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TRIGGERING CHARACTERISTICS OF LOW PRESSURE SWITCHES

R. HANCOX C. S. INSTONE

Culham Laboratory,
Culham, Abingdon, Berks.

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TRIGGERING CHARACTERISTICS OF LOW PRESSURE SWITCHES

by

R. Hancox and C. S. Instone

ABSTRACT

The triggering delay of a low pressure switch has been measured under a wide range of conditions. A mechanism for the breakdown is proposed which is consistent with the measurements and with previously reported results.

U.K.A.E.A. Research Group,
Culham Laboratory,
Nr. Abingdon,
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FIGURES

SYMBOLS

V_o	Voltage across the switch (volts)
Z	Impedance of the circuit being switched (ohms)
d	Electrode separation (c.m.)
A	Electrode area (c.m.^{2})
p	Gas pressure in the switch (m.Torr)
i_o	Initial (or vacuum) space charge limited electron current (amps)
s	Ionisation efficiency (ion pairs/cm. Torr)
v_-	Electron velocity (cm/sec)
n_-, n_+	Electron and positive ion densities (cm^{-3})

For definitions of the delays τ_1 and τ_2, see Section 6.

1. Introduction

Switches used for capacitor discharge duty in the C.T.R. field are commonly gas discharge devices using gas at pressures of either a few milli-Torr or about an atmosphere (1). A great advantage of low pressure switches is that they may be triggered over a wide range of voltages without the use of very high trigger voltages. An advantage of high pressure switches is that trigger delays down to 10^{-9} seconds may be obtained, whereas the delay in low pressure switches is rarely less than 10^{-7} sec. To allow a fuller comparison of the triggering characteristics of these two types of switch, therefore, their properties have been studied in detail in order to show which parameters are of importance if rapid and reliable triggering is to be obtained. This report deals with the results obtained with low pressure switches.

2. Previous Investigations

In view of the wide application of low pressure switches in thermonuclear research it is not surprising that measurements of the delay time have been made by several workers. No detailed investigations have been made, however, nor has the mechanism of breakdown been fully described.

Mather and Williams (2) have used double gap switches for both start and clamp duty (Figure 1). They observed that the trigger delay was dependent on the following factors:-

(a) The gas pressure. The delay increased slowly with decreasing pressure in the range 15 to 4 m-Torr. At lower pressures the delay increased rapidly to more than one micro-second.

(b) The magnitude and polarity of the voltage. Shorter delays were always obtained when the trigger pin was situated in the negative electrode. At low pressures the delay decreased with increasing voltage, but at higher pressures the effect was small.

(c) The type of trigger pin used. In order to obtain a short delay it was necessary that the trigger discharge projected into the main gap.

Nakano, Hayaski and Maio (3) measured the delay in a switch operating at a pressure of 0.5 m-Torr. They found that the delay decreased as the voltage was raised from 200 V to 10 kV.

The fullest investigation published so far is that of Johansson and Smårs (4), (Figure 2). Their results, obtained at pressures of 10 to 40 m-Torr show that the delay increases with increasing voltage when the trigger pin is in the negative electrode, but is greater and decreases with increasing voltage when the main gap polarity is reversed. The delay also decreases with increasing pressure and increasing trigger voltage.

3. Experimental Arrangement

Delay times have been measured in two different switches, both of which were demountable. The first was an experimental high voltage switch capable of withstanding 100 kV, having stainless steel electrodes with 2.5 cm separation (Figure 3a). It was continuously pumped with a mercury diffusion pump through a liquid nitrogen trap. The second switch was specially constructed for these measurements, having parallel plane electrodes of 11.4 cm^2 area and 3.2 cm separation (Figure 3b). This switch was pumped with an oil diffusion pump through a liquid nitrogen trap, and the gas pressure was measured either with an ionization gauge or a McLeod gauge.

The trigger pin used for the majority of the measurements consisted of a single tungsten wire of 1 mm diameter with an insulating sleeve lying flush with the surface of the main electrode (Figure 3c). In some cases the sleeve was withdrawn from the main gap region but this resulted in a longer delay and increased jitter. All the results recorded were with the trigger pin in the negative electrode since the switch did not trigger with the opposite polarity.

Measurements were made with the switches connected to several parallel cables. Cables were used rather than a capacitor in order to reduce the circuit inductance and to give a known circuit impedance since it was found that this affected the results. In most cases eight cables, each 100 yards long, were used, giving an impedance of 6.5Ω.

The voltage across the switch was observed on an oscilloscope by means of a potential divider connected directly to the plates. The delay was defined as the time between the application of the trigger pulse and the collapse of the voltage across the switch to 1/e of its original value.

4. Experimental Results

4.1 Results with high-voltage switch

The first measurements were made with nitrogen for the gas filling. At pressures above 5 m-Torr the collapse of voltage across the switch was smooth and quite repeatable. At lower pressures, however, partial recovery of the voltage occurred and the delay and jitter increased. Typical wave-forms are shown in Figure 4. The variation of delay with pressure at a voltage of 4 kV is shown in Figure 5, and at 20 kV in Figure 6.

Similar measurements were obtained with a gas filling of Argon. Results at 4 kV are shown in Figure 7, and at 20 kV in Figure 8. The delay in hydrogen was found to be much longer, and was only reproducible at pressures above 35 m-Torr. Results obtained at 4 kV are shown in Figure 9.

The effect of voltage was studied in more detail with nitrogen at a pressure of approximately 10 m-Torr. The results are shown in Figure 10, and it is seen that the delay increases slightly with increasing voltage.

