OBSERVATIONS OF PARTIAL DISCHARGES IN HEXANE UNDER HIGH MAGNIFICATION

K. L. Stricklett,[†] E. F. Kelley,[†] H. Yamashita,[†] C. Fenimore,[†] M. O. Pace,[‡] T. V. Blalock,[‡] A. L. Wintenberg[‡] and I. Alexeff[‡]

[†]National Institute of Standards and Technology
Gaithersburg, MD 20899 (USA)
[‡]Department of Electrical and Computer Engineering
The University of Tennessee
Knoxville, TN 37996-2100 (USA)

ABSTRACT

Partial discharges are observed in hexane by shadow photography under the application of dc voltages. A non-uniform field geometry is employed and the growth of cavities associated with partial discharges at a point cathode are photographed at 200× magnification. The use of an image-preserving optical delay allows a record of the conditions which exist in the liquid prior to the initiation of the low-density streamer to be obtained. A concurrent record of the partial discharge current is obtained. Analysis of these data indicate that electrostatic forces are adequate to drive streamer growth.

INTRODUCTION

Electric breakdown of liquid dielectrics is preceded by the growth of a low-density streamer in the liquid. Thus, accurate description of the conditions which influence the initiation and propagation of streamers in the liquid is central to the evaluation of the electrical properties of liquid insulants. The initiation of electrical discharges in liquids has received a great deal of attention. However, despite this activity no clear consensus has been reached as to the mechanism for the initiation of the discharge. Proposals put forward have included: electron avalanche [1], cavitation [2], and electrostatic forces acting on the dielectric [3].

In liquid hydrocarbons, the form and propagation speed of cathode streamers at inception differ dramatically from those in their latter stages [4]. A plausible description for this initial stage of growth has been presented by Watson and Chadband [5], who show that the growth of the streamer is consistent with the propagation of a cavity within the liquid. Similar results are reported for partial discharges: photographic and optical studies [1, 6] have established a clear correspondence between the growth of a cavity in the liquid and bursts of charge emitted from a point cathode. In the present study, the conditions that exist near the threshold for partial discharge activity are examined. For this, a record of the current waveform and frame photographs of the growth of a cavity at a point cathode are obtained concurrently. Such data allow detailed description of the temporal and spatial development of the low-density region and provide a basis for the evaluation of models for the initiation of cathode streamers.

EXPERIMENTAL APPARATUS

The experimental apparatus is shown schematically in Fig. 1. The test gap consists of

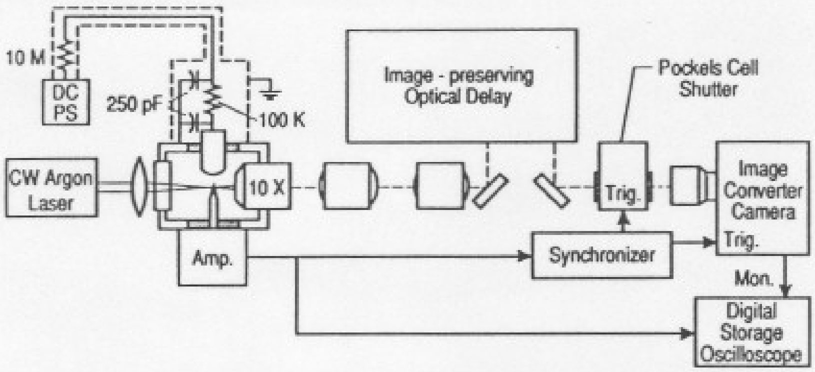


Figure 1. Experimental apparatus. The electrodes and the placement of the microscope objective are drawn to scale.

a steel needle and stainless steel rod separated by 3.2 mm. The rod electrode is 6.4 mm in diameter and has a 3.2 mm end radius. The radius of the needle tip is 1 μm, and the apex angle is approximately 30°. The electrodes are enclosed within a brass cell and are immersed in the test liquid.

High-resolution images of the needle are obtained by mounting a microscope objective within the cell. This configuration provides 200× magnification and an optical resolution of less than 2μm. A continuous wave argon laser is used to illuminate the needle tip, and frame photographs are obtained by use of an image-converter camera. The image-preserving optical delay [6, 7], noted in the figure, offsets the camera trigger delay and thus allows the framing sequence to begin much closer to, and for some frame intervals before, the current waveform.

