

RECOVERY OF DIELECTRIC STRENGTH  
OF EXPULSION FUSES AFTER ARC CURRENT ZERO

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INTRODUCTION Expulsion fuses installed in cutouts are quite extensively used for overcurrent protection on the distribution systems at high voltages of 6.6 kV and 3.3 kV in Japan, a high voltage cutout refers to the switching device consisting of the expulsion fuse and the cutout which can open the circuit within normal service conditions. Most of them are mainly used for protection of lines and high voltage distribution transformers of moderate or less power at distribution primary.

In accordance with stepping up the voltage of distribution systems from 3.3 kV to 6.6 kV in the 1960's, high voltage cutouts have been improved for their performances in normal service and operations of breaking fault current.

Particularly, high voltage cutouts have been developed to be used under the conditions of the ambient air considerably polluted by salt or dust as shown in Fig.1. Under these situations, their applications in the field were investigated [1] and at the same time, the investigations for the characteristics of their breaking current abilities were carried out with respect to the power distribution circuits stepped up voltage.

A lot of breaking tests for modern expulsion fuses were made under the same circuit conditions as the modernized power distribution circuits at the current breaking test facility. In parallel to the tests, we intended to study experimentally their fundamental behaviors of breaking current. For these studies, model expulsion fuses were employed.

Behaviors of arc voltage and current were investigated about the fuses with gas-evolving tubes of the same materials as using for modern expulsion fuses, the various magnitudes of current and circuit conditions.

Generally, current interruption of the current switching device such as circuit breaker depends on the race between the speed of recovery of post-arc space and transient recovery voltage between post-arc terminals. It was supposed that it was important for discussion of the breaking current capability of fuses to clear the characteristics of the recovery of dielectric strength of post-arc space. Accordingly, our research was almost put stress on the measurements of the recovery of post-arc space.

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It has been known that the recovery depends on the arc conditions during arc period, tube materials and geometrical dimension of expulsion fuses. Measurement of the recovery of the model expulsion fuses was made by the method applying rectangular voltage to the post-arc space. At the same time, regions of post-arc current flowing, thermal breakdown and dielectric breakdown were investigated with respect to arc energy.

The test circuit which was easily able to control the arc conditions was devised. Using this test circuit, the performances of breaking current of the fuses with respect to various arc conditions were able to be studied relatively easily.

MODEL EXPULSION FUSES Fig.2 shows a model expulsion fuse. The test equipment is mainly composed of a fuse link, a polyvinyl chloride cylinder and a cylindrical insulation container which simulates the cutout. The fuse link is composed of a fuse element, a metal cap, a metal lead and a gas-evolving tube opened at one end. The copper fuse element of 0.5 mm in diameter is pulled down by weight of about 1 kg after fuse link is set. The material used for the gas-evolving tube is kraft paper using electrical insulation in the greater part of tests. The test equipment is mounted on the large closed box which traps gas discharged from the fuse on the operation.

TEST CIRCUIT To investigate the recovery of dielectric strength of the arc space after arc current zero under the controlled conditions of various arc energy and arc starting current, the test circuit was devised so that arc energy and current were easily controlled.

Fig.3 shows schematically the test circuit. The principle of this circuit is that it is possible to transfer from adjustable energy charged in the capacitor to inductive energy. Then, a capacitor bank  $C_1$  is charged to voltage  $V_1$ . Charged energy of the capacitor  $C_1$  is  $\frac{1}{2}C_1V_1^2$ . Starting the test, a pulse is sent from a trigger pulse generator Trg to a vacuum switch  $V_s$  and a delay circuit  $D_1$ . At first, the current discharged from the capacitor bank  $C_1$  flows through a reactor  $L$ , a breaker  $B$  and the vacuum switch  $V_s$ . On the other hand, the pulse sent to the delay circuit  $D_1$  is delayed by the time duration between the discharge starting instant of the capacitor  $C_1$  and the instant of the maximum of discharged current and is sent to the breaker  $B$  to open. At the instant of the maximum of the current corresponding to the capacitor voltage of zero, the breaker  $B$  is opened, and the current is transmitted to the circuit including the fuse through a high voltage diode  $D_1$ , and a current shunt  $Sh$ .

