken and the future promises much effort in this direction. From the more practical aspects of measurement, the fast growing instrument field is already giving new forms of recording and analysis as tools for the testing engineer. In some areas, the direct analysis of transient phenomena by digital means is a reality and may be accepted eventually by those who need an analogue "picture" to satisfy themselves that the event follows an already established and recognisable pattern.

RESPONSIBILITIES & ACCEPTANCE The fundamental objectives of the Low Voltage Directive are to achieve safety in all electrical equipment whether intended for the low voltage industrial or consumer markets and to remove barriers to trade caused by variations in national regulations. Such legislation, of course, ensures attainment of these objectives by defining enforceable safety requirements.

In order to satisfy Article 10 of the Directive, member countries of the Community must signify compliance with the Directive by providing, in descending order of merit, safety marks, certificates or simply declarations of conformity by the manufacturer.

The four Bodies nominated by H.M. Government have been authorised to grant marks and issue certificates in accordance with the provisions of Article 10. Furthermore, they may give an opinion under Article 9 and make a Report under Article 8 if called upon to do so within the scope of their respective product responsibilities. To provide a forum for matters of common interest, the four nominated Bodies have voluntarily formed the Confederation of British Electrotechnical Approvals Bodies which now has direct representation on the CENELEC Marks Committee.

Included in the list of products allocated to ASTA are circuit breakers, fuses and fuse-links as previously mentioned, fuse boards, switches, isolators, fuse-switch combinations, transformers and reactors.

The most significant feature lies in the stipulation that no product may be put on the market within the Community unless it satisfies fundamental safety requirements which may be demonstrated by compliance with a British or IEC Standard acceptable to the importing country or more desirable with a CENELEC harmonised standard published under national procedures and therefore acceptable to all members of the Community.

MANUFACTURERS' OPTIONS The manufacturer may invoke the right conveyed by the Low Voltage Directive to declare that his products conform with good safety practices in force in the Community. More acceptable in substantiation is the claim of compliance with a national standard. Better still is the enhanced position attained by the successful testing of his product by an impartial national organisation to gain one of its certificates.

With particular reference to ASTA, its Certificate of Complete Compliance is of paramount value since it not only provides verification of all the requirements of the relevant Standard but imparts the added assurance that the manufacturer is making his products precisely as that which has been certified.

For equipments within the scope of the Low Voltage Directive, the use of an approvals mark is inevitably the best means of indicating compliance which furthermore is supported by an ongoing quality assurance control surveillance scheme providing the basis for a successful marketing policy.

Where the appropriate British Standard has also been harmonised through the CENELEC procedures and a mark subsequently issued, the product may be freely marketed within the Community with virtually no risk of challenge since the provisions concerning safety are thereby shown to be in compliance with the Directive.

ASTA MARKING SCHEME To complete the service which industry will eventually desire and to provide for all requirements of the Low Voltage Directive, ASTA is introducing its Marking Scheme based upon the successful compliance of all requirements specified in a British Standard as for the Certificate of Complete Compliance which is supported by an independent quality assurance or surveillance procedure.

Two methods of surveillance are being employed, namely factory based and market based, depending upon the nature of the product. The principles adopted are mainly Part 2 of BS 5179: 1974 Guide to the Operation and Evaluation of Quality Assurance Systems.

Safety and reliability are also criteria of the ASTA Marking Scheme in addition to compliance with an approved Standard. For many products, however, performance requirements are intermingled with safety aspects to such extents that separate identification often becomes impracticable. Other factors, such as installation, usage and maintenance remain the responsibility of either or both the manufacturer and user; these kind of factors are therefore outside the scope of the ASTA Mark.

REFERENCES

1 The Low Voltage Directive (OJ 26.3.73) Electrical Equipment designed for use between certain voltage limits. 73/23/EEC of 19.2.73

2 Low Voltage Directive - The Facts by R. Winckler, J. Cassassolles and D. Verdiani

3 Consumer Protection Act 1961. The Electrical Equipment (Safety) Regulations 1975

4 Administrative Guidance on the Electrical Equipment (Safety) Regulations issued by the Department of Prices and Consumer Protection

5 Health and Safety at Work etc. Act 1974

6 BS 5179: 1974 Guide to the Operation and Evaluation of Quality Assurance Systems

7 ASTA Test Instructions 1974

8 ASTA Publication No.5 1975 Rules governing the composition of ASTA Certificates, ASTA Test Reports and Reports of Performance

9 Draft STL Guide on Measurements

10 Draft ASTA Marking Scheme and Regulations

THE QUALITY ASPECTS OF H.V. CURRENT-LIMITING FUSE PROTECTION

W.R.CROOKS

1. INTRODUCTION. The increase in demand on supply systems and the increase in density of both population and load in urban areas has brought members of the public into closer proximity with items of distribution systems plant such as transformers and switchgear. The safe working of such plant and effective and reliable protection is now, more than ever before, of the highest importance.

High voltage current-limiting fuse-links are now the normal means for protecting distribution transformers from short circuit currents and in combination with suitable switchgear provide protection against the full spectrum of fault currents. Increasing use of h.v. c-l fuse-links is being made for the protection of motor circuits up to 11kV in combination with air breal or vacuum contactors.

In both the fuse-switch and fuse-contactor combinations advantage is taken of the fuse performance, i.e. the limitation of peak current and I^2t to reduce the size of the switchgear contacts and conductors and consequently the operating mechanism, allowing a more compact, lighter and cheaper package without any loss of breaking capacity, on the contrary, fused equipments have breaking capacities that would be difficult and certainly expensive to achieve with circuit breakers.

Modern usage demands not only that the performance of the fuse-links, as demonstrated by type tests, be of a high order and compatible with associated equipment, but that the performance of every similar fuse-link be consistent and in accordance with the published data, except as modified by the effect of enclosure or abnormal ambient temperature.

To achieve the necessary conformity in performance, the quality of materials, the methods of manufacture and the testing and inspection must, at all times, be under strict control. To achieve satisfactory service, the methods and rules of application must be well founded and reliable.

The paper discusses the above requirements in more detail.

2. QUALITY OF PERFORMANCE. The primary requirement for a c-l fuse is breaking capacity for the range of currents dictated by its type. For a back-up type all currents between the nominated minimum breaking current and its rated breaking current must be broken without external manifestation. For the general purpose type the range extends, for practical purposes, from that current which causes melting in one hour up to the rated breaking current.

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It is a relatively simple matter to obtain clearance of high values of current and simple element designs will provide the capability, but the quality of performance may be measured by examination of the transient values of current and voltage at the instant of commencement of, and during, the period of arcing. Other aspects of performance during normal current carrying conditions and under fault conditions, before and after melting, can be assessed quantitatively from data obtained by calculation and test.

2.1. Current Carrying. The fuse-link must be capable of continuously carrying the normal load current, permissible overloads and transient currents of the circuit in which it is installed. Depending on the nature of the installation, temperature rise may be of considerable importance and de-rating of the fuse-link is sometimes necessary where circulation of the ambient air (or liquid) is prevented or restricted. Clearly then, for a given fuse-link, the lower the temperature rise when carrying rated current the better.

2.2. Fault Conditions - Pre-arcing Period. The requirements for the shape of the time-current curve depend on the application and these requirements are quite different between the two most common applications, namely, distribution transformers and induction motors started direct-on-line.

Fuses used in the above applications are not normally used as overload protection, thus consideration of the shape of the time-current curve may be restricted to a range of times from 0.1 seconds to, say, 100 seconds.

For transformer protection the requirements are:

a. That the 0.1 second melting current should be great enough to ensure that magnetising inrush currents are withstood without damage and that discrimination with the secondary fuses or other protection is achieved.

b. For times from, say, 10 seconds up to 100 seconds, the corresponding values of current should be low enough to provide adequately fast clearance of restricted values of fault current such as result from interturn faults on the h.v. winding or secondary earth faults ahead of the secondary protection which may be of limited magnitude due to the effects of arc resistance.

The foregoing considerations dictate that for the range of times nominated the time-current curve should have a "shallow slope".

Consideration of the requirements for capacitor unit fuses, namely, the ability to withstand inrush currents and the ability to disconnect faulted units where the fault current may be restricted due to unearthed star connection or series connected units as quickly as possible also lead to the conclusion that a "shallow" time-current curve is required.

For motor protection the requirements are different, namely,

a) The 0.1 second current should be low enough to provide rapid clearance of fault currents. Where the highest fault currents occur, such as with terminal box flashovers, the clearance should be as fast as possible to prevent disruptive failure.

b) For times in the range of motor run up times, say, 6 to 60 seconds, the melting current should be as high as possible so that starting current is exceeded by sufficient margin.

These requirements indicate the desirability of the time-current curve having a "steep" slope over the range of times considered.

Fig.1. shows time-current curves of practical fuses. The transformer fuse curve shown is one which employs a hybrid type element (British Patent 1294085), designed to give a very shallow characteristic. Other alternative element designs are now becoming available to give moderately fast clearance of mid zone faults.

For limited fault currents, where melting times of many minutes are involved, the temperature which the fuse barrel and endcaps achieve is important. If no control is placed on these temperatures the insulation of switchgear can be damaged and also the fuse barrel may not survive the high temperatures achieved since the fuse elements, normally of silver, must reach a temperature of 960°C before melting occurs. The temperature can be limited by the well known Metcalf effect where a tin bearing low melting point alloy is deposited on the elements and which creates a eutectic effect with the silver elements and limits the element temperature to values lower than 300°C. This consequently limits the temperature attained by the fuse barrel.

<u>2.3. Fault Conditions - Arcing Period.</u> A typical oscillogram of a fuse-link breaking a high value of current is shown in Fig.2.

The salient features of the fuse operation are:

a) The cut-off current. Note that the peak value is quoted. Clearly the lower this value is kept the better since the cut-off current determines the mechanical forces that will be developed between switchgear contacts, cable cores, etc.

b) The I^2t Value. This is the total value of $\int i^2 dt$ over the pre-arcing and arcing periods. This value determines the heating effect of the fault current in the conductors and the amount of damage sustained at the seat of the fault. In certain applications it may be critical in determining the safety of a transformer tank where large volumes of gas are evolved by the fault arcs. (See Section 5). It can be shown that with the type of fuse element used in the fuse from which the oscillogram of Fig.4. was obtained, and which uses deep notch elements that the total I^2t passed by the fuse is less than the pre-arcing I^2t of the unnotched part of the strip. In other words, after arcing commences at each of the restricted sections or notches of the elements, the bulk of the element is burned back by the arcs and not by I^2r heating.

c) Arc Voltage. This stresses the system insulation and is therefore subject to limitation by the various specifications. As shown in Fig.2. the fuse tested gave a peak value of arc voltage limited to approximately 2.25 times the voltage rating of the fuse. Also important is the variation of arc voltage with recovery voltage, since it is this that determines the advisability of using fuse-links in circuits of voltage rating less than that of fuse-links. Fig.3. shows the variation of arc voltage with recovery voltage for fuses of the type under consideration. This curve is supported by Figs.4 and 5, which show oscillograms obtained from identical fuses tested at rated voltage and half of rated voltage respectively, but with all other conditions identical. The arc voltage measured for the 50% recovery voltage test was 59% of that for the 100% recovery voltage test.

<u>2.4. Minimum Breaking Current.</u> In many cases overseas, h.v. fuse-links are applied in such a way that their performance under restricted fault current conditions assumes a high degree of importance. This arises where the fuse-link is used without associated switchgear or where the switchgear is not automatically tripped by a fuse-link striker or where there is a deliberate time delay in the tripping operation. While not in practice always requiring general purpose fuses, low values of minimum breaking current are required. Experience has been that satisfactory service is obtained in many situations where the minimum breaking current is 2 to 2.5 times the fuse-link rated current. Fig.6. shows the breaking of 170 amps by a 15.5kV, 100 amp fuse-link at the end of a 1 hour test.

<u>3. QUALITY AND QUALITY CONTROL IN MANUFACTURE.</u> The nature of a fuse-link inherently prevents complete testing on a routine basis since it is a one operation device. Controls are therefore necessary on the consistency of materials and manufacture to guarantee that all the fuse-links will provide the performance demonstrated by type tests.

<u>3.1. Materials.</u> Clear unequivocal specifications and drawings are necessary which are agreed between the supplier (whether in house or external) and the engineering department responsible.

Incoming goods are subject to inspection and test on a 100% basis or by suitable sampling. Measurement of compliance with specification may, for some materials, involve special tests, e.g. chemical and grading analysis of sand used as the filler, bursting strength and porosity tests of ceramic bodies.

Where non-critical dimensions or other features fail to meet those specified but a relaxation may be allowed, there is a concessionary procedure to maintain control and ensure consistency of decisions.

Duplicate sets of gauges, where one set is held by the supplier are used.

3.2. Manufacture. It is essential that each and every operator be entirely clear on the methods to be used and standards to be achieved in his or her area of responsibility. Adequate training is given and concise written instructions are provided.

Any changes in methods, machines or parts are preceded by appropriate training and modifications to written procedure specifications.

3.3. Inspection and Tests. Work in progress inspection is ensured jointly by patrol inspection and engendering a responsible self-inspection approach by operators. Concise written standards are provided for inspectors and others to work to.

In the case of the fuse-links discussed in this paper, the following inspections and tests are made on a 100% basis.

Resistance Checks. Every fuse-link has two resistance measurements made and for each, compliance with design values is necessary. Resistance tolerances are based on dimensional tolerances achievable in the manufacture of element material. The first measurement is made when the element assembly is inserted into the barrel. At this point, the fuse-link is assigned a serial number and the measured resistance value is logged against that serial number. Later, when the fuse-link is complete, the resistance is again measured as part of the final inspection and the value again logged adjacent to the previously measured value so that an immediate comparison is made. Discrepancies between the two values, other than those arising from temperature difference and normal errors of measurement, are not permissible.

Tests of Seals. Most fuse-links are required to be sealed against the ingress of moisture or oil. In the case of fuse-links to be used in air, compression type seals are used and these are tested by immersing the fuse-link in water at a temperature of approximately 85°C. The air contained between the grains of sand occupies approximately 35% of the internal volume of the fuse and creates an internal pressure which searches the seals. Leaks are observed by the escape of bubbles.

For fuse-links intended for use immersed in oil two seals in series are used, firstly, a compression type seal similar to that used in air fuses and secondly a back-up epoxy resin seal. Since it is not possible to test these two seals independently only the first is tested as described above before the second seal is applied.

The oil sealing tests described in Clause No. 15.1. of BS 2692: 1975 are made on a regular basis.

Radiographic Inspection. An X-ray exposure is made of every fuse-link and the film identified with the serial numbers of the fuse-links. Each film is viewed by an inspector for the following features:

a) Continuity and even spacing of the coiled pilot fuse which energises the striker.

b) Even spacing between the fuse elements.

c) The presence on each element of the deposit of low melting point alloy.

d) The absence of foreign objects.

The radiographic examination is considered to be extremely important since it is the only method available of ensuring the integrity of the striker pilot fuse circuit. The other information obtainable from the X-ray film is also important from the quality assurance standpoint. The films are kept on file for future reference should this become necessary.

Other tests are carried out on a sampling basis, examples are: the checking of compaction of the sand filler; the energy output of strikers.

4. APPLICATION. Three main areas of application are apparent as previously mentioned. These are distribution transformers, motors and shunt capacitors.

4.1. Transformers. The fuse-links must be selected such that they:

a) Withstand the magnetising current inrush. Very little quantitative data is available on the values of magnetising current inrush. For any switching operation on the transformer it will depend on the remenant flux density in the core, the point on wave of switching and the source impedance.

The empirical rule that the inrush current integrates to give the equivalent of 12 x full load current for 0.1 seconds has been proved by experience to be adequate. In North America another equivalent integral of 25 x full load current for ½ cycle, (i.e. ,0083 seconds on a 60 hz system) has been suggested.

b) Withstand permissible overloads as determined by the philosophy adopted for transformer overloading. In the U.K. the maximum overload is specified as 50% for 3 hours with $0^{o}C$ ambient on the -5% tap which evaluates to 157% of full load current.

Since the thermal time-constant of the fuses is less than that of the transformer, the permissible overload period of the transformer should be taken as equivalent to that which produces a steady state condition for the fuse. Accordingly, the overload current should not be greater than the rated current of the fuse, modified if necessary by the effects of enclosure or ambient temperature. Where higher overloads for shorter periods are specified, especially when repetitive, then these must be considered carefully and the fuse manufacturer should be consulted to ascertain the necessary margin between the overload current and period and the melting curve.

c) Provide acceptably fast clearance of faults of limited magnitude such as arise from turn to turn faults in the h.v. windings or secondary terminal earth faults ahead of the secondary protection. With the secondary arcing faults, the volt drop in the arc may limit the fault current but the presence of the arc increases the probability of fire and thus is an important condition.

The value of a time-current characteristic as shown in Fig.1. can therefore be appreciated.

The U.K. supply industry has specified that a secondary terminal earth fault current should, after being reduced to 60% of the calculated value to allow for arc resistance, be cleared by the h.v. fuse in less than 100 seconds. although the preference is to reduce this time to as low a value as possible. Fig.7 shows the time-current characteristic of a 90 Amp oil-tight fuse of improved design which would be applicable to a 1000kVA transformer in the U.K. system. The secondary terminal earth fault current modified by the effect of arc resistance is shown to be cleared in 1.7seconds.

d) Discriminate with the secondary protection. Depending on the type of secondary protection employed, discrimination may not be achievable. This will generally be the case where a definite minimum time circuit breaker or main fuses are used. More common practice, however, is to use separate fuses for each distribution cable fed from the transformer. In these circumstances discrimination is possible. To determine whether discrimination will be achieved the virtual pre-arcing time-current curve of the h.v. fuse must be compared with the virtual total (pre-arcing plus arcing) time of the secondary fuse when plotted to the same current base, i.e. the transformer ratio must be taken into account. For a delta-star connection, the worst condition for discrimination is for a phase to phase fault on the secondary side which gives a 2:1:1 current distribution in the primary. Fig.7 shows time-current characteristics of h.v. and m.v. fuse-links, (plotted to the m.v. current base). Also included in the figure are the maximum through fault and the adjusted value of secondary terminal earth fault current.

<u>4.2. Motors</u>. The majority of applications involve direct-on-line induction motors with their characteristic high starting current of up to 6 times the motor full load current.

The first consideration for selection is that the fuse-link must be able to withstand repeatedly the starting current for the run up time of the motor which is normally in the range of 6 - 60 seconds. A common requirement is that a false start should be allowed for; this simplifies to selecting on the basis of the starting current for twice the run up time.

The passage of the starting current for the run up time represents an appreciable overload on the fuse and the elements experience a considerable temperature rise followed by cooling as the current falls to the running value. The associated expansionaand contraction of the elements causes increasing mechanical stresses during the cooling period until ultimately a mechanical failure may occur.

This aspect of performance has been improved significantly by modification of the fuse elements such that expansion can be accomodated during the heating period without the establishment of stresses during the cooling period. A typical life test made during the development of these "second generation" motor fuses was as follows.:

Fuse-link Rating 315 Amps Test Current 1300 Amps
Duty Cycle.

ON 10 seconds
OFF 4 minutes 50 seconds
ON 10 seconds
OFF 4 minutes 50 seconds
ON 10 seconds
OFF 19 minutes 50 seconds.

The above duty cycle repeated 7000 times (Equivalent to 21000 starts at 6 per hour) without measurable deterioration.

Life Tests similar to the above were made over a wide range of simulated run up times. The results make it evident that the necessary ratio between starting current and fuse melting current is sensibly constant over the range of times under consideration, thus simplifying application. The necessary ratio between starting current and melting current is approximately 1.8 to prevent ageing over a very long period of repetitive starting.

The frequency of starting must also be considered, Fig.8 shows the relationship between frequency of starting and fuse-link rating necessary for a given motor and starting conditions.

Where the drive horse-power demands a fuse-rating greater than that available in a single barrel, then paralleled arrangements may be employed. Much test data exists to prove the validity of such arrangements and no doubts need exist on the part of the user. The paralleling of fuse-links is merely an extension of the principle of using paralleled elements within a single fuse barrel.

For 'n' fuse-links in parallel, the total cut-off current for

Prospective current I_p will be 'n' x cut-off current for a single fuse-link with prospective current Ip/n.

The total I^2t appearing in the circuit components will be n^2x I^2t for a single fuse-link with prospective current Ip/n.

With assisted start motors a much lower fuse rating can be selected and for particularly light starting conditions the determining factor in deciding fuse rating may be the full load current and the effects of enclosure on the fuse current rating.

Fig.9 shows a typical application scheme. Co-ordination of fuse characteristic, motor relay characteristic and contactor breaking and through fault capacity must be considered to ensure the full spectrum of fault currents are covered.

4.3. Capacitors. The fuse rating is normally determined by the necessity to withstand inrush currents. The inrush current depends on many factors and specific data is not normally available, but empirical rules, based on many years of experience, are used and found to give reliable service.

Fuses may be used to protect the individual capacitor units or the bank overall.

To protect individual units from bursting due to internal faults, the fuse operation time and fault current must be considered in relation to the time current 'survival' curve of the capacitor unit tank.

In h.v. capacitor banks, the power frequency fault currents are often limited by the bank connections, as stated in Section 2.2. When calculating fuse operating times, no account is taken of discharge currents from healthy units into the faulted one, since although these normally occur and accelerate the fuse operation, it is possible for the unit to fault at a voltage zero, (i.e. zero stored energy) from such causes as vandalism. When overall protection of the bank is provided by line fuses this does not always afford protection against bursting of individual units.

5. EXAMPLES OF CRITICAL FUSE APPLICATIONS. Under certain and varied circumstances there is no practical or economic alternative to protection problems by means other than h.v. c-l fuses. Examples are given below.

5.1. Protection of Pad Mounted Distribution Transformers. There is a current problem in North America due to the eventful failure of pad mount and pole-top transformers caused by internal faults. Most of the transformers are protected by non current-limiting expulsion fuses and placed in high fault level systems. The transformer tanks are, compared with British and European practice, of lightweight construction and there have been occurrences where tanks have burst, spreading flaming oil over private property with the attendant possibility of personal injury. It has been demonstrated by tests

(Reference 1) that c-l fuses of up to 200 Amps rating limit the pressure build up and dynamic effects of oil movement to prevent such failures and this allows protection of 50 kVA transformers on a group fusing basis.

5.2. Protection of Large Generator Voltage Transformers.

It is not the practice to employ a circuit breaker between the terminals of 500 MW generators and the associated generator transformer in CEGB power stations. Generator V.T's, normally 4 per phase, are used connected to the generator - generator transformer connections. The fault level at this point is approximately 200kA. Fuse-links were developed for these V.T's and have been in use for many years.

Before acceptance it was necessary to prove their performance by a 'per-element' series of tests, since no testing station could provide a current of 200kA at the necessary voltage. It was also necessary to prove the capability of clearing the current which would cause operation in 1 hour.