A broadband transimpedance amplifier is connected directly to the needle electrode and the current waveform is recorded on a digital oscilloscope. The amplifier has a bandwidth of 70 MHz, an equivalent noise of 30 nA rms, and an estimated charge sensitivity of less than 1 fC. The amplifier gain is 10^4 V/A. The rod electrode is connected to a high-voltage dc power supply. A 10 MΩ series resistor is provided to limit the current in the event of a breakdown. The filter circuit shown in the figure is provided to reduce pickup of power supply noise.

PARTIAL DISCHARGE RECORDS

An example of a partial discharge is shown in Fig. 2. The current waveform and the integrated current are plotted in the upper panels and the associated photograph is shown below. An applied potential of 15.5 kV is used, and the frame interval and exposure times are 512 and 102 ns respectively. The frame sequence is indicated in the photograph, and the frame exposures, determined from the camera monitor pulse and an accurate measurement of the frame interval, are shown together with the current waveform. The interference rings in the photographs are due to the coherence of the laser light and may be disregarded.

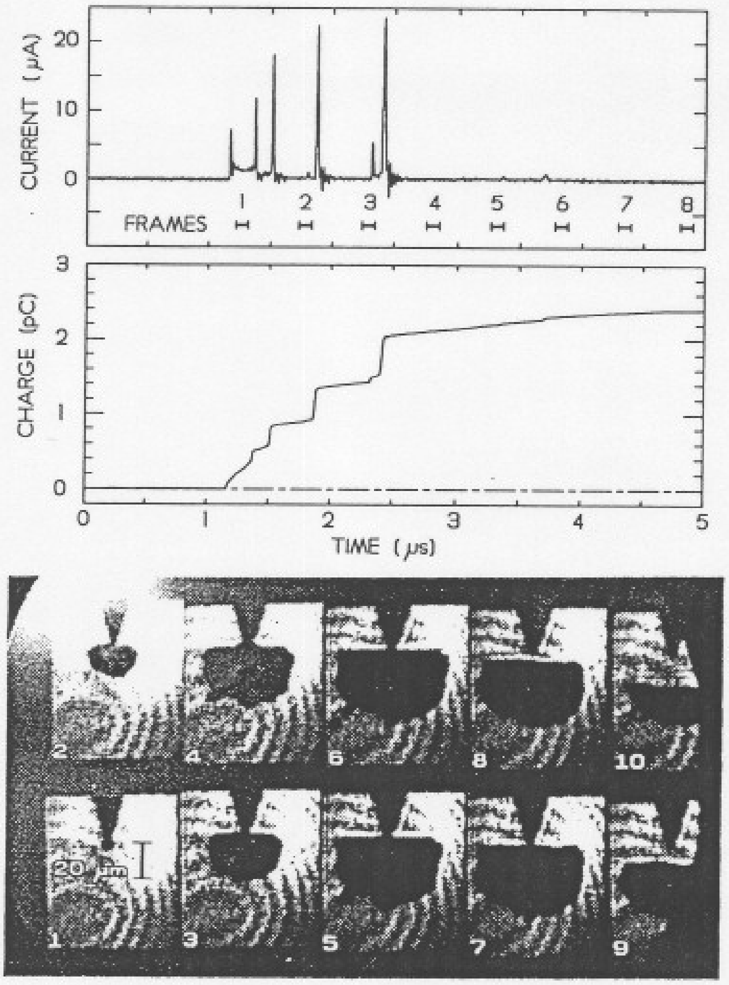


Figure 2. Partial discharge record. The current waveform and the integrated charge are shown in the upper two panels. Frame photographs of the point cathode are shown below. These data are obtained for an applied potential of 15.5 kV. The frame interval and exposure times are 512 and 102 ns respectively. The frame sequence is indicated in the photograph.

The dynamical behavior of these structures is particularly intriguing. During its lifetime, the low-density region first grows in size, then detaches from the needle, and finally breaks apart and collapses, moving away from the tip as it collapses. Although a great deal of variability is observed in the detailed growth, common patterns are observed. The structure appears to be approximately spherical at inception and may grow by stable expansion, as is shown in Fig. 2, or by the growth in amplitude of instabilities in the cavity wall. Upon close examination, evidence for the onset of unstable growth may be seen in Fig. 2. Stable expansion is less likely at higher applied voltages and a preference for growth along the axis of symmetry is noted for unstable expansion.