In this process, almost capacitive energy is transferred to inductive energy, so the following relation is given

$$\frac{1}{2} C_1 V_1^2 = \frac{1}{2} L I_m^2 \dots \dots (1)$$

where  $I_m$  is the maximum value of the discharging current. The current at arc initiation is a little small compared with the instantaneous current transmitted, since inductive energy is partly exhausted in the fuse and the circuit resistance for the pre-arcing period. The following relation is given

$$E_m = \frac{1}{2} L ( I_m^2 - I_c^2 ) \quad \dots \dots (2)$$

where  $E_m$  includes pre-arcing energy of fuse element and circuit loss during the pre-arcing period and  $I_c$  is the current at arc initiation. Therefore, inductive energy  $E_c$  that is utilized for the arcing period is expressed as follows

$$E_c = \frac{1}{2} L I_c^2 \quad \dots \dots (3)$$

After arc initiation, current decreases almost linearly owing to the effect of high arc voltage. Almost all inductive energy is changed into arc energy. Using elements of constant cross section and length, pre-arcing energy of the fuse element and energy of circuit loss are nearly constant for the pre-arcing period, since they are proportional to the pre-arcing Joule integral of the element. Therefore, arc energy is linearly related with capacitive energy which is easily adjusted by charging voltage of the capacitor  $C_1$ .

MEASUREMENTS The circuit applying voltage to arc terminals is shown in Fig.3. A current zero detector ZD generates a single pulse at a few micro-second before arc current zero. The pulse is delayed in a delay circuit  $D_2$  for setting time  $T$ . A gap  $G$  is triggered by the pulse from the delay circuit  $D_2$ . The voltage discharged from the capacitor  $C_2$  which is charged to voltage of  $V_2$  is applied to the arc terminals recovered freely after arc current zero through a diode  $Di_2$ , the triggerable gap  $G$  and a resistor  $R$ .

The recovery of post-arc space between arc terminals is measured by means of following method. On the assumption that for the same fuses and same circuit conditions, arcing phenomena and post-arc space are similar situations, breaking tests are repeated to measure the recovery at the certain instant after arc current zero for the same fuses under the same circuit conditions. The recovery at the some instant is expressed by the maximum impressed voltage over which breakdown of the arc space is brought about.

A digital memory DM7100 was used to measure the impressed voltage and a digital memory DM901 was used to measure breaking current, the appearing voltage between the fuse terminals and the impressed voltage over whole test duration. The data processing system consisted of a data processor SM1330, a microcomputer, a printer and a floppy disk was used for analysis and record of data recorded in the digital memory DM901.

#### ARC VOLTAGE WAVEFORMES WITH RELATION TO ARC CURRENT AND TUBE DIAMETER

At first, arc starts at element blown out and then burns ultimately between a metal cap and a metal lead in the tube. It is seen from oscillograms that current slightly decreases linearly during the pre-arcing period and more distinctly decreases after arc starting.

Fig.4 shows two types of the arc voltage waveforms observed. In the case of Fig.4 (a), a diameter of the tube is small, arc voltage increases

steeply for some time and then decreases and spike voltage appears just prior to current zero. In the case of Fig.4 (b), a diameter of the tube is large, arc voltage steps up abruptly at the instant of arc initiation and keeps almost constant value fluctuating with small voltage.

If the diameter of the tube is smaller than that of free burning arc column, the wall of the tube intensively heated results in huge evaporating gas from surface of the tube and rapid evolving gas from the tube. Thus the pressure in the tube is built up by huge evaporated gas and arc is intensively blown, so that the arc voltage increases steeply while the condition that arc column fills fully the inside of the tube.

