ARC ENERGY AND CRITICAL TESTS FOR HV CURRENT-LIMITING FUSES

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Abstract - Measurement of the arc energy is essential to designers and users of high-voltage current-limiting fuses for assessing the thermal and mechanical stress to which such devices are exposed in service and for determining the conditions under which maximum arc energy will occur.

In the course of research and development work on such fuses, hundreds of tests were performed on 8-kV to 23-kV current-limiting devices from various manufacturers. The paper presents the results of these tests and an analysis of the tests considered critical for maximum arc energy. It also describes a newly developed computer-based system for accurate qualitative analysis which was used during testing.

INTRODUCTION

Research and testing of HV current-limiting fuses intended for distribution networks have been under way for many years with a view to improving their performance in power distribution systems. Some results have already been published [1,2,3].

This paper is limited to describing the results of tests and arc-energy studies on large models made of different metals. Even if present standards do not require measurement of the arc energy, the main purpose of this work was oriented towards defining the conditions giving the maximum arc energy and the maximum stress to which a fuse is exposed in service. The tests were performed according to IEC Publ. 282 [4] and the results are in agreement with those obtained by other investigators [5-8]. Experience has shown, in fact, that specifications for LV fuses are not automatically valid for all HV current-limiting fuses, the differences are explained in the present paper.

Definition of Arc Energy   Arc energy, in the context of current-limiting fuses, is defined by the following equation:

$$E_a = \int_0^{t_a} V_a \, i \, dt \qquad (1)$$

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where E_a : arc energy
V_a : arc voltage
i : arc current
t_a : arcing time

The arc energy values can be determined by means of digital or analog integrators or, alternatively, by indirect methods (e.g. measurement of the weight or the thickness of the fulgurite) which consider that the dissipated energy is absorbed by the melting of the quartz sand.

Consider a simple circuit of inductance L and resistance R. For the case of arc extinction, the voltage may be expressed by the equation

$$V = Ri + L\frac{di}{dt} + V_a \tag{2}$$

which, following transformation, can be written

$$V_a\, i\, dt = (V - Ri)\, i\, dt - L\, i\, di$$

If the circuit is supplied with DC voltage, v = V = constant, and the current, which at the moment of arc initiation is equal to i_o, falls to zero, then the arc energy will be

$$E_a = \int_o^{t_a} (V - Ri)idt - L\int_{i_o}^{o} i\, di = E_s + \frac{L\, i_o^{\,2}}{2} \tag{3}$$

where E_s is the energy received from the source.

If, on the other hand, the circuit is supplied with AC voltage, $v = V\sin \omega t$, and the current in this case is $i = I \sin(\omega t - \phi)$, where ϕ is the phase shift, the energy produced in the half-cycle is:

$$E_a = \int_o^{\frac{T}{2}} (v - Ri)idt - L\int_o^{o} i\, di = E_s \tag{4}$$

where $\frac{T}{2} = \frac{1}{2f}$;

This equation shows that in AC arc all energy produced in the half-cycle is supplied by the source. This extreme case is not fully applicable to the fuse arc, but it can explain that in the case where the current is long and the arc extinguishes at the moment the current crosses its natural zero, one part or the whole inductive energy flows back into the system. This is evident in tests with long arc, cases of test duty 2. However, in fuse arcs, the phenomena are far more complex, owing to the variable phase shift and the arc voltage, which is temporarily higher than the source voltage; this in turn can influence the energy flow.

The difference between the current i_o and the peak let-through current is not easy to incorporate, in mathematical form, in either Eq. (3) or Eq. (4) and, according to the authors, should be supplied by the source energy, which depends directly on the path. The calculation of the inductive energy in Table 1 was therefore performed using the value of i_o.

Since a thorough understanding of arc phenomenon is important for the fuse designer, an investigation was carried out and is reported in this paper.

MEASUREMENT OF THE ARC ENERGY

A large research effort has been devoted to accurate measurement of the arc energy and a special program has even been developed for this purpose (see Appendix 1). In this program, the energy integral Eq. (1) was calculated with a time step of 5 to 20 μs, the higher of these values being preferred because of the noise picked up by the ultrasensitive instrumentation.