The current waveform is relevant to describing the conditions at the initiation of the partial discharge. In over 90% of the current waveforms, clear evidence of a continuous current occurs between the the first two pulses; the current waveform shown in Fig. 2 is representative of this behavior. Furthermore, whereas the later current pulses tend to grow monotonically in amplitude, the first two pulses are frequently of comparable amplitude. Indeed, partial discharges are observed which consist of only a double-pulse structure. Single current pulses are also detected; however, no evidence of cavity growth could be seen in the associated photographs.

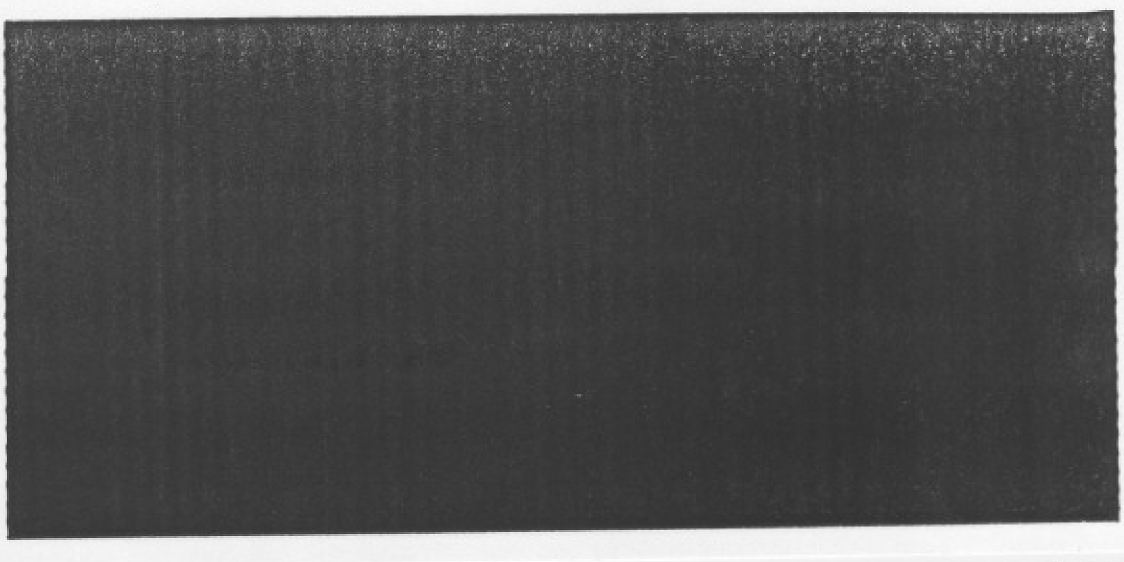
A second example of partial discharge is given in Fig. 3. These data are obtained at an applied potential of 17.5 kV and the frame interval and exposure times are 51 and 10 ns respectively. Note that the first few frames precede the initiation of the current waveform. The data at hand allow an estimate of the time between the initial current pulse and the growth of the low-density region. As shown, the current waveform begins 51 ± 5 ns before the midpoint of the sixth frame, the first frame in which clear evidence of the cavity appears. The estimated uncertainty in the position of frame six is ± 8 ns, thus an upper bound of 51 ± 9 ns is established. However, the extent of the cavity in the sixth frame suggests that the delay is likely to be significantly less. In the upper panel, the length of the cavity is plotted against the frame number and fit to a linear function. Such a fit provides an estimate for the origin of the cavity which is nearly coincident with the initiation of the current waveform. However, in the absence of a determination of the instantaneous rate of expansion of the cavity we are reluctant to apply this correction.

The linear fit also provides an estimate of the average rate of expansion of the cavity. Furthermore, since the rate of expansion depends on the forces acting on the liquid, an estimate of the effective pressure within the cavity, P_{in}, may be obtained. Assuming inviscid incompressible flow, and approximating the cavity by an expanding sphere of radius r, the instantaneous work done in expanding the cavity

$$P_{in}\,dv = P_{amb}\,dv + \frac{2S}{r}\,dv + \frac{3}{2}\rho\dot{r}^2\,dv.$$

The terms include: the work done against ambient pressure, P_{amb}, and surface tension, S; and the kinetic energy imparted to the surrounding liquid. The average rate of expansion of the cavity, $\dot{r}$, is ≈ 70 m/s and the density of hexane, ρ, is approximately 0.66 g/cm^3. At standard conditions the surface tension of hexane is 1.8 N/m. For the conditions described, the kinetic energy is the largest term and P_{in} is approximately 5 MPa.