References

1. A.A.Smith; A.C.Westrom; Controlling Dynamic Fault Pressures on Pad Mounted Distribution Transformers.

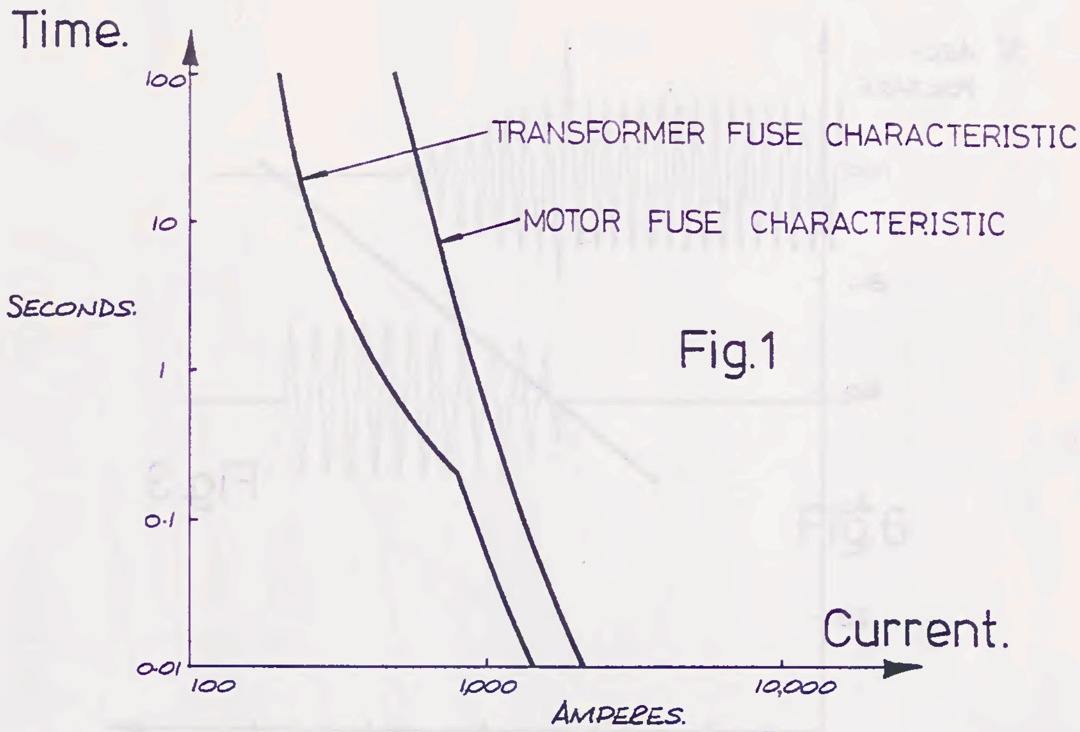

Time.
100
10
Seconds.
1
0·1
0·01
TRANSFORMER FUSE CHARACTERISTIC
MOTOR FUSE CHARACTERISTIC
Current.
100
1,000
10,000
Amperes.

Fig.1

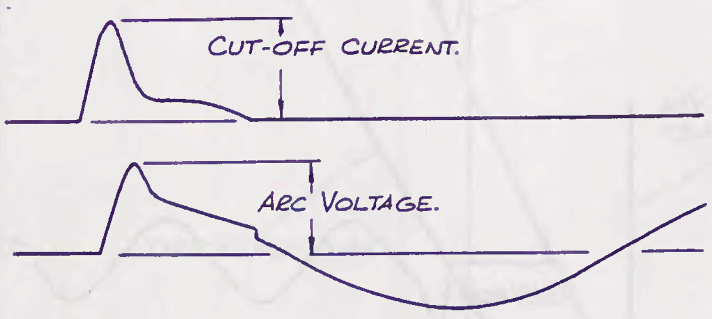

Cut-off Current.
Arc Voltage.

Fig.2

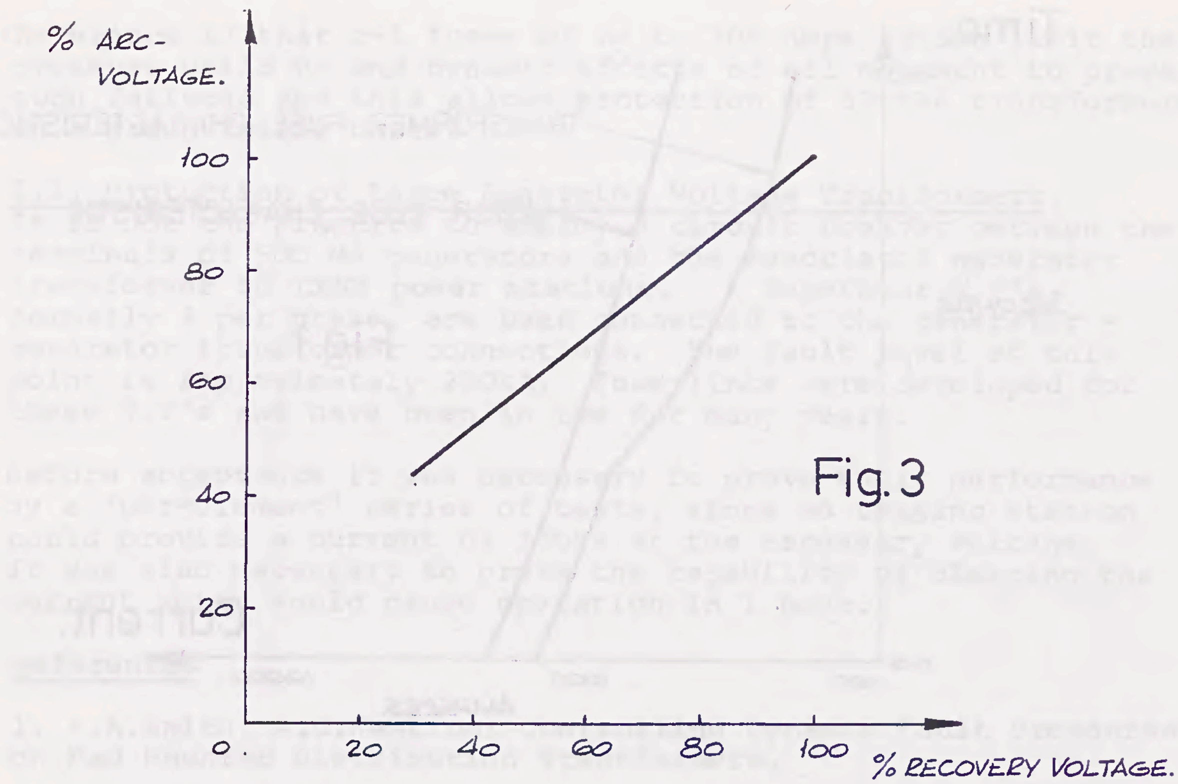


Fig.3

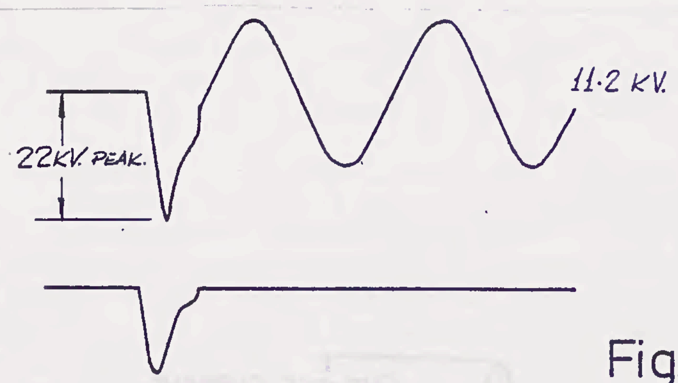


Fig.4

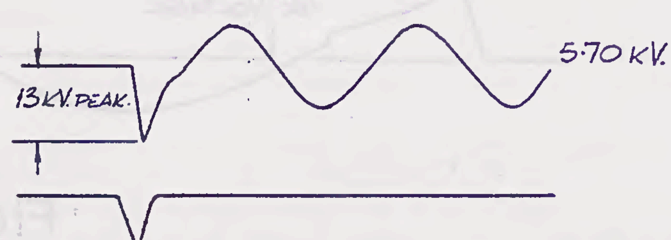


Fig.5

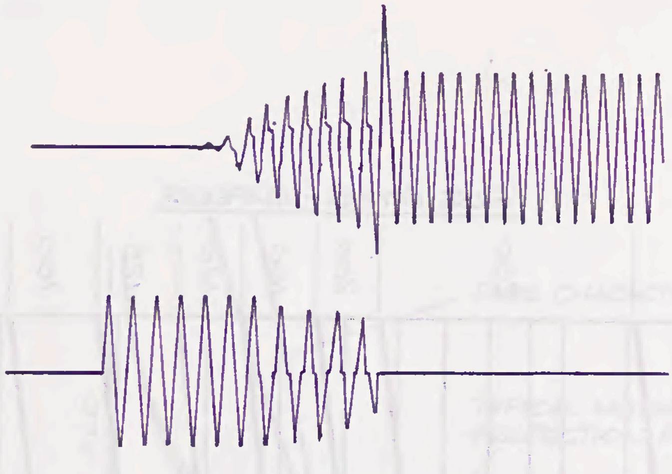


Fig.6

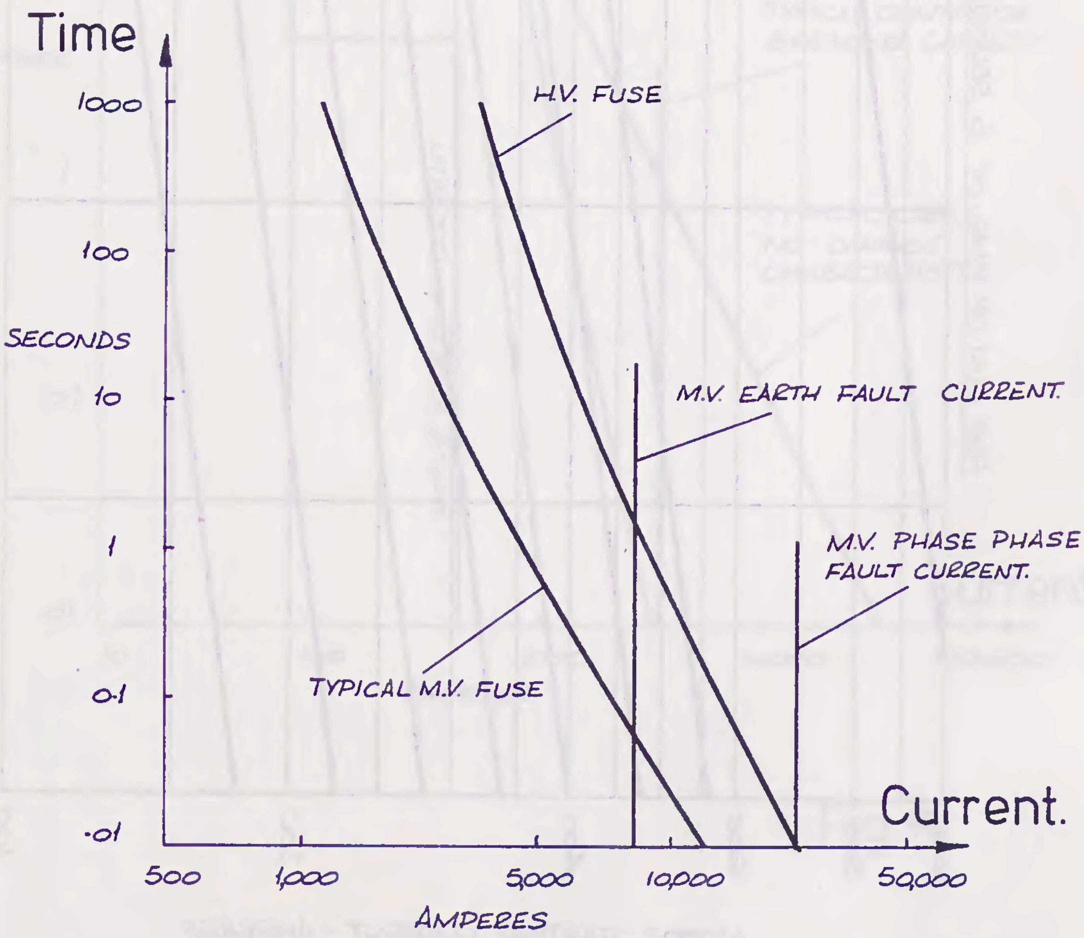

Time
1000
100
SECONDS
10
1
0·1
·01
H.V. FUSE
M.V. EARTH FAULT CURRENT.
M.V. PHASE PHASE FAULT CURRENT.
TYPICAL M.V. FUSE
Current.
500
1,000
5,000
10,000
50,000
AMPERES

Fig.7

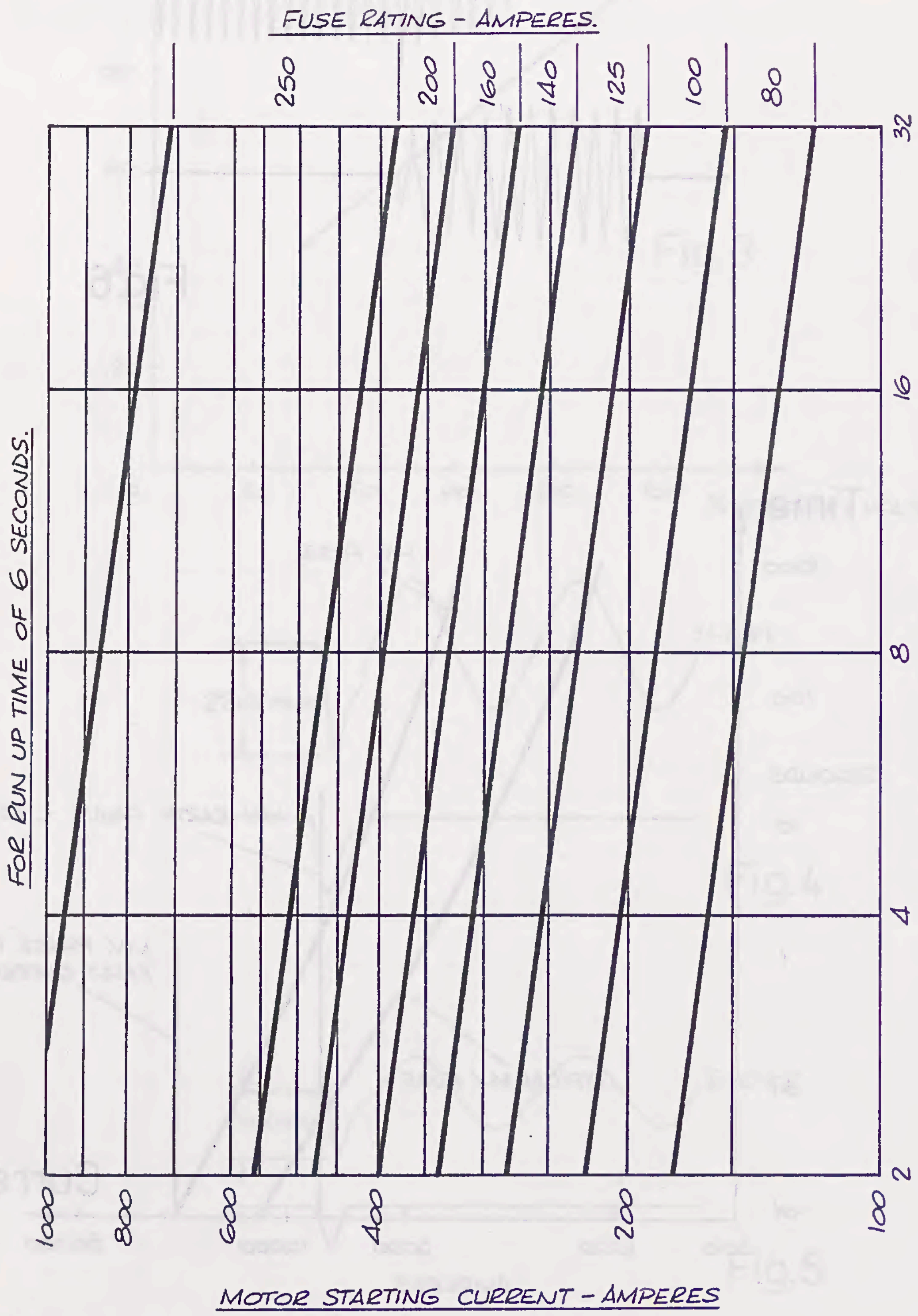

FUSE RATING - AMPERES.
250
200
160
140
125
100
80
FOR RUN UP TIME OF 6 SECONDS.
No OF STARTS PER HOUR
32
16
8
4
2
1000
800
600
400
200
100
MOTOR STARTING CURRENT - AMPERES

Fig. 8

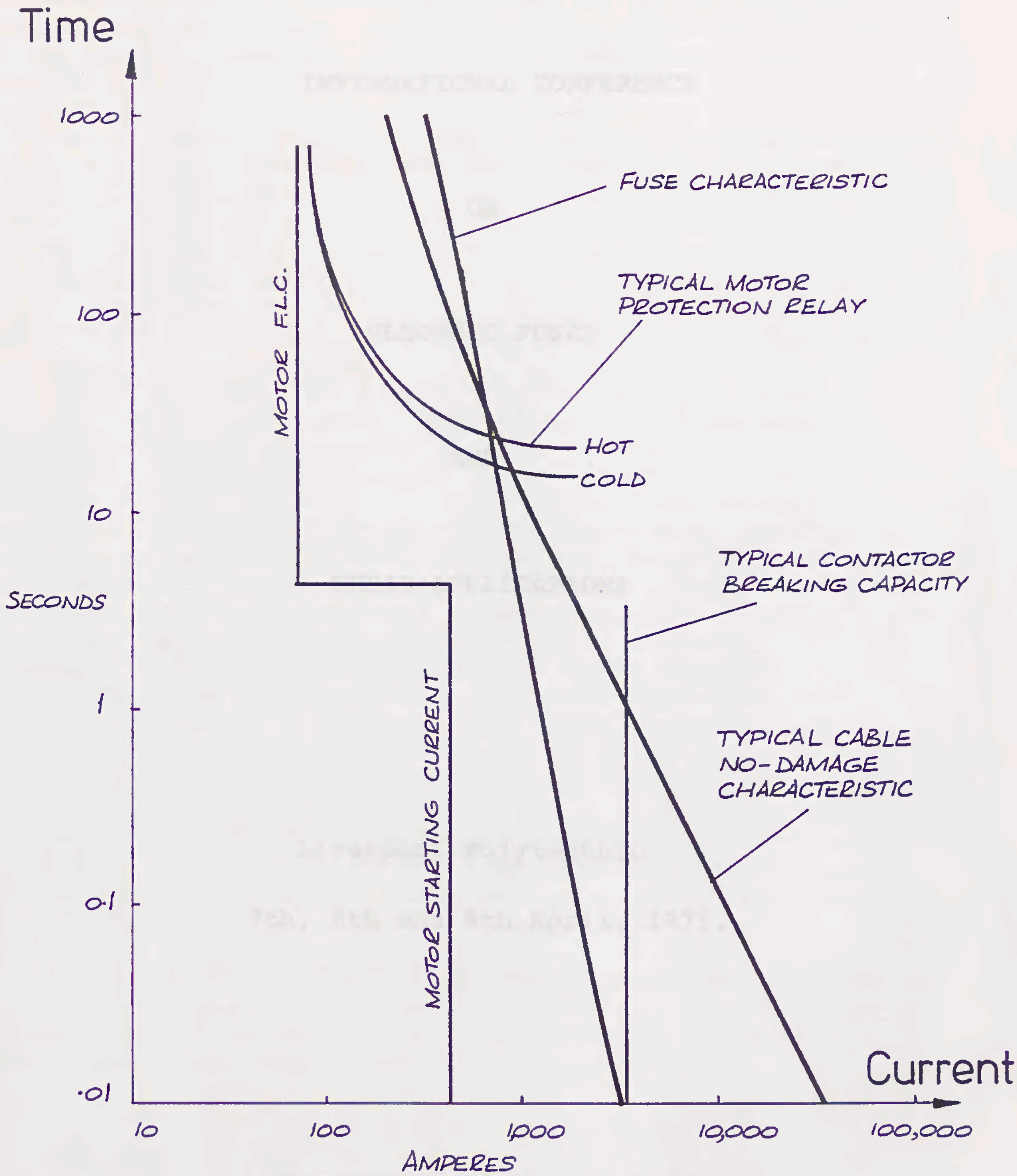

Time
1000
100
10
SECONDS
1
0·1
·01
MOTOR F.L.C.
MOTOR STARTING CURRENT
FUSE CHARACTERISTIC
TYPICAL MOTOR PROTECTION RELAY
HOT
COLD
TYPICAL CONTACTOR BREAKING CAPACITY
TYPICAL CABLE NO-DAMAGE CHARACTERISTIC
Current
10
100
1,000
10,000
100,000
AMPERES

Fig. 9

INTERNATIONAL CONFERENCE

ON

ELECTRIC FUSES

AND

THEIR APPLICATIONS

Liverpool Polytechnic

7th, 8th and 9th April, 1976.

Transcript of Discussions

SESSION 1. Wednesday, 7th April, 11.00 - 12.15.

PREARCING PHENOMENA

Session Chairman: Dr. A. Wright
(University of Nottingham).

Paper No.

2 "Steady-state thermal phenomena in fuses with variable cross-section", by I. BARBU.

3 "Survey of numerical methods for solving time-varying fuse equations", by P.M. McEWAN and L. WARREN.

4 "A decoupled method for predicting time-current characteristics for h.r.c. fuses", by P.M. McEWAN and R. WILKINS.

5 "The influence of the temperature coefficient (TC) on fuse discrimination", by Y. NAOT.

6 "Deformation and disruption of silver wires", by S. ARAI.

Mr. H.W. Turner

First of all I would like to ask Dr. McEwan for his opinion on the best way of estimating the thermal conductivity of quartz for these purposes. It is well known that tiny amounts of moisture give enormous differences in thermal conductivity. Sand, as used in fuses contains some moisture, and transport of that moisture results in a distortion of the thermal conductivity of the material which must affect the long-time behaviour.

Has Dr. McEwan thought of using his digital techniques in other fields? e.g.: looking at fuses from the other point of view; of attempting to discover the possible variations in time-current characteristics that are theoretically possible by varying the geometry; or possibly using the same techniques to solve the problem of association of fuses with other heat-producing units - cables in series, other thermal devices inside a box and so on - the problem of calculating the temperature rise of a combination of electrical devices either in series or within an enclosure.

On p.48 Prof. Naot gives 'hot' and 'cold' characteristics. In investigations which I have carried out on practical fuses, on the effects of preheating, differences of this magnitude, below 1s, I don't generally find in industrial l.v. fuses. For example in this region an operation of M-effect, if it exists, or a dual-element operation if it exists, is not activated, and that means, therefore, that you are on the region where the element is melting at the constriction. This is at a much higher temperature, and thus the small heating that resulted from the element running at its rated current is insufficient to make appreciable difference to the performance in the short-circuit area. If you calculate the temperature of the constriction, typically 100 - 200°C, and you allow for the reduction in I^2t to produce that small rise in temperature, it makes little difference to the prearcing I^2t of the fuse. Is Prof. Naot considering a plain single element fuse, where the effects of preheating are much greater, because if for example it is a silver wire fuse it is going to melt at 960°C or thereabouts no matter what range of current. But if it has an M-effect then it's going to be around 200°C that that spot is going to melt whereas the element will melt at 960°C in the short-circuit region.

I would be most grateful if Mr. Arai could elucidate further on the arc jets which he shows in his photographs on p.56 and I would be interested in his comments on the final appearance of the X-ray of the fulgurite in the location of these jets.

Dr. R. Wilkins

I have a brief comment on Dr. Barbu's paper, and wish to clarify the differences between numerical methods of solution and analytical methods. In our paper we have concentrated upon numerical methods because these are the only methods which we can use to solve the complicated system of partial differential and ordinary differential equations which represent the prearcing behaviour of an electric fuse. Numerical methods are necessary to represent all the complex geometries and non-linearities involved. However numerical methods do have one disadvantage, and that is that it takes a long time to get results for the very large problem which we get when we represent a fuse. It would be nice if we could have an analytical solution, but this is a mammoth task, and I would like to congratulate Dr. Barbu on his efforts in this direction. Dr. Barbu obtains an analytical expression which is so complicated that he needs a computer to evaluate the expression, but it is important to realise that this is a fundamentally different use of the computer from that described in our paper.

Dr. K. Lerstrup

I found it very interesting that Prof. Naot finds some benefit in a negative temperature-coefficient. However if we try to employ that we should lose the very great benefit we have from the positive temperature-coefficient. Normally if something heats up we have the simple exponential rise of temperature to a steady-state value. But with a positive temperature-coefficient we can get to the point where the increase in resistance just keeps up with the higher cooling and then we have a linear increase in temperature with time. If we go to a little higher current, then we can obtain an exponential runaway of temperature - and this is the great advantage of our fuses.

The ordinary operation of a fuse, just a little below the limiting current will be at a temperature so much lower that it really does not matter very much. The so-called 'hot' curves thus have very little significance in practical work. However, the 'avalanche' effect of the positive temperature-coefficient gives very decisive operation, even if we neglect the M-effect.