Despite the fact that in realistic terms it is impossible to measure the inductive energy directly, Eq. (3) can be used to calculate a theoretical value, although it is purely hypothetical to consider that all this energy is converted into heat. It was therefore decided to solve the dilemma by measuring the heat developed in the fuse during operation. The calorimetric method used for this purpose was calibrated and found to be sufficiently accurate, to ± 2% (Fig. 1).

TESTING AND RESULTS

A series of high-power tests was performed on fuses produced by different manufacturers for comparative purposes. The main purpose of the tests was to measure the arc energy under different circuit conditions, because this information is not given in the manufacturers' literature, and the standards do not prescribe measurement of this parameter. Since adequate quantities of samples for every size of fuse could obviously not be obtained, testing was limited to commercially available distribution fuses. The tests were eventually made on 10- to 100-A fuses designed for voltages of 8 to 23 kV. More than 150 fuses from different manufacturers were subjected to either complete or partial tests but in fact, far more tests were performed on in-house designed fuses made from different metals.

The results of the power tests may be summarized as follows:

1 - The closing angle giving the maximum arc energy varies with the prospective-current level. In test duty 2, this angle is approximately 0-10° whereas in the higher current range it is near -25° and 40-50°.

    Actually it is exceedingly complicated to determine the maximum in the -25° range because, once the energy curve has reached the maximum value, it suddenly drops to its minimum before it even reaches the -30° range (see Fig. 2). At very high prospective currents, namely ≥ 50 kA, the closing angle is over 60° and shows a tendency to increase even further as the current rises.

2 - The curve of the arc energy generally rises to a maximum value and then decreases (Fig. 3).

3 - Test duty 2 is well prescribed in the standards.

The test current I_2 usually lies on the point of discontinuity on the energy curve (Fig. 3).

4 - Measurement of the heat developed in the fuse shows that when the arcing process is interrupted by the current crossing its natural zero the heat is less than the total calculated energy. This is frequently the case in test duty 2, when part of the inductive energy flows back into the network (see Table 1, test No. 1, for example). However, in the case of fuse operation with a closing angle in the range of -40°, the total amount of inductive energy is in fact returned because the arc is interrupted, even before the interrupting process is finished, by the approaching voltage and current zero (Table 1, test No. 5 and Fig. 6). Table 1, which gives the results of all tests followed by measurement of the heat developed, shows that in test duty 1 there is generally good agreement between the energy calculated according to Eq. (1) and the measured heat values (see Fig. 7 as an example). Some small differences remain inexplicable, however, as may be seen from tests Nos. 2, 4, 10 and 11.

5 - The calculated values of inductive energy are presented in Fig. 4, from which it can be seen that the maximum inductive energy can, but need not, coincide with the maximum arc energy, even with the test current I_2.

ANALYSIS OF THE RESULTS

The test results for a silver and a cadmium fuse rated 100 A, 15 kV were presented in an earlier paper [3]. It should be pointed out here, however, that the reported arc energy measurements were in agreement with the mathematical calculations of Lerstrup [5] and Wilkins [6]. According to IREQ's experience, these authors' results well represent the dependence of the arc energy on the prospective current and the ratio of the arc voltage to the peak network voltage. However, their model is highly simplified and does not indicate the point of critical current specified in test duty 2.

The results of the tests performed in the work described here show that the maximum arc energy value depends mainly on the fuse design. HV current-limiting fuses have a lower number of notchings per unit voltage than LV fuses: while a LV fuse can have 10 notchings (N) per kV, this relative number is not applicable to the HV devices owing to limited space and also to the fact that high overvoltages are created by a large number of notchings. The number of notchings also has a considerable influence on the breaking process in the high-current range but much less at lower currents, such as I_2.

As far as existing fuses are concerned, several silver fuses tested showed a maximum arc energy in the range of 10-20 kA, while other types of fuse have a maximum arc energy reaching the level I_2. This may be seen in Fig. 4, where the higher curve represents a silver fuse with 3.6 N/kV and the lower dashed curve another silver fuse with 6.3 N/kV. The peak arc voltage of the first was 1.5, and of the second 3.2 times the peak service voltage. It is up to the fuse designer to select the most appropriate design for the purpose. The arc-energy values of fuses made of other metals lie between the two curves in Fig. 4. Not only is the number of notchings per kilovolt a determining factor for the arc energy, but also other design parameters such as the current density in the notchings, the sand quality, grain size, and compacting. All these parameters explain the wide diversity in the arc energy curves.

