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TECHNICAL REPORT

EXPERIMENTAL STUDIES OF UNDERWATER SPARKS

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ABSTRACT

Experimental information is presented concerning a transient high-current discharge through water. Kerr Cell photographic apparatus has been used to study the formation and growth of the spark channel. Under these transient conditions, the current density and gas temperature are unusually high and produce very strong light intensities and transient pressures. For certain experimental situations the spark channel does not form until several milliseconds after the impulse potential is applied to the electrodes, and during this interval symmetrical ball-like structures grow around each electrode. Although a satisfactory explanation of these balls has not yet been obtained, an experimental study of their behavior under varying conditions is reported. Some progress has been made toward determining the size of the current-carrying channel.

EXPERIMENTAL STUDIES OF UNDERWATER SPARKS

I - INTRODUCTION

An investigation of transient high-current discharges resulting from the application of an impulse potential to under-liquid electrodes is being conducted as a University of Michigan Research Project sponsored by the Office of Ordnance Research. The work is administered through the Engineering Research Institute of the University and utilizes the facilities of the Department of Electrical Engineering.

This research is concerned with the effects produced by a capacitor discharge through a liquid medium where 200 to 1,000 watt-seconds of stored energy are employed at potentials of 4,000 to 10,000 volts. The liquid used for most experiments has been Ann Arbor City water which has a volume resistivity of approximately 5,000 ohms per centimeter cube. Under-liquid sparks are affected by so many variables that an extensive program would be necessary in order to survey all of the phenomena involved. Therefore, many of the experimental parameters so far have been held relatively constant. Most of the tests have used 12 μfd of capacitance and the sparks have taken place across a one-half inch gap between 0.030 inch molybdenum wire electrodes.

To date, the research has been concerned primarily with problems of instrumentation and the collection of experimental data. This report presents some of the more significant facts that have been obtained. Although important progress has been made in the interpretation of this data, further information is necessary for a satisfactory explanation of much of the observed phenomena. A more complete interpretation than is now possible will be presented in Summary Report #1 on the present contract which will be published in October, 1953.

II - GROSS CHARACTERISTICS OF UNDERWATER SPARKS

When an impulse potential is applied to a set of underwater electrodes, a chain of events results which displays some unusual features. The breakdown of water occurs as a pronounced two-stage process. The simple electrical circuit used for this study is shown in Fig. 1. Fig. 2 illustrates typical voltage and current wave shapes and depicts these two stages which can be designated conveniently as:

1. The Formative Phase

This stage is the interval between the application of the impulse voltage to the electrodes and the instant that a gaseous conducting channel is established between them. It is initiated when the manually operated switch in Fig. 1 has been closed far enough so that a spark jumps between the switch con-

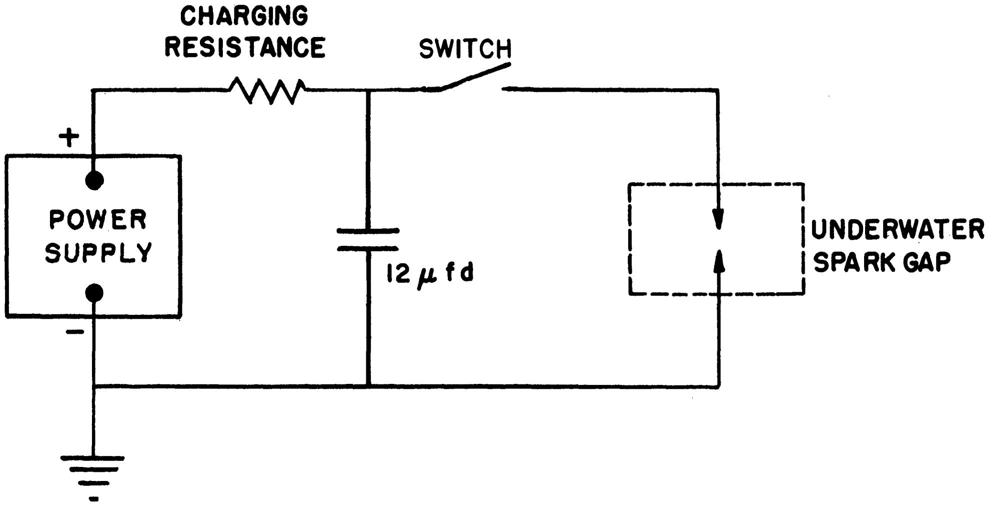

FIG. 1

CIRCUIT FOR PRODUCING UNDERWATER SPARKS

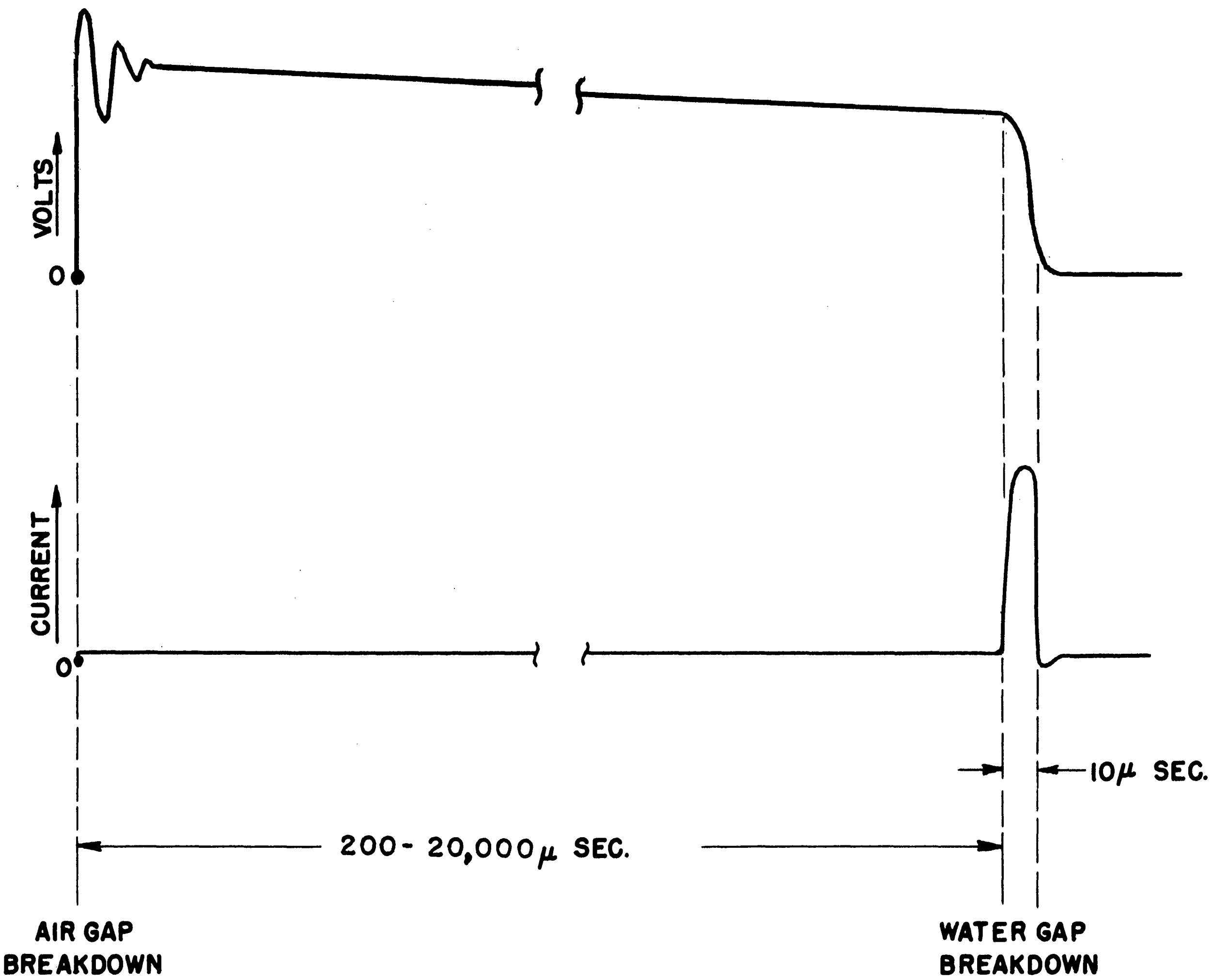

FIG. 2

SCILLOSCOPE WAVEFORMS OF TRANSIENT VOLTAGE & CURRENT OF UNDERWATER SPARK tacts. This is indicated in Fig. 2 as "air-gap breakdown."

