BREAKING CAPACITY TESTS FOR MINIATURE FUSES

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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:

$$v = \sqrt{2}\, V \sin(\omega t + \psi), \qquad (2)$$

$$i = \sqrt{2}\, I \left[\sin(\omega t + \psi - \varphi) - e^{-\omega t/tg\varphi} \sin(\psi - \varphi)\right], \qquad (3)$$

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	0.13	1.4	0.55	0.9	0.03
6.3	0.6	50	45	14	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 $\frac{1}{2} L\, i_0^2$ 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.

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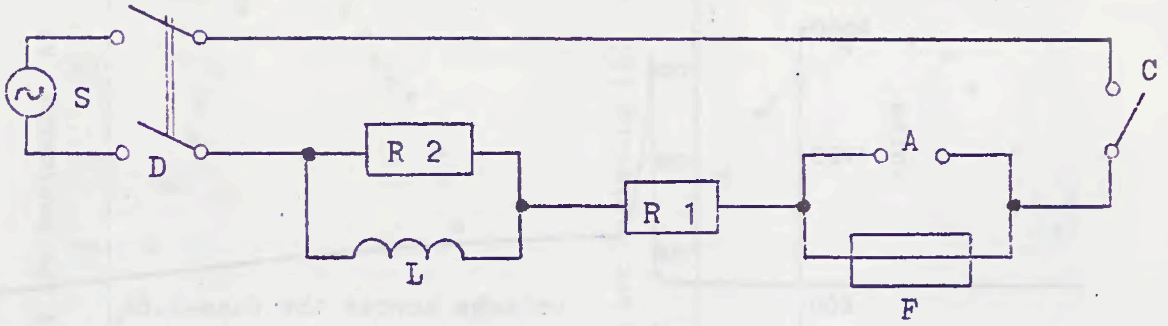


Fig. 1

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.

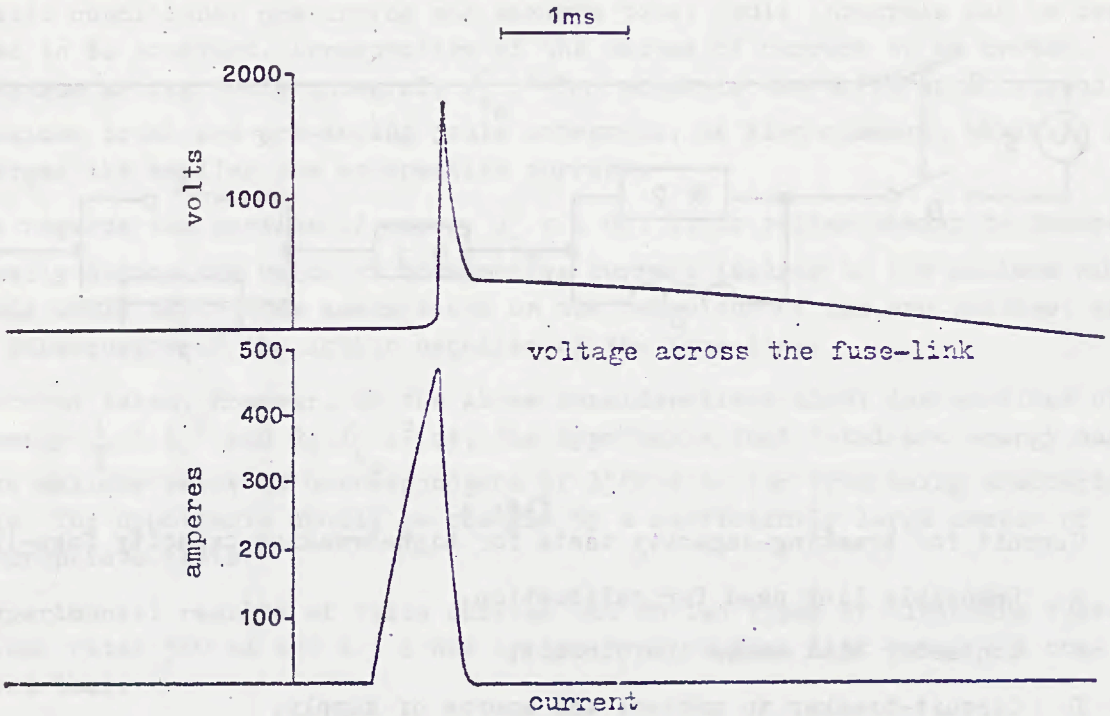


Fig. 2

Typical behaviours of breaking current and voltage across a miniature fuse-link.