CHARACTERISTICS OF RECOVERY Using the model expulsion fuses, the characteristics of the recovery expressed by relations between the magnitude of the recovery in voltage and a lapse of time after arc current zero were investigated in four parameters of arc energy, arc current at arc initiation, inner diameter and length of tubes.

(1) Effects of arc energy Fig.5 shows the characteristics of the recovery for different arc energies. Arc energies were 2.0 kJ, 1.0 kJ and 0.5 kJ. The tubes of sample fuses were 15 cm in length and 6 mm in diameter. Arc current at arc initiation was 1.0 kA on each test.

In the case of arc energy of 2.0 kJ, attainment of the recovery of 10 kV which is the fastest speed of the recovery in three values of arc energy takes a lapse of 30  $\mu$ sec from the instant of arc current zero. It is observed that the speed of the recovery for other arc energy becomes slow in accordance with decreasing arc energy.

Experimental results have shown that mass of the tube lost according to evaporation during arc period increases in proportion to arc energy. Therefore, arc is more strongly blown by the increase of evaporating gas in order to increase of arc energy, so that the speed of the recovery of dielectric strength of arc space becomes higher according to increase of arc energy.

(2) Effects of arc current Fig.6 shows the characteristics of the recovery for arc currents. The arc current which decreases approximately linear is specified by the magnitude of current at arc initiation. In the test, the magnitudes of the arc current at arc initiation were 1.0 kA, 0.7 kA and 0.5 kA. The dimension of sample fuses was same as stated Section (1), and arc energy was about 2.0 kJ on each test.

The speed of the recovery increases in accordance with the arc current at arc initiation. Also, the ratio of arc energy to arcing time, that is, mean arc power increases with the value of the arc current at arc initiation, thus the speed of the recovery increases according to mean arc power.

It is considered that the speed of the recovery becomes higher with increasing the arc current so that the arc space even near current zero is subjected to strong blast action by large quantity of decomposed gas from

the surface of the tube with increase of arc current and mean arc power.

(3) Effects of tube diameter Fig.7 shows characteristics of the recovery with respect to inner diameters of the tubes. Inner diameters were 6 mm, 8 mm, 9 mm and 10 mm respectively. The length of tube was 15 cm and arc energy was about 2.0 kJ and arc current at arc initiation was about 1.0 kA. These constant values of arc energy and arc current at arc initiation on each test were gotten by only charging the capacitor  $C_1$  constant voltage.

It is recognized from Fig.7 that the recoveries of small tube diameters of 6 mm and 8 mm are very fast compared with those of larger tube diameters of 9 mm and 10 mm. The recoveries of smaller tube diameters of 6 mm and 8 mm are very fast in order to strong gas blast so that the inside of the tube is filled fully with arc and is heated intensively and so huge gas is evaporated. Arc diameter of the arc current of 1.0 kA may be smaller than 9 mm [2], so that evaporating mass of the tube wall owing to arc heating is approximately same in the case of exceeding tube diameter of 9 mm. Hence, blowing action of evolving gas of the tube diameter of 9 mm is slightly stronger than that of the tube of 10 mm in diameter.

A change in the cross section of the tube, this fact has been already known, has influence upon the circuit interrupting capacity. With constant rate of gas generation, gas blast action is stronger in small diameter of tube than in large one, therefore the current interruption ability in a small diameter of the tube is superior to a larger one. Corresponding with the phenomena, the speed of the recovery becomes higher in small tubes than that of large ones.

(4) Effects of tube length Fig.8 shows characteristics of the recovery with respect to the lengths of tubes. In this test, the lengths of the tubes were 15 cm, 10 cm, 8 cm and 7 cm respectively. Inner diameter of the tube was 6 mm and arc energy and arc current at arc initiation were same as Section (3).