For an ordinary silver fuse it only requires a current of about 1.3 times the m.f.c. to get a 'straight-line' increase in temperature. Any current greater than this will produce a positive-exponential effect and give very decisive operation. This is what we live on, and if we lose it I don't believe we will have a fuse any more.

Prof. T. Lipski.

Among many very important papers, for me the most important is that of Mr. Arai. From Fig.5 of his paper, I got the current density at the moment of wire disruption to be 14 kA/mm^2 while from Fig.6 the values were 4.8 kA/mm^2, 10 kA/mm^2 and 12 kA/mm^2. We may conclude that these values of current density are in good agreement with those which we can get from Mr. Nasilowski's paper in the region which corresponds to the striated formations, (not unduloids). Does Mr. Arai agree that this is the striated region? - in my opinion it is.

Could Mr. Arai give us some more detail concerning the model of the striated disintegration mechanism? We are interested to learn whether figures we have obtained in Poland agree with those obtained by Mr. Arai.

My last question to Mr. Arai is the same as that put by Mr. Turner.

Dr. J.G. Leach

I would first of all like to make some comments on the two papers by Dr. McEwan, since my own work is referred to. Concerning the choice of the best numerical method for analysing the heat-flow within a fuse, I didn't spend a vast amount of time deciding which method was the best and quickest, I spent the time producing results, which were useful to me. Mr. Turner has asked whether other uses of the program had been made - this is what I was concerned with, the program was used as a tool to analyse fuses and so to produce better fuses. I have in fact published work on the comparison of a fuse connected to a cable, and the effect of the size of the cable on the current rating of a semi-conductor fuse. It is in these sorts of areas where the numerical method is extremely useful, as well as producing an understanding of how the fuse operates.

Concerning the decoupled method described in the second paper, I would like to confirm that this method is very useful - I have been using it for about four years - for times up to about 10s, depending upon the size of the fuse.

I found Prof. Naot's paper very interesting, even though it is a little controversial. It is very important at conferences like this for something new to be introduced, and this is certainly something new. Having prefaced my comments with those words I now have to stand in the fuse manufacturers position, and I am at odds with Prof. Naot's conclusion that a large number of cases occur where discrimination is unsatisfactory because of preloading. I think that the form of analysis used by Prof. Naot has led him to this conclusion. He began with a rather simplified treatment of the heat flow (which is always necessary if analytical methods are used) and took a very theoretical fuse with no M-effect. This means that at rated current the element temperature can be very high - I worked out that on Prof. Naot's assumptions an element with a melting temperature of 1000°C should be expected normally to run at about 600°C. Obviously this is what leads to the discrimination problem, because if the large fuse is running at 600°C and the small fuse is running cold it takes the small fuse a long time to 'catch up' with the large fuse. In practice fuses do not run with such high element temperatures, and the presence of the M-effect will completely alter the picture as far as discrimination is concerned.

Mr. E. Jacks

I would like to make one or two general remarks. I applaud the motivations behind these papers, which I recognise as being largely academic papers, but I do not entirely appreciate the motivation since the authors have not stated it clearly in the introduction. I hope that in the subsequent discussion the authors will answer the questions: Why have they done this work? What was their motivation? McEwan and Warren say that it would be a good thing to predict time-current characteristics without having to do a lot of expensive testing. Of course I agree with them and I think that they have gone a long way towards achieving that objective. But I think that they have'nt gone the whole way and it should be stated in proper context exactly what they are trying to do. Do they for instance want to calculate the time-current characteristics of existing fuses, or do they wish to assist the development of new designs?

Similarly with the paper by Dr. Barbu. When the specialised academic exercise gets down to such narrow parameters as chosen by Dr. Barbu , he should be able to explain, in the context of fuse technology, just where he is hoping to make a useful contribution. After all, fuses are not produced as an academic exercise, they are produced for a job of work in the world outside.

I agree with Dr. Lerstrup and Dr. Leach concerning the paper of Prof. Naot, in that failures of discrimination are due to external forces which he has not investigated. Nevertheless the ideas that he propounds are stimulating and should be taken seriously. I haven't studied this paper in sufficient detail to be able to comment other than in general terms, so I would return to my original plea - would the authors please, for the benefit of us ordinary fuse engineers, who learned our mathematics so long ago that we have now forgotten them, put these papers into context so that we may know how these papers are useful and what contribution to practical fuse technology is intended.

Mr. R. Oliver

Following on from what Mr. Jacks has said, we have seen in the papers that numerical techniques do yield accurate time-current curves out to about 10s and I would like to ask the authors of the papers on numerical methods what they foresee as regards the analysis of pulsed-loading conditions. This requires the calculation of temperature profiles for pulsed loads which may range from milliseconds to many minutes. Can numerical methods be used for this purpose? What experimental techniques could be used for verifying that the calculated temperatures are in fact the true ones, bearing in mind that these temperatures would be well below the melting point.

Mr. J.W. Gibson

Have the authors verified any of their results experimentally, e.g. by the use of temperature-indicating paints, which nowadays are far more accurate than they used to be?

Mr. J. Feenan

To what extent have the authors of the papers on numerical methods considered the question of mechanical fatigue? We know that on pulsed testing, the effect on the time-current characteristic is distinctly different from that of one-shot testing. This is a problem of interest to many people in this room, and I would ask for the authors' observations on this.

Dr. P.M. McEwan (in reply)

I would like to answer Mr. Jacks' questions first of all, as these are at the root of the work. Apart from the interest in academic studies, the reason for developing numerical methods was that we foresaw that these could be an aid to the fuse designer, because numerical methods permit the possibility of varying the parameters of the fuse and seeing how the fuse performance changes. For instance, one can examine any sort of element shape, and see its influence on the time-current characteristic. Also one can vary filler, length of fuse, etc., so this does give the designer an opportunity to see how the fuse performs before he goes on to the shop floor to get it constructed, and then to have it tested. I think that that is clearly an aid.

I detected, maybe wrongly, that Mr. Jacks thought that we were trying to replace existing testing of fuses, by predicting the time-current performance numerically and saying let's do away with traditional tests. If this be so then it is not the case.

Mr. Turner refers to the variation of the thermal conductivity of the filler with moisture content, compacting and temperature. I agree that the thermal conductivity does vary with changes in these parameters; however, I think that his remarks are particularly important for loose fillers, soils, etc. In the fuse we have a different proposition. We have a compacted filler. There is admittedly some moisture content initially (I think 7% is a typical figure), but after the fuse has been made up, tested, and possibly used, then I doubt whether there is anything like that amount of moisture present.

My view on the measurement of thermal conductivity is that principally we are concerned with the performance of the filler in fuses, so we must derive values of thermal conductivity for the filler actually in the fuse. I have developed a method for obtaining the thermal conductivity of the filler numerically. The method is based upon wires in filler - but I would like to leave this topic to some future discussion.

Another point raised by Mr. Turner was the extent of the use of fuse numerical models. I would say on this point that we do not understand the thermal behaviour of the fuse-diode combination and cannot predict its performance. We also lack coordination experience with fuse/thyristor combinations in regard to thermal performance. Numerical methods offer potential for predicting this thermal behaviour because I envisage that it is not beyond the power of the methods we now have to simulate the thyristor and diode in the same way as the fuse. The two can be connected together numerically, the whole performance simulated, and coordination rules obtained.

Regarding Mr. Oliver's comments on pulsed loading, these programs offer similar potential for such solutions also. We can alter the sorts of input currents to the fuse, and see how it performs. He also asked whether we have any experimental results to justify the predictions of temperature along the element. Mr. Gibson also asked this, and whether temperature-indicating paints had been used. I have not used these paints although I know of them; they have been used for quite a time, but I don't think that they are appropriate for the temperatures which we are concerned with because the notch temperature is really the important value to consider and there are great difficulties in obtaining this accurately using indicating paints.

My view is that the important aim in fuse studies is to predict how the fuse operates. It is interesting to know the temperature values and it is also very nice to have the temperature distribution, but we are principally concerned with predicting how it operates, and this has been our main concern. So I don't judge this as being too important - i.e. to actually know the temperature values within the fuse. The final steady-state temperatures we do wish to know, but this requires a separate analysis. Dr. Leach and myself have such programs.

<u>Prof. Y. Naot</u> (in reply)

Before I answer specific questions, may I give some general comments which may answer many of the questions which have been asked.

My paper is intended first of all to clarify some general concepts, and that is why I considered a fuse with constant cross-section, and used many simplifying assumptions.

In reply to Mr. Turner I think he is right in that, for very high currents (very short times), the difference between hot and cold characteristics becomes less important. The difference is far more important for low overcurrents.

I agree with Dr. Lerstrup that we lose one important advantage of the positive temperature-coefficient. Nevertheless I disagree with him in this way. If we go into the runaway period with 30% more than the rated current, it means that the rated current has to be at least 30% less than the theoretical current which melts the fuse. That will give one very important consequence. The deviation factor of the fuse is smaller, the lower the current, but with long melting times the difference between hot and cold characteristics is much higher and this will give a smaller probability of selective action. So on the one we win something, but on the other hand we lose the possibility of having the two characteristics close together. My intent was not to say that we must throw away positive-coefficient fuses, and use only negative temperature-coefficient fuses. Rather it was to say that besides the positive temperature-coefficient fuses, it would be useful to have also negative-temperature-coefficient fuses. My challenge to physical chemists to produce such a material was more or less an academic challenge, but this does not mean that I do not have my ideas on how to solve this problem. I did not put my ideas in the paper because I do not yet have the experimental results.

Mr. S. Arai (in reply)

The first question was about the disintegration photographs on the right of page 56 (e). I believe that the photographs show jets, as suggested by Mr. Turner.

As regards the relation between the striation of fulgurite and the deformation, the deformation is very fine, (short-pitched) but after arcing has continued for some time the arcs unite and then you can see striations on the fulgurite. The striation pitch is then larger than the initial disintegration.

In reply to Prof. Lipski, I am not sure but I believe that the striations correspond to those of Mr. Nasilowski, and they are due to small disfigurations which merge into one, and then sand striation appears.

In reply to Mr. Jacks, we believe that our experiment is not directly connected with fuse design, but the fuse designer may find some hint from our experiments.

Dr. R. Wilkins (in reply)

I would like to reply to Mr. Feenan's question concerning mechanical fatigue, which I believe is tied up with the issues raised by Mr. Jacks. The answer is that we cannot at present simulate mechanical fatigue, but the techniques developed will enable us to proceed in that direction if this is desired. In order to make reasonable predictions of mechanical fatigue it is essential to know the transient temperature distribution along the fuse-element, during any cyclic loading condition.

The numerical methods which have been developed can be used for a variety of purposes. To put them to practical use requires close collaboration between those who Mr. Jacks calls academics and those involved in fuse manufacture. The object of the work as far as we were concerned was to find out how far we could go in the prediction of temperature distributions with practical fuses. Prediction of the pre-arcing behaviour is also a prerequisite for the simulation of the total performance of a fuse. If you want to simulate a complete interruption you must begin with the prearcing period. We believe that we can now do that fairly accurately, and it seems logical that the next step should be to add a simulation of the arcing process. We would then have at our disposal techniques for simulating the complete operation of a fuse, and this would not seem to me to be a bad thing.

The use to which such a program would be put is a matter which must be decided by discussions between academics and manufacturers.

SESSION 2. Wednesday, 7th April, 14.00 - 15.15.

DISRUPTION AND ARCING PHENOMENA

Session Chairman: Dr. K. Lerstrup
(LK-NES, Denmark).

Paper No.

7 "Overvoltages produced by fuses", by J. PAUKERT.

8 "The calculation of overvoltage characteristics of HRC fuses", by J. HIBNER.

9 "The role of fuse filler in circuit protection", by H.W. TURNER and C. TURNER.

10 "Arcing phenomena in HRC fuses under varying test conditions", by P. ROSEN.

Mr. J.W. Gibson

I would like to ask the authors of the first two papers whether they have any experience of the following phenomenon.

If you have a fuse with short and deep recesses the rate of increase of the arc voltage depends upon the rate of burning back of the element. That rate, as can be shown both experimentally and by calculation, is dependent upon the product of the current density and the sum of the anode and cathode drops, for all the arcs in series. However, when the current density is very high, another phenomenon can come into the picture, i.e. that before arc extinction has been completed, the unmelted parts of the silver are melted, not by burning back, but by the I^2R in the silver itself. This is because the rate of burning back is proportional to current, and the rate of heating is proportional to the square of the current. The result of this is that you are likely to get a sudden increase in the arc voltage. Could the authors of the papers on arc voltage quantify those results?

Concerning the paper by the Turners on fuse filler, what alternative fillers can they suggest? I remember that on one occasion, I went to the library and got a lot of physical tables, to find the ideal fuse filler. I thought it should be one with a high thermal conductivity, because I thought that would abstract heat better, and so increase the arc voltage. In addition it should have a high specific heat, a high latent heat of fusion and a high melting point. Having found such a material I tried it and found that it was no use, possibly because it contained impurities. Can the authors suggest their ideal material? Quartz was used in the beginning because you use sand to put out fires, but are we reasonable in continuing to use it? Crystalline quartz has one disadvantage, that its expansion with temperature occurs in nasty jumps and you may reach a condition where the barrel will burst. That trouble can largely be overcome for steady currents by using the M-effect, but it doesn't follow that the effect does not occur when the fuse operates under heavy fault conditions and transmits heat from the fulgurite to the unfused part of the filler. Do the authors have any comments on this?

As regards Mr. Rosen's work, my question refers to the rather unusual patterns of the places where melting occurs in the transition region. Does the author think that this can be due to fortuitous very small inaccuracies in manufacturing I have seen this effect myself and have only been able to explain it on that supposition.

Can the author also comment upon the fact that when a fuse operates on a small overcurrent, the last element to clear shows arcing at many more restrictions than was evident for the first element to melt. In other words, the fuse then seems to be operating in a current-limiting mode, as can often be seen on an oscillogram, where the final loop of arcing is accompanied by an overvoltage which is of the same order as that obtained at higher currents. Can the author say how this phenomenon is related to the number of elements in parallel?

Mr. W.R. Crooks

Referring to the Turners' paper I would request an expansion of a remark made on page 84, that '....... studying arc behaviour by means of transparent plates does not give a true picture of behaviour in a porcelain barrel.....'. In particular, would they suggest that if allowance is made for the reduced ability to absorb arc energy since the element is now a one-sided one as far as the energy exchange process is concerned, the observed behaviour is representative of the two-sided behaviour of elements in the practical case?

The Chairman in his opening remarks, suggested that the rated voltage of a fuse is the highest that the sales peoples think they can get away with. If I could add to that one the condition that the fuse then meets the type tests as laid down in the appropriate specification it is probably a good place to start.

I would like to ask Mr. Rosen to expand upon his reasons for using a rather larger than normal spacing for the restrictions, to prevent the merging of arcs. I would have thought that merging of the arcs is an important aspect of the behaviour, from a practical viewpoint. To have an element which does not allow the merging of arcs is uneconomical in design. On his conclusion 6.2, I question that the prearcing time is the significant parameter. Surely the behaviour is dependent upon current and voltage, the voltage in turn being dependent upon the properties of the arc path. The prearcing time is a dependent variable, related to the current.

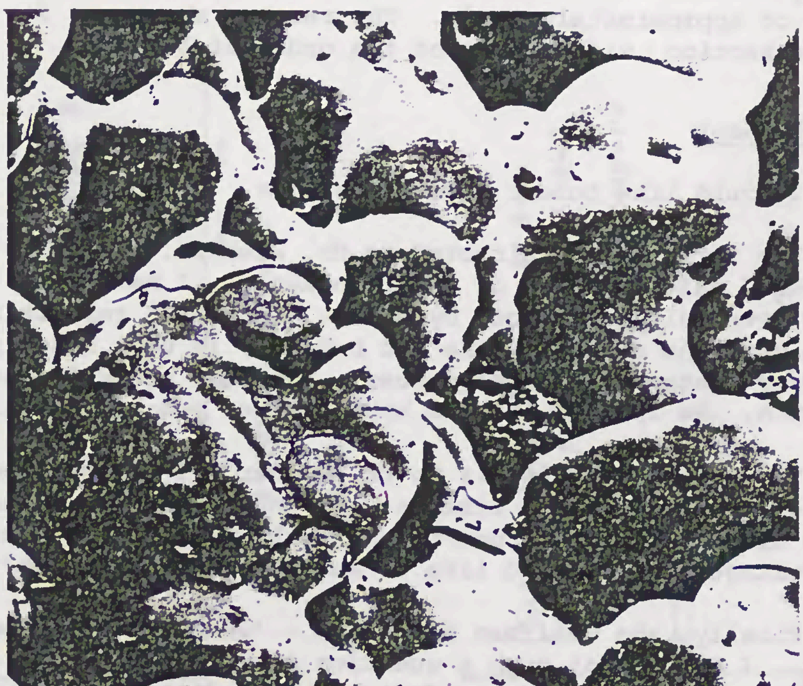
On the film showed by Mr. Rosen, I noticed that at low current levels, on two or three occasions an arc burned on one restriction for perhaps 3 or 4 loops and was then followed by the establishment of 2 or 3 more arcs in a very short time. My question is - why the very large difference in time between the first restriction melting and the subsequent ones?

Dr. R. Wilkins

I can't understand Fig.4 in the Turners' paper; what is the time-scale on this figure, which appears to show an oscillating behaviour of fulgurite resistance?

I would like to show some slides which illustrate some of the points made in the paper. These are pictures of fulgurite from a high-voltage fuse, taken on a scanning electron microscope by Dr. J.K. Critchley of Brunel University. The difference in contrast is due to a difference in electrical conductivity, not colour. Non-conducting regions become charged under the microscope and appear bright on the image, so the dark regions are regions where silver has been deposited on the surface of the quartz particles.

Exterior surface, X25.



Interior surface, X100.

Mr. K. Lerstrup

In connection with the pictures shown of the fulgurite I would like to mention the work of Dr. Huhn, who has considered the formation of the fulgurites, the evaporation of the silver, coming out and, more or less, blocking, and starting melting, thereby making an enclosure, in which we get an increase of pressure. Dr. Huhn's name is not mentioned in the reference to the papers, but I think his work is worth studying.

Dr. P.M. McEwan

With regard to the Chairman's remarks in his opening address on adiabatic melting, and Mr. Turner's paper upon the effects of filler on prearcing performance, I have several figures which I would like to show. The figures show both experimental and calculated I : t_m and I^2t results for notched fuse elements.

An interesting point to note from Fig.1 is that the computed points were determined using the numerical model which was discussed this morning. From the figure one can see a significant departure from the experimental results after 0.03s. The calculated results shown were determined with the thermal conductivity of the filler assumed zero, in other words, neglecting the effect of the filler, thus I think sand filler starts to play a significant role in fuse melting for prearcing times exceeding 0.03s.

On the question of adiabatic melting of notched elements it may be shown using a numerical model that adiabatic melting can only occur in very short melting times. Fig.2 shows calculated values for different switching angles from which it can be seen that as prospective currents increase the melting I^2t tends to the adiabatic melting I^2t for a notched element, as one would expect.

Plotting the same results against melting time, (350 is the adiabatic melting I^2t for this element), it can be seen that adiabatic melting occurs in a time of approximately 10^{-4}s. The results shown are for an element with a reduced section : width ratio of the order of 1 : 4.8.

Prof. Y. Naot

I would like to ask three questions.

The first one is directed to Mr. Paukert. It seems to me that you considered only one part of the phenomenon. I have many times observed that by the over-voltage induced by a fuse there is a restriking of a new arc, not only in the region of the arc but also in some other part of the plant with very destructive consequences. This new arc will change your calculation very much. So I would like to know whether you have considered this.

The second question is to Dr. Hibner. I enjoyed reading your paper but I could not find the link between your calculations and the inductance of the circuit. This is one of the most important parameters which induce over-voltages, so I would like to know where is the link?

Finally, the Chairman has asked - 'what is the rated voltage of a fuse?'. I think that such a question cannot be answered in a simple sentence. You first have to define the condition of the circuit which has to be protected. Then you can define the rated voltage as that voltage at which it can interrupt in 99% of cases.

Dr. P.M. McEwan

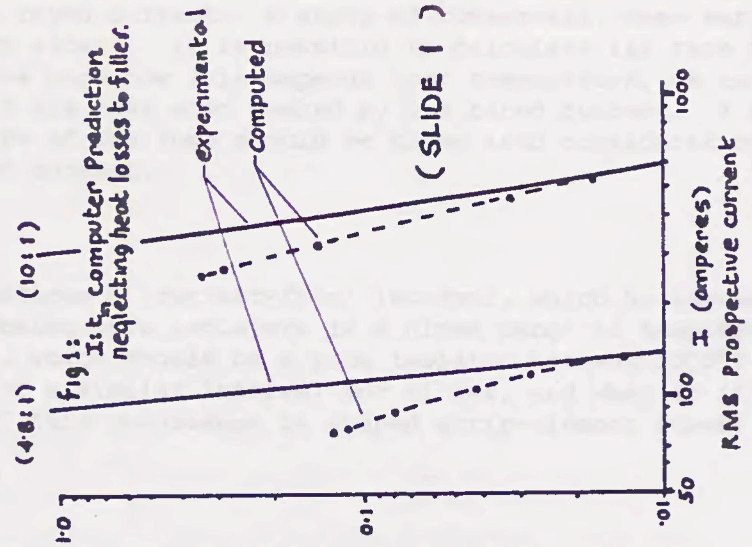


fig 1: I:t_m Computer Prediction neglecting heat losses to filler.
(4.8:1)
(10:1)
Experimental
Computed
(SLIDE 1)
t_m pre-arcing time (secs)
1.0
0.1
.01
50
100
1000
I (amperes)
RMS Prospective current

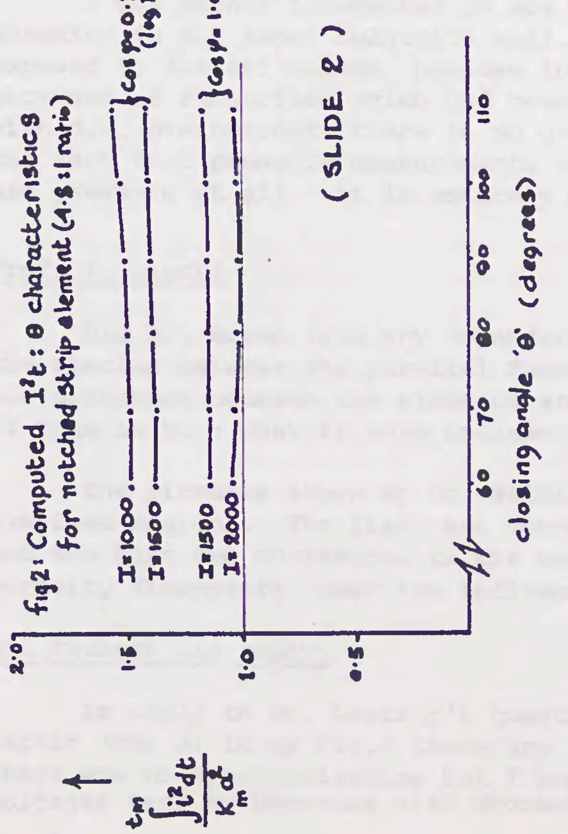


fig2: Computed I²t : θ characteristics for notched strip element (4.8:1 ratio)
I=1000
I=1500
I=1500
I=2000
Cosφ=0.3 (lag)
Cosφ=1.0
(SLIDE 2)
2.0
1.5
1.0
0.5
60
70
80
90
100
110
closing angle 'θ' (degrees)

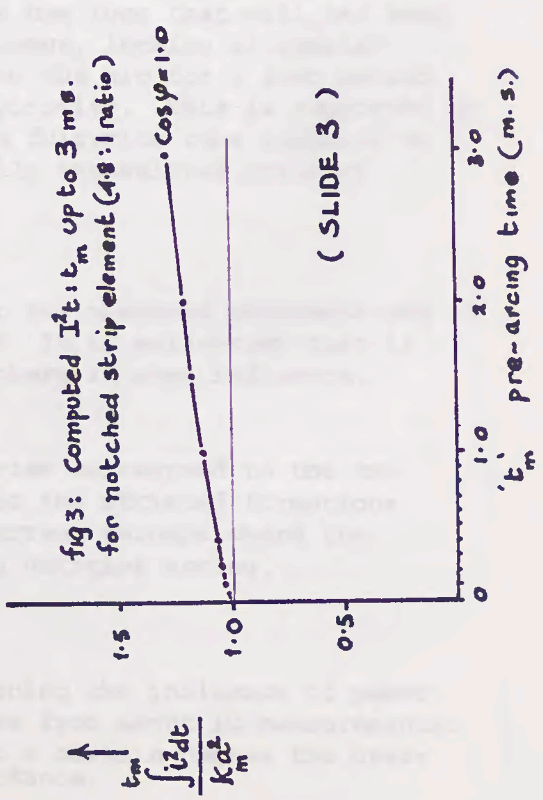


fig3: Computed I²t : t_m up to 3 m.s. for notched strip element (4.8:1 ratio)
Cosφ=1.0
(SLIDE 3)
1.5
1.0
0.5
0
1.0
2.0
3.0
't'm pre-arcing time (m.s.)