Whilst investigating the effect of the trigger circuit on the delay it was found that the length of the trigger pulse did not influence the results, even when it was much shorter than the measured delay. The majority of the results were obtained with a 15 kV pulse of 100 mμsec duration from a 330 Ω cable. The delay was also found to be independent of the polarity of the trigger pulse.

4.2 Results with parallel electrode switch

The delay was again measured with nitrogen at various pressures (Figure 11), and the results were seen to be similar to those obtained previously.

The effect of voltage was also similar, and further measurements were made at low voltages (Figure 12) which showed that the delay was a minimum at a voltage of about 1.3 kV.

The triggering mechanism proposed in Section 5 suggests that the delay should be a function of the impedance of the circuit being switched, and measurements were therefore made with different numbers of cables connected to the switch. The results (Figure 13) show that the delay increases with decreasing circuit impedance.

An interesting feature of the parallel electrode switch was that the short trigger pulse used with the high voltage switch did not trigger the switch except at the highest pressures. The trigger circuit was therefore modified to discharge a capacitor through a resistor giving a time-constant of several micro-seconds. Using this arrangement the effect of trigger voltage and trigger circuit impedance were studied. The delay was found to increase with both decreasing trigger voltage (Figure 14) and trigger current (Figure 15).

5. The Breakdown Mechanism

The mechanism of operation of the switch is most easily understood by firstly considering what happens if the switch is triggered at a very low pressure. In this case application of the trigger pulse results in breakdown of the pin to its adjacent electrode across the insulating sleeve, and a trigger discharge which acts as a source of electrons in the main gap. Since the trigger pin is in the negative electrode, electrons are accelerated across the main gap to the opposite electrode, giving a current in the main circuit. This current is not limited by the current in the trigger discharge since the arc spot on the cathode can grow to give as much current as is demanded of it, but is limited by its own space charge. This current does not itself constitute breakdown of the gap, even though it may continue for a considerable time, since it is too small to cause any appreciable voltage drop in the main circuit. It will, however, lead to breakdown if sufficient gas is present in the switch.

Consider now a switch filled with gas to a pressure of about 10 m-Torr. The first stage of breakdown is the establishment of a space charge limited electron current across the gap in the same manner as in a completely evacuated switch. When gas is present, however, electrons accelerated across the gap may have an ionizing collision with a neutral gas molecule. The probability of any particular electron having such a collision is small (approx. 0.05 in nitrogen at 10 m-Torr), but sufficient to result in the build-up of a positive ion space charge. Since the electron current in the gap is space charge limited the formation of ions immediately allows an increase in the electron current, and provided the rate of formation of positive ions is greater than the rate at which they are lost by being accelerated to the negative electrode, an unstable current growth occurs which results in complete breakdown of the switch.

If the gas pressure in the switch is too low ions are accelerated towards the negative electrode as fast as they are formed. In this case complete breakdown cannot occur until the gas density is increased to the point where ion formation is sufficiently rapid. This increase in density may be caused by evaporation of material from the positive electrode due to high energy electron bombardment, or evaporation from the insulating walls of the switch, or may be gas generated by the trigger discharge. In any of these cases the delay will be much longer and very variable.

6. Calculation of Trigger Delay

The trigger delay of a low pressure switch is seen to consist of two parts:-

τ_1 - The time taken to form an arc spot on the negative electrode by means of the trigger discharge. This will depend on the trigger voltage, the impedance of the trigger circuit, and the actual construction of the trigger pin. It may easily be reduced to about 25 mμsec, and is therefore only a small fraction of the total delay.

τ_2 - The time required for the positive ion density in the main gap to grow to the point where the current in the switch is only limited by the external circuit. This may be calculated approximately, assuming that the voltage distribution across the gap is independent of time.

Since the electron current is determined by the positive ion space charge:-

$$\frac{dn_-}{dt} = \frac{dn_+}{dt} \quad \text{at all points in the gap}$$

Therefore ${}^{di}/dt = p(sv_-)\,i$

$$\text{or} \quad i = i_o e^{p(sv_-)\,t} \qquad \ldots\ldots (1)$$

where i_o is the initial (or vacuum) saturated electron current. (It should be noted that s and v_- are both functions of electron energy, and thus vary across the gap. The product (sv_-) is, however, insensitive to electron energy for voltages above 500 V. It is only because of this that the original assumption concerning the voltage distribution has any validity.)

If the impedance of the main circuit is resistive, rather than inductive, the voltage across the switch is

$$V = V_o - Z\, i_o e^{p(sv_-)\,t} \qquad \ldots\ldots (2)$$

and since the delay, τ_2, has been defined as the time until the voltage falls to $^1/e$ of its original value

$$\tau_2 = \frac{1}{p(sv_-)} \log_e \left\{ \frac{0.632\, V_o}{Z\, i_o} \right\} \qquad \ldots\ldots (3)$$

If the current distribution is uniform throughout the volume of the switch

$$i_o = 2.3 \times 10^{-6} \; \frac{A \; V_o^{3/2}}{d^2} \qquad \ldots\ldots (4)$$

and therefore

$$\tau_2 = \frac{1}{p(s v_-)} \; \log_e \; \frac{2.75 \times 10^5 \; d^2}{Z \; A \; V_o^{\frac{1}{2}}} \qquad \ldots\ldots (5)$$

Using equation (5) with the appropriate parameters for the parallel electrode switch and nitrogen at 15 m-Torr pressure, gives $\tau_2 = 93$ mμsec at 2.5 kV compared with the experimental value (from Figure 11, subtracting $\tau_1 = 22$ mμsec as found in Figure 17), of 103 mμsec.

Equation (5) is only valid if the rate at which ions are formed is greater than the rate at which they are lost, and an estimate of the limiting pressure for which this is true can be obtained.

