CLM - L4

SOME INSULATION STUDIES FOR PULSED HIGH-VOLTAGE EQUIPMENT

by

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1. Introduction

Much of the insulation of equipment used for fusion research is energised intermittently by pulses, and relatively high voltages are used when rapidly-rising magnetic fields are required. The rate of rise of current in an inductance, L, subjected to a voltage, V, is V/L, and if L were independent of the voltage, the rate of rise could be increased by energising at higher voltages the coils used in experimental equipment. However, increasing the voltage increases the insulation clearances required to prevent electrical breakdown; this increases the inductance to which the voltage is applied, and therefore reduces the rate of rise of current. To minimise this increase in inductance, it is necessary to have very small clearances, and therefore to operate at high stresses - say, 500 kV/cm. It is because of these high stresses that some interesting insulation problems arise in thermonuclear engineering; the voltages are not particularly great (up to 100 kV or so) and their magnitude does not in itself pose any complex problems.

Several long-term studies are in progress at Culham Laboratory to determine the maximum stresses which can be used, and an account is given in this Lecture of work on solid and gaseous insulants, and also of a technique for controlling the voltage distribution by means of high-resistivity electrolytes.

2. Solid Insulation

Compared with gaseous and liquid insulants, solids have the advantages that they can also provide mechanical support, and that their intrinsic electric strength is higher. However, when subjected repeatedly to voltage pulses, solid insulation fails at stresses well below the intrinsic strength, due to erosion by discharges in voids and on surfaces. The life of insulation - measured as the number of pulses it can withstand - decreases as the stress increases, and depends not only on the insulating material, but also on the electrode configuration and voltage waveshape.

In the present state of knowledge, life-stress relations have to be obtained by experiment, but certain generalisations can be made about effects due to variation of waveshape(1). Consider the waveshape of Figure 1 (solid line), which is applied to the configuration of Figure 2; this configuration may be represented to a first approximation by the circuit of Figure 3(a), in which C_v represents the capacitance of the void, and Cs the capacitance of solid insulation in series with the void. As the applied voltage rises from zero, the voltage on the void rises also (in the ratio $C_s/(C_v + C_s)$) until a discharge is ignited (see dotted line in Fig. 1). The voltage on the void then collapses, the discharge extinguishes, and the voltage rises again until another discharge is ignited. This voltage waveshape is shown in Fig.1 for the first two discharges only, but the sequence continues all the time the applied voltage is changing, through ΔV_1, ΔV_2, ΔV_3, and ΔV_4.

Discharges erode the insulation; consequently the damage to the insulation increases if the total voltage excursion, $\Sigma|\Delta V|$, increases. It is this consideration that has sometimes led to the statement that "the life of insulation depends on the total excursion voltage".

This statement is, however, incomplete, because other factors may affect the issue. As erosion proceeds, the stress in the insulation becomes intensified, and ultimately intrinsic breakdown occurs. Intrinsic breakdown depends on the peak value, V_p, of the voltage pulse, and therefore increasing this quantity decreases the life of insulation.

Experiments have shown that a conducting path may be formed on the walls of a void under the action of discharges(2); this can be represented in the equivalent circuit by a resistance, as shown in Figure 3(b). If the resistance is sufficiently low, it may short-circuit the void capacitance, and prevent the occurence of further discharges. It is readily deduced from Fig. 3(b) that the effect of resistance decreases, if the rate of change of the applied voltage is increased; consequently, increasing $\frac{dV}{dt}$ decreases the life of insulation. Again, experiment shows that the discharge-induced conductivity decreases in time[2], so that increasing the time interval between pulses, t_i, decreases the life of insulation.

The importance of $\Sigma|\Delta V|$ is well established, and Mason(3) gives quantitative data which confirm that the life of insulation may be decreased significantly by increasing V_p. No quantitative data were available as to the decrease in life due to increasing $\frac{dV}{dt}$ and t_i, and the effects of these parameters were therefore investigated experimentally at Culham(4), with the waveshapes of Figure 4; these waveshapes will be referred to respectively as "rectified 50 c/s" and "1/50 microsecond". The experiment was made on polythene samples, 0.6 to 1.3 mm thick, between electrodes designed to give a uniform field in the polythene in the absence of voids. Each sample had an artificial void at one electrode; the void was cylindrical, 2.5 mm diameter, and its axis, which lay in the direction of the voltage, was 0.04 or 0.25 mm long in different experiments.