[illegible]

In connection with the [illegible] I would like to mention the work of Mr. [illegible] the [illegible] of the [illegible] [illegible]

[illegible]

[illegible] the figures [illegible] have been [illegible] for [illegible]

[illegible] the computed points were determined [illegible] from the [illegible] results [illegible]

[illegible] adiabatic [illegible] it can be seen that [illegible] the adiabatic [illegible]

Plotting the same results against [illegible] the adiabatic [illegible] it can be seen that [illegible] occurs [illegible]

[illegible]

[illegible] would like to [illegible] discussion.

[illegible]

The second [illegible] is [illegible] Mr. [illegible] [illegible]

[illegible]

But I wonder why you did not ask another question - 'What is the rated current of a fuse?' - this is a far more intriguing question. The only thing you know, scientifically speaking (if you look at the rules of IEC it is very simple to define the rated current), but scientifically speaking, all we know is that it must be less than the minimum fusing current. But how much less? I am not able to give you formula, but I am able to suggest a way to determine the rated current. A strip of fuse-metal, when very hot, evaporates very, very slowly. It is possible to calculate its rate of evaporation, and if we know how this depends upon temperature, we can calculate the life of the fuse when heated by its rated current. I suggest that the expected life of the fuse should be taken into consideration when determining the rated current.

Mr. O. Norhølm

Mr. Paukert mentions a 'current-free' interval, which he assumes is caused by the metal vapour being pure isolators in a given range of temperature. He mentions only copper, which should be a pure isolator between 2300°C and 3500°C. Is the author aware of a similar interval for silver, and what is it? Has he ever seen evidence of this phenomenon in shaped strip-element fuses?

Mr. R. Oliver

I am interested in the 'thermite' effect with aluminium mentioned in the Turners' paper. I've heard about it before, but seen nothing quantitative. It sounds a rather dangerous process to me, with respect to aluminium-element fuses.

Concerning the transmission of mechanical pressure by sand, all the evidence I have found on the transmission from the fulgurite (arc) column out to the body wall indicates that the mechanical thrust is transmitted directly via the sand, perhaps with some preset involved, where the grains slide and take up a set position, but thereafter there is a direct relationship between the arc column pressure within the fulgurite tube and the pressure detected at the body wall which can be largely accounted for by the geometry of the fulgurite and the ceramic tube.

I was rather interested to see that in Dr. Wilkins' photographs there was porosity in the inner fulgurite wall. I wonder how long that wall had been exposed to the arc column, because in my experience, looking at similar pictures of fulgurites which had been exposed to the arc for a long period with d.c. overcurrents there is no detectable porosity. This is supported by the fact that pressure measurements outside the fulgurite tube indicate no gas pressure at all - it is entirely mechanically transmitted pressure.

Prof. T. Lipski

Did Mr. Rosen find any dependence between the observed phenomena and the spacing between the parallel fuse elements? It is well-known that if the distances between the elements are small, there is some influence. If this is so - what is this influence?

The pictures shown by Dr. Wilkins in my view correspond to the two overload regions. The first set corresponded to the striated formations and the last two correspond to the small overcurrent perhaps where the porosity disappears under the influence of long duration arcing.

Mr. Paukert (in reply)

In reply to Dr. Lertrup's question concerning the influence of power factor (cos ø) in my Fig.8 these are mean values from about 10 measurements. There was no synchronisation but I hope that to a certain degree the over-voltages tend to decrease with decreasing inductance.

In reply to Mr. Gibson the answer is that I have not made such experiments, to check the speed of burning up of the fuse element. However, in Czechoslovakia current-limiting fuses are used which have the cross-section of the restriction about 10% of the cross-section of the whole, and we have not observed any excessive burning up of the fuse-element.

I think that Prof. Naot meant that if a fuse is correctly constructed, restriking cannot occur. It is known that the filler is influenced to a thickness of about 2 mm, and if the fuse is constructed so that the elements cannot go nearer than 2 mm to the wall, restriking cannot occur.

To the question of Mr. Norhølm, I think that the current-free interval exists with silver too, but I cannot give any exact range. To my knowledge, such phenomena have not yet been observed in fuses.

Prof. T. Lipski (in reply for Dr. Hibner)

The effects of the arc burning back after initial arc ignition does not appear in Dr. Hibner's paper. The method is concerned only with the moment of arc ignition. That is one point, but the main point is the fuses considered by Dr. Hibner have long notches, where arcs are initiated along the whole length. You may have only one strip or one wire, of uniform cross-section. This method is not a universal method; it is not possible to use this method for instance for the notches which we have in semi-conductor fuses.

Coming to Prof. Naot's question concerning the link between the inductance of the circuit and the overvoltage. There is such a link. Generally speaking, this method is valid only when $\varepsilon > 25$ W-s/mm^3 (equation (2) on page 72), i.e. the electro-magnetic energy stored in the circuit should be greater than 25 W-s per cubic millimeter of element. That is the relationship between the magnetic energy and the design. In transformed form, you can see the same value on page 74 for the d.c. characteristic and on page 73 for the a.c. characteristic.

Dr. C. Turner (in reply)

In reply to Mr. Gibson, we would all like to know whether there was another, more suitable filler. The only thing we can say is that up to now people have looked at natural fillers and there is quite a possibility that there would be some synthetic material or mixture of materials that would combine all the properties that Mr. Gibson announced, also including one that is very important, namely, the post-arc conductivity of the material, which should be good. If we had found such a material we would have patented it, but we haven't found it yet.

On Mr. Crooks' question, that a one-sided element could not correctly represent a cylindrical barrel, Mr. Rosen has shown that a flat geometry can give useful information on what a fuse can do. However, you have to take a bit of care, especially if you are talking about low-voltage fuses, because if you do take photographs with a glass plate, the chances are that your glass plate will crack and you will lose all the data as far as the arcing period is concerned. Of course, the prearcing period is all right if you take into account that it's one-sided.

Dr. Wilkins asked about our Fig.4. The test arrangement is shown in Fig.5, and since this is an a.c. measurement the change measured is not a change in resistance but a change in the current in the high resistance circuit, which is simply 50 Hz, so that gives you the time scale.

I found the slides from the scanning electron microscope very interesting. Of course you can see the same kind of striped layers if you take X-rays.

Prof. Naot asked 'what is the rated current of a fuse'. This is a very interesting philosophical question, which has been debated quite seriously in IEC, especially in regard to miniature fuses, which are widely distributed throughout the world and are exchanged over borders between countries because they are built in to equipment. In fact the question is very serious because of the differences in philosophy that there are in rating. The Americans believe that the rated current of a fuse is the current that it can carry for a certain period, while the Europeans believe that a fuse should carry its rated current for ever. There is the whole problem. Of course it's true that it should be able to carry its current at least as long as the equipment that it sits in.

In reply to Mr. Oliver, the thermite effect is simply a chemical reaction between the aluminium and SiO_2 which gives aluminium oxide and an exothermic reaction.

<u>Mr. P. Rosen</u> (in reply)

I would like to answer Mr. Jacks' general question - 'what is it all for?' As a design engineer I have very little time to exercise my intellectual curiosity, things have to be for a purpose. What I have been trying to do is to build up eventually a complete picture of how commutation works between parallel elements, so that in trying to optimise, particularly high-voltage fuses, in terms of the right number of elements, the right number of notches and the spaces between them, I will have some more of the answers.

Mr. Gibson asked about the 'patterning' effect, i.e. that you generally saw some of the arcs igniting before others. This is because I used a pattern of notches along the element, some long, and some short. Of course the long notches always started to arc first.

Mr. Crooks asked why I had deliberately kept the reduced sections far apart. This was because I was trying particularly to study commutation, and I realised that if I had the notches the normal distance apart, and merging did occur it would rather foul up the thing I was looking for. The next phase of the work which I hope to do is to bring the notches to the correct sort of distance and study how merging affects the commutation effects which we have seen. The central notch seemed to arc for longer than the others because on the low overcurrent tests we had a spot of M-effect there, so the arc began to burn there before the other places broke in the elements.

With regard to the question about randomness and manufacturing tolerance on elements, no attempt was made to try and match the elements in these tests, they were normal production fuse-elements with a tolerance of about 5% on resistance. We did about 60 tests and hoped to randomize the results that we got. As we were trying to see that happened in production fuses rather than in academic test-boxes I thought that this was the right sort of thing to do.

One other point about the position of the elements. We did initially have them buried beneath the surface of the cell, with about 2 - 3 mm of sand between the face of the element and the glass. We then tried moving them right up to the face of the glass and found no perceptible difference. The fulgurite barrel, instead of being around the element simply dropped,as it were, below the face of the element - we still got the same size of fulgurite barrel, but this time buried into the sand.

As regards Prof. Lipski's question concerning the distance between the elements - they were mounted about one inch apart. I have not tried to find what happens if you move them closer together.

SESSION 3.   Wednesday, 7th April,   15.45 - 17.00

ARCING PHENOMENA

Session Chairman: Mr. H.W. Turner
(Electrical Research Association).

Paper No.

11 "The behaviour of d.c. overcurrent arcs in fuses", by R. OLIVER.

12 "Pressure in enclosed fuses", by M.R. BARRAULT.

13 "Spectroscopic observations of arcs in current - limiting fuse through sand", by T. CHIKATA, Y.UEDA, Y. MURAI and T. MIYAMOTO.

14 "Chain of arcs as determining factor in electrical explosion of wires", by J. NASILOWSKI.

15 "Optical observations of ultra high pressure sodium arc in the permanent power fuse", by H. SASAO, T. MORI, Y. UEDA and T. MIYAMOTO.

Dr. L. Vermij

A small question to the paper of Mr. Chikata et al. From Fig.6 of the paper we can see that temperatures have been obtained experimentally which range from 20,000°K to 30,000°K roughly, and these are seen a fraction of a millisecond after the start of arcing. Since this is so close to the beginning of arcing, have the authors some indication of the temperature at which the evaporation of the metal has taken place? I have brought forward this question because as you know, the temperature of evaporation is estimated by several authors in the order of magnitude of 7,000°K - 10,000°K. There is a large difference between these evaporation temperatures and the temperatures shown in Fig.6, a fraction of a millisecond afterwards, - a difference of 10 - 20,000 degrees. What is the reason for this large difference - is there no local thermodynamic equilibrium? One of your assumptions is that there is local thermodynamic equilibrium. Therefore I ask the question 'what is the evaporation temperature'?

In connection with the discussion earlier, there is no evaporation at normal operating temperature. Evaporation occurs at temperatures of at least 7,000°K. At 7,000°K the metal vapour is partly ionised.

My second question is on the paper by Mr. Sasao et al. On page 136 you see '...... under the assumption that the plasma is an ideal gas of the temperature 2,000 - 5,000°K.... ', and they conclude that the pressure should be less than 10^4 atmospheres. What is the value of such an assumption when the temperature is far beyond the critical temperature of such a plasma?

Dr. C. Turner

On page 104 Mr. Oliver states: 'It has been suggested that the behaviour of the fuse arc may be modelled by assuming that the mass of electrode metal eroded is directly proportional to the electrical charge passing through the arc column'. We have proved over and over again that this is not the case. In fact, looking at arcs on contacts, which are very similar to arcs in a fuse, we have shown very clearly that there is a relation between the current and erosion which is proportional to a power of the current, and directly proportional to the arcing time. The power of the current is at least 1.6. So it isn't Coulombs in the arc that are mainly responsible for the erosion.

The other thing is the sudden change in the behaviour of the arc, where you get sudden drops in arc voltage. Again, in our studies on arcs on contacts, we have shown by high-speed photography quite clearly that if you have an arc between two points you often get the arc bowing out, and then the arc will short-circuit this bowing-out point, so that you get a change because of the shortening of the arc distances. In the same way, if you have an element in a fuse you can have a shorter path somewhere which is bridged by the arc which always tries to find the shortest distance, and then you get a lowering of the arc voltage.

Prof. T. Lipski

I would like to give some further comments concerning the question raised by Dr. Turner. It is very interesting to note that in Mr. Oliver's equation the last member is not so good - the 'Coulombs' member. I agree with the author's remarks that in fact it is not so. In Poland Mr. Ossowicki found that in the overload region there appears an additional member, which has the form which is proportional to the I^2t value of the current. But we don't know yet the physical reason for the appearance of this additional member.

Dr. K. Lerstrup

I would like to follow up this question of the burning away of the metal. It is quite clear that if we take a constant anode and cathode drop, we will have a release of energy which is proportional to the current. However the erosion is somewhat higher. We also have the arc energy in the plasma, which is given off by the plasma itself; and a good deal of that is transmitted by radiation. There is the possibility that we have an additional energy released at the metal surface by radiation from the arc plasma. This may explain some of the developments, although in many practical cases it is sufficient to figure it proportional to the current.

Mr. H.W. Turner

Dr. Lerstrup has omitted one very important point. That is the concentration of current in the spot at the base of the arc, where the current density is considerably greater than elsewhere; where you have a super-critical region beneath the spot and consequently heating in the metal which is proportional to a power 1.6 of the arc current which is responsible for causing this jet of metal to appear from the surface.

Dr. D.R. Aubrey

On the same topic, of erosion, although I am not a physicist, and knowing nothing of the erosion which takes place in fuses, Dr. Turner has referred to the erosion which takes place with contacts. I have experience of large-scale short-circuit tests on some half-a-dozen bulk-oil circuit breakers. This resulted in many hundreds of oscillograms which were not perused in pedantic detail but averages were used where possible, and the erosion appeared to be a function of I to the power x times the time, where x would vary between 1.1 and almost verging on 2 with one circuit breaker, the others being in the region 1.5 - 1.6. But I can say that one of them appeared to be an outstanding circuit breaker and the value of x there was close to 1.1, however for another outstanding circuit breaker the value was almost 2. I am prone to a half-hearted conclusion that it might be with fuses that the nearer 1 that value can be got, whatever the physics, it might just be that that is a criterion on which to judge a fuse.

Mr. R. Oliver (in reply)

Dr. Turner, Prof. Lipski and Prof. Lerstrup all raised the question of the charge model. I don't know whether I have created a misunderstanding - I am not 'selling' the charge model. I would draw your attention to the top of page 105 where I say 'Experimental results indicate that the charge-controlled model is not entirely satisfactory in describing the fuse arc under d.c. overcurrent conditions' - so we agree?

I have in fact demonstrated that in my case, under d.c. overcurrent conditions, that the charge model does not work. The questioners have evidently found that under different conditions, the charge model is similarly invalid. In fact Prof. Lipski mentions Dr. Ossowicki's work, which is in a similar area to mine, and of course I know that a term has been introduced into the equation, which is a function of $\int i^2 dt$. This produces answers which fit, but I think that Prof. Lipski and Dr. Ossowicki would admit that there is no validity in terms of the physics, as yet, to justify the inclusion of that term, so for the moment it can only be described as a way of fitting the experimental results.

In reply to Dr. Turner, rapid changes in arc voltage were observed. Dr. Turner indicates that bowing of the arc had been found: I have called this 'lateral movement'. I think this is open to discussion. There is undoubtedly evidence on the wide elements where this phenomenon occurs, and not on the narrow elements, that the anode and cathode spots do in fact move laterally across the strip as can be observed from an examination of the strip erosion pattern after extinction.

I think that it is interesting to note the somewhat anomalous behaviour in final arc lengths, which can be demonstrated by looking at Figs.5,6 and 7. Figs. 5 and 6 follow a rising characteristic, the increase in width from Fig.5 to Fig.6 results in a somewhat shorter final length. In Fig.7 we have this unusual behaviour, where the curve turns over with increased thickness. This is a rather interesting anomaly. I have a suggestion, although I can't prove this, that the reason why it turns over is because we are looking at the largest cross-sectional area of strip investigated and therefore the element which probably had the highest axial heat loss. What we may be observing is the increasing significance of axial losses from the ends of the arc, producing an increase in the field in what I have generally termed in the body of the paper as the second phase of arcing.

Referring briefly to this second phase of arcing, it would appear that the behaviour of the arc can be generally segregated into two parts. The higher-current sector, which is the early part, where the axial field is maintained at a fairly constant level (this was investigated by the crowbar system), the fields obtained being shown in Fig.9. However, as the current falls, and Fig.10 shows, if you move towards zero on the current-axis the electric field declines, particularly below 80A. Whatever the reason for this it explains why extended arc lengths are found under d.c. conditions, and why the d.c. overcurrent arc is probably the most difficult condition for an h.r.c. cartridge fuse to interrupt.

Dr. M.R. Barrault

In the equation at the bottom of page 110, the 2 should be multiplying w rather than squaring it.

I want to say a few words about the interaction between some of the things we have just been discussing and the pressure in the fuse. I would like to indicate a scheme (Fig.) whereby we can relate the pressure which is within the arc to pressure which we measure at the wall of the cartridge and with the power and arc processes. We can imagine that we are dissipating some power within the arc, which is leading to an increase in the space available for the arc to burn in. This is because we consider the melting of the sand when we start out, by having a solid element embedded in some sand. We convert this into a void which is constrained within a molten silica tube, and this process takes in the space which was originally present between the unmelted grains of sand. In addition to this we have a certain 'set', which is introduced into the problem, because the sand is not in perfect contact with the element at the start of arcing. There is therefore some small area which I call a_o which is immediately incorporated in the lumen size occupied by the arc once the arcing process has developed.

We also have to take account of the final destination of the silver element. This will take up some space, and so will subtract from whatever space is available for the arc to burn in.

In order to build up a model, (we have just seen a model for the creation of an arc space), we can imagine that the amount of molten material will be proportional to the power dissipated. That is a simple first approximation which may not be correct since some energy may be radiated away. That closes this part of the process (Fig.) - we have this part under control, I think.

We must then somehow join these two parts in order to work out what the pressure is going to do, and this can only be done through an arc model. On the next figure (Fig.) I have illustrated a few of the sorts of arc models which we may use to try and solve this very difficult problem. There are basically three types of arc models which one can consider as applicable to the fuse domain.

We could imagine that we have radial conduction cooling. This may in fact occur under certain conditions, and if this occurs then the radial heat flux from the arc must be matched up with the current of the arc, and the final result is that one obtains this sort of arc equation, which relates the local electric field to the current and to the dimensions of the arc. This I have taken to be somewhat elongated, and depends upon the initial proportions. Most fuse arcs have electric fields which vary quite slowly with current, and this is certainly so in the overcurrent domain which Mr. Oliver and myself have been looking at. Under these conditions the second half of this equation is almost a constant, and we find that the electric field depends inversely upon smallest section of the arc.

The second model is a black-body cooling model. Here we can imagine that the arc is being cooled purely from the surface at a rate determined by Planck's Law. In that case we get a different form of scaling for the electric field. We see that the electric field in this case varies as the square root of the size of the arc. I think that that is quite an interesting fact.

The third case corresponds to cooling through what I would call optically thin radiation, and I think that this case is the most likely one. We can think of the arc as having a central zone with an almost constant temperature. From that central zone radiation is being lost (it may be re-absorbed at the boundary but finally it will be re-emitted) and the result is that we will have volume loss rather than an area loss, and in that case the theory works in this way: here I have used certain relations to show that we will have to introduce a pressure term in this. The pressure term does not apply in the other two cases, because in one case Planck's Law does not require a pressure to be present and in the case of the conduction cooling, there is not very much variation of either the electrical conductivity, except for very high densities, or the resistivity, upon pressure. In this last case then, the electric field is more or less constant, and depends only upon $p^{\frac{1}{2}}$.

One of these three schemes, or all three of them, have to be used in order to close our system of equations.

The last problem connected with pressure is one of measurement. The pressure which we measure at the cartridge wall is not the pressure which is generated within the arcing column, and this is because most unfortunately, or happily in some other way, the sand is not just a fluid, but it made up of a large number of little beans resting upon each other so that the transmission of pressure through this sand takes place in a non-fluid manner. In the paper I have indicated one sort of relation which may be used. That relation implies that there is a constant ratio between the amount of shear and the amount of pressure which is applied to the sand. Clearly, under these conditions, one would expect to find hysteresis in the behaviour of the pressure. When the arc pressure goes up at the centre, you would expect the pressure at the cartridge wall to increase at some reduced rate, then when the arc pressure decreases, you would expect the pressure at the wall to remain constant for some time until the ratio of shear to pressure has been reversed sufficiently, so that the sand grains can start slipping again and transmit this change. Experimentally however, it is found that the pressure changes within the column are very easily and rapidly conveyed to the tube wall, albeit at reduced values.

I would conclude this short talk by showing some results taken with different bore fuses (Fig.), which illustrate quite well that, taking for instance the 90 mm bore cartridge, when the power dissipated within the fuse changes, so we can find the pressure at the body wall changing also in synchronism. This is quite contrary to what a simple theory of transmission of pressure from the arc column to the wall would indicate. Understanding the transmission of pressure provides us with an initial diagnostic means on the arc and it is also extremely important in understanding the performance of the arc, because if we look here at these three different body walls we have quite different behaviours for the amount of energy dissipated and of course finally for the voltage behaviour as a function of time. The whole performance of the fuse is affected by the body wall. The only way that the body wall can affect the performance of identical elements for the same current is either a change in the lumen size available for the arc, or a change in atmospheric pressure between the grains of sand. However, measurements which we have made show that there is no significant increase in the pressure of the atmosphere between the grains of sand and that the pressure measured at the body wall is in fact being transmitted through the sand and not through the atmosphere, and therefore the conclusion is that it is the change in the lumen size which is a result of the change of the bore, which is in fact controlling the performance under these conditions.

Prof. Hirose (in reply for Chikata et al and Sasao et al)

I would first like to make some corrections. On page 134, '..... during Ta + τ ....." should read '..... during Tp + τ ......'. In reply to Dr. Vermij's first question, Dr. Miyamoto believes that the fuse metal will be heated up to 2000 - 3000°K, and the surrounding sand granules would begin to vaporise at this point,because as the oscillograph on page 119 shows the intensity of Si II and Si III reaches a high value in a very short time after arc initiation, so he believes perhaps that sand is always? vapour?.

Some informal discussion took place here regarding Dr. Vermij's question concerning the 'ideal gas' assumption, and it was agreed to refer this question back to the authors.

Mr. C.B. Wheeler

I would like to present some equations which give a result bearing upon the rate of growth of arc length, as to why it depends upon a power of the current between 1 and 2.

For a radial-conduction cooled cylindrical arc,

$$\sigma E^2 = \text{div}\ (K\ \text{grad}\ T)$$

assuming that the gas is fully ionised, $\sigma \alpha T^{3/2}$ and $K \alpha T^{5/2}$.

Solving we obtain: (J. Phys.D., 3, 1374-1380, 1970)

$$E \alpha R^{-7/5}\ I^{2/5} \quad \text{where R is the arc radius.}$$

Hence the power/unit length:

$$EI \alpha I^{1.4}$$

Mr. H.W. Turner

What we were talking about here is not a column effect but an electrode effect. Erosion is taking place within the little cone of energy within the electrode itself and you could postulate this, as something going on just below the surface of the contact and causing an erosion rate to a power of the current. So you are referring now to the compressed plasma within the base of the arc.