The remaining length of the metal cap and the metal lead in the tube is 5 cm, so that arc is drawn out after the element blown out and the length between arc terminals ultimately becomes subtracting the remaining length of the metal cap and the metal lead in the tube from whole tube length. It is measured that significant slow speed of recovery occurs for tube length of 7 cm, however, the length of the tube is longer, the speed of the recovery is higher. The recoveries of tube lengths of 10 cm and 15 cm are very fast compared with those of tube lengths of 7 cm and 8 cm.

From the results of severe decreasing arc current according to the high arc voltage of longer tube, it is suggested that the pressure of the inside of the tube is quite high. Owing to the longer gas flowing channel for the longer tube, post-arc space of the longer tube is more intensively blown by high pressure evolving gas than that of the short one, thus the speed of the recovery of the longer tube becomes higher than that of the shorter one.

POST-ARC CURRENT In this test, post-arc current was observed in the region over arc energy of about 0.5 kJ. Fig.9 shows the regions of observed post-arc current. The experiments were undertaken for three cases of arc energy in the gas-evolving tube of inner diameter of 6 mm and length of 15 cm and arc current at arc initiation of 1.0 kA.

No post-arc current flows within the impressed voltage under dotted line as shown in Fig.9.

Post-arc current occurrence is observed between recovery characteristics and the dotted lines. The regions of post-arc current flowing depend on arc energy. The region of post-arc current in arc energy of 0.5 kJ is quite smaller than those of two other conditions of arc energy.

However, instant of impressed voltage elapsing from arc current zero and approaching the dotted lines in every arc conditions, post-arc current diminishes so small that it is difficult to distinguish clearly post-arc current.

It has been known that successful current interruption depends on the magnitude and the speed of recovery of the post-arc space. From above mentioned results, it is considered that states of the post-arc space which depend on arc conditions, the elapsing time after arc current zero and the value of impressed voltage fall into four regions I, II, III and IV, as shown in Fig.10.

No post-arc current is observed in the region I, one reason of the phenomena in this region is that the impressed voltage is not enough to flow post-arc current in the case of a short elapsing time after arc current zero and another is post-arc space recovered enough in a passing long time. The typical waveform of impressed voltage in this region is shown in Fig.11 (a).

Post-arc current is occurred in the region II. The conductance of post-arc space is enough to flow the post-arc current when impressed voltage is applied. However, overcoming the impressed voltage, post-arc space recovers its dielectric strength in this region. Typical waveforms of impressed voltage and post-arc current are shown in Fig.11 (b).

In the region III above region II, thermal failures occur. Fig.11 (c) shows the typical voltage and current waveforms in the thermal failure. As shown in this oscillogram, breakdown occurs at the instant of impressed voltage applied.

In the region IV, dielectric failures are caused. Fig.11 (d) shows the typical voltage and current waveforms in the dielectric failure. Dielectric breakdown occurs at an elapsing time of about 310  $\mu$ sec after instant of impressed voltage applied as shown in the oscillogram.

CONCLUSIONS Using model expulsion fuses, fundamental phenomena are observed in respect to behaviors of breaking current of expulsion fuses.

The waveform of arc voltage depends on the relation between the diameter of gas-evolving tube and that of arc column, and arc voltage continues

rising while arc fills fully the inside of the tube.

It is investigated that the recovery characteristics of the model expulsion fuses are obtained under arc conditions and various dimensions of gas-evolving tubes. It is confirmed that the speed of recovery is higher according with increasing arc energy and arc current for the tube of narrower cross section and the longer length in the case of the tube without destruction.

The regions of flowing post-arc current are evident under the influence of the arc condition and the impressed voltage.

REFERENCES [1] Technical research report, " High voltage cutouts in our country. " IEEJ, (II) No.102, 1980.

[2] D.J.Siddons, " Arc diameter in a gas blast. " PROC.IEE, Vol.119, No.9, 1972, pp.1423-1425.