Results are given in Figure 5, in which stress is plotted against life for different conditions. Comparison of results obtained at approximately 550 kV/cm shows that much longer lives were obtained with the rectified 50 c/s wave than with the 1/50 microsecond pulses. This confirms that decreasing $\frac{dV}{dt}$ and increasing t_i may decrease very considerably the life of insulation; experiments are now in progress to determine the relative importance of these two parameters. A practical consequence of the results obtained so far is that the life of insulation subjected to pulses cannot be predicted from its performance at 50 c/s.

Figure 5 shows also that life increased very considerably when the void depth was decreased, and that shorter lives were obtained when the void was at the positive electrode than at the negative electrode. These results suggest that relatively little erosion occurred before intrinsic breakdown set in under conditions which gave lives less than 10^4 pulses(4).

3. Gaseous Dielectrics

Gaseous dielectrics have the advantage that they fail by one mechanism only - the equivalent of intrinsic breakdown in solids. Because of this, their performance is much more predictable, but unfortunately they have relatively low strengths at atmospheric pressure; for air and nitrogen, this is about 30 kV/cm. Strengths of 1 MV/cm may be obtained by using high pressures, but this introduces obvious mechanical problems.

Problems due to pressure may be alleviated to some extent by using SF_6 or CCl_2F_2, which have between two and three times the electric strength of air. An important property of these gases is that they maintain a high strength even if mixed with air or nitrogen(5,6), as shown in Figure 6. It follows that if SF_6 or CCl_2F_2 are used at atmospheric pressure, their containers need not be airtight, because the ingress of moderate quantities of air does not affect the strength significantly.

It would be desirable to use gases of even higher strengths and preliminary experiments at Culham have shown that several compounds have 4 or 5 times the electric strength of air, but unfortunately their boiling points exceed 50°C. It so happens that the molecular characteristics which result in high electric strengths tend also to give high boiling points; this is illustrated in Figure 7, which was obtained by Mr. P.G. Dawson, for compounds consisting of C, Cl and H. It will be seen that as the molecular content of Cl increases at the expense of H, the electric strength increases, and so does the boiling point. However, there appears to be no basic reason why a compound may not be found which would have a boiling point nearer 20°C, and perhaps five times the electric strength of air. A research programme has been sponsored at Birmingham University to study the production of such a compound.

4. Voltage Grading with Liquid Resistors

A method of voltage grading using high-resistivity electrolytes has been developed at Culham by Mr. D.N. Cornish, principally in order to prevent surface flashover. Figure 8 shows the application of this technique to the prototype of a collector plate. The inner and outer conductors of several cables are connected to the plates marked A and B, and the cable insulation between them is immersed in electrolyte (in this case water containing sodium dichromate). Perspex sheet is used to contain the electrolyte between the plates A and B, and perspex blocks have also been inserted between these plates to reduce the amount of electrolyte.

With this technique, 110 kV have been withstood along an air-exposed surface of 10 cm between A and B, for voltage pulses which were oscillatory with a frequency of 200 kc/s and 80% reversal. However, when unidirectional pulses were applied, gas bubbles formed in the electrolyte and these may produce a breakdown. This phenomenon is now being studied.

5. Conclusions

Several interesting insulation problems arise in thermonuclear engineering. Considerable experimental work is required to obtain comprehensive design data, but there is no basic reason why equipment should not be designed for operation at 100 kV or higher voltages.

6. Acknowledgements

The studies described here have been the subject of numerous discussions with my colleagues, and my thanks are due to them and particularly to Mr. R. Carruthers.