Mr. C.B. Wheeler

I am suggesting that the bulk of the heat loss is radial, and that some small fraction of it is transmitted longitudinally, giving the same power dependence at the electrode. I would add that this relation has been verified experimentally for capillary discharges as opposed to discharges in a fulgurite. (J. Phys. D., 4, 400-406, 1971).

Dr. J. Nasilowski (communicated)

In my paper there should be an arrow inserted in Fig.9, from the phrase 'disintegration of the fuse-wire into segments' towards the phrase 'cut-off current'. Also Fig.10 was missing from my original paper. This is reproduced below.

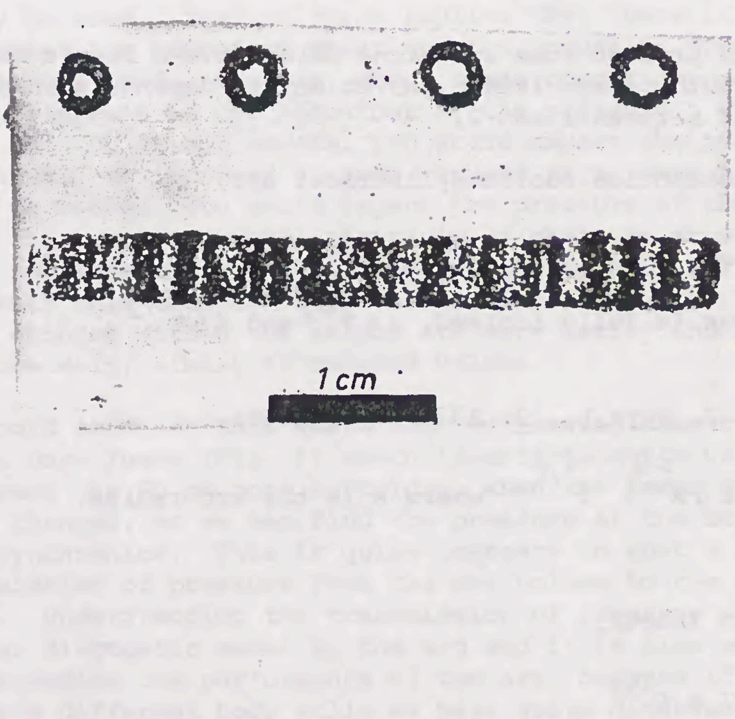


Fig.10. A fulgurite produced from d = 0.75 mm. Cu wire in quartz-sand. U_o = 400V d.c. L = 1.5 mH; $I_{cut-off}$ = 2300 A. Dark strips are post-arc zones which divide the fulgurite into individual rings.

SESSION 4. Thursday, 8th April, 11.00 - 12.15

APPLICATIONS & DEVELOPMENTS 1

Session Chairman: Mr. J.W. Gibson
(Brush Power Equipment)

Paper No.

17 "Current-limiting capability and energy dissipation of high-voltage fuses", by L. VERMIJ and H.C.W. GUNDLACH.

18 "Design and application of expulsion fuses in 123 kV networks", by S. GRUDZIECKI, A. WISNIEWSKI and B. KAPRZAK.

19 "Self-rehealing performance of the p.p.f. for a control centre", by Y. WADA, S. HAMANO, T. MORI, T. MIYAMOTO, T. INOUE, I. ISHII and T. SHIRASAWA.

20 "Mathematical analysis of breaking performance of current-limiting fuses", by A. HIROSE.

21 "The role of the semi-enclosed fuse in circuit protection", by P. MORRELL.

Mr. H.W. Turner

What is the maximum number of operations a p.p.f. can make, and how does this depend upon prospective current? What is the influence of filler on the work described by Dr. Vermij and Prof. Hirose?

Does Mr.Morrell foresee any developments in semienclosed fuses to retain their convenience yet improve their performance?.

Mr. P. Rosen

It is apparent from the papers presented on the p.p.f. that beryllia is used as one of the component parts. Beryllia because of its thermal properties also has great attractions for the h.r.c. fuse designer, but considerations of its extreme toxicity under certain conditions tends to preclude its use. I should like to ask the authors of the paper on the p.p.f. how they justify the use of beryllia in their device, from a health hazard point of view.

My second question is directed to Dr. Vermij and Mr. Gundlach. They say that you cannot have a current limiting high voltage fuse of compact dimensions, moderate watts loss and high current rating. Yet such fuses are in fact widely available commercially. The point I wish to make is that in a well designed fuse, the provision of reduced sections on the fuse elements to ensure current limitation need only add 30% or less to the watts dissipation of the fuse at its rated current. So where is the problem?

Mr. E. Jacks

I would like to ask Prof. Hirose whether his model adequately represents all the fortuitous conditions which can occur in the system and whether he is satisfied that his calculations do really give what we call the worst-case condition so that when a fuse is tested to it it can be considered safe under all circumstances in service.

Dr. P.M. McEwan

I would like to make a comment on Dr. Hirose's paper. The analysis on the prearcing performance is directly related to Meyer's equation, which implies that the analysis is sound for wires and possibly also for long notched elements. For modern fuses containing notched elements Dr. Wilkins and myself have found that the heat conducted away from the notch is considerable, and in these conditions a different approach would have to be adopted. We have in fact put forward a different approach on this.

Mr. W.R. Crooks

I should like to ask two questions relating to the paper on expulsion fuses.

Would the authors like to comment on the effect upon the arc voltage of different materials in the fusible element?

Secondly, I would ask whether there is in fact any value in producing a rather high value of arc voltage, since this increases the arc power, without, I think, changing the conditions too much at the current zero.

Mr. R. Oliver

A very brief question to Prof. Hirose, with reference to Fig.5, which he derives from his model. I find it rather interesting that in fact the arc energy increases with falling current to a peak and then drops away rather rapidly.

I would have expected in fact, perhaps some fall, but quite a rapid turn-up at the lower current, i.e. the low overcurrent region. I wonder if perhaps it is the type of fuse he is looking at, or if he feels this is maybe a defect in the model he is using.

Prof. Y. Naot

I would like to make a brief comment on Mr. Feenan's review paper. He showed some slides showing that the rated current of a motor protection fuse depended upon the starting current of the motor. On has to define first what we wish to protect. If the case is to protect the motor only against short-circuits, leaving the overload protection to other devices, which may also be thermal devices, then the problem is very easy. But if we wish to protect with a fuse against short-circuit and overload, it becomes a very complicated problem, because the rated current of the fuse in every case exceeds very much the rated current of the motor.

It is possible to demonstrate that if we have a fuse with a long enough time constant, of the order of 15 - 60s, it will be possible to protect the motor with a fuse having the same rated current as the motor itself.

But I know that the tendency of the fuse manufacturer is not to have too many types. I don't think this is right. In my opinion a fuse is a device which has to be coordinated with the protected circuit, and we cannot include every case with only two or three types of fuse. I think that the IEC should consider this.

Mr. Feenan described a multiple fuse, consisting of a parallel connection of many fuses. In Israel, a hot country where conditions are not favourable we have had bad experience with parallel-connected fuses. After a given period of time of service, the contact resistances start to increase unevenly and the current partition amongst the parallel fuses changes. Has Mr. Feenan experienced this problem in cooler countries?

Dr. D.R. Aubrey

I would like to compliment Mr. Grudziecki and Mr. Wisniewski on a fine piece of work, and simply ask them if they could describe for us in some detail the actual fuse element. A humble point in relation to the rest of the paper, but it would be interesting. Mr. Gibson poses the question as to whether the protective configuration described in the Polish paper would be of help in the British Area Board set-ups. Basically expulsion fuses are used in the greatest quantity at 11 kV on rural overhead networks, and their protective scheme is quite the opposite of what we want. In many instances, say 50%, it is not certain that the fault behind a fuse is a permanent fault, it is frequently a transient fault caused by some flashover caused by the vagaries of the weather, typically lighting and clashing conductors, and therefore it is necessary to trip the circuit-breaker first, before any fuse operation occurs.

I could demonstrate this on the first slide, which shows the type of characteristics we require from an expulsion fuse on the 11 kV overhead network. I show there two characteristics, of a 30A and a 60A fuse of a standard type and the black curve is one that we felt was needed. At the low current end, the I^2t let-through at 10s is something in the order of 16 times less than the I^2t at 0.1 seconds. Now this of course cannot be achieved with a piece of wire. We had to go to extreme measures to get this degree of non-linearity, and the second slide shows the adaptions we made, in cooperation with G.E.C. The bulk of that is the standard unit, but there is an additional contact plus a transformer. The fuselink itself has three tails .... (detailed description of two slides follows ......).

Mr. S. Grudziecki (in reply)

I wish to make some comments on the work described in the paper; they are connected with the questions. The 123 kV fuse short-circuiting switch is one of several types studied at Gdansk Polytechnic over twenty years. They include different types of lightning arresters, fuses, reclosers, protective apparatus, switches and circuit breakers.

Investigations in this field led to observations which have been taken into account in the design of apparatus described in the paper.

As we know, in gas-expulsion apparatus, a special type of insulating material produces gases under the influence of an electric arc. Its extinction is achieved by volume cooling. According to one theory, the so-called expansion effect from the gas-evolving material which depends upon the rate of decrease of the gas pressure during the passage through current zero, makes this extinction possible. Another theory takes into account a stream of gases accumulated from the special container before the current zero.

In reality both phenomena exist and the extinction condition is given by the relation on page 162. Depending upon the type of the apparatus the share of the components on the left side of this relation is different.

As we observed in the right type of extinction chambers, the inside diameter is very important. ..... (detailed description of slides follows ....).

Dr. L. Vermij (in reply)

Mr. Turner asked whether the filler has any influence upon the characteristics of the fuse which we describe. Yes, it has definitely. This is shown by the following equation for the factor G which we used in our paper, and which represents the heat flux from the wire to the surroundings for a cylindrical model (long wire).

$$G = \frac{1}{2\pi\lambda_f} \ln \frac{\gamma_2}{\gamma_1} \quad *$$

where λ_f is the thermal conductivity of the filler. So when you change λ_f or γ_2 then you have a different value of G. But this is a very simplified model. The problem is much more complicated because you have a medium which is inhomogeneous, with grains and moisture and so on. Because this model is so simplified, we prefer to work with a value of G which is determined experimentally. Then you find that G is not constant, either as a function of the current, or as a function of the wire, the filler and so on. As also mentioned by Dr. Lerstrup, I think that the work of Dr. Huhn is very important in this respect.

Previously a question was asked concerning what was an 'ideal' filler. Huhn points out that a much more important factor may be the form of the grains and the distribution of the grain size in order to give an opportunity for plasma jets to build. If Huhn's suggestion that plasma jets are a very important factor in the heat dissipation to the surroundings is true then you can forget this factor G - (during the arcing period).

* γ_1 is the radius of the wire and γ_2 is the radius at which the temperature of the surroundings will be found.

I refer you also to the experiments of Prof. Salge from Braunschweig who made experiments on wires in water. Then you see a very different factor G.

Mr. Rosen has asked a question about the constrictions and he said that only 10% of the length of a high-voltage fuse gives only 30% more energy dissipation so what is the problem? In fact the work was initiated by a question we got from the Americans - to develop a high-voltage fuse which should be built-in, which should have a large nominal current, and which should also be current-limiting, up to 300 kA, for a 400A fuse. (That is an impossibility with normal wire).

So you have these two requirements. Because the fuse is to be built-in the energy dissipation should not exceed 50-60W. The other requirement is that it should be current-limiting. Then you have to design fuses with necks, with short parts in it, and that increases the power dissipation. That was the reason we studied this problem in depth, to compute theoretically what can be expected. Then you arrive at the conclusion that it is hardly possible to build a high-voltage fuse with a high nominal current and a low energy dissipation and with current-limiting capabilities which exceed the normally required current-limiting capabilities.

I have some remarks about the p.p.f. We have computed some parameters of sodium, in our paper; this was not connected with the p.p.f. but it may be important.

We also are very busy in the field of supercritical states of a metal, sodium amongst others, and we have also some experience with the p.p.f. In our experience the maximum number of operations is three, no more. And the third time you have quite different characteristics, compared with the first time you break a current. The Chairman mentioned the problem of the enlargement of the diameter of the hole - that is a real problem, yes, we have seen it, and also we have had very nice explosions with it.

There was a question about the reliability. In my opinion you may not ask this question now, because it is a research phase. It is not yet a product, but it is promising.

Prof. A. Hirose (in reply)

First of all I would like to express my sincere thanks to all those gentlemen who have submitted their comments on my paper. On page 182, in equation (1) K is the constant prearcing Joule integral; for silver it is:

(equation written on board)

n is the number of parallel elements. S is the constricted cross-sectional area.

$I_{T/2}$ is then $\sqrt{K/(T/2)}$

In some cases this is not the same as the current on the time-current characteristic, but my paper is based upon this assumption. Hence equation (5) is established. This is my answer to Dr. McEwan. Diagram (1) on page 184 was published in Japan about 6 years ago, and the upper half of this diagram is very useful for determining the making angle when making I_1 tests. The upper half of this diagram is being introduced into our revised Japanese recommendations for high-voltage fuses as an Appendix. Diagram (2) on page 185 is also being introduced as an Appendix.

This is useful for determining the required sensitivity of current-mesuring instruments. On the oscillograph the value of i_o should be as high as possible, without being off-scale. For this purpose diagram (2) is useful. Diagrams (3) and (4) are also used in Japan.

Mr. Turner asked what influence the filler would have on equation (4) (page 188). This is a very rough equation, and the constants V_o and r depend rather largely on current and voltage. So I think that equation (14) is not a strict equation. However in the past we have used only V_o, not r, and so the representation in equation (14) is one step forward, and not more. Fig.2 and Fig.3 are of technical interest, they may be the hobby of a teacher. But nevertheless they teach us something. For example, the hump in Fig.3(b) will rise if V_o or r are decreased, meaning that the arc energy increases. Fig.5 shows that the I_2 current is about 3. But the I_2 current (maximum arc energy current) moves to the right when V_o and r are decreased. What does this mean? If low-voltage fuses are tested at increasing voltage the summit moves to the right and the arc energy increases. This is because V_o and r are normalised with respect to the test voltage and $I_{T/2}$.

So if you test a fuse with a higher test voltage, the normalised r decreases. This is qualitative, not quantitative, but I believe that it teaches us something about the behaviour of a current-limiting fuselink. This would be my reply to Mr. Jacks, and Mr. Oliver.

On the p.p.f. I would say that nothing can endure the heat of an arc for a long time. The sun's temperature is comparable with the arc temperature, and on the sun everything evaporates or dissolves.

It was confirmed that the questions on the p.p.f. should be referred back to the authors. Ed.

Mr. P. Morrell (in reply)

Mr. Turner asked whether there are likely to be any improvements to semi-enclosed fuses in the future. I can only reply that continual research and development is being carried out, mainly in respect of the possible replacement of the asbestos, due to health hazards in the manufacture, and who knows what may result from this work. However, if circuit conditions do require any improvement in breaking capacity, all semi-enclosed fuses of our manufacture, and I believe that this also applies to other manufacturers, can easily be replaced by h.r.c.

SESSION 5. Thursday, 8th April, 14.00 - 15.15

APPLICATIONS & DEVELOPMENT 2

Session Chairman: Mr. P.G. Newbery
(Brush Fusegear Ltd.)

Paper No.

22 "Overcurrent protection of cables by fuses", by S.B. TONIOLO, G. CANTARELLA, and G. FARINA.

23 "The protection of industrial capacitor banks by current-limiting fuses", by M.J. SMART and B. WADCOCK.

24 "Protection by fuses of mechanical switching devices", by S.B. TONIOLO, G. CANTARELLA and G. FARINA.

25 "Calculation of the course of the current and voltage of a current-limiting fuse", by M. DOLEGOWSKI.

Dr. K. Lerstrup

I would like to say a few words about the cable loading. There is a lot of discussion on this at the moment, but to my mind much of this discussion is actually superfluous, because the discussion centres around finding a thermal device (a fuse) to give thermal protection to the cable, and trying to fit close to what the cable can stand. In by far the most cases it is not necessary. Really we cannot afford to load the cable that heavily, because we are just paying for kilowatt hours instead of paying for kilocopper. It actually turns out that if you have a use time of about 2,000 hours a year as is usual for most industrial installations, then you cannot afford to carry more than 2A/mm^2. That is quite far from what most small cables can carry thermally, and this question of fuse protection of cables is in particular of interest to the small cables. When you come to the large cables you can usually afford a divided protection between short-circuit and overload, on another thermal device for instance, and therefore this whole discussion in TC 64 is more academic than of practical value, once you consider the economic conditions too. Now these remarks go very well with the fusing of capacitors, because to have advantage of e.g. power-factor correction capacitors, we are normally running for 2,000 - 3,000 hours/year. When you are in that region, and you are keeping between 1.5 and 2 A/mm^2 on the cables, even on the somewhat heavier cables needed for capacitors, there is no difficulty in finding a suitable fuse for that. In particular, as you consider that the capacitors do not have any starting current to cope with. There is perhaps an inrush current, but after that there is no more problem.

Turning now to the other paper of Toniolo et al, I would say that this is not said as a criticism of the paper, but only the mention of some additional problems, because this matter Toniolo and I have been discussing for about twenty years now and none of us have come to the true solution, but I will just point to some difficulties. He is coming to the conclusion that you should look at the time when the fuse lets so much current through that you will just lift off your contacts. That certainly is the most dangerous position for most contacts. However, the interesting thing is that if you take a larger fuse, then you will have no welding. It so happens that if you can get a current peak that just barely lifts off the contact you will just have a little short arc, on that spot where it has lifted off. You get two soft spots, and you will have the contact back in place before these spots solidify and then the contact will stick.

If you take a fuse of a couple of numbers higher current rating, you will have the contacts thrown off much further, the arc will be magnetically blown away and will burn in other places, the two original touching spots will have solidified before the contacts come back to rest, and you will have no welding.

So there is far more to this problem than appears here on the surface of the paper. There is simply no answer to it, except the one which is now embodied in the IEC specification for contactors, which simply says that welding of contactors is something you must consider a possibility, irrespective. And that is just about the only solution we have, which again leads to the conclusion that one should never rely on a contactor in matters of safety.

Mr. J.W. Gibson

Concerning the paper by Toniolo et al, it seems to me that in the old days, the fuse manufacturer would claim that his fuse was a good one because it did not deteriorate. Should he now alter his claim to say that it does deteriorate, but at just the right rate to match the cable?

The paper by Smart and Wadcock contains a great deal of useful information for the fuse manufacturer who is called upon to supply capacitor fuses. Sometimes to a fuse manufacturer capacitor bank design seems very abstruse, but it is rather well elucidated in this paper. There is one point on fuse selection which is not covered by the paper. Assuming that one unit of a number in parallel fails, you would expect that normally the fuse of that unit would be blown by the discharge current from the other units. But I was told a long time ago, by a colleague of the authors that you can't always rely on that, because small boys have air-guns, and the bullet may arrive when there is zero voltage, and then one has to rely on the power frequency follow current, which it is desirable should be cleared rather quickly, and I understand that the capacitor manufacturer knows roughly how long this unit will survive if it is faulty before the current is removed and before the can will explode.

My other point is that, in selecting a capacitor unit fuse, the principle is the same as for selecting any other fuse. That is that the best current rating is that which will withstand any normal transients without blowing the fuse, but without too large a margin. It seems to me that in this case the fuse has to be chosen essentially of a current rating to withstand the switching inrush transient, and there seems to be rather a lack of information on that point. I think that often the capacitor manufacturer does not know very well the system on which it is being installed, but he probably knows the fault level of the system which means he knows the L of the system. He has built the capacitor, so he knows what the C is, so from that you can calculate the natural frequency and peak value of the inrush. But this does not give any direct help in choosing the fuse. You choose the fuse on the basis of I^2t, and for that you also need to know the decrement of the inrush current. In the IEC, we were trying, with help and advice from the capacitor manufacturers, to write a specification for capacitor fuses, and test requirements were laid down and included a statement that 'the natural frequency of the test shall be so-and-so.....', and gave values of the decrement. The fuse manufacturer didn't know much about that, and had to take the word of the capacitor people. I am wondering whether the capacitor manufacturer could, when he wants fuses, give the value of the decrement, based upon what has recently been agreed in IEC.

Another point is, again on the choice of fuse with respect to I^2t, can the capacitor manufacturer also give some idea of how much the I^2t is increased when one bank is switched into another? The fuse manufacturer generally knows that that is rather a vicious condition; the frequency is much higher of course but he would like some guidance as to just how much allowance he should make for it. As with most cases of fuse selection, there is a lot of guesswork (based of course on previous experience) but the more the fuse manufacturer's hand can be held, by people who understand capacitors, the better.

Dr. K. Lerstrup

Mr. Gibson prompted me to speak again. The capacitor manufacturer knows a good deal more - because when you put a capacitor in for some reason, you want to switch it on and off without disturbing anybody. You don't want the voltage to change by more than about 4% when you switch it on. That means that you know right away that you will have a power follow-up which is 25 times the rated current of the capacitor.

Dr. C. Turner

I would like to make a few short remarks on the paper by Toniolo et al, on the protection of switching devices. I don't quite agree with Dr. Lerstrup's remarks just now because, if you have a modern contactor material, and it arcs, it won't weld. If it doesn't arc, it might weld. So the most dangerous condition is not when it separates, but just before it separates.

It is of course dependent upon your switching device, and in fact if you plot your weld force, for different I^2t against your contact force, the relation is as shown in Fig.1.

At one end, if your contact force is small, it will blow off and it won't weld. In the middle it will weld strongly and further on when the contact force is very large the contact area will be so large that it won't weld. However, if you have a larger I^2t it moves and the trouble is you can't really decide beforehand where you will be. You know what your I^2t is, but you don't know the point-on-wave and other things. But there is another complication, and that is that a modern contactor does not just have two contacts, but a pair of contacts. (Fig.2).

Now that has many more degrees of freedom and the trouble is that instead of having a nice simple curve you have got something like Fig.3. And now you don't know where you are because the curves move in a 3-dimensional way, and it gets very complicated. We are giving a paper on this in Tokyo in August.

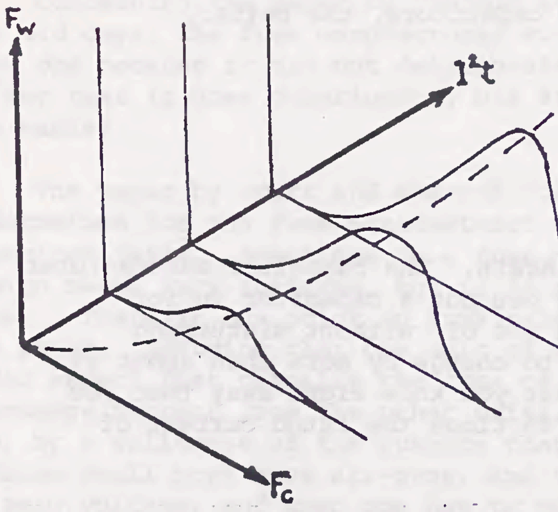


Fig.1. Relation between contact force, weld force and I^2t.

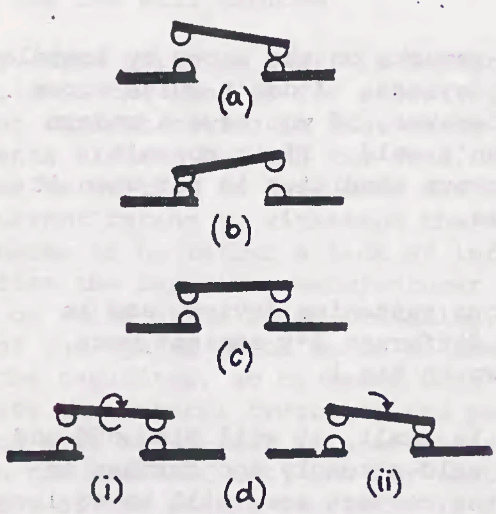


Fig.2. Effects of throw-off on double-break contacts.