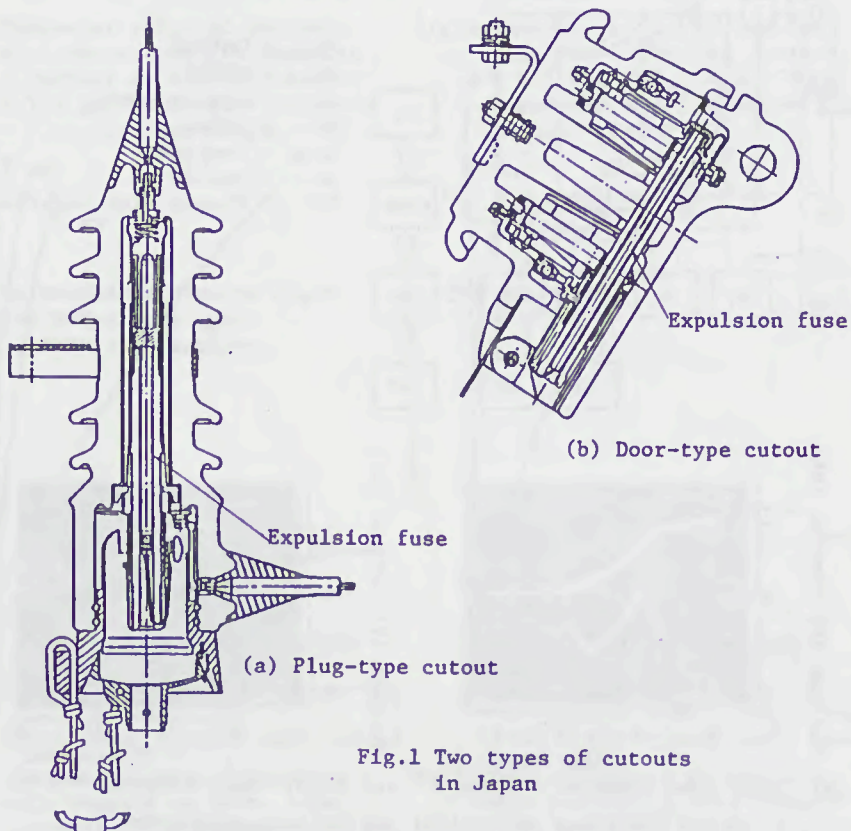


Fig.1 Two types of cutouts in Japan

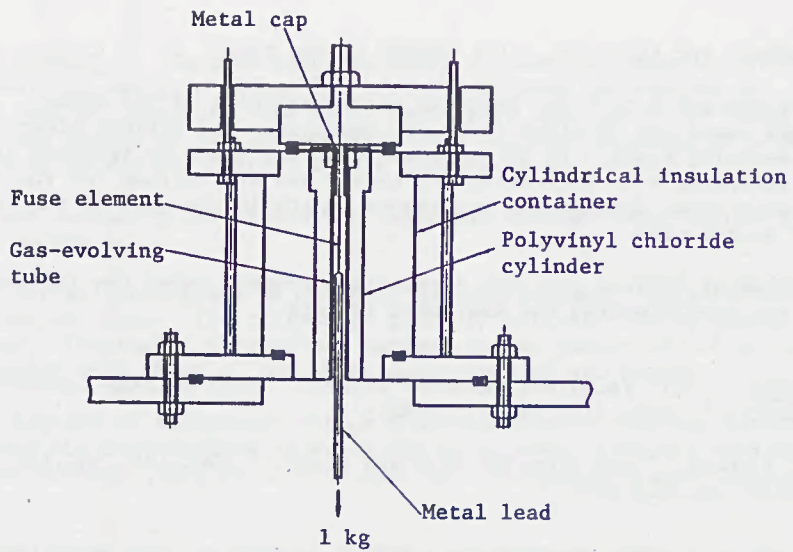


Fig. 2 Test equipment

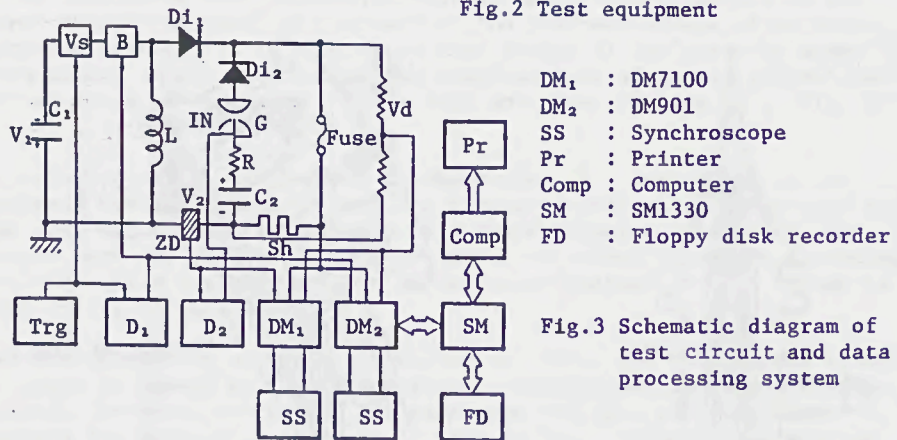


Fig. 3 Schematic diagram of test circuit and data processing system

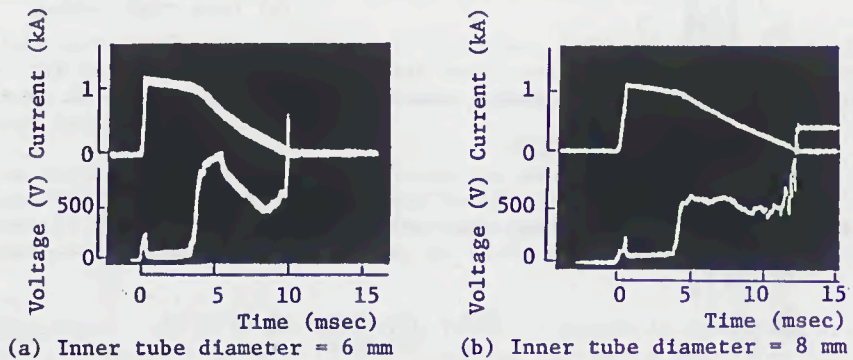