2. The High-Current Gaseous Conduction Phase

This stage starts at the instant that a gaseous conducting channel is formed, and ends when the stored energy has been dissipated. It is designated in Fig. 2 as "water-gap breakdown."

The formative phase may be a few hundred to several thousand microseconds in duration. Its characteristics are strongly influenced by the applied voltage, the water conductivity, and electrode spacing and geometry. During this interval the voltage across the electrodes is essentially constant except for a few initial transient oscillations, and the current is limited to about an ampere. Very little light, and no mechanical disturbances are produced during this phase.

Once a gaseous channel is established between the electrodes, the current rises to a high value and the discharge is completed in about ten additional microseconds. The peak currents are of the order of 20,000 amperes. An underwater spark results in an intense flash of light and is accompanied by a loud "hammer-impact" noise and an explosive disturbance in the water.

III - APPARATUS AND METHODS OF MEASUREMENT

The circuitry for producing underwater sparks is completely enclosed in a grounded metal cabinet in order to protect personnel from the high voltages, and to shield measuring equipment from the high energy electrical transients. The inductance of the discharge circuit is kept to a minimum by using flat copper straps and by placing components as physically close together as possible. The sparks are produced approximately at the center of a steel tank holding twelve gallons of water. The tank is fitted with a cover to confine the vigorous splashing produced by the discharge. Photographs of the sparks are taken through a three inch diameter plexiglass window located in one side of the tank.

The energy storage capacitor used for most of the present tests consists of two General Electric type E80398 Pyranol 25 μfd 6,000 volt capacitors connected in series. Because of the rapid rate of discharge, it was necessary to determine the manner in which these capacitors departed from idealized behavior. The impedance versus frequency characteristics of these units was measured over an appropriate frequency range. If the approximate equivalent circuit for transient conditions or for high frequencies is assumed to be a series circuit of "pure" capacitance, inductance, and resistance at the capacitor terminals, this measurement indicated an internal inductance of 0.22 μh and an internal resistance of 0.081 ohms.

Fig. 3 is a photograph of the electrodes which are used for the study of underwater sparks. The white material is a Teflon rod. A 0.030 inch diameter molybdenum wire projects from each rod forming the active electrode area. The scale in the picture is a machinist's rule numbered in tenths of inches. It is necessary to keep the area of the metal exposed to the water as small as possible, otherwise the capacitors will discharge through the water by electrolytic conduction without forming a gaseous conduction channel. This type of electrode construction is necessary in order to withstand the severe mechanical shock and erosion resulting from the spark, and still give consistent and reproducible results.

Measurements of the transient voltages and currents in the discharge circuit are made with a Tecktronix type 513-D oscilloscope and suitable voltage dividers and shunts. In order to observe the extremely large currents, a special "current-viewing resistor" was developed which has a resistance of 0.018 ohms and an inductance of less than 10^{-11} henry. The resistance element of this shunt consists of a thin Chromel ribbon which is folded back on itself and clamped between copper blocks in order to minimize the inductance. Careful shielding and attention to the physical orientation of components and grounds is necessary in order to eliminate extraneous inductive pickup and "ringing" in the oscilloscope signal leads.

A photographic study of underwater sparks has provided thus far the most satisfactory method for securing experimental data. A Kerr Cell electro-optical shutter is used to obtain extremely short exposure times. Fig. 4 is a photograph of the camera which was