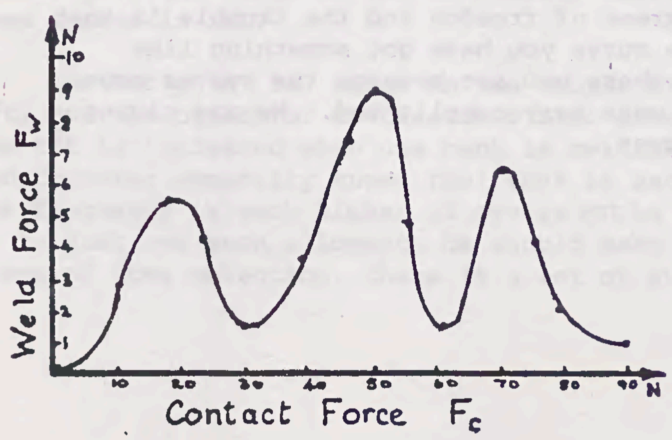


Fig.3. Contact force-weld force, double-break (I^2t = 72000 A^2s).

Dr. J.G. Leach

I was very interested to read the paper by Dolegowski. I am not so much speaking for myself but for my colleagues, Dr. Wright and Dr. Beaumont, who have done some work on analysing the arc in a fuse, with which I have been moderately involved. We have been trying to do it from a totally theoretical point of view, looking at the arc from an energy balance and looking at the rates of burnback and so on, with the minimum amount of experimental work, on the principle that if you only do a model based upon experimental work, then as you move outside the range of types of fuses that you have done the experimental work on, your equations become suspect. Most previous attempts to do a mathematical model of arcing have always taken a lot of assumption and simplications, and we were very impressed with Dolegowski's paper in that a vast amount of work has gone into looking at almost everything that can be considered during the course of the arcing. I think that in general this is the way analysis of arcing has to go; it is not sufficient to make sweeping assumptions like a rectangular arc voltage and so on. It's very important to either get down to fundamentals to find out what is really going on in the arc, or if you can't do that, you have got to try absolutely everything to find out what is influencing the arc.

Mr. H.W. Turner

I would like to pose a question on the paper on overcurrent protection of cables. The fusing current, and the non-fusing current of the fuselink are measured under standard conditions, with standard cables.

The protection that we are looking for here is at the maximum current rating that you can get with a given cable. Under those circumstances the fusing current is going to be lower than the value determined in the standard condition. Consequently, it would imply that a lower value than the authors have stated could perhaps be used. Therefore the fusing factor could be higher when measured under the standard conditions than it turns out to be when it is used with these smaller cables where the heat from the cables causes the fuse to melt at a lower current than it would in the standard test condition.

I agree however that if this 1.45 factor is adopted then there will be a further degree of safety added because of the methods of measurement used in the standard tests.

Mr. E. Jacks

I have not had the opportunity to study the last paper, but looking at the title prompts one or two questions in my mind which have also arisen during the presentation of other papers in this conference. One of the most fundamental problems facing the fuse designer is how to test his product in such a way that the test represents what he calls the 'worst-case' condition. I would have thought that at a gathering of this sort

the evaluation of the 'worst-case' condition would have been more in evidence. In the paper I can see no evidence that the fortuitous behaviour of the system has been taken into account. Many of the mathematical models are constructed on a number of simplified assumptions. Rectangular arc voltages have been mentioned - (I think that they probably exist, somewhere) and beautifully sinusoidal system conditions. Of course in service you don't get that sort of thing at all. You get two arcs in series, you get the arc in the fault and the arc in the fuse and it is the interplay between these two arcs and the way the energy is shared between them which in many cases can give rise to the maximum dynamic stress conditions in the device. These variations again do not follow any nicely uniform pattern. They vary very fortuitously, some very rapidly with very great rates of change, and it is always a question when one is, as a manufacturer, spending huge sums of money in testing fuses, whether he can really say to the user that the fuse has been tested to represent the worst case condition and can be confident that no condition can arise in service which will cause the fuse to fail.

I have not received any more evidence at this conference than I have received at other conferences of this kind on this particular topic, and I would plead for considerations of system behaviour to be looked at more closely.

The same applies of course in the case of cable protection. Everybody knows that you can't protect anything until you know its essential withstand. We still don't know the essential withstand of cables under all the fortuitous circumstances in service. I think we know a lot more now than we used to do, but it's not very long ago since it was almost impossible to obtain from any cable manufacturer any idea of the short-time rating of his cables expressed in a simple time-current characteristic which could be related to the time-current characteristic of a fuse. You could get one or two points but what happened between these points nobody knew. Of course there are complications due to the diversity and load-factors in service, but I suspect that the main reason that this information has not been forth-coming is because really speaking, the cable manufacturer has very little commercial incentive for producing this information. After all, his cables work all right, they carry the current and as Dr. Lerstrup has said, very often if you can protect whatever is at the end of the cable the cable can look after itself. It's also quite true that in service a lot of the theoretical hazards that are supposed to affect cables never actually occur. I can quote cases where cables have been subjected to very severe tests and then subjected for analysis, and no significant change of state was discovered in them. Similar cables which had been standing on the shelf still on the drum, not carrying current have been similarly analysed and a greater change of state had been discovered in these. So the problem is not simple. I would suggest that more of these fortuitous circumstances are taken into account in papers such as have occurred in this session.

Mr. L. Vermij

I would like to comment on the remarks of Mr. Jacks.

When we have a lot of circles, small ones, large ones, and not-so-large ones, then if we want to know what is the circumference of these circles, then you can take a measuring tape and you can measure the circumference of each circle, and you can write under each circle what its circumference is. Another way is, when the radius 'R' is given for each circle, to calculate it using $2\pi R$.

In our subject, in fuses, arcs, and so on, what we are doing is to determine the circumference of each circle by measuring it, because we do not know the formula to come from R to the circumference. Mr. Jacks asks for the 'worst-case' condition. To give an answer you should know exactly how and under what conditions it operates, and what physical processes are involved. So we ask for the formula 2π times R. We do not know yet that formula and therefore research is necessary, to find an answer to your question, 'what is the worst-case condition for fuses etc. .... ?'

In the paper by Mr. Dolegowski, who tries also to find an answer to this question, (what is the formula connecting the circumference of a circle with the radius?), he gives an answer from experiments, from what he measured. Other people gave an answer from theory about a theoretical model, but we know that we don't have the physical parameters to solve these models. As long as we do not have a good insight into these physical parameters to solve this problem theoretically, the only method is the method as given by Mr. Dolegowski. Then you can reach some result, and that is a step on the way, a step on the way to find the formula $2\pi R$. When we have that formula $2\pi R$, then we can determine the circumference of the circle by computing it from R. Not now.

Prof. L. Lipski (on behalf of Mr. Dolegowski).

Mr. Dolegowski gave me permission to make some remarks concerning his work. As Dr. Vermij said just before, he tried only to get more detailed information concerning the arc behaviour in the inductive a.c. circuit, which is described by Kirchhoff's Law, from the point of view of laboratory investigations. That is the main idea of Mr. Dolegowski. He takes the a.c. network into account and therefore the solution has very close connection with the actual conditions appearing in an a.c. circuit.

The Chairman raised the question of the range of applicability of Mr. Dolegowski's method. This method is valid of course only in the case of short-circuit, and in the case with deep and short notches. It is not the same case as that considered by Dr. Hibner. It is a quite different case. It is interesting to note that in equation (6) the electrode voltage drop has two members. One is independent of current, while the second is dependent upon the current. (On page 219, in equation (2) U_N should be U_B).

Prof. Y. Naot

I would like to ask the authors of the paper on capacitor-bank protection why they did not consider one phenomenon which is important. The inrush current of a capacitor bank is extremely short in time because the time constant is generally some nanoseconds, but it can be extremely high in magnitude. I had many times the occasion to observe that the electrodynamic forces acting on the fuses produced some distortion of the contacts, starting a trouble which may become serious some weeks or months later. It seems to be that in choosing a capacitor fuse, not only the thermal properties should be taken into consideration, but also its fitness to withstand shocks.

Dr. R. Wilkins

I would like to make a few remarks in support of Dr. Vermij's view. The approach should I think be to try and represent a fuse, a circuit, and maybe a device as well at some later stage,by some sort of model, and it is only necessary to have a model which is sufficiently accurate for the particular phenomenon you are interested in. Development of such a model is a very difficult process, but that is no reason for not attempting it.

There are various degrees of sophistication. Mr. Jacks has mentioned in particular the use of a rectangular arc voltage. A recent paper of mine gave many characteristics and interactions between a fuse and a circuit based upon the assumption of a rectangular arc voltage. If you interpret that value of arc voltage as, say, the average arc voltage during the arcing time, the answers you get do have some value. A slightly more sophisticated approach was presented this morning, by Prof. Hirose; this seems to be definitely a better arc model which gives transients under short-circuit conditions which look very similar to those which can be seen on oscillograms. This is a step forward.

But in order to use these models you have to have experimental data, and I support also Dr. Leach's view, that the paper by Dolegowski represents an enormous amount of work, gives experimental data which is of great value. Some of the modelling techniques should also prove useful.

As regards the ideas about the 'worst-case', it depends which particular thing you are talking about. If you are talking about Test 2 current, when you are testing for maximum arc energy dissipated within the fuse, the studies I have made, and also presented by Prof. Hirose this morning, indicate quite clearly that critical current depends upon the arc voltage of the fuse. These are the things which can be illuminated by the use of models, even though they be very simple ones.

Another 'worst-case' may be discussed in the next session - the maximum I^2t let-through by a fuse will depend upon the point-on-wave at which the fault occurs. So when we talk about 'worst-cases' we must make sure that we know which worst case we are talking about.

Mr. B. Wadcock (in reply)

I would like to take the point Mr. Gibson raised regarding damping in capacitor switching circuits. Ideally of course the prearcing I^2t of the fuse should be related to the I^2t of the capacitor inrush current, and we realise that this I^2t value is affected by the damping in the circuit. Unfortunately, in the size of capacitor bank that we are considering in this paper these factors are very difficult to obtain.

We can generally obtain them on large capacitor banks, but on small banks of this nature, which are essentially off-the-shelf designs, the resistance, or damping in the circuit is very difficult for us to obtain. We really rely entirely upon the capacitor user to provide this information for us. If they can do this we can then of course tell the fuse manufacturer.

I think also Dr. Lerstrup mentioned a factor of twenty-five times. In other words, the inrush current of the capacitor, for an isolated capacitor bank, be approximately 25 times the normal capacitor current. This is a rule-of-thumb measure that we are quite well aware of. In actual fact, on multistep banks this figure is substantially increased. To reduce the figure to some value more reasonable from the fuse point of view, we have to introduce some inductance between the sections of the capacitors.

Mr. M.J. Smart (in reply)

One thing I should clarify with regard to our paper is that it is related particularly to small banks, for industrial purposes, and a significant factor of these is that the capacitor is designed so that on capacitor failure, the fusing current is largely power-frequency. There are very few capacitor units connected in parallel, so that there is very little inrush current from the healthy capacitors into the failed capacitor.

The application of current-limiting fuses to bigger banks where there is a very large inrush current into the failed capacitor from the parallel-connected healthy capacitors makes fuse operation and application much more difficult. The inrush current into the failed capacitor in these circumstances, largely the discharge frequency current, can be up to 10 kHz. Perhaps some of the fuse experts would care to give thought to the operation of fuses under these high-frequency conditions. It is an area where we could do with a little more knowledge.

In extreme cases, we can find that because the frequency of the current is so high, and fuse operation can take place in less than one-quarter of a cycle of the high-frequency current, which at 10 kHz is less than 25 μs, the fuse can be damaged due to thermal shock effect on the fuse barrel.

Another thought here is whether there is in theory any limit to the numbers of capacitors you can connect in parallel, from a fusing point of view. This is something we are very sure about and we like to keep our banks down to about 60 kJ level of available energy.

The Chairman asked whether the motor-circuit fuse would be a useful fuse for capacitors. This may be so, because obviously it is designed to withstand mechanical strain of motor starting. I must say that when we have applied fuses in accordance with the rules laid down in our paper, we have no evidence of problems from current shock on switching, and perhaps this answers Prof. Naot's question about thermal shock on inrush currents.

I think that one of the snags of the motor-protection fuse is probably expense, because a motor needs three fuses, while a capacitor bank needs one fuse per unit, and we are talking about a lot of fuses, in some cases.

Prof. Lerstrup raised a question about relating fuse, cable and capacitor ratings. I think the problem arises here where the fuse is on the feeding end of the cable and has to protect the cable and the capacitor. The fuse has got to be oversized to withstand the capacitor inrush current, and something like 200% is typical for a high-voltage capacitor bank. If that same fuse has also to protect the cable, then the cable must likewise be oversized, by something of the same order. This is where the problem can occur.

Mr. Gibson mentioned 50 Hz fusing and bursting curves. It is true that it is difficult to get a current-limiting fuse to discriminate with our unit-bursting curves, all the way throughout its length. In fact if we take the time-current characteristic of the capacitor units, we normally take the 10% probability curve because unit bursting is not a precise thing, it's a question of probabilities. We find that when we apply a fuse in accordance with the parameters laid down in the paper, that it crosses the curve something like that. So that we only get correct discrimination down in this area. But with banks arranged as we have stated in the paper, the fusing current on capacitor failure is very large, because it is only limited by the system impedance, so that we can ensure that operation is in this region, and we do get correct discrimination.

* Figure drawn on blackboard. *

Mr. G. Farina (in reply)

With reference to the first paper, I would only remark that the fuse is not able to carry the current I_{nf} indefinitely, for a time exceeding the conventional time. The temperature rise of a fuse although less than that necessary to reach the melting temperature, is high enough to cause accelerated ageing of the fuse element. Consequently the permanence at such high temperature causes the operating characteristic to drift to the left, eventually bringing the fuse to melt with the conventional non-fusing current.

These tests have been carried out in our laboratory. The tests were carried out on about 20 samples of fuses of 50A rated current. The fusing time was scattered from 1 hour to about 5 hours. On this basis the current-carrying capacity of the cable to be protected against overload, may be exceeded to a reasonable extent by the conventional fusing current of the fuse itself, the characteristic of which is subject to a drift to the left when high temperatures are maintained. This criterion does not apply for protective devices operating on different principles, e.g. a circuit breaker.

For the other paper, with reference to the question of Dr. Lerstrup, if we use a fuse exceeding the rated current of the contactor, welding or heavy erosion of the contacts will very probably occur. The high rated current of the fuse causes a high energy between the contacts, and when contacts come back together, although the current has been terminated, the contacts are still at a high temperature, and welding can occur. This was confirmed by many years of tests, on fuse-contactor coordination in Italy. We have verified that the worst condition occurs at a current slightly exceeding the current that equals the contact force, because in this way the contact comes back to touch together suddenly, and the current is not terminated. If in these conditions welding occurs, we must reduce the rated current of the fuse, to avoid risk of welding.

SESSION 6. Thursday, 8th April, 15.45 - 17.00

SEMICONDUCTOR PROTECTION

Session Chairman: Mr. E. Jacks
(G.E.C. Fusegear Ltd.)

Paper No.

26 "I^2t values of real and ideal semiconductor fuses", by T. LIPSKI.

27 "The dimensioning of fuses for the protection of diodes and thyristors", by K. LERSTRUP.

28 "Advances in the protection of semiconductors by fuses", by J.G. LEACH.

29 "Liquid-filled fuses for the protection of thyristors", by Y.A. PASTORS.

30 "The desirable short-circuit parameters of semiconductor fuses", by J. CZUCHA.

31 "Cyclic loading of fuses for the protection of semiconductors", by G. STEVENSON.

Dr. R. Wilkins

I would like to raise a question for comment by Prof. Lipski and Dr. Leach.

Dr. McEwan pointed out this morning that where you have a fuse-element with a deep notch in it then the prearcing I^2t is certainly not constant. He has made this point and Dr. Leach has also emphasised this.

There are instances in the protection of power converters when we do not want the fuse to operate, i.e. we wish it to discriminate correctly with another protective device. What is the point of using I^2t values for discrimination when we know that what really matters is whether or not the element will actually reach melting point.

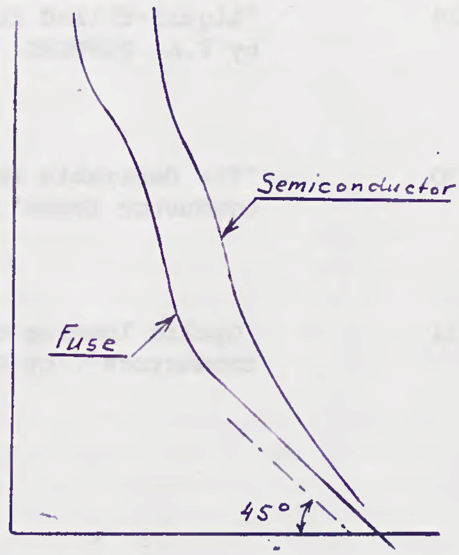
Power converter fault current waveforms can vary quite widely, and the I^2t values vary widely, as Dr. Leach has shown. So numerical methods must be used to predict the transient temperature at the hottest point on the fuse-element.

Since the prearcing I^2t values are so variable, what is the point in using them?

Dr. Lerstrup

I have one question to Dr. Pastors. Why has he not tested the most obvious liquid of all - water? It will give us hydrogen for interruption and incidentally is readily available in most places.

Apart from that I would like to turn to the I^3t. Normally we will have curves like this, coming down to the 45° line. This is typical of having two different time constants, that of the fuse element and that of the fuse body. If we are dealing with semiconductor devices, we have very short times, we have some very thin layers which have to transfer heat from the places where the losses take place. So the semiconductor device probably has something like this, giving something that, on the whole, may approach a higher power than 2. Not necessarily 3, but higher than 2.



The next thing is that this is not at all an improbable thing within fuses. In fact we have sitting here Mr. Nørholm, who to my great academic irritation has designed a fuse element that did not behave the way my theory wanted it, namely to follow I^2t, but actually followed a steeper motion. And therefore actually in its melting characteristic comes closer to I^3t. However, this is no good if you have a fuse with too small an arc voltage so that for higher current you have a greater I^2t during arcing, but if you combine this with sufficient arc voltage to be sure that your actual operating current also falls down along the same line, we may get that fuse which lifts up a little higher here, and allows better utilisation of the semiconductor, and a closer approach. So, even if they should start talking about $I^{2.5}t$ or I^3t, I think we are still up to it and we are capable of delivering the goods.

Mr. R. Oliver

I would like to ask Dr. Lerstrup a question which I think he will be very keen to answer. I asked a question yesterday about the exothermic reaction with aluminium. I actually used a rather important word which perhaps wasn't heard; I said "quantitative" information on the exothermic reaction and whether such information is available and whether it has been studied. I knew that an exothermic reaction took place, but I would certainly be interested in what Prof. Lerstrup has to say as to how he contains this reaction and absorbs the energy released. A further point on aluminium is that as an element material I think that serious consideration must be given to its low-current arcing behaviour, which I have found is distinctly inferior to silver. It can exhibit, under low-current arcing conditions, phenomena where the second phase of arcing referred to in my paper is even worse with aluminium, to the extent that the increase in length during the arcing period is equalled in effect by the fall in the axial field with the consequence that the arc burns with constant arc drop. I would be interested in any comments Dr. Lerstrup might have in that direction.

The other question, to Dr. Leach, I was interested in his temperature predictions under various conditions, shown in several figures. The one which interested me was Fig.13, where his resolution axis runs from 200 to 220°C, so the curves which are shown are obviously very accurately resolved from a temperature point of view. I would be interested to learn if Dr. Leach has established the effects of manufacturing tolerances on the predicted temperature bands, under the same conditions.

Prof. Y. Naot

I would like to make some general remarks. Let us try to see the problem in a different way.

I don't think that the I^2t, or I^nt is relevant in this case, because I^2t is an integral measure. This is like saying that the total number of calories developed in the fuse should not exceed a given value. I think the problem looks somewhat different.

Let's look at the circuit. We have a fuse, then we have a semiconductor device, then we have a load.

Now a semiconductor device and an arc have typically a negative 'temperature' coefficient. If you look at the two main equations I gave in my paper yesterday, and you suppose two bodies having the same time-constant, T, you see that inherently the negative temperature coefficient brings to much shorter times of temperature rise than the positive one, for the simple reason that by positive temperature coefficient the heating process starts slowly and increases thereafter, and by negative coefficient it is exactly the reverse. The heating process starts strongly and decreases thereafter. So I think the problem is that which one of these two elements reaches the dangerous temperature first. We want the fuse to reach the melting point first. What we are looking for, since the fuse has a positive temperature coefficient, is a fuse with a very short time constant. It is not a matter of how many calories we are dispersing in it; it must be very very quick in order to be first to reach its dangerous temperature. I am sorry, I shall go the way of the famous Roman Cicero, who said: 'Ceterum censius Cartago delendam esse'. If you would have an n.t.c. fuse the problem would be solved.

Dr. P.M. McEwan

Speaking specifically about this problem I find I am in full agreement with Dr. Leach's recommendations, and I would like to make a point on the previous speaker's remarks. For correct fuse performance in this case we would also have to consider the arcing performance surely, and it would not just be a case of the fuse reaching melting temperature. I would also add that the time constant of silver is the shortest that I have come across, and I doubt if we will find a better element material. In the slide I showed yesterday I think it was evident that adiabatic conditions existed for about 10^{-4} seconds, which indicates the time constant of heat flow from one section of the element to another is extremely short.

Looking at this particular arrangement here, my view is that we do in fact have to model both devices and pass the same current through both since they are connected in series, and see how they perform, but this would involve modelling the arcing period also, which takes us back to this morning's sessions.

Mr. J.W. Gibson

I just want to ask Dr. Leach a question arising from remarks that have been made about the very short time constant. 10^{-4} seconds has just been mentioned, but if we look at Dr. Leach's Fig.7, the curve for symmetrical current at 10^{-2} s almost has a characteristic of $I^{10}t$ or $I^{20}t$. Does that ever finally reach the adiabatic condition? It still seems concave to the left. Does it finally turn to the right and reach the constant I^2t condition?

Mr. J. Feenan

Picking up a point that Dr. Wilkins made. When he queried whether prearcing I^2t was essential or necessary, I would like to enlarge on that and ask the authors their views. I think that the answer to his question is that it is the best we have for the moment. It is a reference point from which to assess what the fuse will withstand, but we are, as you will have gathered from the papers, a long way from the final solution.

There are in Dr. Leach's paper methods of calculating the prearcing I^2t, methods of calculating the state of the element under certain pulse conditions, and there are in Mr. Stevenson's paper methods of trying to determine the same information by empirical methods.

One of the factors which has been mentioned during this conference, but which I don't think is mentioned in any detail in the papers is the effect of mechanical fatigue, and I wonder whether any of the authors could comment on this particular point. I think an attempt has been made using empirical methods using prearcing I^2t as a reference point.

On the comment that I^3t might be a good idea, having been involved with a number of people in this conference in trying to formulate IEC 269 part 4 on semiconductor fuses, and in the application guide, we did of course get some measure of agreement that I^2t was not a bad basis on which to commence work.

It took us some time to produce the document, (although not as long as part 2 and part 3 - so we are improving), but I think that a consideration of a different form of presentation of data is dependent to some extent upon the available information on devices. This has already been mentioned, and one of the tasks which is still left to the working group concerned, (I personally feel that it is an impossible task) is to produce simple rule-of-thumb methods for selecting fuses, even for the most complicated equipment arrangements. Information from the fuse viewpoint whilst not perfect, is available, but not from the device viewpoint.

I would like some observations from the authors in this session on those particular points.

Dr. K. Lerstrup

In my many discussions with Mr. Feenan he has never given me such a beautiful opening as he just did. He always insists that we should give the I^2t characteristics on a separate sheet of paper, because that ties down to the I^2. If instead he had stayed with the original idea of giving the characteristic curves of time and current, he would know then that a 45^o slope represents the second power (I^2), because we have a scale ratio of twice as long per decade for current than for time, and therefore a deviation from this direction will show an approach to a higher power, or a lower power. Therefore if we went back to the original and did not speak about any separate curve, we could present the facts to the users in such a way that with a little thinking (of course that is necessary) they would be able to use them.

Prof. T. Lipski (in reply)

Generally speaking I may say that my paper is only a very small attempt at the very large problem of semiconductor fuse selection. To characterise my paper, I would say that I only try to show how far we are from heaven. And that is I think the main point in my answer. From this point of view I will try to answer the more detailed questions.