The critical region is that adjacent to the positive electrode where the rate of loss of ions is greatest. If all the ions were removed from a thin layer next to the electrode the current could again be limited by the electron space charge. Using the parameters for the high voltage switch at a voltage of 4 kV, the time for an ion to move far enough to prevent completion of the breakdown process is found to be:-

70 mμsec for Nitrogen
85 mμsec for Argon
19 mμsec for Hydrogen.

If the time constant for ion formation $\frac{1}{p(s v_-)}$ is greater than these values complete build-up of space charge will be prevented. The critical values of gas pressure are therefore:-

3.2 m-Torr for Nitrogen
2.7 m-Torr for Argon
43 m-Torr for Hydrogen

which agree reasonably well with the experimental results of Figures 5, 7 and 9.

7. Discussion of Results

Equation (5) predicts the effect of several factors on the trigger delay of a low pressure switch, many of which have been observed experimentally.

(i) The most important parameter is seen to be the pressure of gas in the switch since the time for positive ion space charge build-up is inversely proportional to the pressure. This is demonstrated by the results in the high voltage switch with Argon (Figures 7 and 8) which have been re-plotted in Figure 16 as a function of $^{1}/p$. The curves for 4 kV and 20 kV intercept the axis at a delay of 25 mμsec, which corresponds to the delay in establishing the trigger discharge τ_1. The same dependence is shown by the results for the parallel electrode switch with nitrogen (Figure 11) which are re-plotted in Figure 17.

At pressures below the critical pressure the delay should become longer than the value predicted by equation (5), and the jitter increase. This was found to be the case for all the results obtained with the high-voltage switch. The results obtained with the parallel electrode switch, however, gave delays shorter than expected, and this is thought to be due to evaporation of material from the wall of the switch which was in contact with the discharge.

(ii) The time for the growth of positive ion space charge at gas pressures above the critical pressure should be inversely proportional to the cross-section for ionization of the gas molecules. The relative delays for nitrogen, argon and hydrogen in the high-voltage switch are in agreement with this. The critical pressure, below which jitter occurs, is also a function of the ionization cross-section as well as the mass of the gas molecules, and the agreement between experimental results and theoretical values was demonstrated in the previous section.

(iii) The delay should be only slightly affected by the voltage across the switch since it depends on the terms $1/(sv_-)$ and $\log_e (V_0^{-\frac{1}{2}})$, both of which are insensitive to voltage. The experimental results of Figure 10 show that the effect of voltage is small, the delay increasing slightly with increasing voltage.

At voltages below 1 kV the product (sv_-) changes more rapidly with voltage due to the maximum in the ionisation cross-section, and this is reflected in a minimum in the delay, as shown in Figure 12. At voltages below about 400 volts the switch will not trigger.

At gas pressures below the critical pressure the effect of voltage may be reversed. This is due to the fact that the gas pressure in the switch must be increased before breakdown can occur, and if this is achieved by the evaporation of material from the electrodes the process will be more efficient at high voltages. This effect is seen by comparing the results for nitrogen at a pressure of 0.5 m-Torr at 4 kV and 20 kV (Figures 5 and 6), and is also seen in the results of Mather and Williams (2), and Nakano et al.(3).

(iv) The delay should depend on the impedance of the circuit in which the switch is used. In Figure 13 the results obtained at different impedances have also been plotted as a function of $\log_e(\frac{1}{Z})$, and are seen to lie close to a straight line which is consistent with equation (5).

If the switch were used in an inductive circuit instead of a resistive one, an equation similar to equation (5) could be deduced. If measurements are made in a high impedance circuit the self capacitance of the switch must also be taken into account. Results obtained under these conditions are not, however, a reliable guide to the performance of the switch in a practical circuit.

(v) The delay should depend on the area of the switch and on the electrode separation. Neither of these effects, however, were studied directly.

There is a secondary effect of electrode area which showed itself in the difference in behaviour of the two switches. As soon as the trigger discharge occurs a current flows in the main gap, which is given by equation (4). If this current is sufficient to maintain the arc spot on the cathode (i.e. greater than about 1 amp) the operation of the switch is no longer dependent on the trigger discharge. In this case only a short trigger pulse is necessary, even when the total delay in the switch is long, as was found with the high voltage switch. If, however, the initial current in the switch is insufficient to maintain the cathode spot, as occurred in the parallel electrode switch due to its smaller electrode area, then the trigger discharge must be maintained for a longer time.

The trigger delay of a low pressure switch may be reduced by reducing the electrode separation since τ_2 is proportional to $\log_e (d^2)$. Reduction of the separation also allows higher gas pressures to be used, since the static breakdown voltage of the switch is a function of the product of the gas pressure and the electrode separation, giving a further reduction in delay. The shortest delays are therefore obtainable in the thyratron type of switch where high gas pressures and small electrode separations occur.

(vi) The total triggering delay of a switch depends on the time taken to initiate the trigger discharge as well as the time taken to build up the positive ion space charge. The effect of trigger voltage and trigger circuit impedance cannot be calculated, but it is seen from Figures 14 and 15 that the delay is fairly constant for trigger voltages above 10 kV and currents above about 5 amps. Under these conditions the delay due to the formation of the trigger discharge is about 25 mμsec.

(vii) An effect which has not been studied in the present experiments is the delay when the trigger pin is in the positive electrode of the switch. In these circumstances an additional delay occurs, being the time taken to form an arc spot on the negative electrode due to the trigger discharge at the positive electrode. In order to form the arc spot positive ions must bombard the electrode (5), and therefore the major part of this delay will be the time taken for positive ions to be accelerated across the gap from the original trigger discharge, which will be longer than either the time for the original discharge to form or for the positive ion space charge to build up in the switch. Under these conditions the total delay will approximately equal the transit time of a positive ion across the gap, and will therefore decrease with increasing voltage, as found by Johansson and Smårs (4).