Fig. 4 Two types of typical arc voltage waveforms  
 ( Tube length = 15 cm, Arc energy = 2.0 kJ  
 and Current at arc initiation = 1.0 kA )



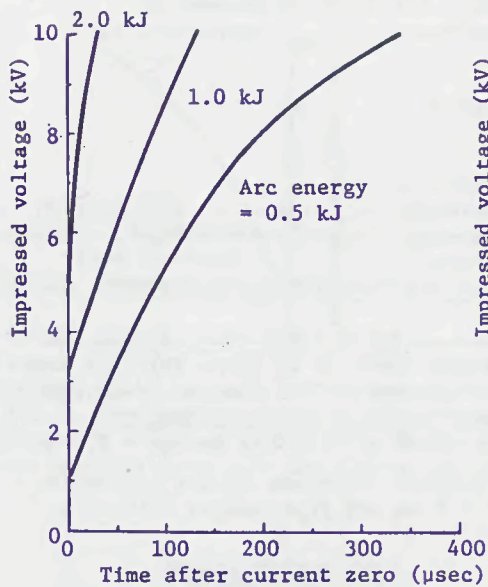


Fig.5 Characteristics of recovery with respect to arc energies ( Current at arc initiation = 1.0 kA, Inner tube diameter = 6 mm and tube length = 15 cm )

