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RAPID COMMUNICATION

Electrical breakdown time delay and breakdown propagation velocity in polypropylene under a highly non-uniform field condition

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Abstract. The electrical breakdown phenomenon in polypropylene for point-to-plane gap configuration has been investigated using a photo-optical current-measuring technique and a 760 ns rectangular high-voltage pulse generator. The waveform of prebreakdown current in polyethylene is essentially the same as that in liquid nitrogen. A linear relation to formative time delay and gap spacing is obtained for gap lengths greater than some critical value, indicating a constant propagation velocity in this region. The velocity is deduced to be 1.7 km s^{-1} for a positive point at 60 kV. This value is coincident with that of polyethylene, and close to that of a longitudinal wave in polypropylene at 193 K.

Polypropylene has been used as a film insulator in a capacitor. However, there is still no generally accepted breakdown theory for solid dielectrics, including polypropylene.

It is known that breakdown of solid dielectrics occurs with a substantial delay (of the order of ns to μs) after a voltage application. A small prebreakdown current of the order of mA flows during the delay period until total breakdown takes place with an abrupt current increase. Time to breakdown in solid dielectrics usually contains a statistical time delay and a formative delay [1]. The formative time delay is mainly associated with the time for a breakdown channel to propagate across the gap. Therefore the measurement of breakdown time lag, namely the time from voltage onset to total breakdown, is a method of analysing the breakdown process quantitatively.

The experimental set-up is shown in figure 1. It comprises three basic parts: a test cell, a fast high-voltage pulser and an electro-optic coupled current sensor. The test cell, fabricated from brass, has two windows and a polymer high-voltage bushing. A point-to-plane gap configuration was used for the test. The point electrode was a sewing needle with a tip radius of about 10 μm. The solid dielectric test sample was polypropylene of density 0.90 g cm^{-3} (Mitui Petrochemical Industries Ltd, Noblen). The sewing needle was inserted into the solid at 170 °C, followed by an annealing of the solid at 110 °C for 5 h. The sample was then cooled to room temperature at a rate of 1.25 K min^{-1} to reduce inner mechanical stress. The bottom surface of the specimen was painted with conducting paint to form a plane electrode. This plane electrode was set in contact with a flexible conductive filament connected to the ground through a resistor, thus avoiding the mechanical stress induced in the solid by rigid contact. Proper contact was ensured by direct inspection through the windows. The test sample was immersed in transformer oil to prevent flashover along its surface. Rectangular voltage pulses of 60 kV amplitude, 20 ns rise time and 760 ns duration were used. The line pulser and its connection diagram are shown in figure 1. The pulse generator and test cell system were enclosed in a shielded enclosure to confine internal electromagnetic interference. The polarity and amplitude of pulse were set up by the DC charging cable. A typical voltage pulse shape is shown in figure 2.

Prebreakdown currents were measured by means of a light-emitting diode (LED) put in series between the high-voltage pulse source and the point electrode. To exclude the noise current the LED was located in a metal guard having the same potential as the point electrode. The signal from the LED was carried to a photomultiplier through a fibre-optic light guide and

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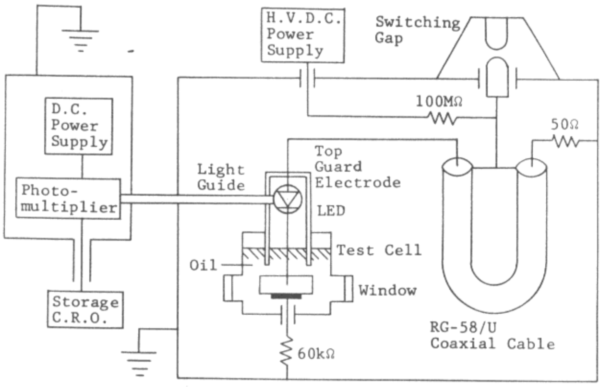

Figure 1. Current measurement system.

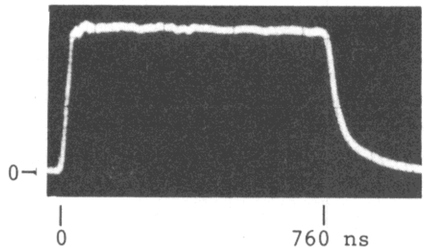

Figure 2. A typical applied voltage trace.