7. References

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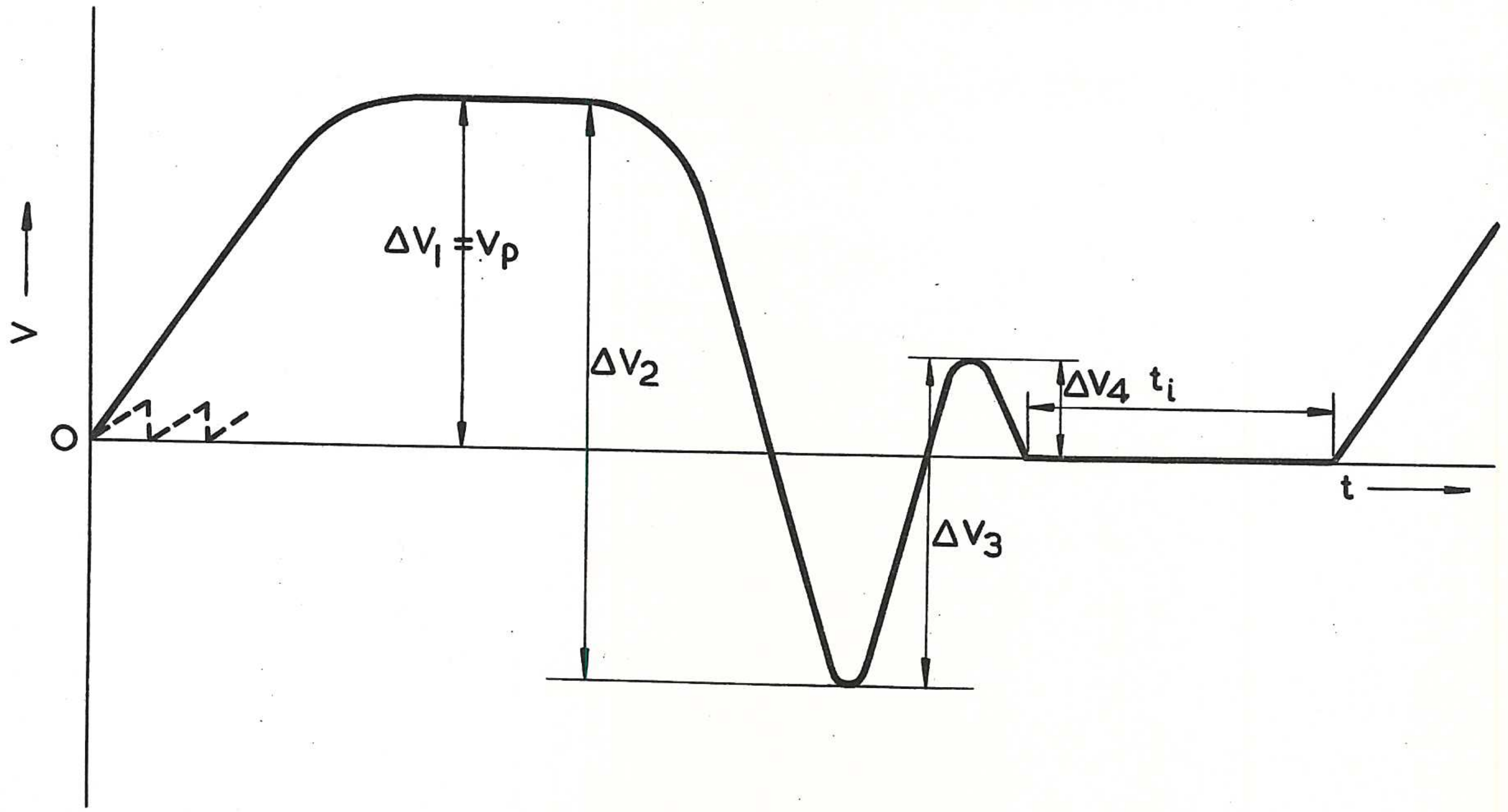