8. Conclusions

The triggering delay of a low pressure switch with the trigger pin in the negative electrode is seen to consist of two components. First, the delay in initiating the trigger discharge, which is a function of the trigger voltage and trigger circuit impedance. Second, the time required to build up sufficient positive ion space charge in the switch to neutralise the space charge due to the electron current. For gas pressures above a critical level this time is given approximately by

$$\tau_2 = \frac{1}{p(sv_-)} \log_e \left\{ \frac{2.75 \times 10^5 d^2}{Z A V_o^{\frac{1}{2}}} \right\}$$

Below the critical pressure the delay becomes very variable.

If the trigger pin is in the positive electrode a further delay is added which is approximately equal to the transit time of an ion across the gap.

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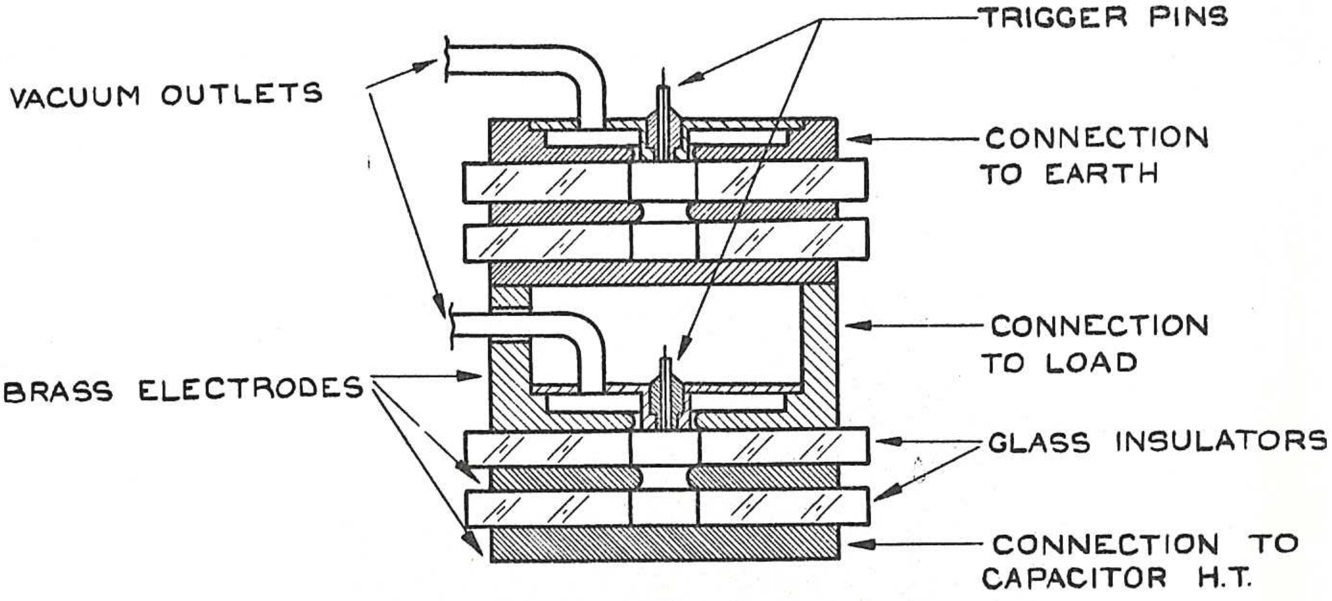
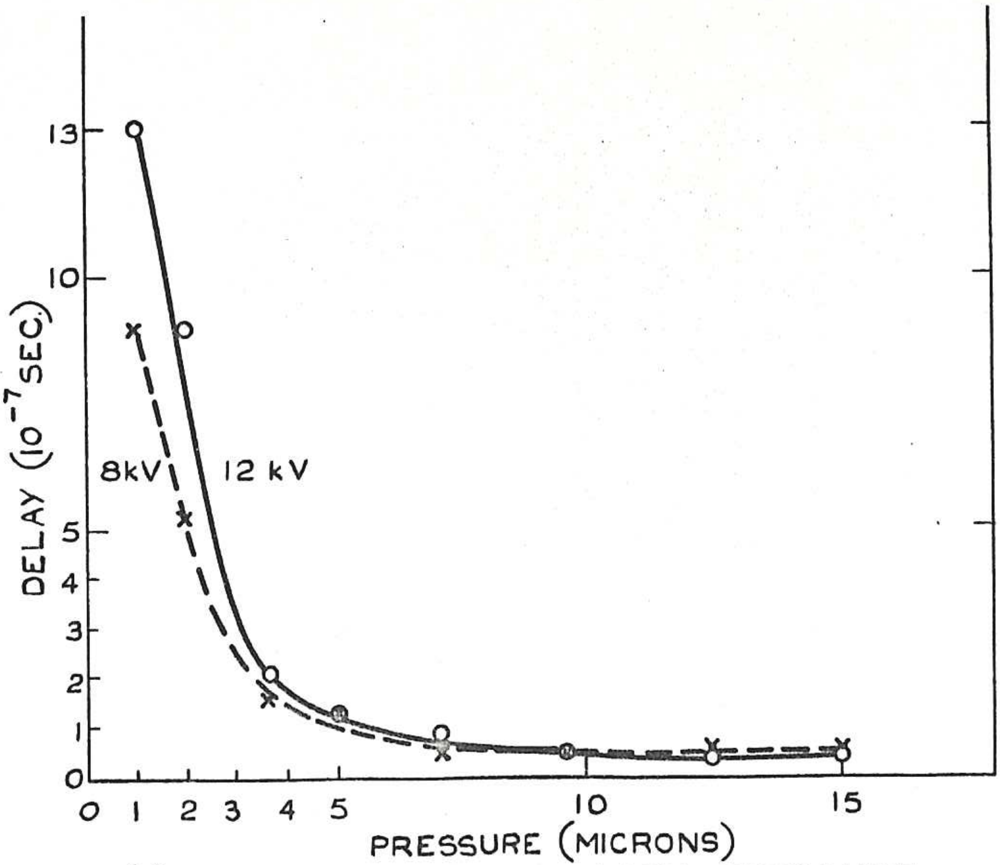
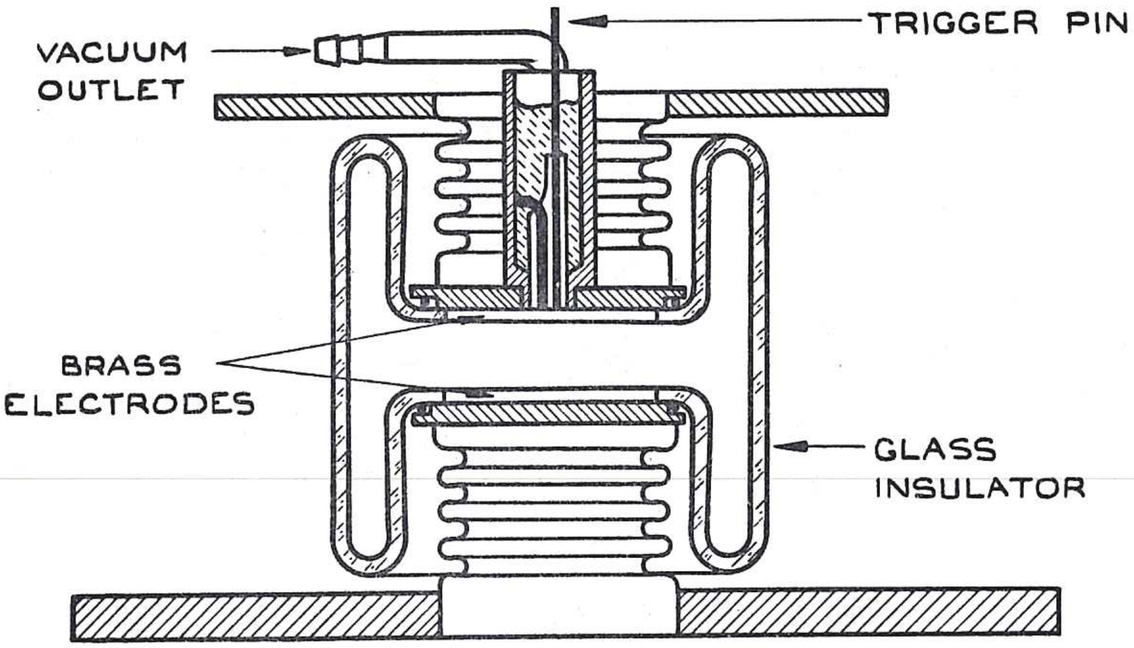