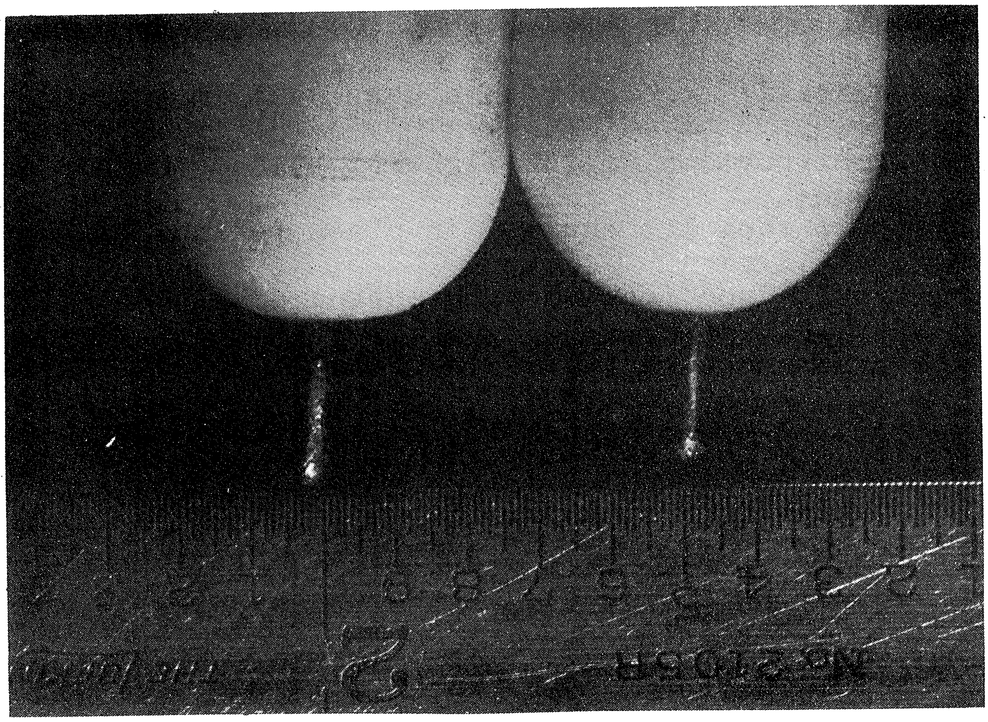

Fig. 3

Underwater spark electrodes - Molybdenum wire in Teflon insulation

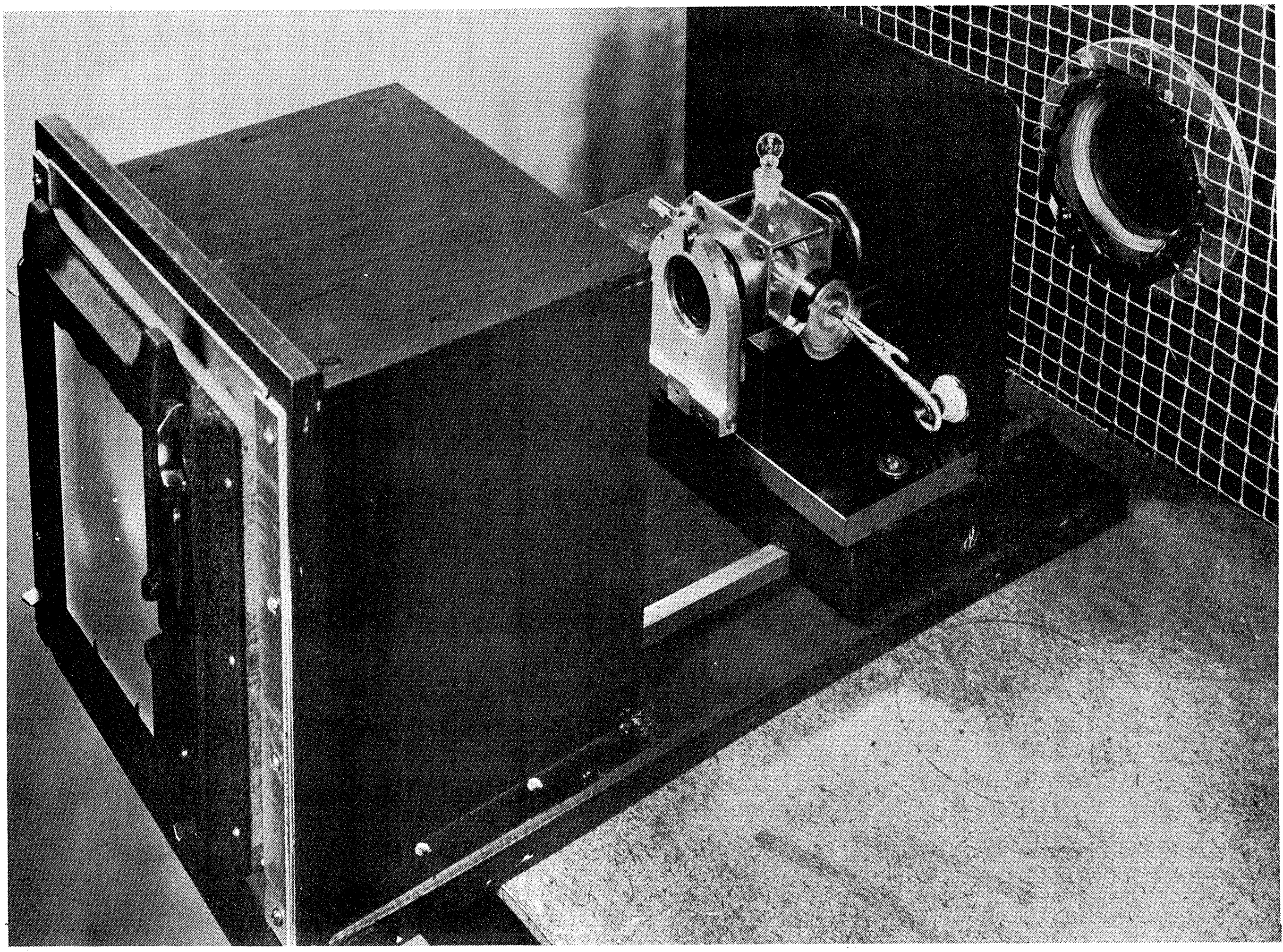

Fig. 4

Camera for Kerr Cell photography

designed specifically for use with a Kerr Cell shutter. In this figure, the front portion of the light-tight housing has been removed in order to show the shutter in place behind the camera lens. A high-quality six inch focal length photographic lens is used, and pictures are made on four by five inch cut film. The Kerr Cell and polaroids comprising the shutter can be removed in order to take conventional photographs of much longer exposure time.

The Kerr Cell constructed for this research was based upon information derived from several references.[1,2] The design of the camera is based upon an analysis of Kerr Cell optics which was made in order to determine the optimum conditions which can be obtained with a given cell (see Progress Report #3).

An artificial line, or pulse-forming network, and a hydrogen thyratron "switch" are used to obtain the 8,000 volt pulse necessary for operating the electro-optical shutter. The duration of this pulse, and thus the exposure time, are determined by the network employed. The present pulse length (and exposure) are about 1.2 microseconds. Pictures are taken of the desired interval, during the approximately ten microsecond duration of the discharge, by triggering the hydrogen thyratron at the proper time. This is accomplished by using the "delayed trigger" output from the Tecktronix oscilloscope and a trigger amplifier employing a type 2D21 thyratron.

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1. A. M. Zarem, F. R. Marshall, and F. L. Poole, "An Electro-optical Shutter for Photography," Electrical Engineering, 68, 282, (1949).
2. A. M. Zarem and F. R. Marshall, "A Multiple Kerr Cell Camera," Rev. of Scientific Instruments, 21, 514 (1950).

IV - GROWTH AND DECAY OF THE DISCHARGE CHANNEL

Fig. 5, 6, 7, and 8 are a sequence of Kerr Cell photographs which illustrate the growth and decay of the discharge channel. The electrodes are the same as shown in Fig. 3. Each figure is a photograph of a separate discharge for which the experimental conditions were as nearly identical as possible. The pictures were taken with a 1.2 microsecond exposure time and show the discharge at progressively later stages of its twelve microsecond duration. The delay time given in each figure is the number of microseconds between the initiation of the gaseous conduction phase and the time at which the Kerr Cell shutter was opened; i.e., it is the delay between the time that the oscilloscope sweep was triggered and the time that the "delayed trigger" fired the hydrogen thyratron pulser. The ball-like structures surrounding each electrode occur under certain conditions which will be discussed in the next section. The white line passing vertically through the discharge region in Fig. 6,7, and 8 is a fine thread which was used in an experiment to determine the velocity of the pressure wave adjacent to the channel. This experiment will be discussed in Section IX. The only light used for making these pictures was the light coming from the discharge itself.

One of the original objectives of the Kerr Cell photographic study was to gather experimental information about the cross-sectional size of the discharge column, and thus to determine the