Very similar results may be found in the work of Kato et al. [7], who reported a maximum arc energy with a prospective current of 10 to 20 kA. Meanwhile the findings of Baxter [8] should also be mentioned. This author reported that the maximum arc energy occurred at a larger prospective current than that corresponding to the maximum inductive energy in the testing of LV current-limiting fuses and, in addition, found that in certain cases (closing angle less than -40°) the inductive energy is higher than the total measured energy. This is in full agreement with conclusions 4 and 5 above.

ADDITIONAL TESTS WITH RESPECT TO THE ARC ENERGY

The aim of every fuse designer is to minimize the arc energy produced in a fuse during the interruption process. The study of parameters influencing the arc energy demands further research so that this section will be limited to describing three different tests performed with the critical current prescribed by the standards (I_2).

a) Influence of circuit parameters on test duty 2

A 30-A cadmium distribution fuse for a voltage level of 15.5 kV under development successfully passed all tests performed. Test duty 2 originally had a short-circuit ratio of 10, in accordance with the relevant standards. in order to find the design limit, the test was repeated under more severe conditions, decreasing the resistance in order to increase the short-circuit ratio to 30. In the latter case, the fuse failed because the current-zero at $t = T$ is delayed by the higher short-circuit ratio, thus causing a higher arc energy; furthermore the recovery voltage is also higher and rises more rapidly.

Two cases of transient recovery voltage are presented on the oscillogram in Fig. 5, where it can be seen that in both cases part of the inductive energy flows back into the system. (This model-fuse was object of the design modification as explained in the following paragraphs. It is presented here merely to illustrate the influence of the circuit parameters on arc energy).

b) Tests with high-speed camera recording

A high-speed camera (5000 frames per second) was used to record the comparative tests of the arc behavior during current interruption in the two critical tests under study. Two fuse models (100 A, 15.5 kV) were therefore prepared using plexiglass tubes with a very thin layer of sand between the fuse elements and the walls. (Plexiglass is not suitable for long-term testing but it proved sufficiently rigid for observation of the first loop).

Test duty 1 (Fig. 8a) was performed with a current of 20 kA and a closing angle of 40°, test duty 2 with a current of 6 kA and a closing angle of 5°. The photographs show that, in the case of the higher current, the arc forms simultaneously all along the strip and is extinguished in less than 200 μs. In the case of the lower current (Fig. 8b) partial melting occurs and the arc is established only gradually along the strip because of insufficient energy. Under such conditions, the arc duration is considerably longer and it is only when natural current zero occurs that the arc duration is long because of the asymmetry, which represents the "worst" interrupting condition, but a basic difference exists between the two. In case a), at the moment the current reaches zero, the voltage is also at zero and, because of the high current involved, the angle between the voltage and the current is zero. In case b), the current is not very high and the angle between the voltage and the current is consequently fairly wide, which explains the sharp rise in voltage following interruption (see Fig. 5).

These comparative tests led to the conclusion that test duty 2 is very severe, even if the arc energy is not at its maximum, and that knowledge of the prospective current giving the maximum arc energy is essential for determining the maximum thermal and mechanical stresses on current-limiting fuses. The tests confirmed that fuses capable of withstanding such stresses have an infinite interrupting capacity, at least up to 50 kA, which was the maximum level tested.

c) Influence of fuse design on arc energy in test duty 2

Previous tests and oscillograms had indicated that the stress on the fuse in test duty 2 was due mainly to a low prospective current. In order to better understand the nature of this stress, a number of additional tests were performed. For this purpose, an identical fuse was selected from Fig. 5 with the same number of identical notchings but variable spacing. Figure 9 presents the results of tests using five different spacing schemes between the notchings, three equal (cases 1,2,3) and two unequal (cases 4 and 5).