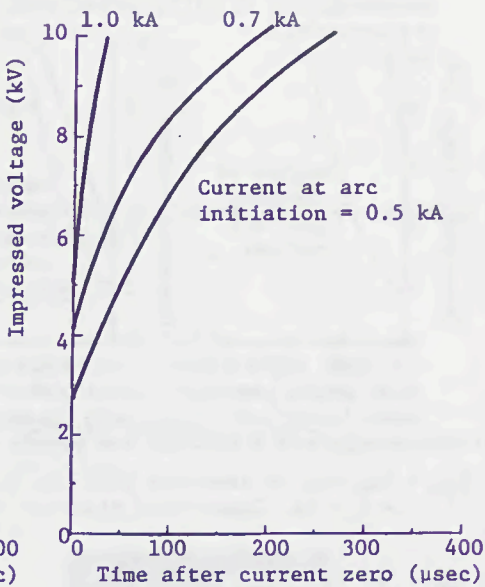


Fig.6 Characteristics of recovery with respect to arc currents ( Arc energy = 2.0 kJ, Inner tube diameter = 6 mm and Tube length = 15 cm )

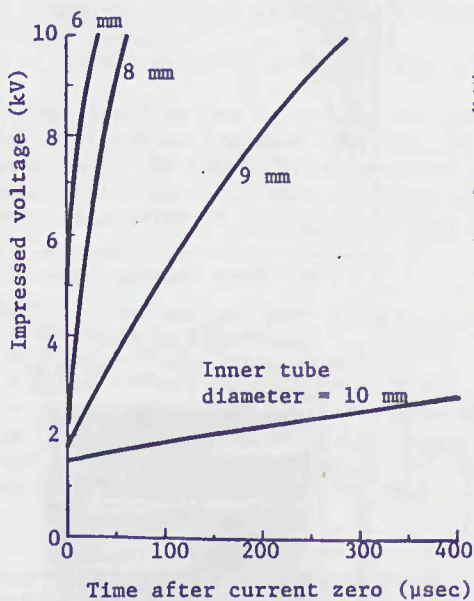


Fig.7 Characteristics of recovery with respect to inner tube diameters ( Arc energy = 2.0 kJ, Current at arc initiation = 1.0 kA and Tube length = 15 cm )

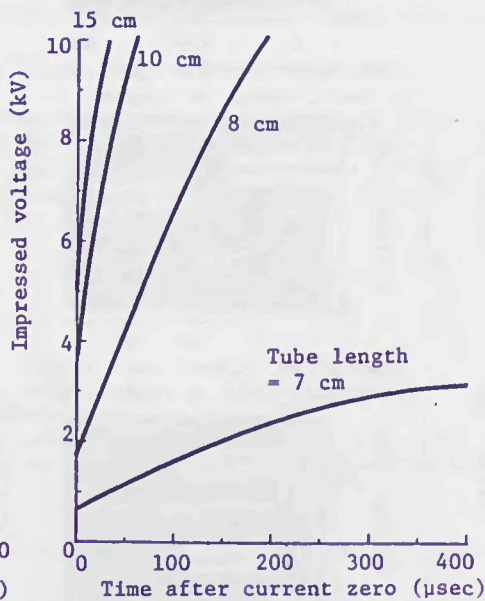


Fig.8 Characteristics of recovery with respect to tube lengths ( Arc energy = 2.0 kJ, Current at arc initiation = 1.0 kA and Inner tube diameter = 6 mm )