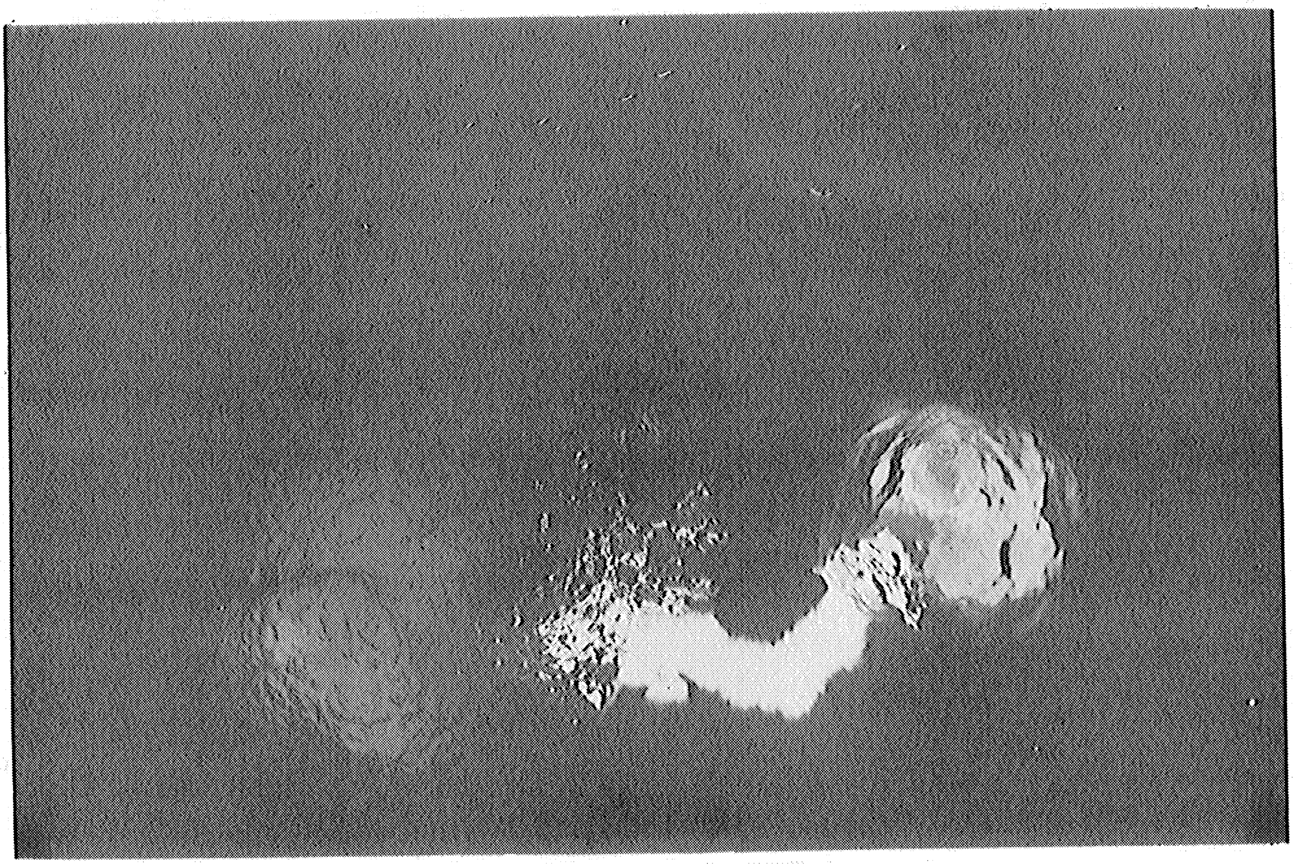


Fig. 5
Kerr Cell picture - 1 μ sec delay; Impulse potential - 6 kv

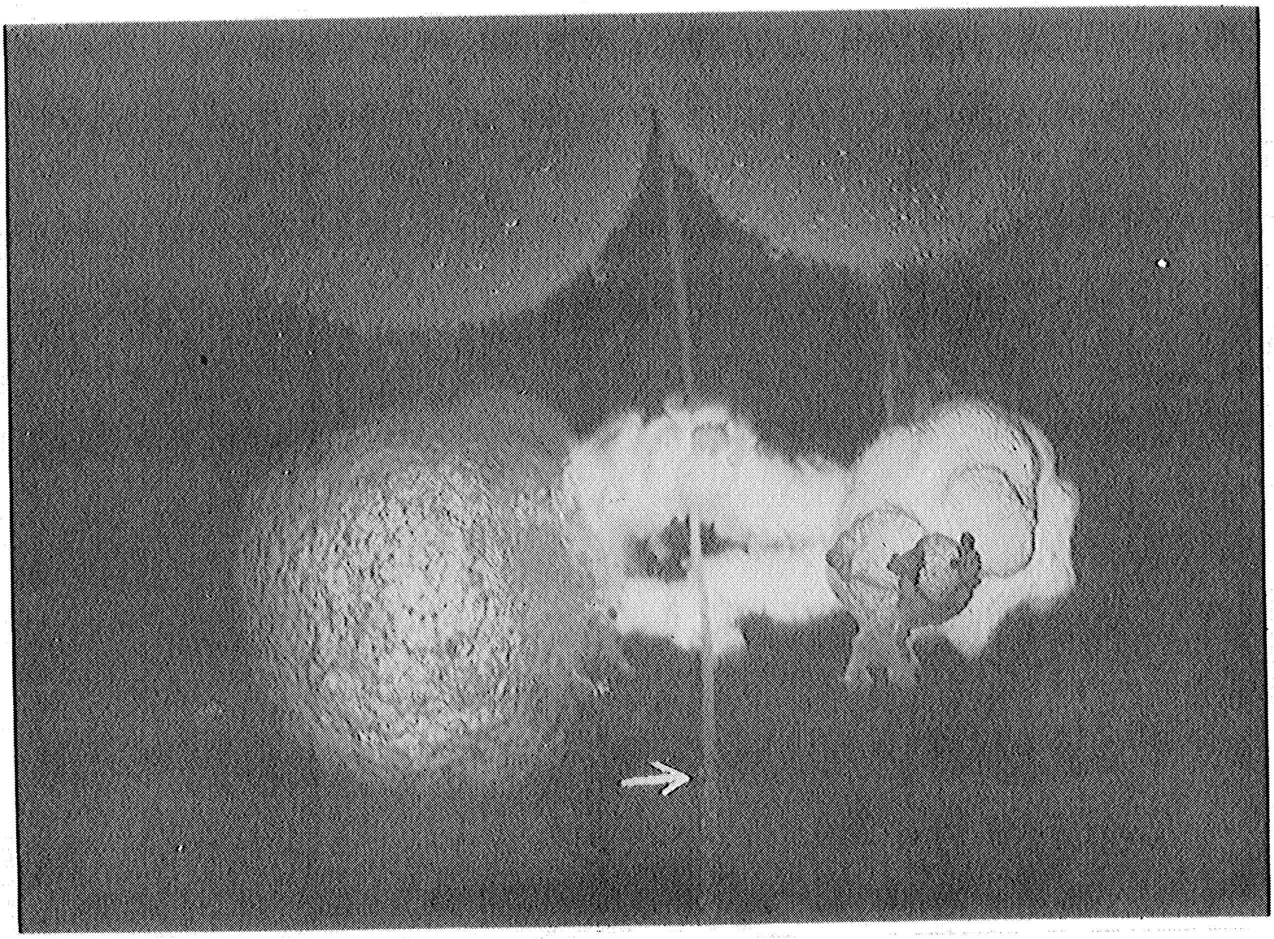


Fig. 6
Kerr Cell picture - 3 μ sec. delay; Impulse potential - 6 kv

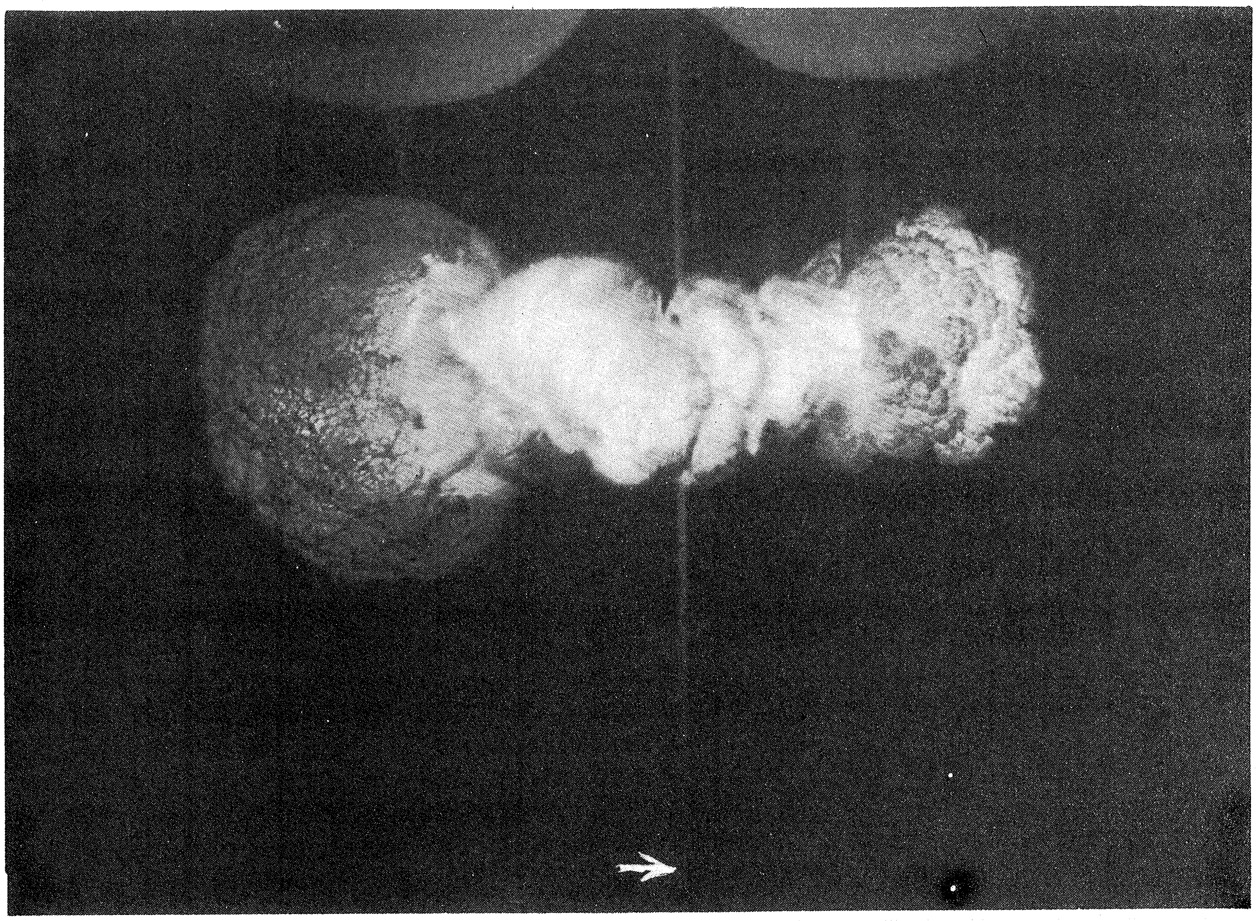


Fig. 7
Kerr Cell picture - 6 μ sec. delay; Impulse potential - 6 kv

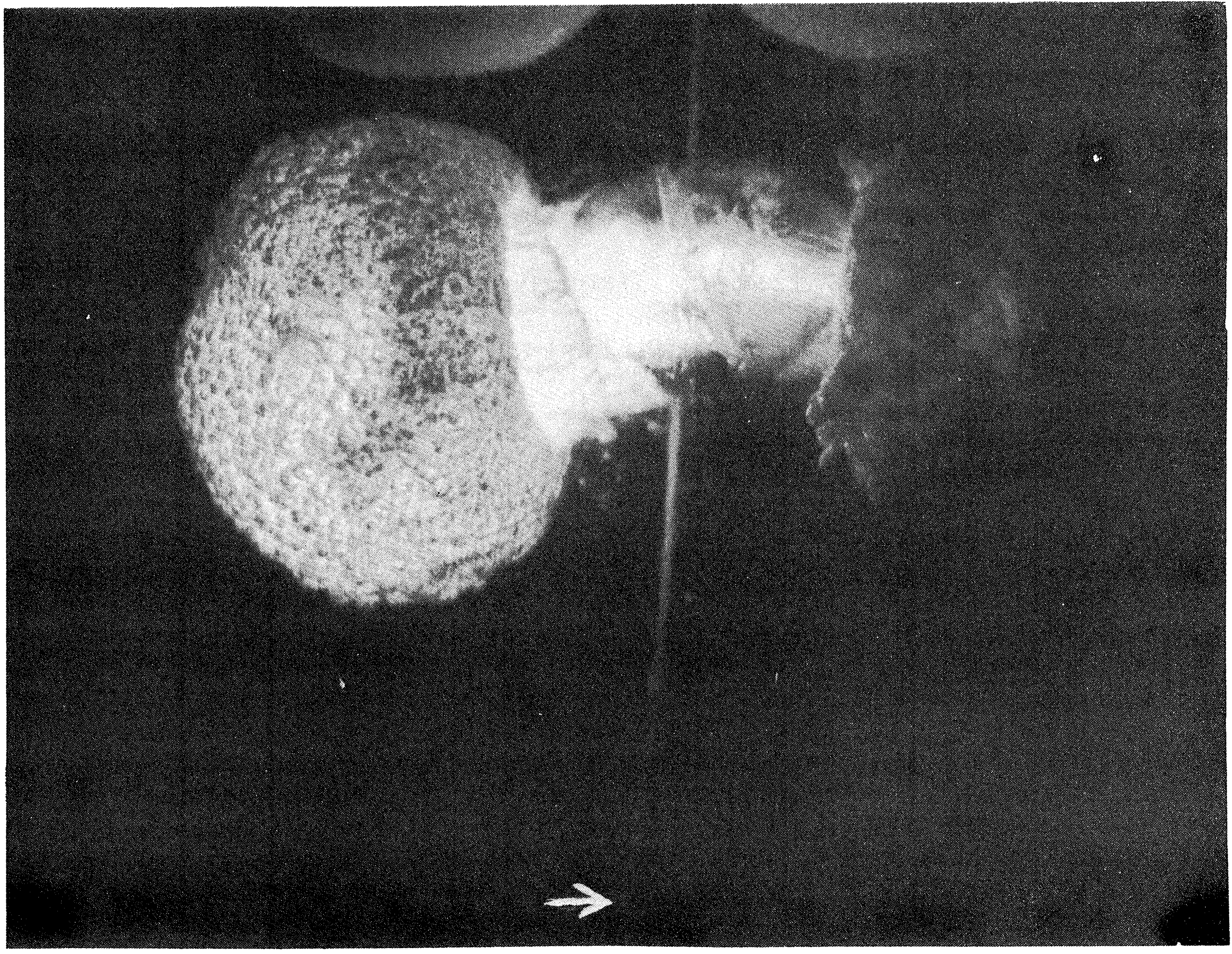


Fig. 8
Kerr Cell picture - 12 μ sec. delay; Impulse potential - 6 kv

current density in the channel. For all photographs taken so far, no clearly defined channel can be seen. Instead, the discharge appears as a billowy structure, something like a column of smoke. The billowy column grows in size and luminosity up to the time of maximum current which occurs about six microseconds after the initiation of the gaseous conducting phase (Fig. 7). From this time on, the column expands more slowly and the luminosity decreases and shrinks back toward the center. Fig. 8 is a photograph taken with a twelve microsecond delay, at which time the current had dropped to about 1/10 of its peak value, and only the central part of the column appears luminous. A picture taken two microseconds later was too dim to make a usable enlargement.

For the values of stored energy, voltage, electrode spacing, etc. used in these tests, the discharge is approximately critically damped. As the voltage is increased, the discharge becomes more oscillatory. However, in order to prevent damaging the energy storage capacitors, oscillatory discharges have been avoided. Consequently, the tests with a one-half inch electrode spacing involve a relatively limited range of voltages.

V - EXPERIMENTAL FACTS ASSOCIATED WITH THE BALL-LIKE STRUCTURES

The prominent ball-like structures surrounding the electrodes in Fig. 5, 6, 7, and 8 are an interesting feature which apparently has not been reported in the literature. They are present in many of the Kerr Cell photographs and in some of the "total exposure" pictures taken previously (see Progress Report #2). One of the objectives of the research program has been to gather experimental facts pertaining to these spherical regions and to find a satisfactory explanation of their behavior. A theoretical explanation is still in the process of being clarified and correlated with the large body of facts, and will be included in the Summary Report to be published in October.

The spherical regions at the electrodes are always associated with a long duration formative period. When the pre-breakdown time is two to three milliseconds or longer the balls are present, but when the conditions are such that the formative period is less than two milliseconds the balls do not appear.

There is not always a sharp distinction between the long-duration formative periods which give rise to the balls, and the shorter duration phase for which there are no balls. This trend is demonstrated by Fig. 9 which is a Kerr Cell photograph taken under the same conditions as Fig. 5, 6, 7 and 8 except that the impulse potential was 9 kv instead of 6 kv. The size of the ball-like formations