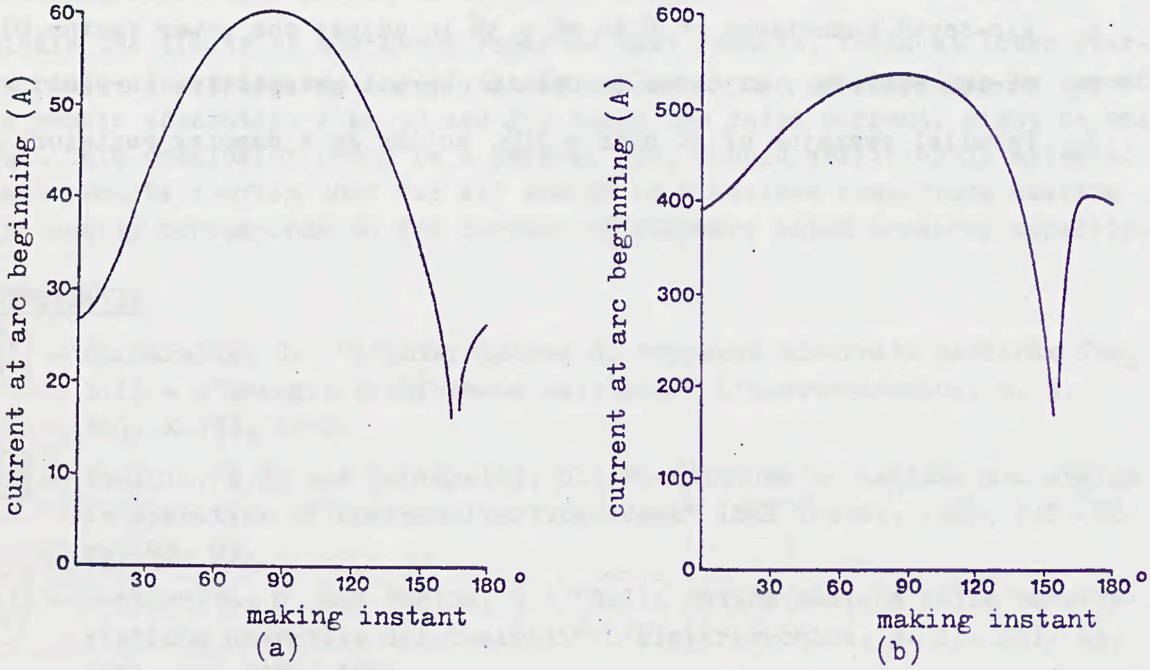
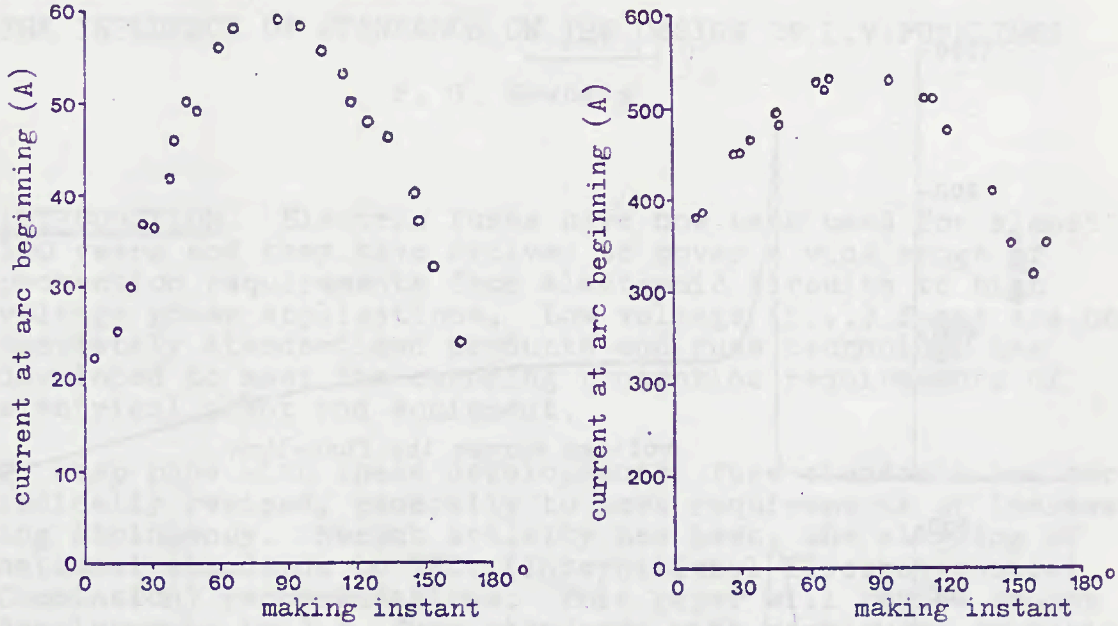