First of all the question of the I^2t value as a constant value. In my paper it is not necessary that this value be taken as a constant, because the main results, shown in Fig.4 and in Fig.5 are calculated on the basis of the 99% for diodes and thyristors. These two devices are shown here by conventional means, and taking into account these 99% lines, or 50% lines which one can get from the marks given on the figures, and which correspond to actual state which we have at the moment for semiconductor devices in production now, I only used idealised semiconductor fuses to show you how far the total I^2t lines should be for ideal semiconductor fuses.

On page 235 some dependences are shown. Especially interesting is the third relationship which gives the ratio of the prearcing I^2t to the total I^2t, independent of the I^2t value of the shoulders. I take into account only the present state in semiconductor devices, and I calculate on this basis the values for ideal fuses.

Of course I agree with Dr. Wilkins and with Dr. McEwan that this influence is very great in some time region, but in this paper it is not necessary.

Of course this answer is in close connection with the problem of discrimination. It is right that in the case of discrimination between two fuses in series the influence of cooling by the shoulders must be considered. This may be affected by the fact that the current in the two fuses may not be the same.

Once more I would repeat that my main intention was to show how far we are from heaven.

Dr. K. Lerstrup (in reply)

It appears that all I have is the question about the aluminium.

In reply to Mr. Oliver, there has been nothing said about using aluminium for fuses that operate on a sneaking overload. It is useable only for short-circuit protection on the high overcurrents. That is what it is for, and that is what semiconductor fuses are for. If we take a long, slow, heating up of it, all we get out of it is a nice fire bomb.

Now we come back to the question of the chemical reaction. The chemical books will tell exactly how many calories you will get out of every gram of aluminium that you melt and react, but I believe this was not the question asked, but 'what will it do in conjunction with the amount of energy released in the fuse otherwise, and how do you get rid of it? Fortunately, when you have very short arcs you have a greater amount of the voltage drop very close to the surface of the metal. That means that the bigger part of the arc energy goes into melting more metal and to be conducted away from the rest of the metal provided there is plenty, and this is one of the most important things, you must have plenty of metal, to cool. That is, very deep indentations, and what 'very deep' is, is something you had better ask the toolmaker about, because the technique of making successful fuses in that direction depends upon how deep he can make the cuts.

Now, we have this additional energy released by the chemical reaction. That too, fortunately is released near that surface of molten metal where the foot-points of the arc are. In other words, the chemical reaction and the electrical reaction work in the same direction, namely to elongate the arc and to give some higher pressure around the small arc. It means in practice that you get - and shall I give a figure? - 25% higher average arc voltage than you would get with silver under the same conditions. Now when you have a higher arc voltage then you will have a quicker decrease of the current and you will have a shorter arcing period, and this is where you gain. I can tell you, just to give exact figures, that we have compared a silver and an aluminium fuse, as closely alike as you can make them, as to the melting I^2t and so on, and found that the total integral plus the chemical reaction of the aluminium fuse was less than the electrically released energy in the silver fuse. This is not always the case, but the fact that it is possible to get so far that you actually have less energy shows that this is not such a far-fetched idea at all. So even if you have to pay the price of having the chemical release as well as the electrical release, you still may have a smaller total release of energy. I hope that these clear figures will satisfy Mr. Oliver.

Dr. J.G. Leach (in reply)

First of all Mr. Oliver's question concerning the y-axis resolution. The reason it is so fine of course is that this particular test was to determine the effect of current waveform on the generation of heat within a fuse. It seemed obvious that very high form-factor currents, for example, would lead to higher notch temperatures and consequently a higher rate of energy production. The question is whether we should derate our fuses if it's on half-wave rectified current compared with the sinusoidal current it's customary to test with. The model was set to take steps of a cycle, very similar to the other model, but this was with the rated current of the fuse rather than an overload and so time-steps of the order of 1 ms were taken. The results showed that it doesn't make much difference to the energy; manufacturing tolerances, cables etc. have a greater effect upon the current rating than the waveform, at least for up to 120° conduction.

I used my mathematical model for doing some studies on the effect of manufacturing tolerances, though I must admit in this particular case I haven't; however, I have done curves like Fig.13 for different notch shapes, and as you can see, since the fluctuation is only of the order of 20°C or so, a different notch shape doesn't make more than say 50% difference. So with manufacturing tolerances, even if they made 10% differences, we are only talking in the order of half a degree. In fact in that connection I would draw your attention to one of the earlier papers by Dr. Barbu, which didn't receive much discussion, mainly because I think he was considering a very complex mathematical model of a fuse neglecting radial heat loss. One of his conclusions was that at rated current the axial temperature gradients were fairly small, and this is borne out by my Fig.13. When we get near to minimum fusing current, or higher currents than that, this situation changes and this is shown in some of my other figures, where very large fluctuations of the temperature of the restriction do occur.

Another point raised on various occasions was the shape of time-current curves. I should emphasise that all the time-current curves that I have drawn are drawn for <u>real</u> time. Because I live in a real world, unlike possibly one or two analysts, I like to use real time and not virtual time. And this goes along with device manufacturers, who always use real time. I have never seen I^2t values quoted for anything other than real time.

Mr. Feenan talked about the effect of mechanical fatigue. It is mechanical fatigue that I was mainly concerned about with my suggestion for using curves of prearcing I^2t against prearcing time to decide how close we can take a fuse to its time-current curve. This is something that I am always getting asked, in one form or another. Obviously if one fuse is meant to discriminate with another fuse, the question is, O.K. well if one curve is there and the next curve is next to it, they will discriminate, but what will it do to the fuse that is being discriminated with? Will it cause mechanical fatigue? So I thought it was a good idea to throw out a few simple rules - perhaps not so simple because no-one has commented on them, and I have presented these basically as a basis for discussion. Perhaps you would all like to go away and try using them and let me know in a few years time. The idea is that if we limit the element temperature during what is in effect an overload caused by the fuse having to sustain a current before a breaker trips out for example, the situation where you don't want the fuse to operate, it's a problem then to ensure that the fuse won't be mechanically fatigued.

So what I propose is that if you limit the element temperature during this pulse of current then the chances of mechanical fatigue are considerably reduced. Because obviously the higher the element temperature gets, the more stress is put on the restrictions and the more chance of mechanical fatigue occurring. So these percentages I have quoted are as to how close one can go to the prearcing I^2t curve.

I would point out that I use a prearcing I^2t curve rather than a time-current curve for times of less than a second or so, because time-current curves in this region are very susceptible to the wave-shape, far more susceptible than the prearcing I^2t against time curve. This gives a curve which is a one-stage better approximation to what is going on. So I would be very interested in anyone's comments on this, at some future date. As to this principle of how close you can get to this minimum prearcing curve consistently, I have based recommendations on either a few operations, the sort of fault you expect the fuse to see only a few times during its life; I have said 10, perhaps it's 20, my rules are pretty conservative I believe, or frequent, 1000 times/year or perhaps 2000 times/year.

I think I said yesterday all I want to say about negative-temperature coefficient fuses.

The only other comment I have got is on Mr. Stevenson's paper, as he is to speak next. I thought that this was a different approach to mine, in that he is looking at repetitive cycles, for which I just give a rule-of-thumb, because I haven't got round to doing the sort of tests he did, so I am grateful for him for doing the tests for me. I will obviously be looking at it too and it seems to me a very good idea, to produce curves of number of cycles against pulses to give more information to the user. I am all for anything that gives extra information to the user.

<u>Mr. G. Stevenson</u> (in reply)

My paper was primarily concerned with cyclic loading, or fatiguing of fuses. I would just like to make it quite clear that as far as we are concerned, this fatigue problem is mainly a function of fuse design, and there are many fuse designs on the market, not particularly in the U.K. but from other countries where the basis of rating is different, such that cyclic loading or the pulsed loading of fuses causes mechanical fatigue. In the U.K. the general practice has been to use fast-type fuses, rather than ultra fast-type fuses which means that the current densities in these fuses are a lot smaller, so the element itself is less susceptible to mechanical fatigue. The other point I would like to make is regarding Dr. Wilkins when he talked about the importance of element temperature, and not allowing the element to melt. I think that from a discrimination viewpoint, that is not the whole story because as Dr. Leach points out, it's not just a question of preventing the fuse from melting, but it is a question of how many times you want to go there. If you want to go there, say, 10 or 20 times in a fuse lifetime, well then of course you can go very close to the time-current characteristic ordinate for that particular time, but if you want to do it a lot of times then you must bring in quite a large safety margin to ensure that there is no mechanical fatigue.

There was one query raised concerning the overload on page 277, where I mention that you can go to 85% of the time-current characteristic from a discrimination viewpoint. In this particular section I had in mind where the equipment is only liable to say 100 or less faults in its lifetime. For another equipment, such as a chopper, a traction application, where you can get motor flashover quite frequently across the commutator, and the fuse has to withstand this value while you bring out a circuit-breaker, further back so the train can continue to its destination, well that's where the 70% factor comes in. So the first section there is just concerned with overloads which only happen 100 times or less in the lifetime of the equipment.

What I think we ought to start thinking in terms of, from a particular application viewpoint is how frequently we want to go to the time-current characteristic, and then by the use of the curves that I propose you can determine how long the fuse is likely to last.

The other thing regarding mechanical fatigue is that one can get round this problem by kinking the element, as was mentioned by Mr. Feenan early this morning, and this technique has been employed successfully. It may be that in the future, for very large fuses and very fast fuses, that in fact there is an upper limit whereby this mechanical fatigue becomes the major factor in fuse design. At the moment this is not the case; I think that it is mainly on the basis of rating primarily American fuses and others where this desire for information on the withstand value for a fuse, this is where the emphasis has come from rather than from the U.K.

Dr. Y. Pastors (communicated reply)

The use of water in the liquid-filled fuse link appears difficult in view of the following factors.

When water is in a continuous contact with various metals and plastic materials, its electric conduction is increasing. In addition to that, continuous heating causes water to liberate hydrogen. The latter, forming a gaseous obstruction, disturbs the process of vapour condensation in the fuse link.

Experiments with water, however, are highly useful for finding out the role played by the liquid phase in a heterogeneous filler, as water has a high critical boiling heat flux.

SESSION 7. Friday, 9th April, 11.00 - 12.15.

TESTS AND STANDARDS 1

Session Chairman: Mr. J. Feenan (GEC Fusegear Ltd.)

Paper No.

33 "Optimum conditions for testing fuses at maximum prearcing energy" by C.B. WHEELER.

34 "Breaking capacity tests for miniature fuses" by G. CANTARELLA, G. FARINA and S.B. TONIOLO.

35 "The influence of standards on the design of l.v. fuselinks" by P.G. NEWBERY.

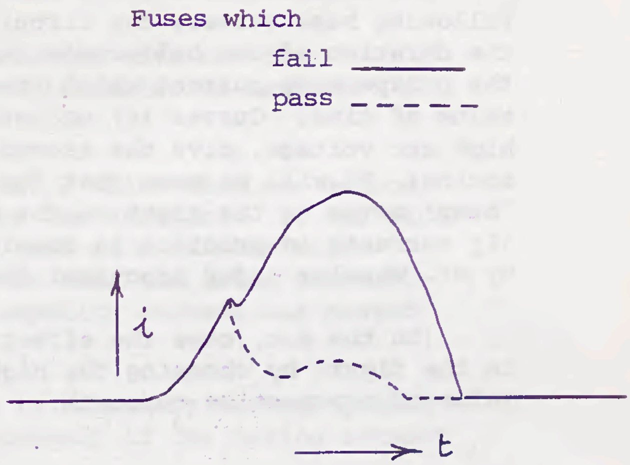
Mr. H.W. Turner

I would like to comment on Mr. Farina's paper, which I think is an interesting theoretical and practical study of this subject of miniature fuse testing, and as a summary, I would say that what he says is undoubtedly true for good fuselinks, but I would suggest that it is not suitable to be introduced at this moment. One point is that the suggested angle of arcing that should be sought is 80° - 90°. With the tolerance on making switches, this would undoubtedly mean that the 90° arcing would be extended to a value beyond 90°, on a falling voltage. I would submit that this would be unsatisfactory.

Accepting the evidence presented here, one would say that one could perhaps reduce the number of fuses tested by selecting certain current ratings from a homogeneous series and testing them solely at this value. However this would not result in a reduction in cost, because in order to do this it would be necessary to take an oscillogram of every shot and to measure the arcing angle and adjust the making angle of the subsequent shot to make sure that it lay between 80° and 90°, and this will increase the cost of testing tremendously. It may mean that you might (on the basis of this evidence) reduce the number of fuses tested, but the cost of testing for example, a fuselink to B.S.88 on the breaking capacity test, (which involves this type of arc instant measurement) is over 100 times the cost of making a breaking capacity test to IEC 127, where you use a test switch set at 30° ± 10° and test all the fuses at that same setting, which is a considerable economy. This is permitted because, with miniature fuses (unlike other fuses), all the ratings in a homogeneous series are tested. Because of the nature of these little fuses, it is essential to do this, and consequently there is much more general control over miniature fuses. In fact it is possible to test 48 fuses in all the different tests, for power loss, millivolt drop, dimensions, breaking capacity time-current characteristics, etc. for less than one-fifth of the cost of making a breaking capacity test on one rating of a B.S.88 fuse. Now, even allowing for the higher power involved, this should be considered when evaluating cost, because the cost would not, as is suggested, be reduced by this procedure.

However, would it mean that the devices were tested more satisfactorily? Again I would submit that this is not the case because with the miniature fuse the value of 1500A is far in excess of what is ever experienced on the sub-circuits at the end of a piece of flex that these little fuses are subjected to. There are special uses where they might get up to prospective currents of this kind, but the manufacturer of the device which uses them for that special use should introduce some form of resistive protection, which increases the power factor to a higher value than the 0.7 at which these are tested. So, in that case also the specified test is more severe than normal practice. And then again I would turn to the actual evidence, which I do not dispute at all in the way in which it has been presented here, but I would ask Mr. Farina if these are tests on actual manufacturer's good fuselinks. I would also ask him how many failures there were in the tests which he carried out, because my experience of testing these fuselinks over about 15 years is as follows. The ones that pass the test follow the forms that we see in these curves, Fig.2, for example (page 314), with a very rapid reduction in the current immediately after cut-off, and Fig.6 (page 316) which shows the kind with the beginnings of a "camel's hump". However, the ones which fail usually fail by a more extreme case than this, namely, something like the sketch shown.

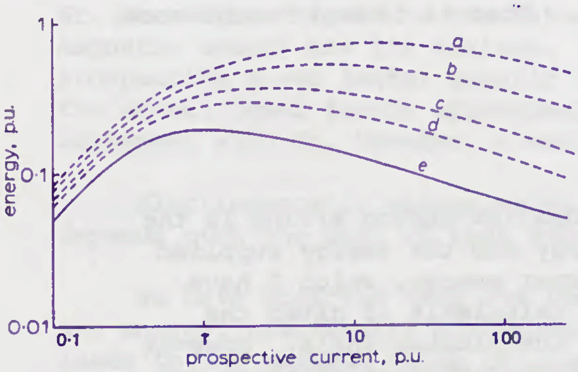
A year or so ago I tested a number of internationally obtained fuselinks in helping to set these breaking capacity conditions, and I found that there were some that would fail at 30° making angle, but when tried at later point-on-wave, including 90°, arcing commenced on a falling voltage and cleared, and the fuses did not explode. Thus I repeat my question to Mr. Farina, asking whether he did this with a set of fuselinks, not only the best ones from his best Italian manufacturers, but also with some bad ones with filler deficiency, and other inferior characteristics.



Dr. R. Wilkins

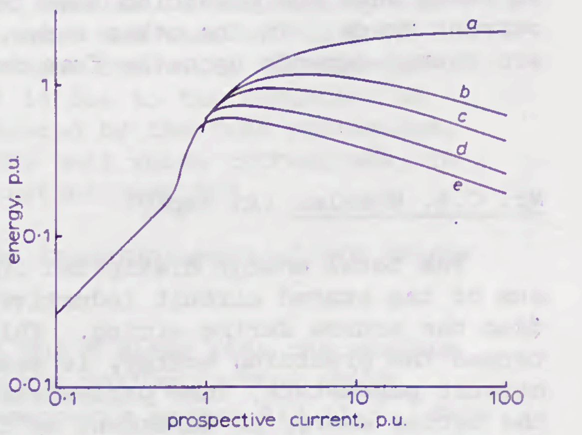
The stored inductive energy at the start of arcing, discussed by Mr. Wheeler, is only one component of the total energy dissipated in the fuselink during arcing. The energy supplied from the source during the arcing period must be added to the stored inductive energy to obtain the total.

Using a rectangular arc voltage waveshape, these characteristics have been computed and published elsewhere, (Proc. IEE. 122, 1975, pp.1289-1294) and are shown in the figures, for both d.c. and a.c. circuit conditions.



D.C. arcing energy characteristics

$a\ V_a = 1{\cdot}1$ $\quad d\ V_a = 2{\cdot}0$
$b\ V_a = 1{\cdot}2$ $\quad e\ V_a = \infty$ (inductive energy curve)
$c\ V_a = 1{\cdot}5$



A.C. arcing energy characteristics (cos $\phi = 0{\cdot}3$; maximum values shown)

$a\ V_a = 1{\cdot}5$ $\quad d\ V_a = 5{\cdot}0$
$b\ V_a = 2{\cdot}0$ $\quad e\ V_a = \infty$ (inductive energy curve)
$c\ V_a = 2{\cdot}5$

The characteristics are shown in normalised form using the following base values; the circuit time-constant (L/R) for d.c. and the duration of one half-cycle for a.c. The base value of current is the prospective current which produces element melting after the base-value of time. Curves (e) on both diagrams, corresponding to an infinitely high arc voltage, give the stored inductive energy at the start of arcing. It will be seen that for more realistic arc voltages the 'hump' moves to the right on the curves, and so the critical current (I_2 current) in practice is considerably higher than that calculated by Mr. Wheeler - for practical fuses usually about 3 - 4 times.

(In the a.c. case the effect of point-on-wave has been eliminated in the figure by choosing the highest values of arc energy for each value of prospective current).

Prof. T. Lipski

It is well-known that the fuse-resistance (R_F) of miniature fuses may considerably reduce the prospective current during the prearcing time.

High-breaking capacity (2500A) quick-acting fuses, particularly for smaller rated currents, may have $R_F > R_1$ or even $R_F >> R_1$. The reduction of the current trace in such cases leads to the alteration of the instantaneous value of the current at arc beginning. Then arise questions concerning:

(i) the calculation errors of the function in Fig.3 in comparison with the measured values in Fig.4,

(ii) the influence of R_F on the energy equation (1),

(iii) the influence of R_F on the making instant giving maximum arc energy.

It seems to me that the first part of the conclusions is limited to cases when the prearcing fuse resistance does not reduce the prospective current trace. In the other cases, the making instant giving maximum arc energy depends upon the fuse design. That is indeed troublesome.

Mr. C.B. Wheeler (in reply)

The total energy dissipated in a fuselink during arcing is the sum of the stored circuit inductive energy and the energy supplied from the source during arcing. This former energy, which I have termed the prearcing energy, is exactly calculable if given the circuit parameters, fuse parameters and the closing angle. However the latter energy is dependent on the current-voltage relation for the arc which, in practice, is found to be a very variable quantity. Dr. Wilkins' calculations are for an assumed rectangular arc voltage waveform.

Mr. G. Farina (in reply)

The test current of 1500A is in agreement with the IEC Publication 127 in which this current was indicated as maximum breaking capacity for miniature fuses.

With regard to the cost of the tests, I think that our method is not more expensive than that stated by the standard. In our paper we have observed that in most cases the test at a current below breaking capacity, but sufficiently higher than the rated current, can be omitted if the test at breaking capacity current was passed successfully.

Certainly oscillographic recording is necessary to verify that making instant is near 90°, as it is necessary if the making instant is 30°, as stated by IEC 127.

In our tests we have tested only four types of fuses of many rated currents. Only one type does not pass successfully the tests and corresponds to the type of Fig.6, in which piercing of the external surfaces of the end caps occurred. In this case the maximum of arc energy occurs with making instant near 0°.

In reply to Prof. Lipski I would observe that expression (1) is referred to the arc period and the fuse resistance cannot have importance at this time.

The fuse resistance is very important for the prearcing time and it modifies substantially the prospective current. We have taken into account this resistance to calculate the peak current at arc beginning. A certain error can appear from Fig.3 and 4, due to the fact that we have considered for the fuse resistance a constant value instead of variable value as a function of temperature, during the prearcing time.

The fuse resistance is very important to determine the making instant giving maximum arc energy.

With reference to the paper of Mr. Wheeler, a discrepancy can be noted between our diagram of Fig.3 and 4 and that of Fig.5 of Mr. Wheeler as regard to the making instant for which the electromagnetic energy has its maximum. This is due to the variation of prospective power factor greatly influenced by the fuse resistance; the actual power factor approximates the unit which corresponds, in agreement with Mr. Wheeler, a making instant near 90°.

Electromagnetic energy which is an important part of arc energy depends upon the peak of test current.

We have observed that the instant which gives rise the maximum arc energy, practically corresponds to the making instant which leads to the maximum value of electro-magnetic energy $1/2\ LI_o^2$. This condition for all the tests carried out occurs near 90° and is confirmed by experimental results.

Mr. P.G. Newbery (in reply)

In view of the recent revision of IEC 269 and the subsequent revision of national standards to meet these requirements it is unlikely that further fundamental changes will take place for perhaps a decade. In the meantime the fuse manufacturer and user will be assimilating the present specification.

The only aspect which could perhaps influence a quicker evolution of a new specification would be the publication of the International Wiring Regulations. In practice, however, the fuselink does give adequate protection to wiring installations and, therefore, even this problem should be able to be resolved within the framework of the present specifications.

The dimensional standardisation of fuselinks is a difficult technical and commercial problem. It is, however, hoped that the British practice of having discrete dimensions for different categories of fuselinks will prevail, i.e. Domestic, industrial and semiconductor. In addition if more than one standard voltage is common then again for safety reasons discrete dimensional systems should be used. This is particularly applicable in the fast developing field of semi-conductor fuses.

During this conference little mention has been made of the miniature circuit breaker or moulded case circuit breaker, a growing competitor of the fuse. We are all aware of the limitations of these devices particularly regarding breaking capacity which is evident in their associated type test requirements. There may be some merit in the future of standardising breaking capacity type test requirements for all overcurrent protective devices. As indicated in my paper the type test requirements for fuses are so severe that many national testing houses are unable to fully test all fuses, this has hopefully been noted by such bodies.

On the subject of national testing authorities there may be considerable pressure for approvals marks to be extended for industrial products. It is, however, advocated that the well proven system of independent short circuit certification coupled with manufacturers' self certification of other type tests should be adopted in the fuse industry.

Finally I would like to comment on the discussions relating to the practical use of theoretical investigations. My own company has sponsored research at University level for some ten years and I can only reiterate the comments given in my paper that such investigations although very fundamental have given great assistance in our developments.

SESSION 8. Friday, 9th April, 14.00 - 15.15

TESTS AND STANDARDS 2

Session Chairman: Dr. R. Wilkins
(Liverpool Polytechnic)

Paper No.

36 "The standardisation of HV current-limiting fuses, by J.W. GIBSON.

37 "The role of ASTA as the U.K. certification body", by J.G.P. ANDERSON, R.E. BLAKE, B.S. CHALLENGER, R.H. GALLAND and D.G. MEE.

38 "The quality aspects of HV current-limiting fuse protection", by W.R. CROOKS.

Dr. L. Vermij

Regarding the paper of Mr. Crooks, I have the impression that this is the only paper which goes into the question of how to manufacture a good fuse. It is a general experience that the design of apparatus can be very good, but that the apparatus delivered to a customer can be bad. We have the problem of the quality control during the production process, which is not a simple one. Unfortunately there is no test which makes a good fuse from a bad one, so quality assurance is extremely important, and especially for the manufacture of fuses.