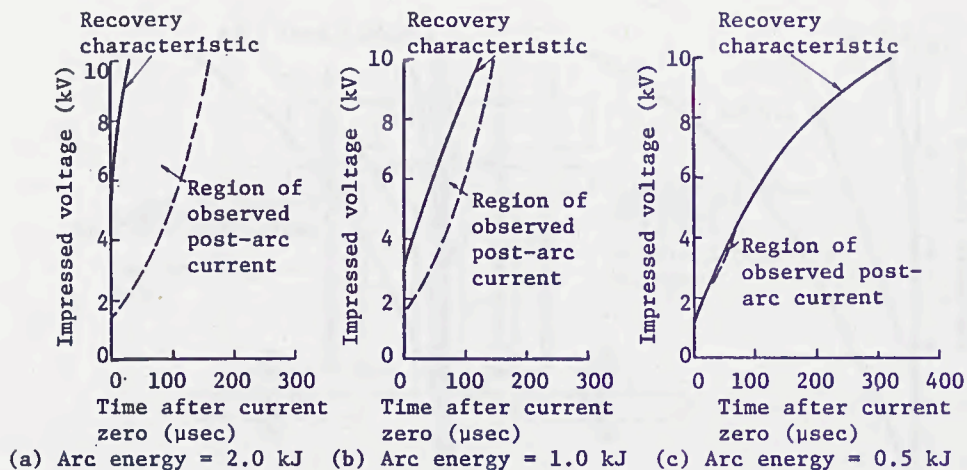


Fig.9 Regions of observed post-arc current ( Current at arc initiation = 1.0 kA, Inner tube diameter = 6 mm and Tube length = 15 cm )

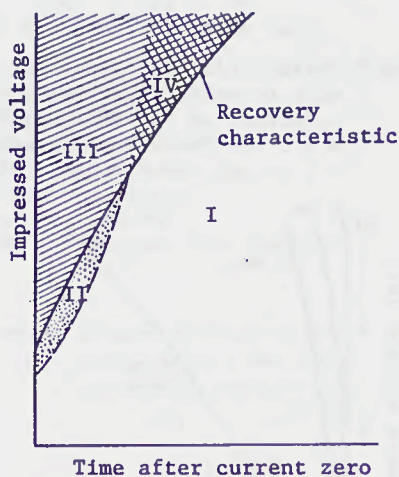
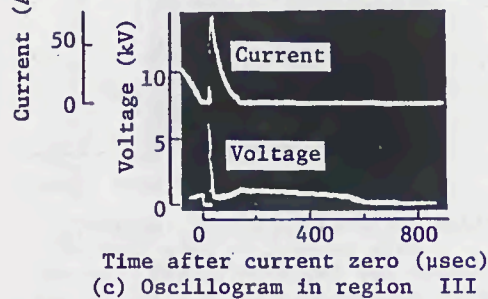
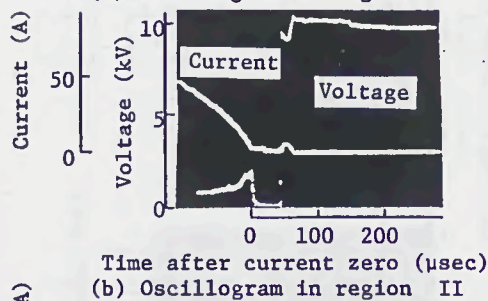
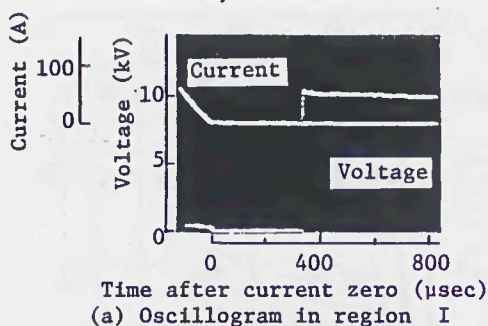


Fig.10 Four regions on characteristic of recovery of dielectric strength

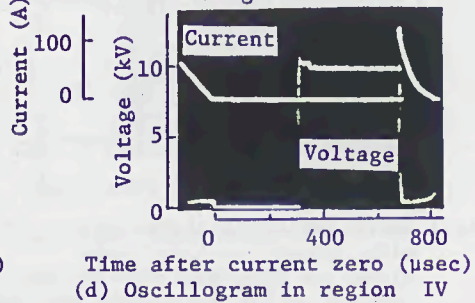


Fig.11 Typical waveforms of current and voltage in four regions