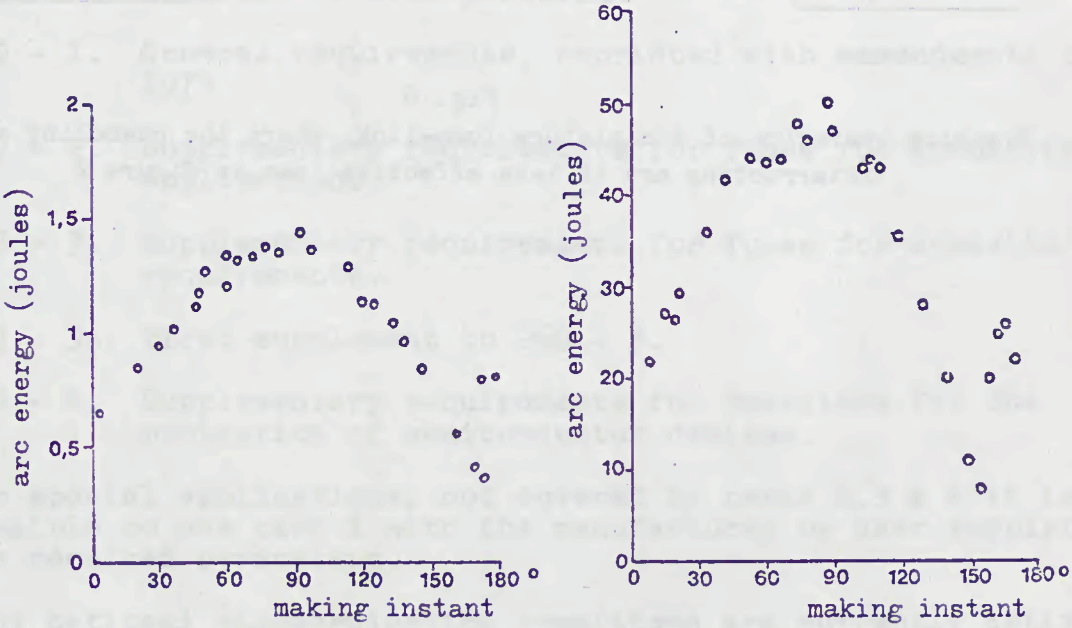
Fig. 3

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



(a) (b)

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



(a) (b)

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

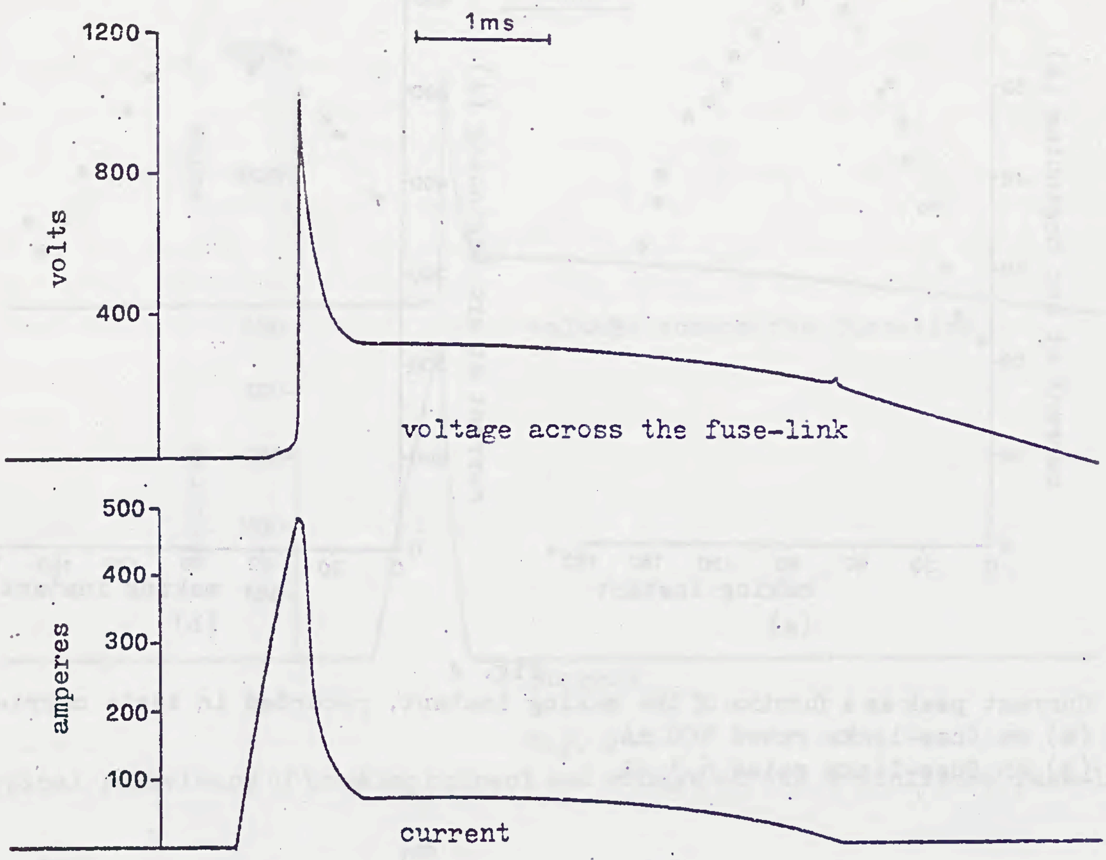


Fig. 6

Breaking operation of a miniature fuse-link, where the quenching of the interrupting arc is less effective than in figure 2