There are many many problems associated with quality assurance and there exists at present a lot of literature on it and also much investigation, especially in Japanese industry. There is much literature on the quality assurance of products where the product is less important, I think, than it is for a fuse. Maybe this, the last paper of this conference should be the first subject for consideration at the next conference. My impression is that when, as a customer, I want to buy a fuse from a manufacturer, which can guarantee the quality of the fuse on the basis of an adequate quality assurance, then I have the problem of deciding 'what is an adequate quality?' This is a serious problem for the user of fuses.

In Mr.Crooks' paper there is I think at least one omission in the field of quality assurance, that is with respect to the inspection of tools, which from my experience is a very important factor with respect to quality. I would like Mr. Crooks' comments on this.

Could Mr. Crooks also tell us something about the ageing effect with motor fuses, particularly when M-effect is used, due to the diffusion of the low melting-point alloy into the silver carrier. This diffusion is stimulated by the fact that the low melting-point alloy can melt under the influence of high current pulses, which do not disrupt the element. This changes the characteristic of the fuse, and I suppose especially for the case of motors, where you have heavy inrush currents. Is this a problem?

Mr. M.J. Smart

I would like to refer first of all to Mr. Gibson's paper where, towards the end, he refers to capacitor testing, and particularly paragraph 6.2, where he refers to the voltage for the breaking test. He suggests that for the current-limiting fuse it should be at two times the rated voltage, because of the overswing which occurs on capacitor switching. He doesn't mention what the factor should be for expulsion fuses, non-current-limiting fuses, and I would suggest there that the voltage should be maximum system voltage because the expulsion fuse normally arcs until the energising transient has disappeared, so that the voltage which is relevant is the maximum system voltage.

He also mentions that it is proposed that the frequency and the decrement of the inrush transient should be proportional to those for system conditions and we had some argument about this yesterday -

what are system conditions? It was even suggested that we could base on a constant factor of 25 times for the maximum frequency and inrush current level. Damping is dependent upon system damping which is a very variable thing as I think we all know. It is also suggested that frequency of inrush varies as system voltage; well I think we would like to dispute that. I can think of many applications for instance on weak systems where capacitors are installed for voltage regulation reasons, they tend to put fairly large banks on a fairly weak system, causing a fairly low frequency of inrush transient. On the other hand in this country we can get relatively small banks on quite high fault levels, for tariff reasons for instance, where the transient currents are of very high frequency. So perhaps Mr. Gibson could elucidate further on this question of frequency being proportional to rated voltage.

Prof. T. Lipski

I would like to comment upon the problem of ageing of fuses with M-effect, and the suggestion to eliminate this kind of fuse. Some old investigations made in Poland showed very clearly that in the case of this kind of fuse, in the M-effect region we have two curves limiting the ageing region, as shown in Fig.1. Curve 1 is the one-shot time-current characteristic and curve 2 is the non-deterioration time-current characteristic. The difference Δt_1 between these two characteristics depends of course on the values of overload current in this region. In our case the difference was about 50% of t_1 on average.

Our colleagues from Hazemeyer found more or less the same value. Recently Siemens very clearly showed in an official explanation for users of this kind of fuse that on average in their case this factor is 35%. If you take into account, by designing the low-voltage network not characteristic (1) but this non-deterioration time-current characteristic (2) of course in a circuit on the end of which we have a motor, which has a starting current not higher than the points lying on the non-deterioration time-current characteristic, and you use these time-lag fuses, selected on the basis of this characteristic, and then you compare with the same low-voltage network, with a normal quick-acting fuse, without M-effect, then generally speaking there is no difference between the two networks. The cross-sections of the cables are more or less the same; the electrodynamic stresses are less; selectivity - generally no change, in some respects it's better. The problem is power loss, which is a little bit higher. In our calculation we took into account a 10m length of circuit to the motor, and the next example was 100m. Another problem of replacement of time-lag fuses with M-effect by quick-acting fuses without M-effect is a higher temperature at the point of installation.

Nevertheless, we found that from the point of view of the network these two solutions are very similar.

On the other hand you should know that if you have a time lag characteristic in a low-voltage network, then operation of the fuse may occur, say, after 500 starts for a motor. (Of course only in one phase. Then you will have two-phase running and possible failure of the motor).

We concluded in Poland that we should go in the direction of eliminating this type of fuse from our systems. Besides that, we tried to improve our quick-acting fuses to get better time-current characteristics from this point.

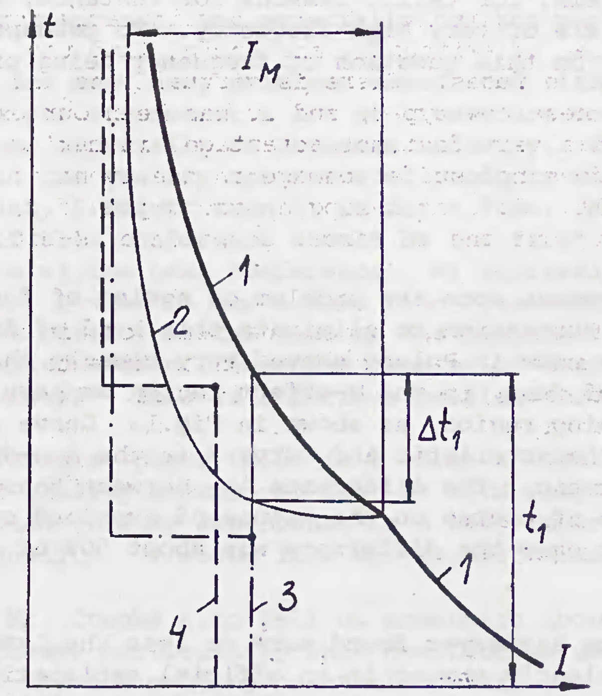


Fig.1. Time-current characteristics of a time-lag fuse with an M-effect.

I_m - M-effect region,

1 - one shot characteristic,
2 - non-deterioration characteristic,
3 - substitutional motor start current in the non-deterioration region,
4 - substitutional motor start current in the ageing region.

Mr. P. Rosen

I would like to compliment Mr. Crooks on an excellent and very informative paper, and my comments are not criticisms but perhaps expansions of a couple of points.

One is in defence of M-effect, particularly for h.v. fuses. We have heard at this conference quite a lot against the use of M-effect for low-voltage fuses but my own feelings, and I am sure those of Mr. Crooks, are that for h.v. fuses it is very difficult to make full use of all the advantages of an h.v. fuse if you don't have M-effect. The practical advantage tremendously outweigh the theoretical disadvantages that have been advanced against the use of M-effect. If we take first the distribution fuse, this is normally switched on once and left for many days or weeks, and we have done many deterioration tests at our Liverpool GEC factory to see what happens to M-effect when the fuse is used correctly, under continuous conditions, and we have detected no sign whatsoever of migration of the alloy point into the silver. On motor-circuit fuses it is true of course, as has been said, that if you pulse a fuse at too great a value, you will eventually start the migration process off, but I think that most manufacturers of h.v. motor-circuit fuses now publish data which show the highest current and largest run-up time that can be used and so on, and this should always be based upon doing exhaustive tests to see what happens to a motor circuit fuse to make sure there is no deterioration when it is used in accordance with the manufacturer's specified data.

The advantages of the M-effect of course are that the body temperature is kept down and this is becoming particularly important now where cast resin types of switchgear are coming into use, into which you have to put these fuses. There is virtually no air circulation in some of these new types, and it has been our experience that the M-effect fuse has very distinct advantages in making sure that the switch itself does not suffer damage in the event of a low overcurrent type of fault. So I am making a strong plea for, not doing away with M-effect, but the universal adoption of M-effect for h.v. fuses.

In paragraph 2.4 of Mr. Crooks' paper, he talks of minimum melting time, and mentions very briefly the fact that on continental equipment you may not have instantaneous trip-all-phase feature. It is my experience that the advantages of the use of instantaneous trip-all-phase features to give complete protection are very poorly understood. We fuse designers know about this but almost invariably I find that when talking to other people about this it is not well understood. Would Mr. Crooks in his reply explain briefly how this operates for the benefit of others.

Mr. E. Jacks

I was very pleased that Mr. Gibson has been brave enough to point out the dangers of overstandardisation. One gets the impression once people get enthusiastic about standardisation, that standardisation becomes an end in itself, and I think Mr. Gibson's warning on this is timely. I know how much time he puts in on standardisation work, and I know that he believes, as I'm sure we all do, in standardisation where it is useful. In fuses there are many areas which can be standardised to good effect, but he is quite right in my view in warning us against any move towards standardisation which will denigrate the versatility of fuses. This is one of the main advantages in fuses. They are wonderfully versatile, and standardisation can rob us of this versatility if we take it too far.

I also welcome the ASTA paper. There is one aspect which I'd rather hoped they might have mentioned,which is I think peculiar to fuses rather than to other devices. That is, since we have to do type tests for fuses and since we have legal obligations, or at least contract obligations for the performance of fuses in service, it is necessary to be able to identify fuses in service with the ones which were type-tested by approvals authorities such as ASTA. This means that ASTA and other approvals authorities have to go to a great deal of trouble to identify the items they have tested. They dismantle them, they take physical measurements of all the components in great detail.

They do this so that if at any time in the future, there is a need to identify a fuse in service with one which was type-tested and carries a certificate, this can be done to satisfy any legal or contractual arguments which arise. Since we are dealing with safety the legal and contractural aspects which manufacturers and users have to face together,these matters are very important. So I would hope that the authors would expand their next paper to include this.

I would also like to join in on the M-effect argument. M-effect has been a bogey for at least the last fifty years, and there are just as many arguments in favour of it as there are against it. My own view is that it can be a very excellent servant but it can be equally a bad master. Our job is to make it into a good servant, and if we do that it can have very obvious advantages and I would go further than Mr. Rosen who advocates it for h.v. fuses and say that it is far too useful a tool to neglect even for low-voltage fuses. When we talk about deterioration of the element we must not forget that other components in the fuse may also deteriorate, and if you get to the point where a fuse is being misused and something has got to give, it is a lot better that that failure should take place in a controlled manner, so that you get failure to safety. Now M-effect does allow you to do this over quite a big area, and if the geometry of the fuse is carefully looked into, the correct metallurgical decisions made regarding the choice of alloy, and so on, then it is my view that M-effect can be extremely useful. It is also useful in the more active function of the fuse, in arc control - deciding where the arc starts and so on, under certain circumstances. This is a very big subject and I would just content myself by coming down on the side of the people who favour M-effect, providing that it is used properly.

Mr. S. Norton

We have said quite a lot about ageing, but one or two of us will be aware that it's not so much ageing, in the case of the motor fuse, it is fatigue of the actual element, mechanical breakage of the element, independent of the M-effect. I mention this for two reasons, because it brings in the point of the standardisation of curves, and I am in agreement with Mr. Gibson and others that standardisation can be restrictive, but I would like to raise this point, that considering the time-current curve of a fuse,

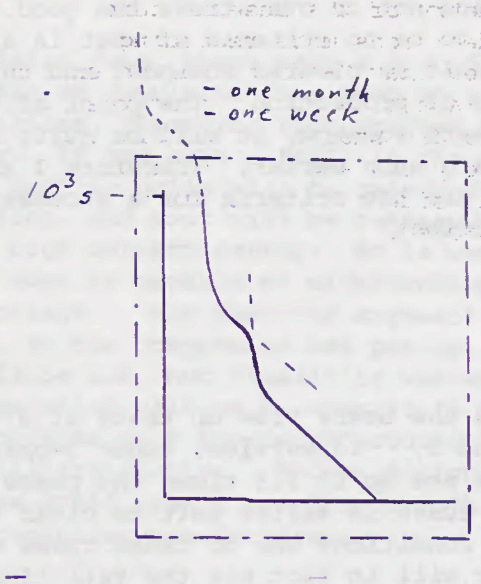
* Diagram drawn on

blackboard *

in the early days, distribution fuses were used for motor protection. We were in trouble because of mechanical fatigue. In the interim period we moved this curve over here. When we solved the problem, by a new element configuration which allowed expansion and contraction, we then found that you could move this back here. Basically what I'm getting at is that the bottom part of the curve is an electrical part of the curve, the top part is a mechanical thing, so we end up with something like that. This is fine, just to talk about it, but what I'm saying is that you've changed the overall characteristic of that fuse employing that element. That is, it's not only the time-current characteristic, it is also the mechanical characteristic of the fuse so that you end up with a somewhat steeper characteristic which is required for a motor fuse. This is just a general thought. What I'm getting at really is that if you had a nice steep curve time-current-wise, it still might not be suitable for motor protection if its element were not designed to withstand this pulsing characteristic.

Dr. K. Lerstrup

I just want to join the anti-M people by pointing to another end of the curve. If we take our regular curve here; if we go up in this region we find something else. The metal may creep over the surface



of the silver and then get into the reduced sections, and we have something like an extension of the curve, like that. So it is not only the short pulses that Prof. Lipski spoke about, it is also the accumulated time at rated current that can produce a bad ageing effect in the long run. But the biggest trouble comes back to what Mr. Gibson says, namely, we have standardised curves, and when you have standardised curves as we have, on rather narrow bands, then we are forced to use the M-effect in order to make it at all. So we simply couldn't get away from it, so therefore I would suggest how to get away from it on high-voltage fuses, where it is quite important to get away from it.

It is a Patent that already has run out, but if you put a striker on a high-voltage fuse, a string with a spring holding it, and you break it in the middle before you put it in and then join it together again with a low melting point solder, you can get something that at a certain temperature will trip out your switch. In other words, it's equivalent to what you do on the true motor back-up fuse, where you have the sand-filled fuse for the short-circuit protection, and you have the contactor or switch, with a kind of thermal relay to break it, and here we can put it in instead. But the important thing is that we should retain, or should we say regain the freedom of making fuses of proper characteristics, giving us a possibility of making progress in the art of making fuses and not be bound by too strict standardisation of what we produce, neither in dimensions, nor in the curves. And I should like to mention just one thing in that connection - whom of you has seen houses travel from one country to another? So why should we necessarily have a standardisation of domestic fuses? Each country is sufficiently great to support the industry supplying one type of locally standardised fuse for domestic use.

Dr. D.R. Aubrey

Short-circuit tests are used as a justification for years of production, and on test it is therefore agreeable if the clearances achieved are good ones. Mr. Turner tells us that tests are used to sort out the good from the bad, and not to overstress the good. It simply puzzles me that there seems to be no criteria of what is a successful test, other than that the fault is cleared somehow, and this seems to be a strange basis for years of production. The point of view seems to be that on test if it clears somehow, it will be quite satisfactory because service conditions are much easier. Therefore I ask Mr. Gibson or the ASTA gentlemen, what are the criteria for a successful test, and are those criteria sufficient?

Mr. B.M. Pryor

I would like to express the users view on tests at 87% of rated voltage for test duties 1 and 2. In service, under 3-phase conditions the first fuse to clear will see up to 1.5 times the phase voltage, then after that we will have two fuses in series left to clear the circuit. In many cases under 3-phase conditions one of those fuses will not blow, and the second fuse to clear will in fact see the full line voltage across it. Now I would like to ask what justification there is for tests at 87% of the rated voltage and whether any tests have actually been done under 3-phase conditions with a fuse designed specifically on the basis of the test at 87% of the rated voltage.

Mr. H.W. Turner

Just before the authors reply, I just want to take up one point Dr. Aubrey raised. I didn't say that the fuses would pass anyhow. The point I raised concerned the testing of miniature fuses, of the higher breaking capacity type. The bad ones tested at the earlier closing angle exploded in the test, while similar ones passed when tested at a later point-on-wave, more severe for good ones. What was really wanted was a test that picked out the bad ones rather than putting a slightly higher arc energy through a good one.

The criterion with these particular fuselinks is that they should be completely intact at the end, and other requirements in the standard which virtually come to similar requirements to ASTA criteria for passing high-voltage fuses.

Prof. T. Lipski

In East Germany, in the standard for low-voltage fuses they have 3-phase short-circuit tests. This means that the conditions are not so severe as we have in IEC and many other countries.

Mr. J.W. Gibson (in reply)

Mr. Smart refers to the test voltage for the breaking discharge test. The new standard will suggest that for current-limiting fuses it it twice times, subject to some small tolerance, because in capacitor work tolerances are looked at rather differently, but in principle it's twice.

For the expulsion fuse, there were a lot of talk about that. It was pointed out that an expulsion fuse when on a discharge test can have two boundary conditions, depending upon whether the element is high or low current rating. If you have a fault in the unit, most of the energy in the paralleled healthy units will be released in the fuse if it is of low current rating, and most will be released in the faulty unit itself if the fuse is of high current rating. So it was said that both the unit and the fuse must be capable of withstanding the energy associated with twice peak voltage. But then the argument came about that the can wouldn't stand it, so the compromise was put up, and discussed for a long time that it should be 1.6, but finally it was whittled down to 1.2, which is the figure which will go in when it is printed. I think it's a pity, if only because as a fuse manufacturer I wouldn't find the figure of 1.6 at all restrictive. Modern designs of high-strength tubes for expulsion fuses would permit compliance with 1.6 and we feel it might be of use to the capacitor manufacturer.

Why was the frequency of the breaking discharge test chosen to be proportional to the rated voltage? Well, the capacitor people who advised us said that if you have a given can, of a given kVAr, and you double the voltage, that means that the rated current is halved, and so the capacitance is one-quarter. Since the inductance of the connections is relatively constant, the frequency is then inversely proportional to the square root of C, and so will be doubled. That seemed to have general approval, we had no adverse comments upon that proposal from the committees of any country.

I agree generally with Mr. Norton's comments.

I was pleased that Mr. Jacks and Dr. Lerstrup both caution against over-enthusiasm on standardising dimensions.

On Dr. Aubrey's point regarding the criteria of failure, I feel that it is not necessary to specify these very elaborately in testing a current-limiting fuse or any other fuse. A fuse is a GO/NO GO device - it either works properly or goes off with a tremendous bang, but on the other hand there are criteria laid down in the IEC specification. They must not emit flame or powder and the components other than the fuse-link should be in the original state and it should be possible to remove the fuse-link in one piece after operation.

At one time in the British Standard we had a stipulation about the insulation resistance of the blown fuse, but that has been withdrawn as being unnecessary.

Mr. Pryor asked why 87%, and have any tests been made under 3-phase conditions to prove that 87% is sufficient. I think that Dr. Lerstrup mentioned this morning that this is rather a grey area. When the 87% was first proposed in IEC, we were told by the proposers that it was only a coincidence that it was $\sqrt{3/2}$, it was nothing to do with the 87% voltage on the first phase to clear because that doesn't apply to a device like a current-limiting fuse that doesn't clear at a natural current zero, but the argument was that although two fuses only may blow on a 3-phase fault, if one or other of them is having some difficulty the arcing will be prolonged and that will bring in the third one, which will then assist. That's what we were told by the proponents of it, who seemed to be in the majority. In the U.K. we were not very much in favour of it, although now it's there we are rather in the hands of users. If users agree to 87% we think it's a good thing, they get a standard fuse in accordance with IEC and BS and so on, but if they want 100% well then the customer is always right and we give them that. We have not had any adverse effect through using the 87% and on the technical side, some test results were produced in IEC many years ago, seeming to show that you needn't use 100%, but they weren't very complete. There is another point, that on the maximum arc energy test, if that were applied to a 3-phase group, it would be difficult to imagine that one fuse would remain unblown. It's only on a heavier current that that could happen.

Prof. Lipski's comment that 3-phase tests are used in East Germany (for low-voltage fuses) is very surprising. This strikes me as an enormous easement. I know that on the high-voltage side, in discussing it with the West German delegates to IEC about a year ago they told us that they weren't very happy about keeping the single-phase test. We told then that we used to have 3-phase tests with one-phase solidly linked in our specifications but they were nothing but a nuisance. No one could ever interpret them.

Mr. J.G.P. Anderson (in reply)

I shall respond to your kind treatment of the ASTA paper by being equally brief, in dealing with I think only two points which emerged.

Firstly, it is interesting to see and to experience Mr. Jack's change of view, of putting himself in the attitude of the customer by asking himself 'how does he know that he is getting what has in fact been certified?'. This of course is a very important matter and is dealt with only in one paragraph in the paper, but nevertheless it is covered in great detail in the new STL guide which is being prepared for high-voltage fuse testing which should emerge hopefully early next year. In the meanwhile, pending the issue of the STL guide for fuses, ASTA also has a publication dealing with this in great detail.

Referring now to Dr. Aubrey's comment on what are the criteria for successful test, it depends upon one's point of view, whether one is being creative or destructive, optimistic or pessimistic. As you know, standards, no matter whether IEC or British, tend to define the verifications required for problem areas, either in performance, design or some other characteristic, of the product being prescribed. Strangely enough - I don't know whether Dr. Aubrey has looked at it from this point of view - having prescribed what verification testing it necessary for a product. all standards then describe the criteria for failure, not the criteria for success. So if he applies a negative point of view I would suggest that he has the basic criteria for success.

Mr. W.R. Crooks (in reply)

To be the last may be the least, but it is to have the last word. So far, I count the votes on M-effect - three for, two against. I declare the motion carried.

First of all I thank Mr. Rosen for having answered most of the questions on my paper, but there are one or two points I will take up.

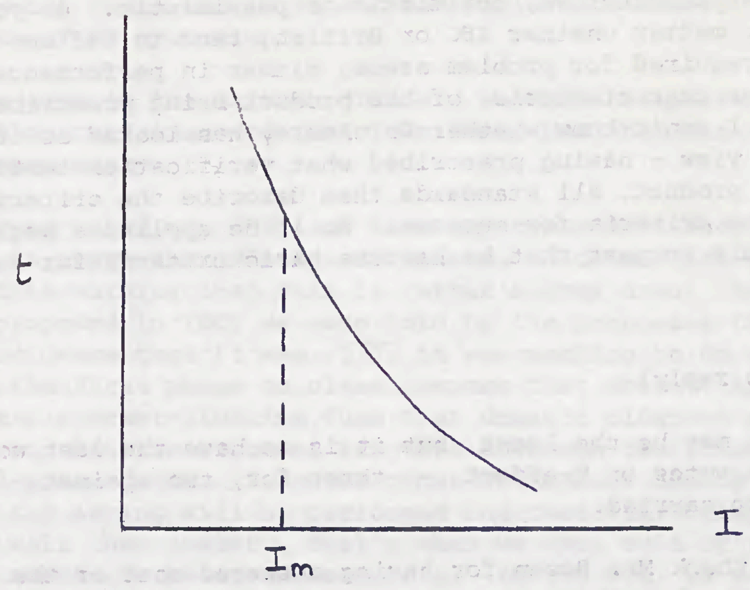
Dr. Vermij's point about inspection of tools is of course important, and this is covered in the programme, but also it is covered by the inspection of material made by those tools, on the normal acceptance basis. His remarks about M-effect can be coupled with those of other speakers and I would like to look once again at Prof. Lipski's diagram.

If we draw his curves again, this one he said was for $n = \infty$. Who is interested in $n = \infty$? The only occasion that you will some anywhere near to that is for a motor-circuit and we are taking of the motor-starting region here. Then we choose the fuse accordingly. I would suggest that he should also have drawn another curve, for $n = \infty$ for the pure element material, because it would not be the same as for $n = 1$, as we have shown very well with our experience with motor fuses, where the failure will eventually occur by mechanical means.

On Dr. Lerstrup's remark about M-effect, the spread of the M-effect alloy under more steady-state conditions, all I would say to that is that there are means to prevent it.

I have yet to see evidence of M-effect being a problem in the service life of high-voltage fuses (I speak only of high-voltage fuses), but on the other hand, without M-effect we are certain that the problems of very high temperature rise will occur. Also, equally severe, the very real possibility that a porcelain tube will not withstand the associated temperature.

Finally, Mr. Rosen has asked me to expand a little on the combination of fuses which have striker pins and their function with trip-all-phase switchgear.



We have a minimum breaking current I_m. We know that if the fuse should melt at a current less than I_m the fuse may fail. So it is arranged that the striker pin shall operate the mechanism of the switch to provide 3-phase tripping of the switch, and the current then being within the range of the switch can be successfully cleared. It is necessary that the fuse must be capable of withstanding the effects of arcing at the particular current (less then I_m) for a period greater than the tripping and clearing time of the associated switch. Having said that, I must also say that the experience with switchgear not having trip-all-phase features is also very good, provided that fuses have a good performance.