(a) ELECTRODE ARRANGEMENT (HALF FULL SIZE)

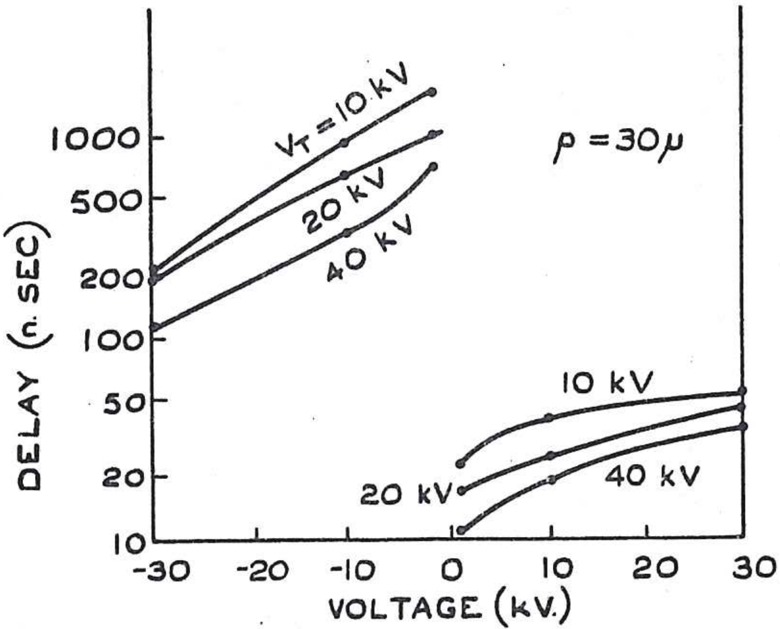


(b) VARIATION OF DELAY WITH PRESSURE.

CLM-R14 FIG. 1 RESULTS OF MATHER & WILLIAMS.