CLM L 4. FIG. I. VOLTAGE WAVESHAPE

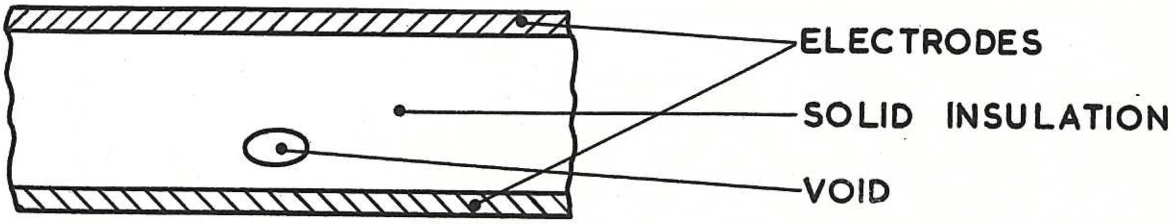
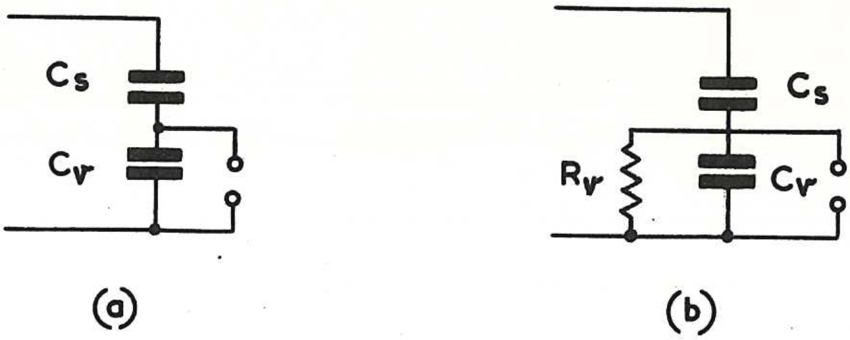


FIG. 2. SOLID INSULATION WITH VOID



(a)

(b)

FIG. 3. EQUIVALENT CIRCUITS

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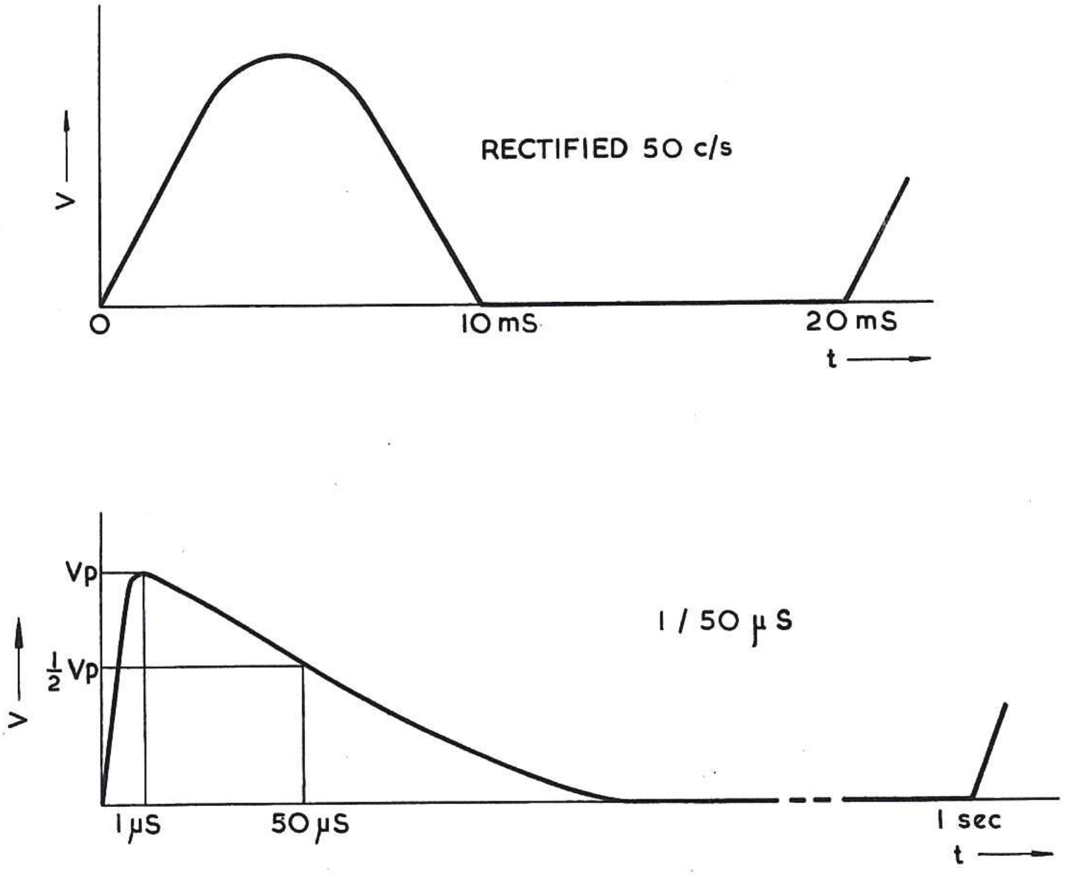