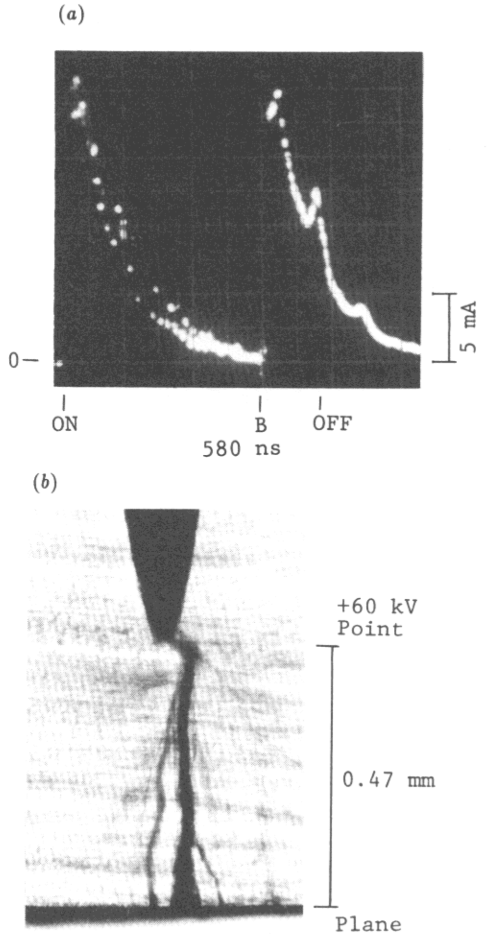

Figure 3. (*a*) Current trace in polypropylene for a +60 kV point voltage and (*b*) the corresponding breakdown channels.

transmitted to a storage oscilloscope. The LED was used without a protective bypass circuit to ensure a fast transient response of 10 ns. A 60 kΩ resistor was connected between the plane electrode and the ground to limit the gap current and to protect the LED. The smallest current detectable by this system was about 10 μA. The light amplitude from the LED was proportional to the current flowing into the point electrode up to about 12 mA. Each current measurement was carried out at room temperature with a fresh sample. After voltage application the sample was sliced to inspect the breakdown channel and to measure gap spacing using a microscope.

A typical current trace for a positive point and 60 kV application is shown in figure 3(*a*). The symbols ON, OFF and B show the points corresponding to the voltage onset, the onset of voltage reduction and the onset of total breakdown respectively. The current zero level is shown by the symbol O. The first large current pulse which occurs just after voltage onset is considered to be the combination of injection current and charging current. After the appearance of this initial pulse the prebreakdown current, which includes many pulses of high recurrence rate, flows until total breakdown takes place. The time from voltage onset to total breakdown was measured to be 580 ns in this case. The trace after point B does not correspond to the real current amplitude according to the space charge effect in the photomultiplier. Breakdown channels shown in figure 3(*b*) were formed by the breakdown event corresponding to the current trace shown in figure 3(*a*). The essential time behaviour of a negative current is similar to that of a positive one, but the gap spacing for total breakdown is less than 0.17 mm. The critical gap spacing is considerably smaller than that for a positive point (0.8 mm). The trace of figure 3(*b*) is similar to that of liquid nitrogen for both point polarities at a gap spacing of about 10 mm [2].

The time interval from voltage onset to total breakdown can be measured from each current trace. The errors in the measured values of the time interval are estimated to be ±10 ns. The dependence of this time interval on gap spacing for 60 kV with positive and negative points is shown in figures 4 and 5 respectively. Each plot in these figures shows a measured value, and the plots of infinite delay time show the case where no total breakdown took place, or only a tree of partial breakdown was observed. It is also shown that considerable statistical breakdown time lag is included in the total delay for most breakdowns. However, it can be expected that the shortest time lag for each gap spacing would show delay without a statistical part, that is formative time lag. Figure 4 shows that six plots indicating the shortest delays for each corresponding gap spacing are on or near a straight line: five of these six points for gap spacing larger than 0.4 mm deviate from the gap axis. A very similar characteristic was found for polyethylene [3] for both polarities and polymethylmethacrylate [4] for positive polarity, at about 50 kV point voltage. This linearity, in relation to time lag and gap spacing, has also been observed for several liquid dielectrics in both point polarities, except for the fact that no statistical delay has been observed