In case 1, the distance was sufficient for successful breaking of a high prospective current but the fuse failed test duty 2, owing to high burn-back in the middle. In case 2, the distance was increased by 25% but was still not sufficient to prevent failure. Finally, with a further increase of 50% (case 3) the distance proved adequate for successful interrupting.

If unequal spacings are used (i.e. longest spacing in the middle, with the pitch slowly decreasing according to the heat distribution along the fuse), interruption is achieved at a lower arc energy. In case 4, the spacing in the middle was 25% longer than at the ends, while in case 5 it was 50% longer; interruption in the latter case was more successful. The reason for this improvement is that the heat was better distributed, which resulted in a greater number of notchings melting simultaneously. The entire test series was performed under identical circuit conditions, proving that an important role is played by fuse design besides the power-system conditions.

Selected spacings proved very useful also in test duty 3, improving the simultaneous melting in the middle of the fuse, which is usually sufficient for interrupting low currents.

These tests were all performed on low-melting metals (cadmium and zinc alloy) but the results should be valid for any metal if account is taken of the electrothermal properties of the chosen metal. The best proof for the above-mentioned considerations can be seen in Fig. 4. The number of notchings becomes more effective as the current increases because this causes more notchings to melt at the same time. By way of comparison with uniformly notched fuses, the tests revealed that local overheating in a silver fuse with a ceramic housing very often leads to cracks in test duty 2.

CRITICAL TESTS

According to the experience described above, it is possible to conclude that the HV current-limiting fuse faces in fact two critical tests: test duty 2 and the test giving the maximum arc energy.

Selection of the current for test duty 2 is well prescribed in the standards, and the stresses imposed on the fuse during this test are described earlier in this paper. The test with maximum arc energy can be more severe if it is performed with a current close to test duty 2, i.e. if it introduces more energy followed by a sufficiently high voltage jump after breaking. At higher currents, this jump tends to decrease and eventually disappear, and the fuse absorbs the energy without danger of damage, even if the arc energy increases. Test duty 1, in fact, is a mean of verifying the fuse design and assembly. In developing a fuse, it is extremely important to verify the stress imposed by different circuit conditions, but it is up to the designer and the user to decide whether or not more tests should be performed than prescribed.

CONCLUSION

On the basis of many tests on HV current-limiting fuses at IREQ the following conclusions can be drawn:

- HV fuses must not be judged on the same basis as LV fuses: the number of notchings per unit voltage is generally much lower than in LV devices owing to space requirements and permissible overvoltages.

- Test duty 2 intended to verify the interrupting capability in region of the high value of inductive energy does not necessarily produce the maximum arc energy.

- Even if it does not produce the maximum arc energy, test duty 2 provides the strongest stress owing to the long arc and high voltage jump after the arc is extinguished.

- The test with maximum arc energy, if not associated clearly with test duty 1 or 2, is important for the designer but not necessarily for the user.

- The tests show that the shape of the arc energy curve versus fault current can be influenced essentially by design characteristics, not only by the power system conditions.

- Measurements of the heat developed in the fuse during operation showed good agreement with the time integral of arc voltage and current. In some cases, especially in test duty 2, it was found that all or part of the inductive energy returns to the system. During the research described in this paper many questions and problems were raised with regard to arcing phenomena and further research is required to provide explanations and to find a means of reducing the energy developed during fuse operation.

APPENDIX A

DATA ACQUISITION AND PROCESSING SYSTEM

The high-power laboratory's data acquisition and processing system performs such functions as magnetic data recording, digital conversion and computer processing. During a test, 22 channels bring the data to a magnetic recorder, which acts as a memory between the measuring devices and the computer. Immediately after a test, the analog data is converted into digital form for immediate storage in a large computer. A sophisticated tape-positioning system ensures a high level of efficiency. At the operator's request, curves and results are displayed on CRT screens for consultation, and copies may be obtained using electrostatic plotters.

The telemetering system not only offers several enlargement and zoom facilities but comprises a program library for calculating the integrals of a curve or the product of the two curves, precise aperiodic components, rms values, arc resistance, arc energy, frequency measurements of harmonic content, etc. It is also used for statistical processing. The accuracy and operating speed of the telemetering system are such that it is not necessary to wait for values based on test measurements, so that decisions can be made immediately about the next test program as testing proceeds.