CLM L4. FIG. 4. TEST WAVESHAPES

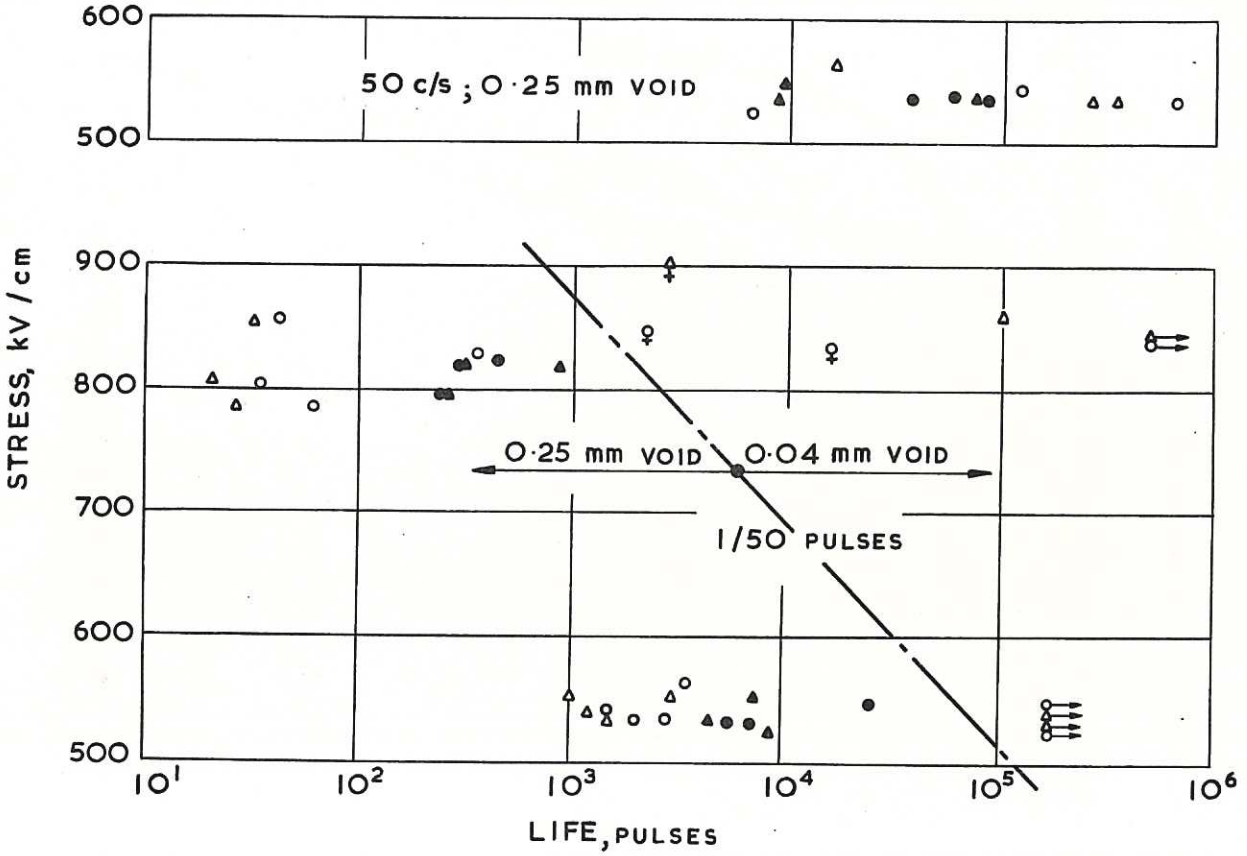


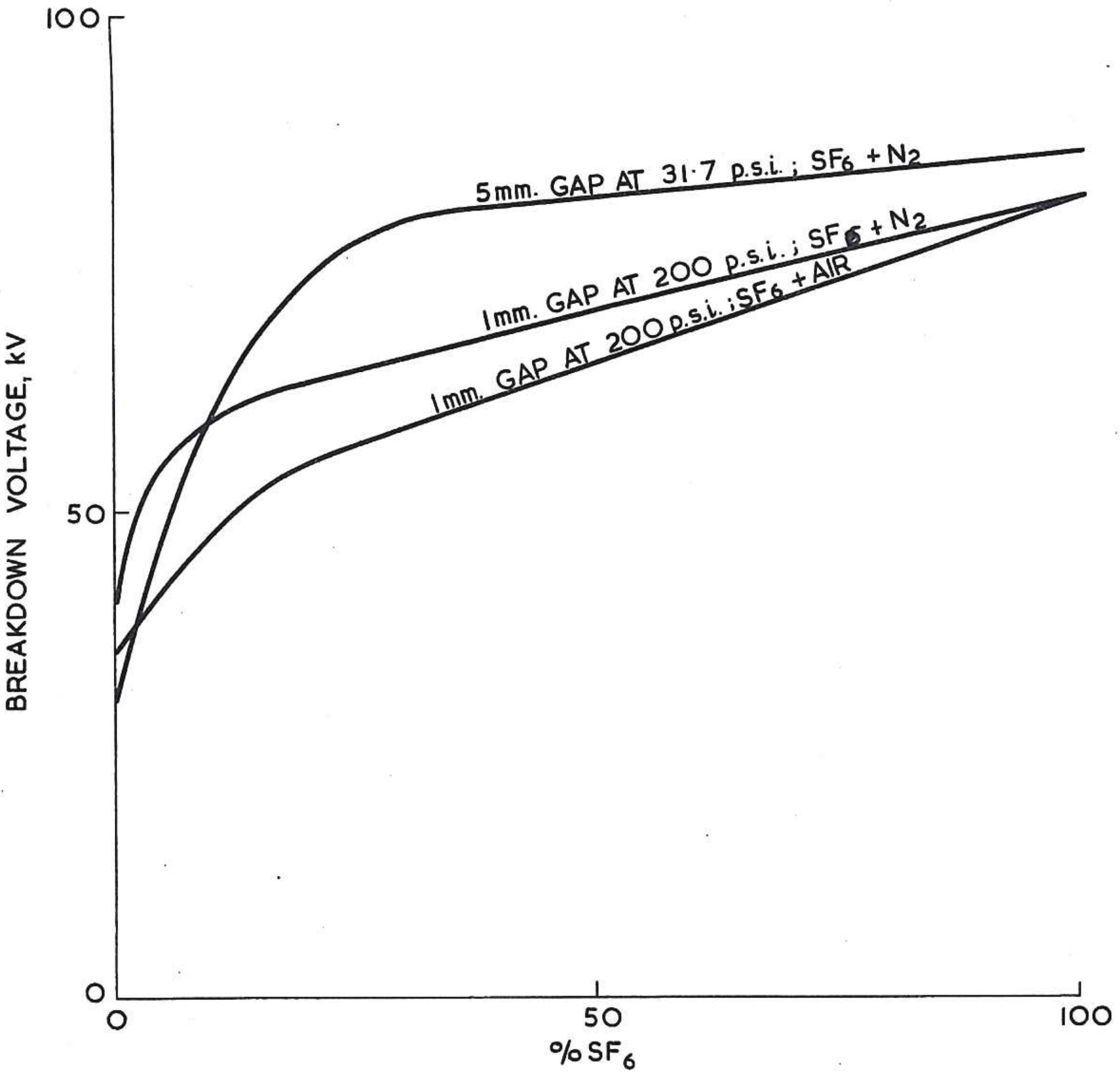
FIG. 5. EFFECTS OF STRESS, WAVESHAPE, POLARITY AND VOID SIZE ON THE LIFE OF INSULATION.