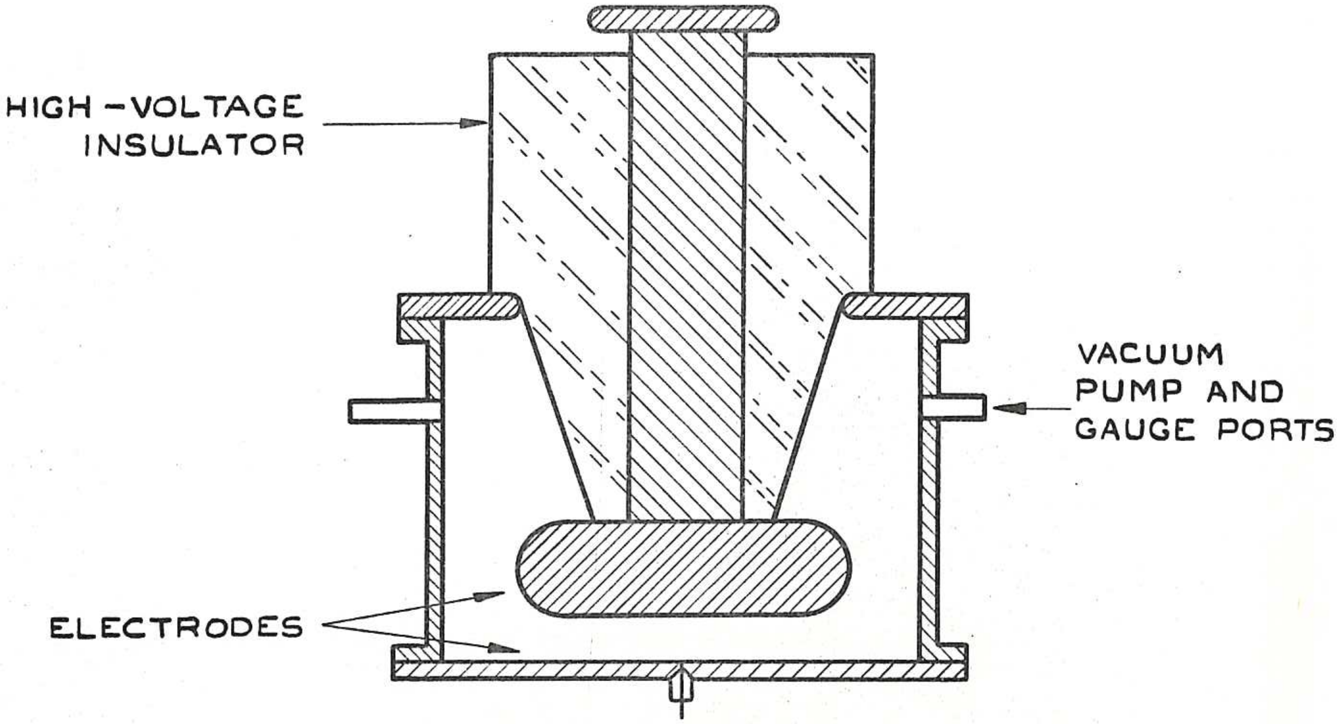


(a) ELECTRODE ARRANGEMENT.

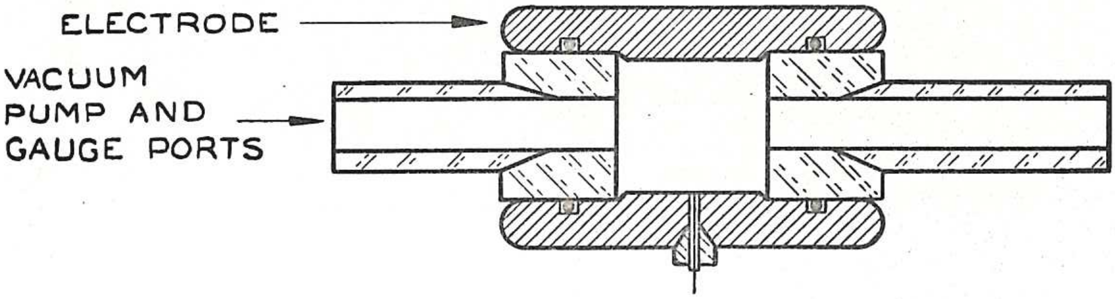


(b.) VARIATION OF DELAY WITH VOLTAGE

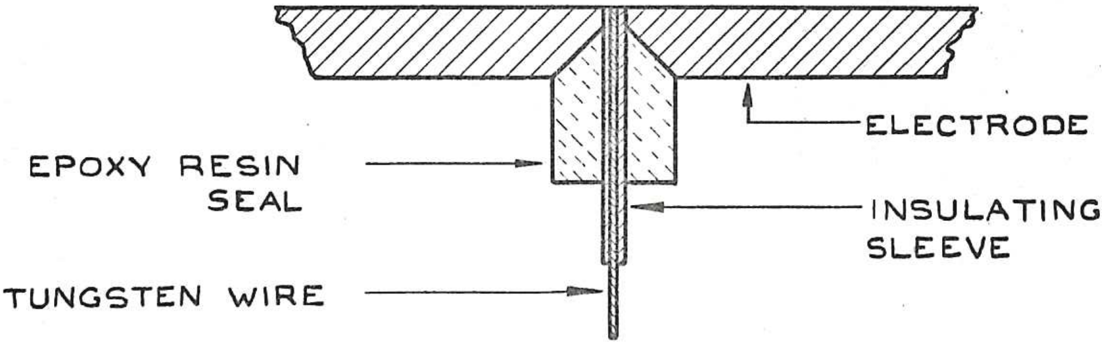
CLM-R14. FIG. 2. RESULTS OF JOHANSSON & SMÅRS



(a) HIGH VOLTAGE SWITCH ($\frac{1}{4}$ FULL SIZE)