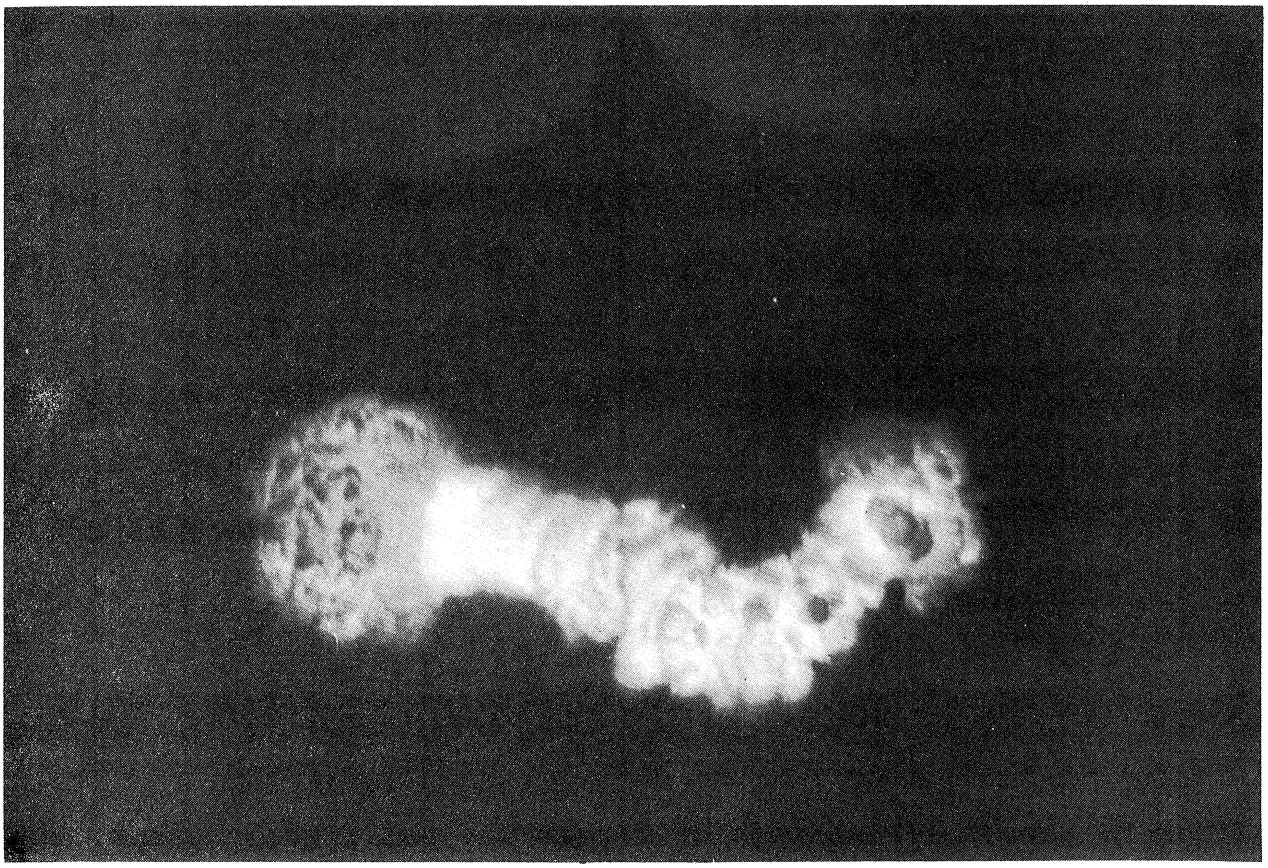


Fig. 9

Kerr Cell picture - 1 μ sec. delay; Impulse potential - 9 kv in Fig. 9 is much smaller than the size of those in Fig. 5, 6, 7, and 8. As will be discussed in the next sub-section, a higher impulse potential results in a shorter formative time lag. This indicates that ball size depends upon the length of the pre-breakdown period, and that possibly, for a sufficiently short formative time, the balls do not grow to an observable size before the gaseous conduction stage is initiated.

The size of the spherical structures in Fig. 5, 6, 7, and 8 remains essentially the same in all of the pictures and thus does not change much during the twelve microsecond interval of the gaseous conduction phase. The differences in the brightness of the balls is probably due to changes in the internal illumination. Slight variations in their size between the succeeding pictures is to be expected since each figure is a photograph of a different discharge. The general features shown in these pictures are surprisingly consistent and reproducible when the experimental conditions are held reasonably constant.

Another characteristic of the balls, which is probably related to the mechanisms of the formative stage, is their difference in relative size and appearance. In Fig. 5, 6, 7 and 8 the ball on the left is always larger and has a rougher surface, something like the skin of an orange. The left-hand electrode for all of these pictures is the anode of the discharge. When the polarity is reversed, the appearance of the spheres is also reversed; the larger ball always being associated with the anode, and not due to any dis-symmetry which may exist between the discharge circuit and the steel water tank.

The closely spherical shape of the balls is a feature which is very difficult to explain. The overall electric field adjacent to each of the electrodes is far from symmetrical, and any situation which would give rise to symmetrical fields surrounding the electrodes, or cause the balls to grow contrary to the existing fields, cannot readily be postulated. These effects are probably the result of electrolytic conduction phenomena which occur during the pre-breakdown stage. Since the production of the balls appears to be only one of the complex mechanisms present during the formative phase, an explanation of their behavior requires further knowledge as to the whole formative process and, in particular, the phenomena present during the long formative periods.

Factors Influencing the Formative Phase

The formative stage of an underwater spark appears to be quite sensitive to a number of environmental conditions such as the impulse potential, the water conductivity, the electrode geometry and spacing, and the amount of energy storage capacitance (the amount of capacitance across the electrodes determines the constancy of the impulse voltage during the pre-breakdown period). A coherent investigation of these factors is currently in progress; the effect of varying the impulse potential and water temperature so far have been surveyed for a moderate range of values but no conclusions are as yet warranted.

Fig. 10 illustrates the influence of the impulse potential upon the formative time lag. If all other experimental conditions are held reasonably constant, increasing the potential appreciably shortens the delay between the application of the impulse voltage and the initiation of the gaseous conduction phase. This effect is somewhat erratic and results in a considerable scatter for the experimental data.

Variations of water temperature between 10°C and 15°C have a pronounced influence upon the formative phase. Increasing the water temperature has two effects: 1) the minimum impulse potential which will produce complete breakdown is lowered, and 2) the duration of the formative time for the minimum firing voltage is strikingly shortened. For example, at 12°C the minimum firing potential is about 5 kv and the maximum time lag is about six milliseconds, whereas at 15°C the minimum potential to produce breakdown is about 4.5 kv and the longest formative times are about two to three milliseconds. As mentioned previously, the ball-like structures are not observed for a very short formative period. Consequently, no balls have appeared in any of the Kerr Cell pictures taken with a water temperature of 15°C or higher. This condition is illustrated in Fig. 23 and 24.

Freshly running tap water has been used for all experiments to date, and the results are reasonably constant provided the temperature is the same. Recent measurements of the volume resistivity show a pronounced variation with temperature. For example, the resistivity at 5°C is about 7,000 ohms per centimeter cube, while at

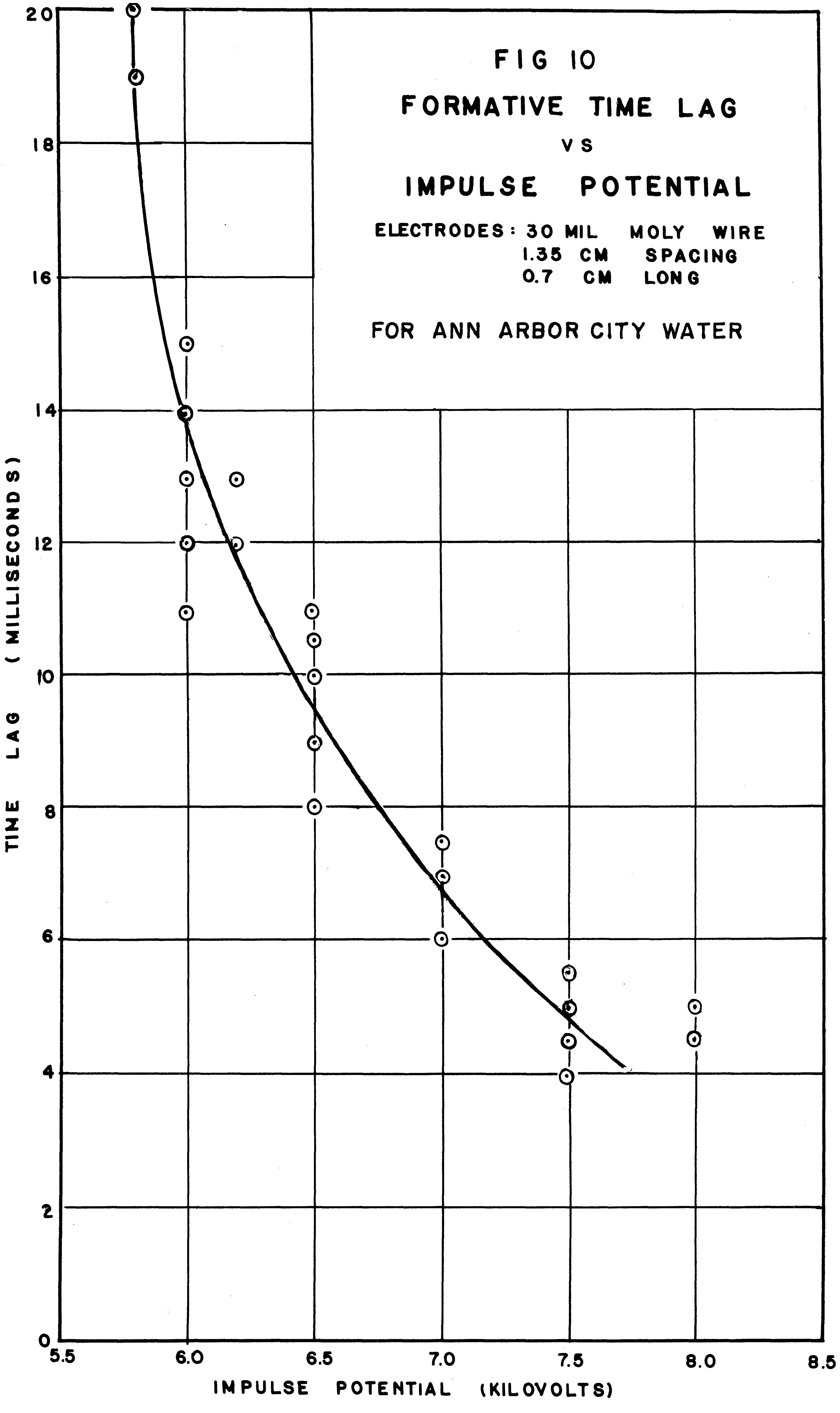


FIG 10

FORMATIVE TIME LAG

VS

IMPULSE POTENTIAL

ELECTRODES : 30 MIL MOLY WIRE
1.35 CM SPACING
0.7 CM LONG

FOR ANN ARBOR CITY WATER

20°C it has dropped to about 4,000 ohms per centimeter cube. The influence of water temperature upon the formative phase mentioned in the preceding paragraph is probably due to this variation in conductivity, although other purely temperature effects also appear to be present. Increasing the conductivity by adding salt to the water has the same qualitative effect as increasing the temperature. An appreciation of this striking temperature effect is fairly recent; therefore, much of the early data, such as given in Fig. 10, is only of qualitative value.