At the present time, the system records every 1-µs signal and can handle frequencies up to 80 kHz with an error of less than ± 1%.

Figure 10 shows the CRT screen and tape recorders in the central control room.

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Fig. 1 Photograph of calorimetric equipment

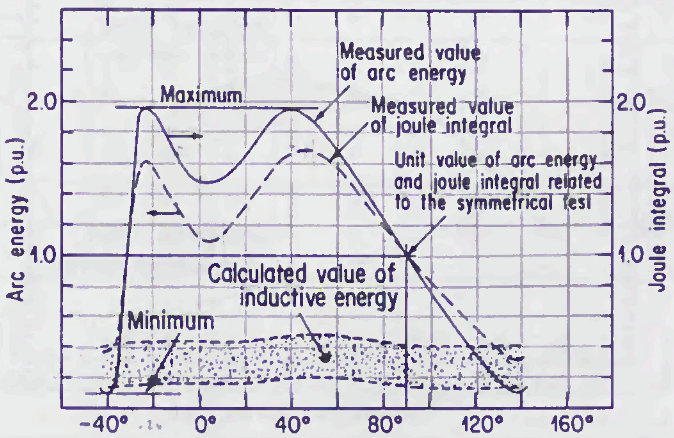


Fig. 2 Arc energy and joule integral for HV current-limiting fuses as a function of the closing angle. The inductive energy varies with the magnitude of the test current.

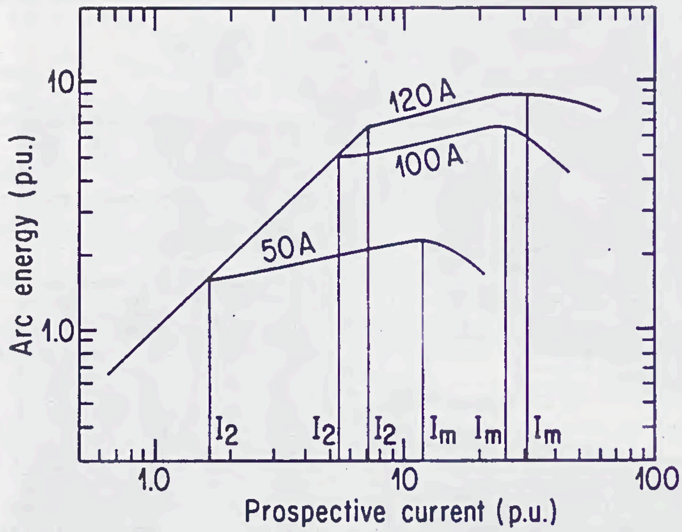


Fig. 3 Arc energy versus prospective current in HV current-limiting fuses designed for a rated current ranging from 50 to 120 A

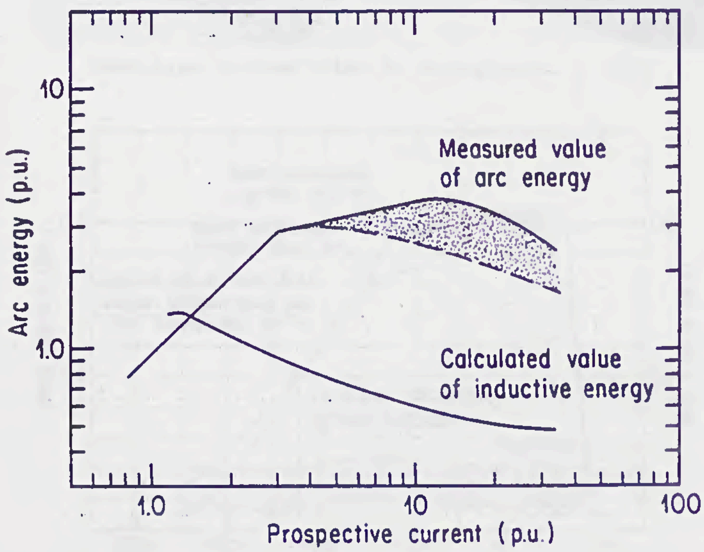


Fig. 4 Measured values of arc energy and calculated values of inductive energy versus prospective current in high-voltage current-limiting fuses