VOID AT ANODE: △ GOLD ELECTRODE
○ COPPER ELECTRODE

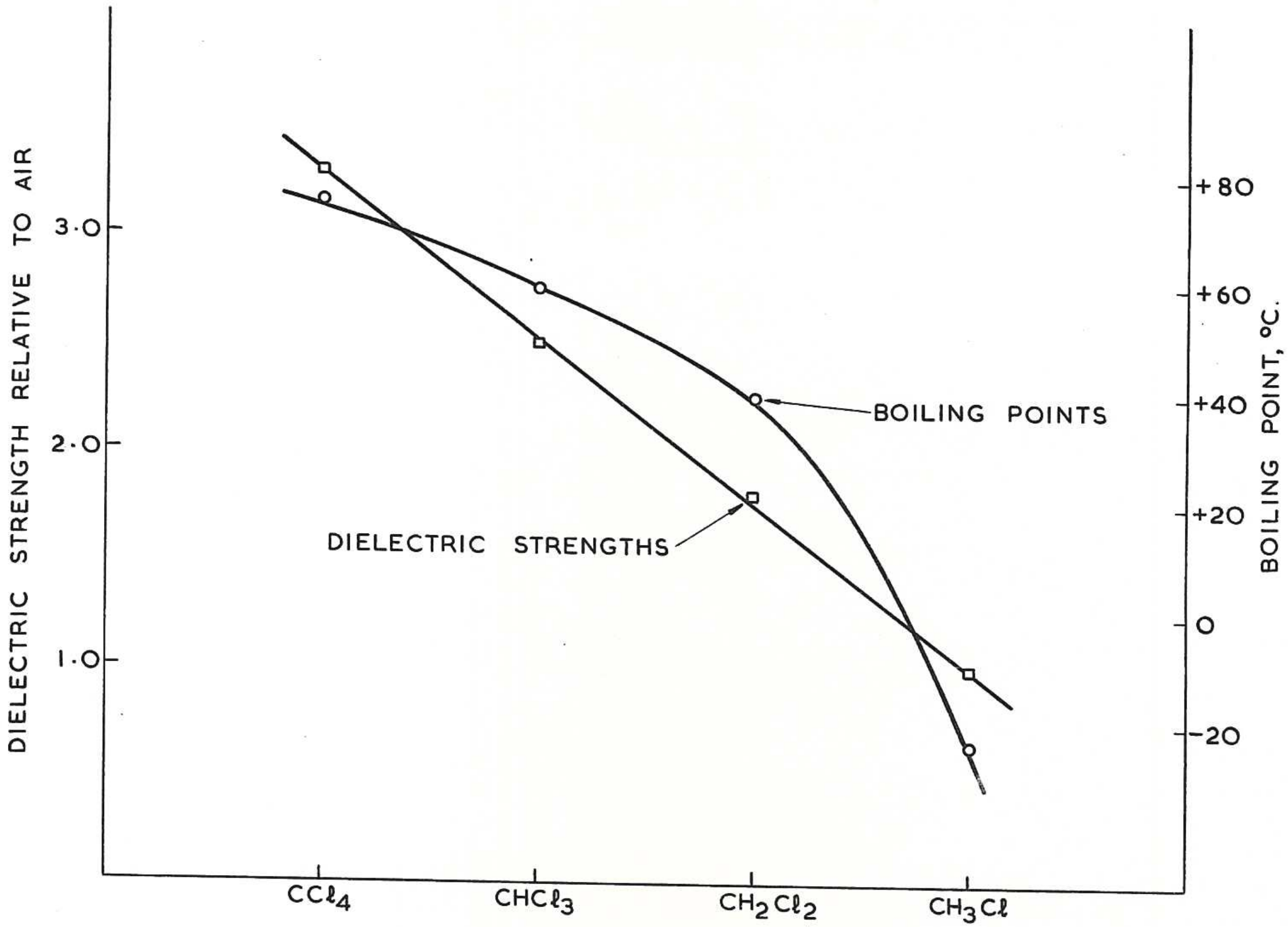
VOID AT CATHODE: ▲ GOLD ELECTRODE
● COPPER ELECTRODE

\+ INDICATES BREAKDOWN NOT THROUGH VOID

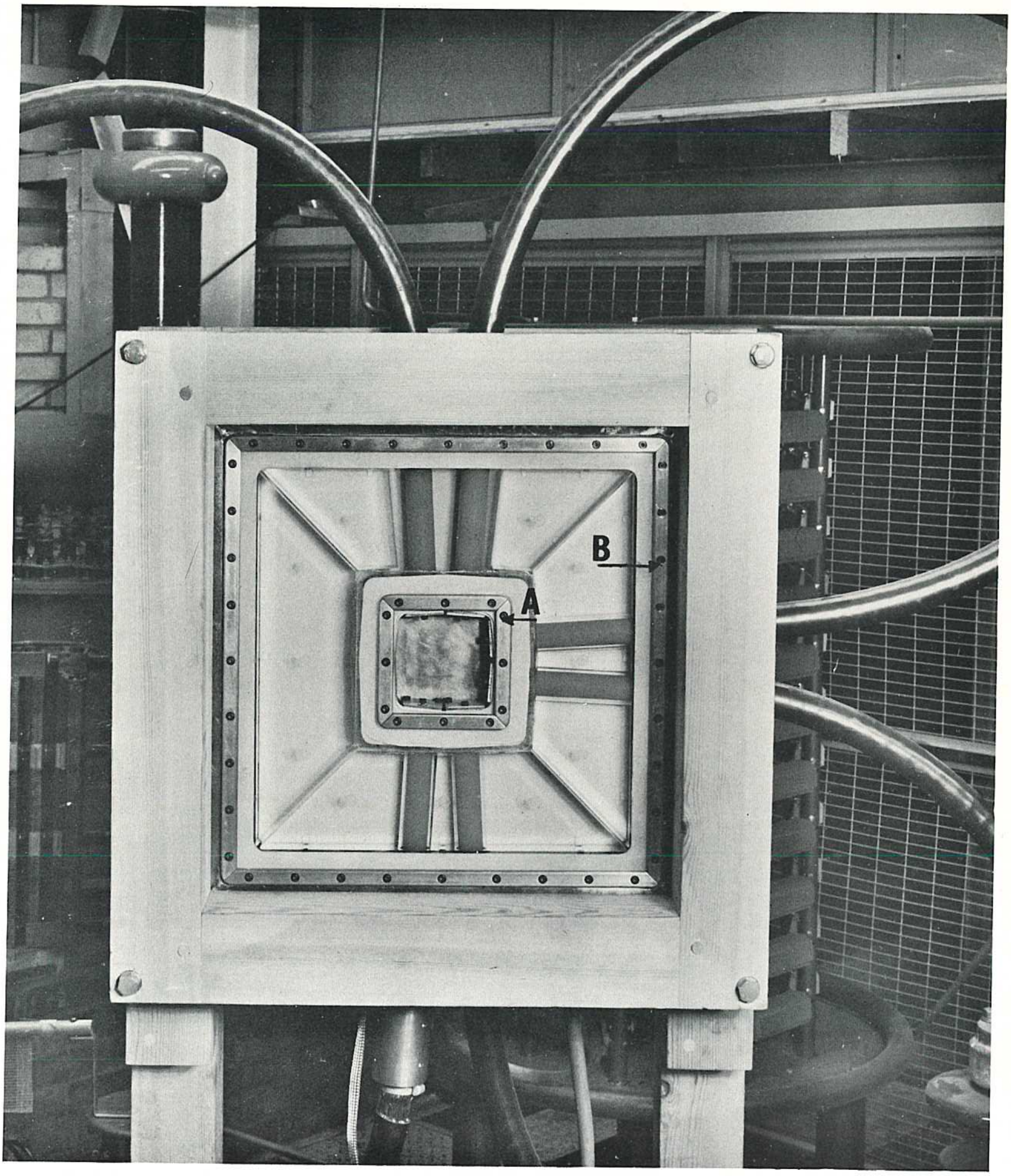
→ INDICATES TEST DISCONTINUED BEFORE BREAKDOWN



CLM L 4 FIG. 6. DEPENDENCE OF BREAKDOWN VOLTAGE ON SF_6 CONTENT FOR MIXTURES OF SF_6 WITH AIR AND NITROGEN. THE ABSCISSA IS THE PARTIAL PRESSURE OF SF_6 EXPRESSED AS A PERCENTAGE OF THE TOTAL PRESSURE OF THE MIXTURE. FROM DATA BY HOWARD[5] AND COHEN[6]



CLM L4 FIG.7 DEPENDENCE OF ELECTRICAL STRENGTH AND BOILING POINT ON MOLECULAR COMPOSITION



CLM - L4 Fig. 8
Prototype of Cable Termination