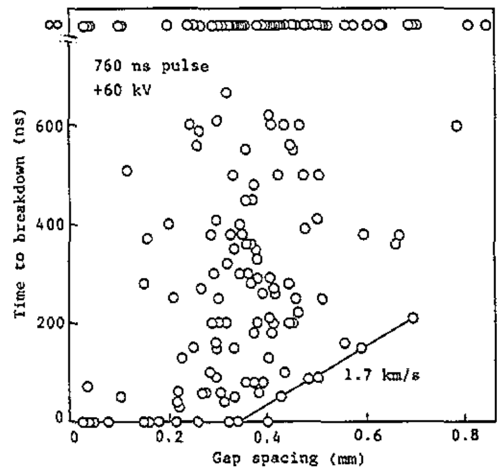

Figure 4. Dependence of time to total breakdown on gap spacing at a fixed voltage of +60 kV.

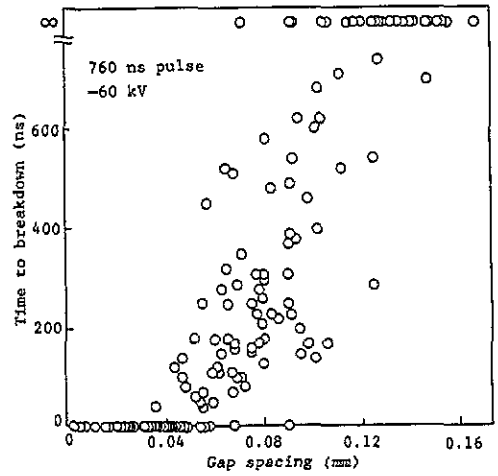

Figure 5. Dependence of time to total breakdown on gap spacing at fixed voltage of −60 kV.

for liquid dielectrics using a similar experimental set-up [5].

In the case of liquid breakdown the streamer propagation velocity obtained from the linear relation agrees with that measured using an image converter camera [6]. Consequently, the slope of the straight line in figure 4 is expected to give a propagation velocity for the breakdown channel in the solid. When the gap spacing was less than 0.4 mm (in figure 4) a time lag of less than 20 ns was sometimes observed. This remarkably short delay suggests that a conductive region was suddenly produced throughout the whole gap shortly after voltage onset. It was supposed that there would be two different channel propagation regions divided at a distance of 0.4 mm away from the plane electrode, and that the breakdown channels relating to those five plots in figure 4 would change their propagation velocity at this critical point. Hebner and Kelley [7] have also reported that a primary streamer in several liquids changes its slow velocity discretely into a secondary fast one during propagation. A similar characteristic has been reported for 50 cSt silicone oil with a positive point [5] and liquid nitrogen [2]. Considering the results obtained from this study and from other solid and liquid breakdown studies, it seems that breakdown channels, as regards those five plots in figure 4, develop with a constant velocity in a propagation region from the point electrode to the plane electrode. The propagation velocity of the breakdown channel is deduced from the slope of the straight line, which yields 1.7 km s^{-1}. It must be noted here that the value is a velocity along the axis of the point electrode. The value is equal to that of longitudinal waves in polypropylene at 193 K [8]. The order of velocity values obtained in this study agrees with those obtained for liquid dielectrics [5, 6]. The propagation velocity, for plots near the gap axis, is estimated to be of the order of 10 km s^{-1} for both polarities. Figure 5 indicates that a negative time delay is more sensitive to gap spacing than a positive one: no breakdown is seen at a gap spacing of greater than 0.17 mm, and total breakdown sometimes takes place at gap spacings in the range 0.07–0.17 mm.

From these results the basic mechanism of ns breakdown in polypropylene may be supposed to be the same as that in polyethylene and polymethylmethacrylate and to be similar to that in liquid dielectrics, for both polarities. The constancy of the propagation velocity of the breakdown channel in condensed dielectrics would suggest that a wave-like propagation mechanism originating from the structure of the matter may be responsible for the development of the breakdown channel. This idea is supported by the study of Cooke *et al* [9] in which a mechanical shock was employed as a trigger for the discharge in polymethylmethacrylate.

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