Table 1. Numerical results of tests

Test No.	Fuse maker and metal element	Rating		Circuit parameters			Closing angle	Test duty	Current (A)		Time (ms)		Joule int.	Arc energy (kJ)			Remarks
		kV	A	Prosp. current kA	Cos ϕ	$\frac{X}{R}$	(°)		At arc init. i_o	Let-through i_m	Melting	Arcing	$10^3 A^2 s$	VI	Heat	$\frac{Li_o^2}{2}$	
1	Brand 1 Ag	15.5	50	3.8	0.10	10	5.	2	3900	5120	3.5	5.6	98	298	–	82	Fig. 4
2	Brand 1 Ag	15.5	50	20.0	0.083	12	89.	1	6550	8692	0.57	2.4	85	243	257	43	Fig. 4
3	Brand 1 Ag	15.5	50	20.0	0.083	12	42.7	1	5969	8287	0.69	4.8	88	325	324	35	Fig. 4
4	Brand 2 Ag	15.5	100	20.0	0.083	12	43.	1	12400	13200	1.36	4.3	260	585	565	153	
5	Brand 3 Ag	17.5	100	20.0	0.10	10	-40.	1	5658	5829	1.36	1.42	40	32.3	~30	32.9	Fig. 6
6	Brand 4 Ag	17.5	100	20.0	0.10	10	91.	1	7615	10560	0.95	4.5	140	327	315	60	Fig. 7
7	Brand 5 Cd.	15.5	30	1.65	0.10	10	4.	2	1794	2246	3.19	6.26	20	160	120	40	Fig. 5
8	Brand 5 Cd.	15.5	30	1.65	0.033	30	8.	2	1684	2660	3.13	6.8	23.6*	181*	–	–	Fig. 5
9	Brand 5 Cd.	15.5	100	20.0	0.10	10	88.6	1	10418	12480	0.97	3.17	244	425	432	108	
10	Brand 5 Cd.	15.5	100	20.0	0.10	10	45.2	1	9800	12200	1.23	5.6	413	790	770	96	
11	Brand 5 Cd.	15.5	100	7.0	0.10	10	2.	2	6973	8648	3.33	5.9	268	627	595	142	

* Calculated up to first current zero

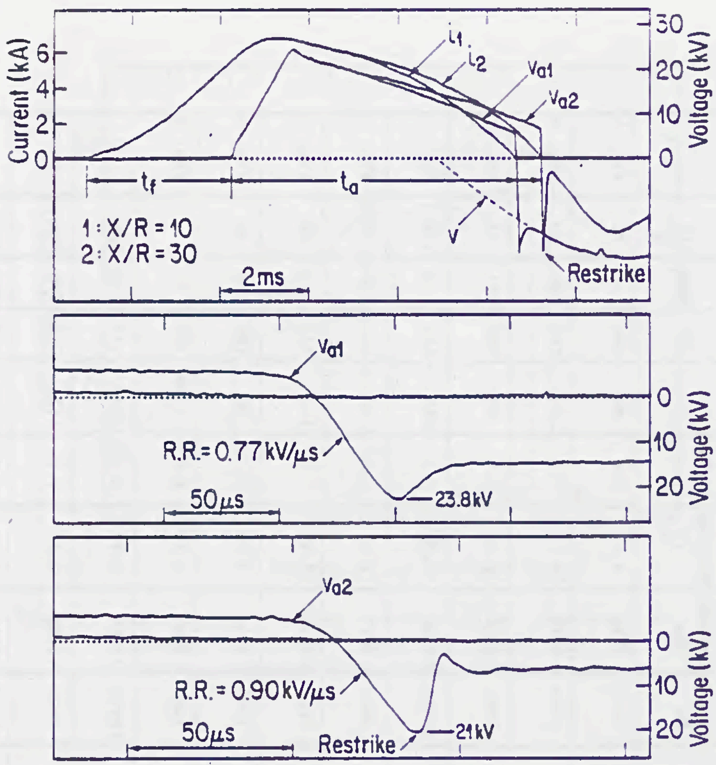


Fig. 5 15.5-kV, 30-A cadmium fuse. Test duty 2 with the same test-circuit parameters except the resistances required to change short-circuit ratio (x/R = 10 and 30)