Observations for Incomplete Breakdown

For a given set of conditions there is a minimum firing potential below which the gaseous conduction phase does not materialize, and the capacitors discharge through the water by electrolytic conduction. When this happens there is no noticeable disturbance in the water and only a very weak flash of light can be observed in the immediate vicinity of the electrodes, while at still lower voltages the flash of light also disappears. The question arose as to what processes were present and, in particular, whether the ball-like formations occurred under these conditions.

Fig. 11 and 12 indicate that the balls do form during incomplete breakdown, and thus they furnish significant evidence that the spheres are associated entirely with the pre-breakdown phenomena. These pictures were taken as a "total exposure" with the Kerr Cell shutter removed from the camera, and the film exposed for the total duration of the event. For Fig. 11 the source of illumination was a photo-flash bulb which was fired five milliseconds after the

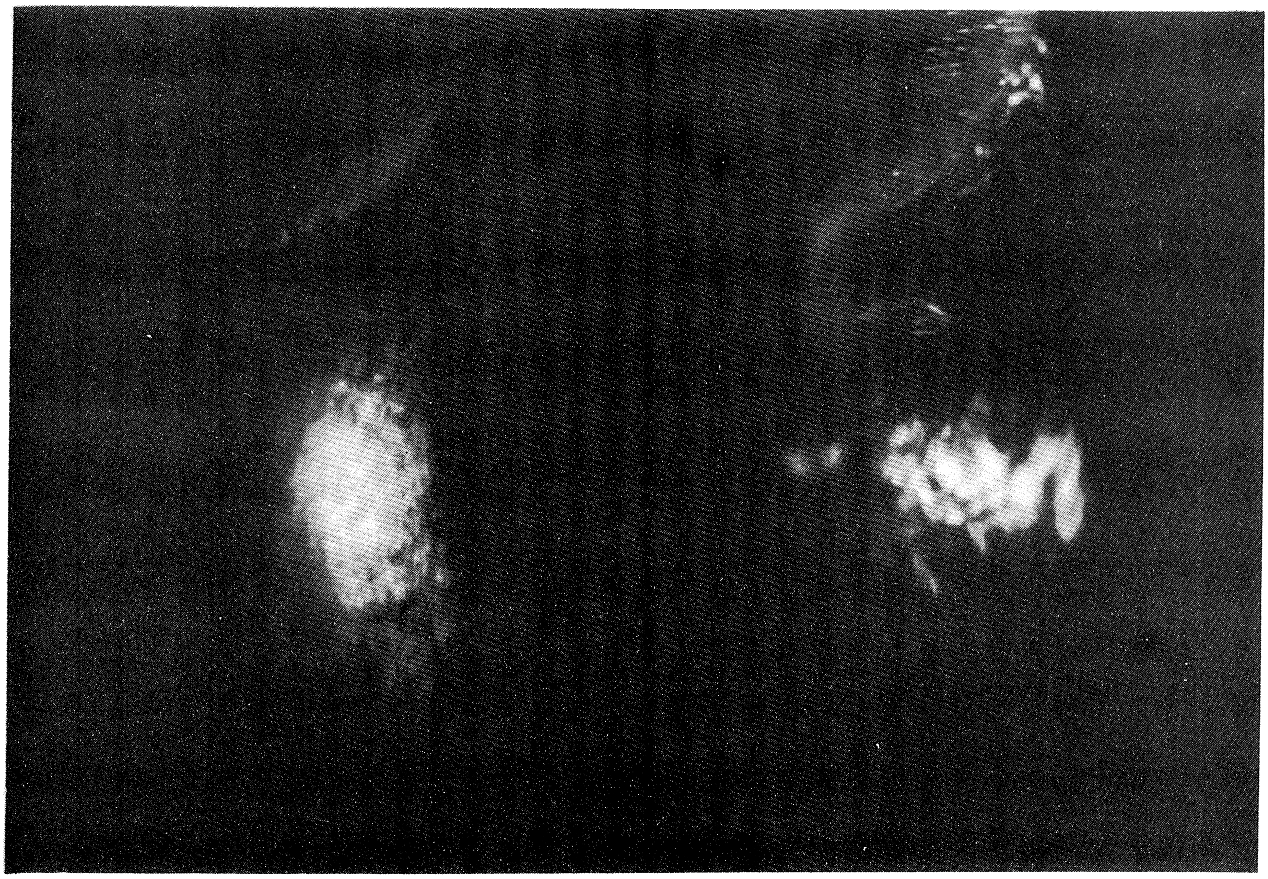


Fig. 11
"Total exposure" picture; Impulse potential - 5.5 kv
External flash illumination