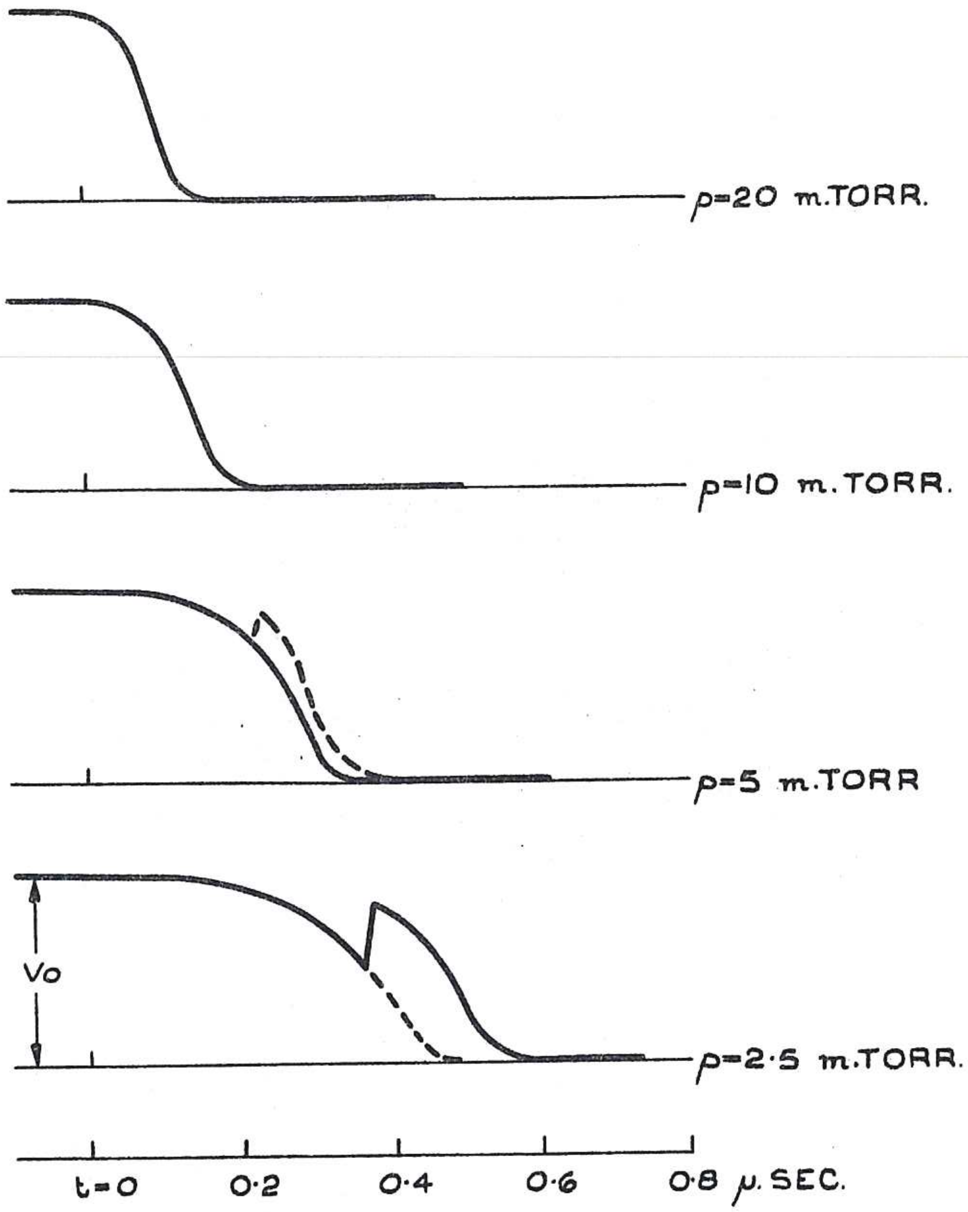


(b) PARALLEL ELECTRODE SWITCH ($\frac{1}{2}$ FULL SIZE)