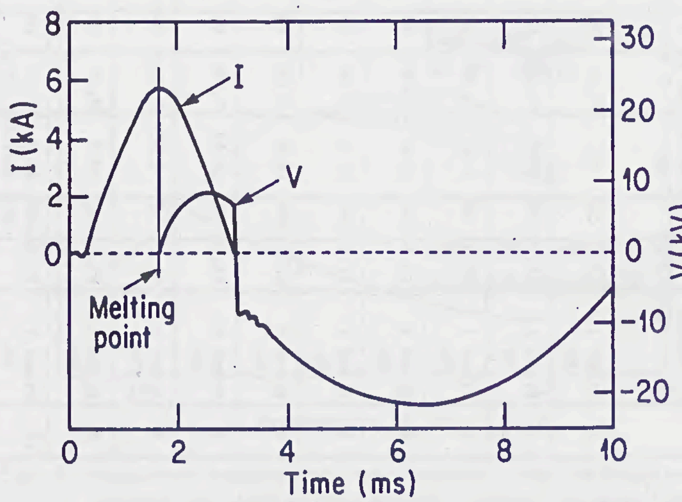


Fig. 6 100-A, 17.5-kV silver fuse. Oscillogram of a test with a prospective current of 20 kA and closing angle of -40°

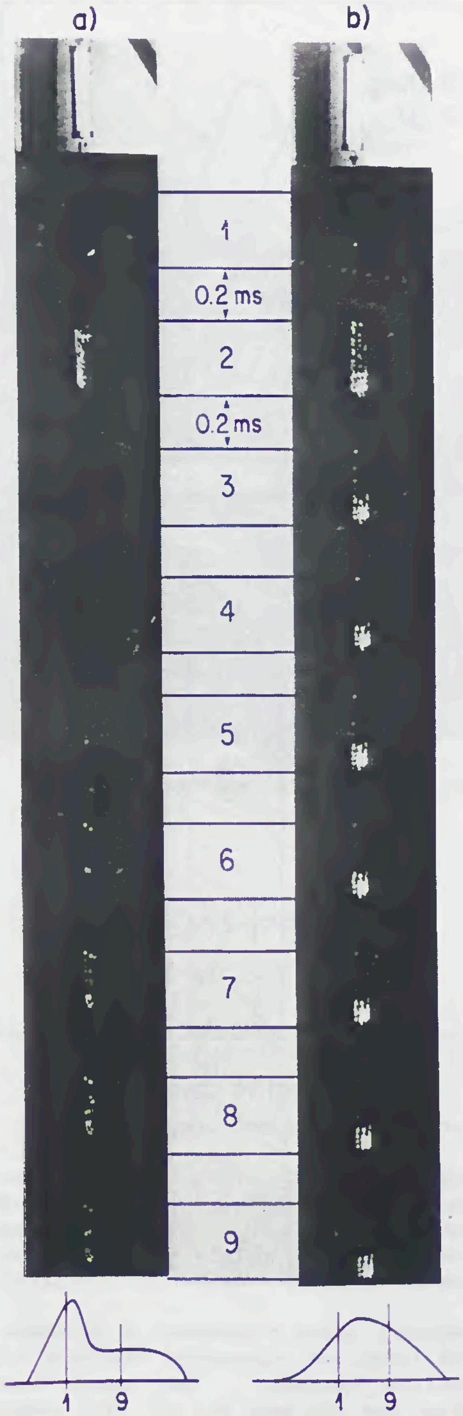


Fig. 8 High-speed camera record of test duties 1 and 2 for a current-limiting cadmium fuse rated 100 A, 15.5 kV (5000 frames per second)