The required pressure may be provided by local heating of the liquid, as may occur during electron avalanche, and by electrostatic forces. The form of the cavity, however,



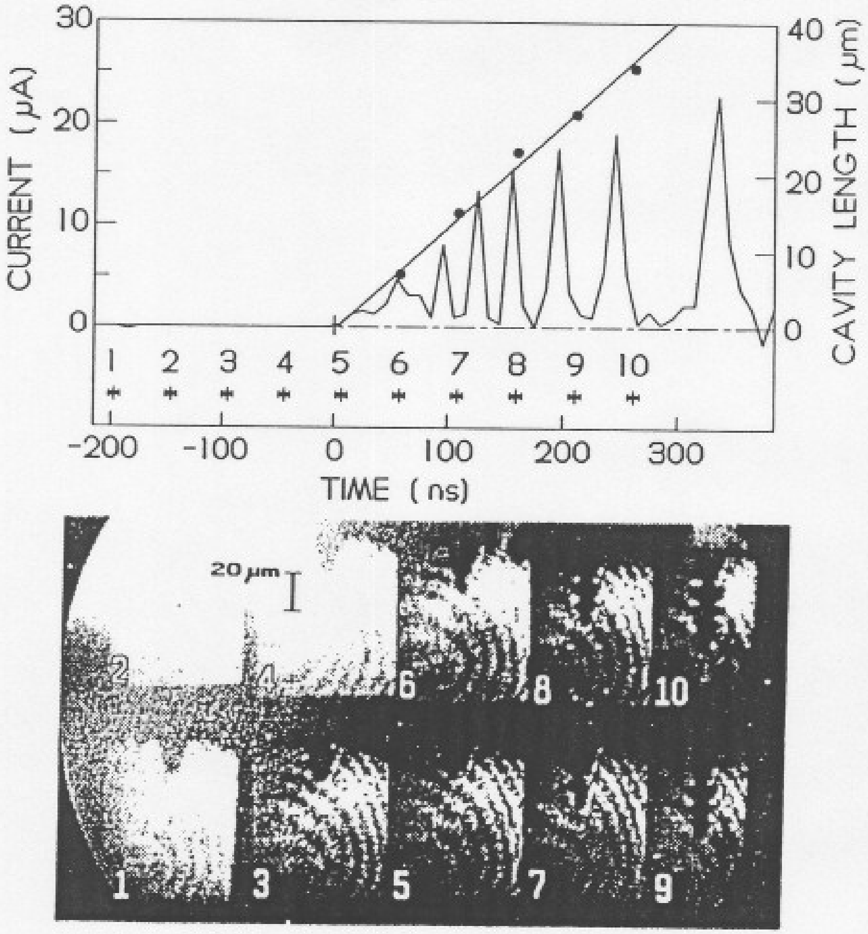


Figure 3. Partial discharge record obtained at 17.5 kV. The frame interval and exposure are 51 and 10 ns respectively. The current waveform and the extent of the cavity are plotted in the upper panel.

suggests that the forces acting on the liquid are highly directional, and thus that the gas dynamic pressure is of limited importance. This observation is supported by an estimate of the energy density at the needle tip, $\epsilon E^2/2$. The electric field at the tip may be approximated by $E = V/5R$ [9], where R is the radius of tip and V is the applied voltage. Using $\epsilon = 2\epsilon_o$ and $V = 15\,\mathrm{kV}$, an energy density of 80 MPa is obtained, which is well in excess of that required to drive the cavity wall at the observed rate. These observations lend support to the results reported by Watson and Chadband [5] and suggest that near threshold the growth of the cavity may be completely described by the electrostatic forces acting on the liquid.

CONCLUSIONS

Highly resolved photographs of the initiation of partial discharges in liquid hexane are obtained. The cavity growth at a point cathode is nonisotropic, which suggests that electrostatic forces are of primary importance in driving its expansion. The onset of instabilities in the cavity wall is suggested. The initial partial discharge current pulse precedes or is concurrent to the growth of the cavity. An upper bound of 60 ns between first current pulse and the growth of the cavity is obtained.

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