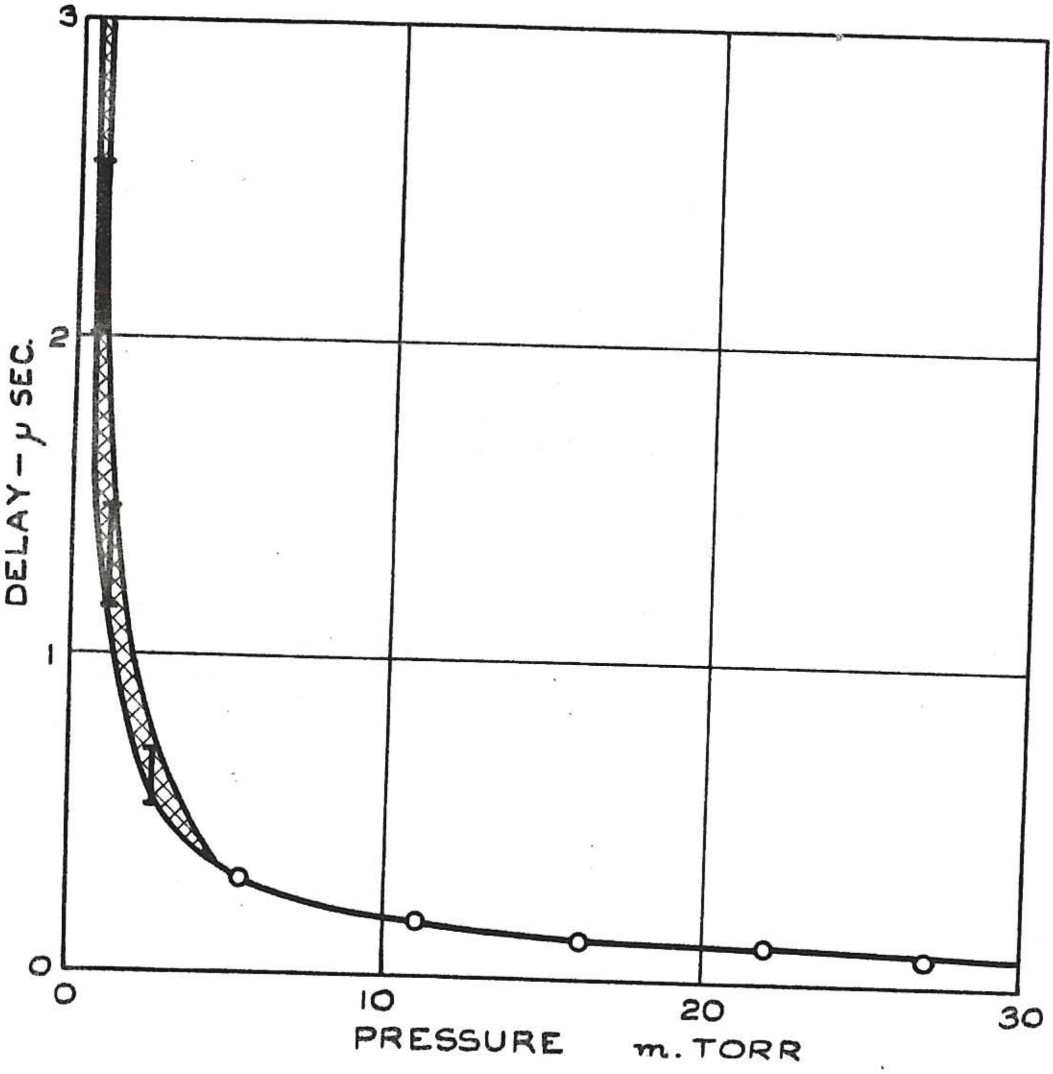


(c) TRIGGER PIN (FULL SIZE)

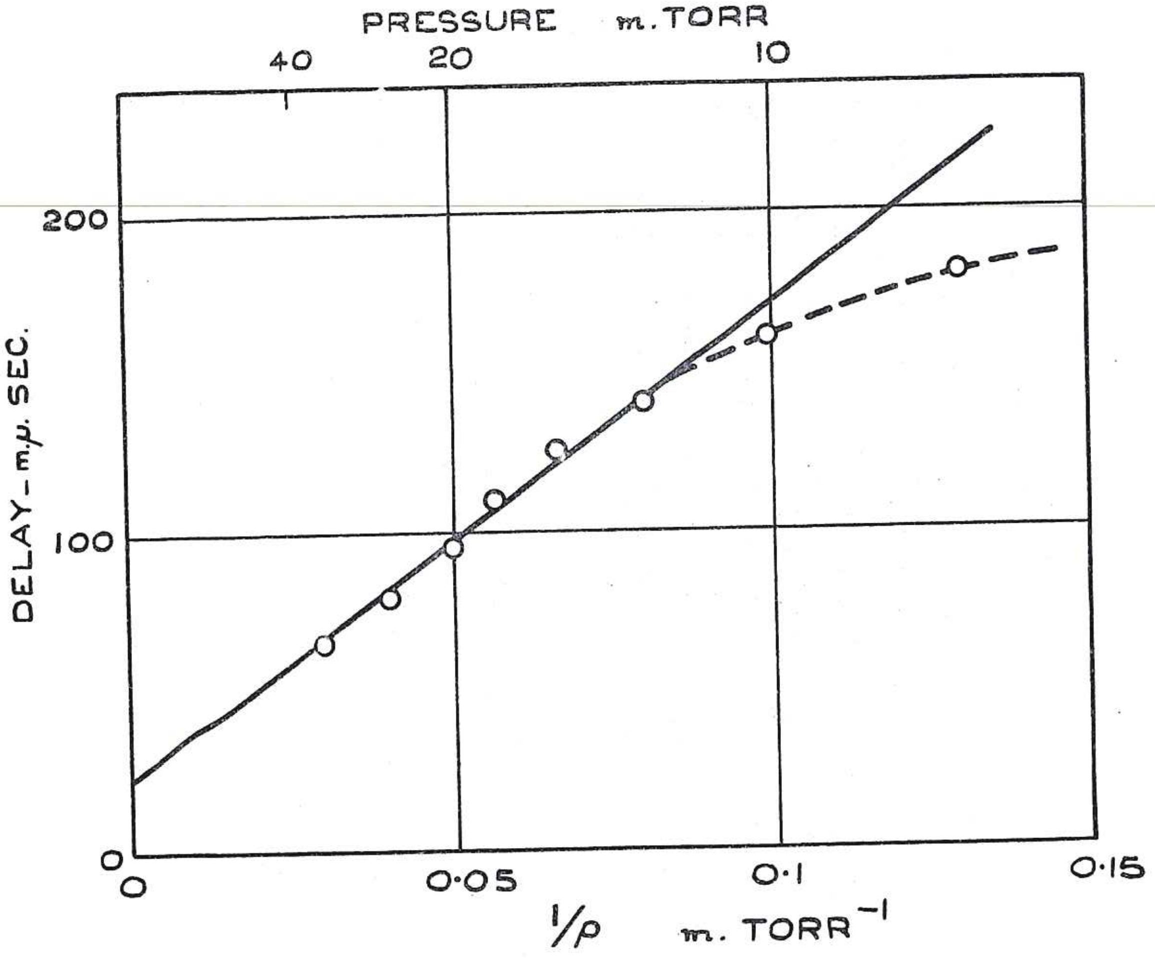
CLM-R14 FIG 3. SWITCHES USED IN THE PRESENT INVESTIGATION



CLM-R14 FIG. 4. WAVEFORM OF VOLTAGE COLLAPSE
(NITROGEN 4 kV.)



CLM–R14 FIG. 5. HIGH VOLTAGE SWITCH. NITROGEN. 4 kV.



CLM–R14 FIG. 17. PARALLEL ELECTRODE SWITCH. NITROGEN. 2·5kV.