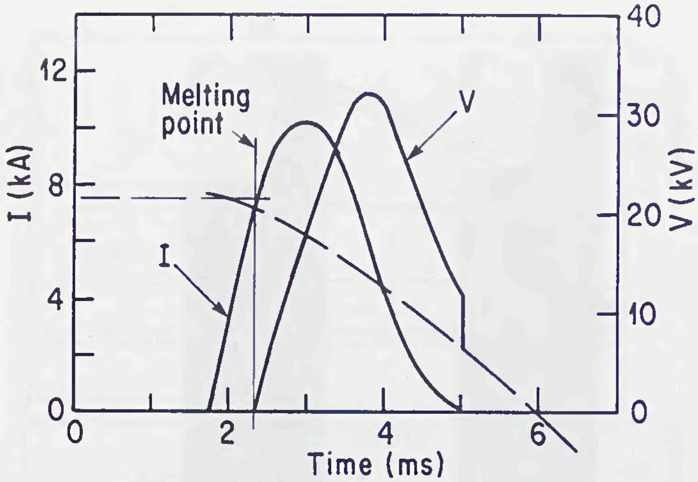
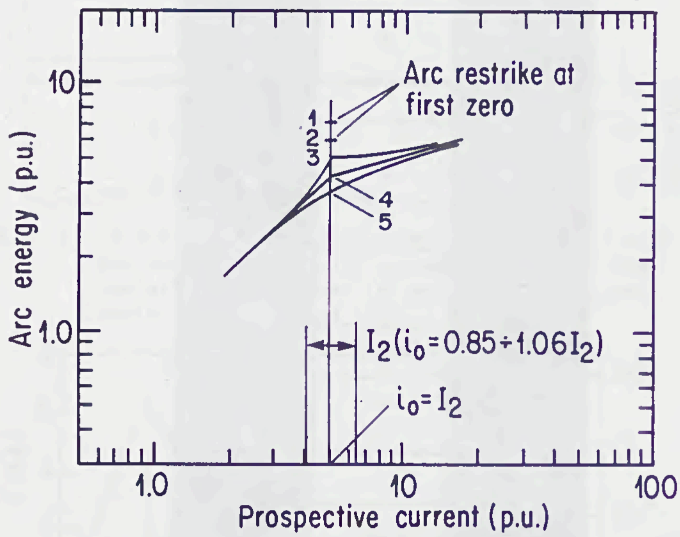


Fig. 7 100-A, 17.5-kV silver fuse. Oscillogram of a test with a prospective current of 20 kA and closing angle of +90°



Distance between notchings (in p.u.)

case 1	1	constant
case 2	1.25	constant
case 3	1.50	constant
case 4	1 - 1.25 - 1	variable
case 5	1 - 1.50 - 1	variable

Note: The per-unit value represents a distance sufficiently large for successful breaking of a high prospective current. The total number of notchings was the same for all five cases.

Fig. 9 Arc energy in a HV fuse as a function of its design in test duty 2

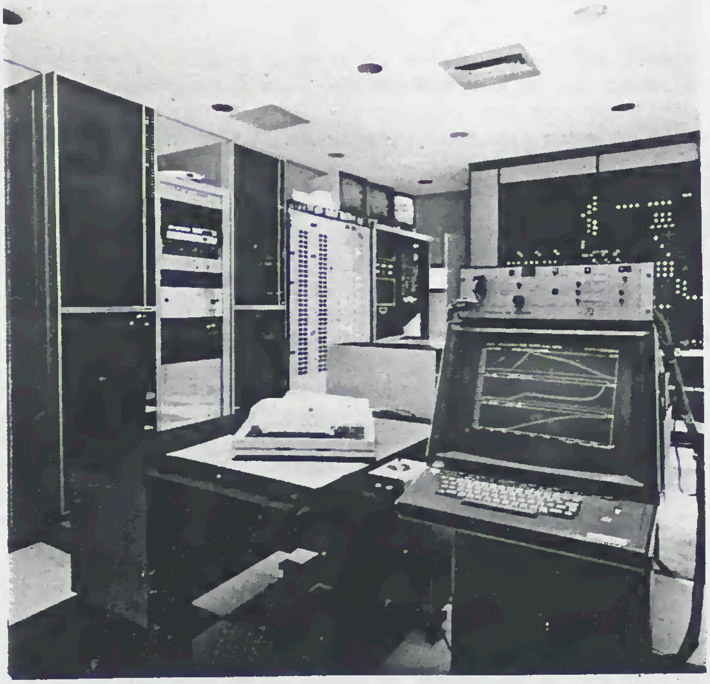


Fig. 10 Photography of control room with CRT screen and tape recorders in high-power Laboratory.