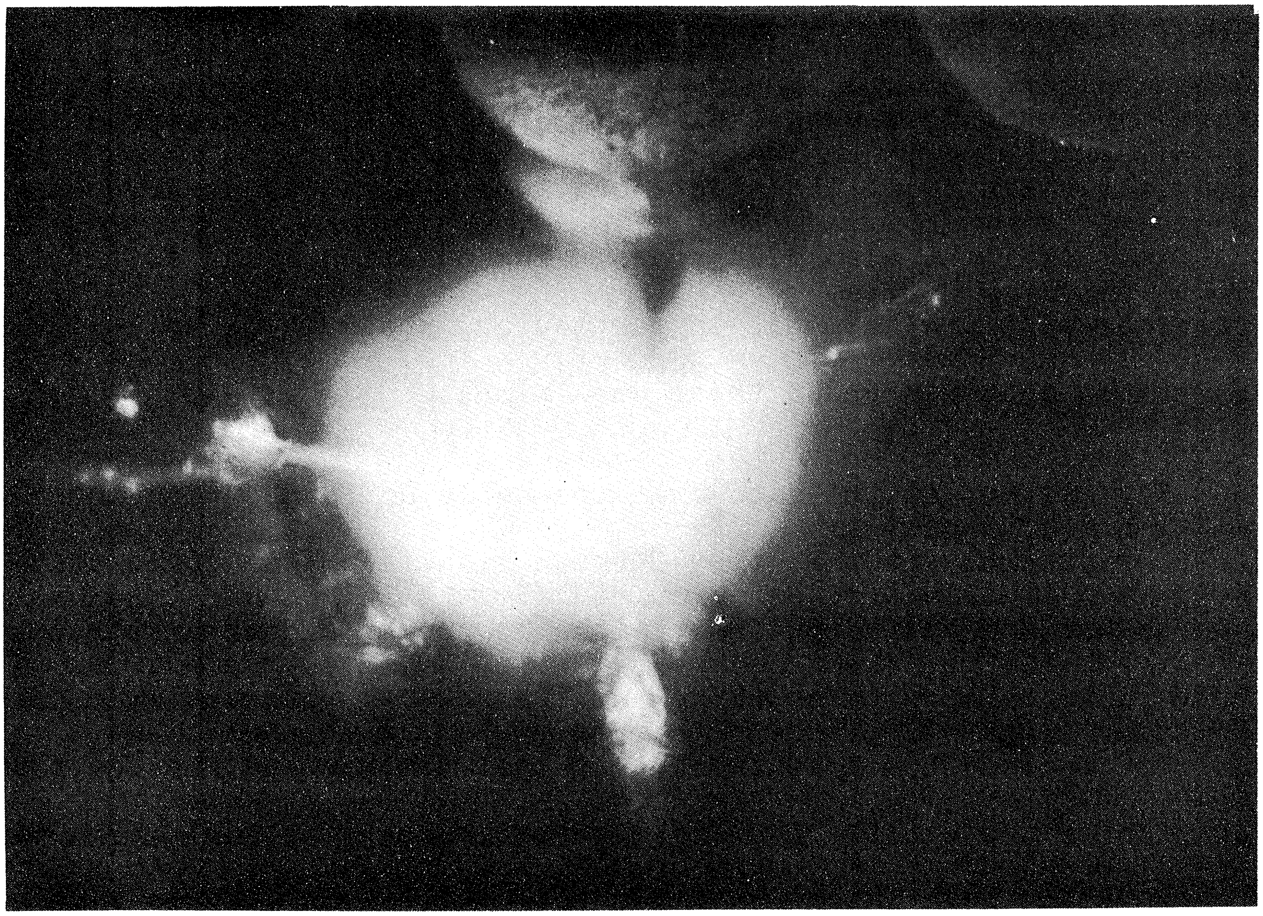


Fig. 12
"Total exposure" picture; Impulse potential - 4.5 kv
Cathode region self-luminous

impulse voltage was applied to the electrodes and lasted for about five milliseconds. The light was directed onto the spark gap from the right-hand side and from a little to the rear. Part of the outline of the balls can be seen, but only where the light is brightest and shining on them at the proper angle.

It was necessary to make many trials before a successful picture of the spheres could be obtained under these conditions. Very intense illumination either from the discharge or from a properly placed auxiliary light source is required in order to make the balls visible. These facts indicate that the spheres are rather insubstantial and represent only a slight change in the density or light-scattering properties of the water.

Fig. 12 is also a "total exposure" taken for the case of incomplete breakdown. The only light for this picture came from the weak flash occurring at the electrode. Luminosity appears at the cathode alone for voltages that are slightly lower than is required to produce light at both anode and cathode. In Fig. 12 the luminosity is present only at the cathode, although many other photographs show light around both electrodes. This self-luminosity is also faintly visible in Fig. 11 at the tips of the electrodes. The intensity of these flashes is very weak, and a much greater exposure is necessary in order to get a picture.

The luminosity in Fig. 12, and also in other "total exposure" pictures, suggests the presence of a ball-like formation lighted from within. This picture was selected as being particularly significant because it was taken for a water temperature of $48^{o}C$.

As previously mentioned, no spheres have ever been observed in Kerr Cell pictures taken at this water temperature. This evidence implies that the balls will occur if given sufficient time, but that other mechanisms, such as streamers growing out from the electrodes, terminate the formative phase before the balls have a chance to form.

Fig. 13 and 14 are two "total exposure" photographs which illustrate the effect of changing the impulse potential. In this experiment only one Teflon and wire electrode was used; the steel water tank acted as the other electrode in the discharge. As for Fig. 12, these pictures were taken by the light of the weak self-luminosity which occurs during incomplete breakdown. Fig. 13 was taken for an impulse potential of 6 kv, and gives the suggestion of a ball, just as in Fig. 12. For Fig. 14, the impulse potential is 9 kv and no indication of a ball is present; instead tenuous luminous streamers branch out from the "hot" electrode.

All of the information contained in these pictures cannot readily be correlated. In Fig. 14 no ball is present and a considerable length of time is required in order to discharge the capacitors for a case of incomplete breakdown, while other evidence suggests that the ball structures will occur if the formative period is sufficiently long.

The process of "ball" formation requires a considerable amount of energy since the voltage across the capacitors drops quite a bit when the balls occur during a long formative period. During this interval the electrode current increases with time up to the

Fig. 13
"Total exposure" picture; Impulse potential - 6 kv
Single "hot" electrode

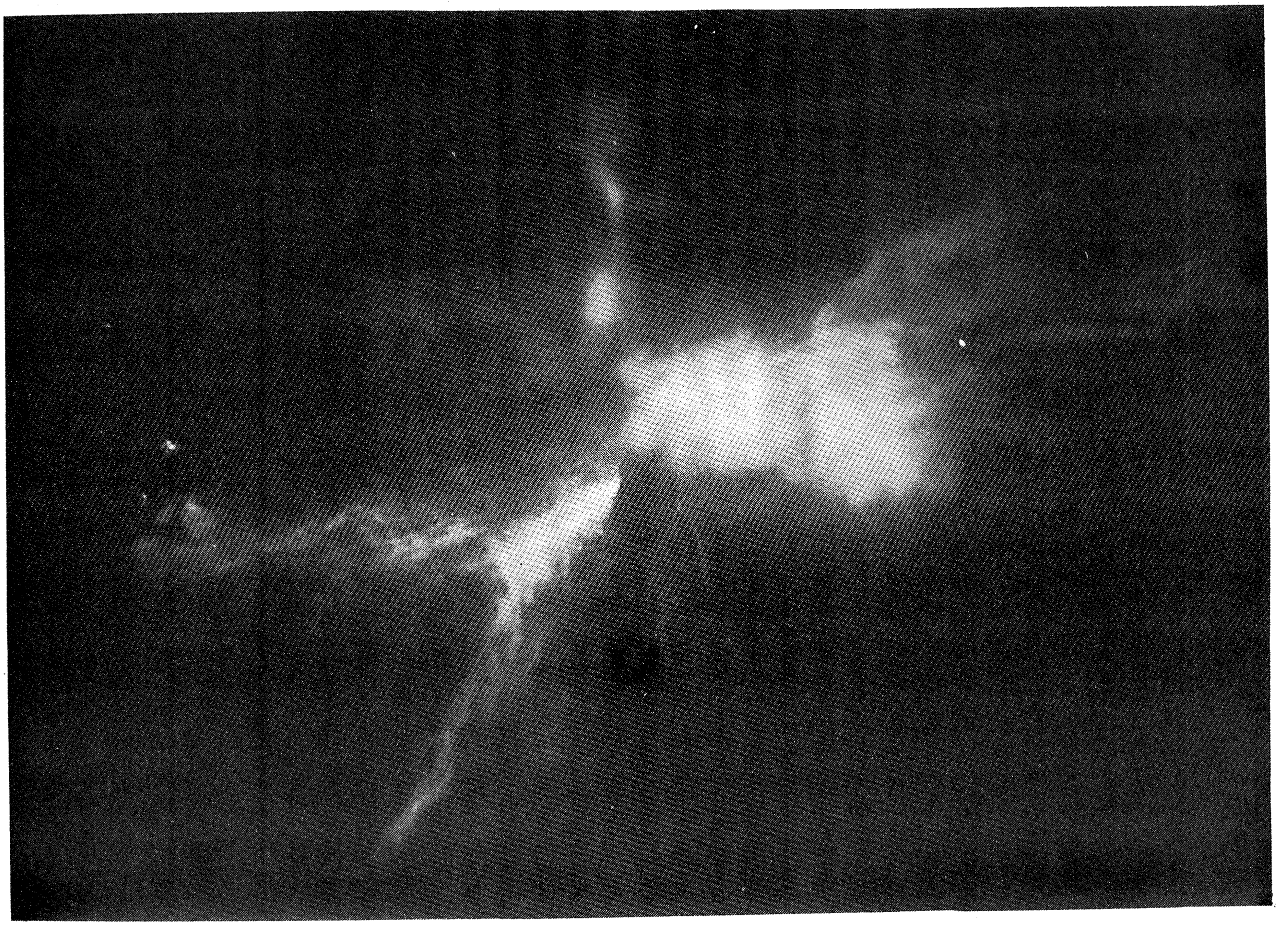


Fig. 14
"Total exposure" picture; Impulse potential - 9 kv
Single "hot" electrode

point of breakdown, or until the capacitors are about half discharged. This indicates that as the balls enlarge they require more and more energy to keep growing, and that under certain conditions they could "choke off" the gap-bridging mechanism by using up all the available stored energy.

Another observation which can be made for incomplete breakdown is the appearance of tiny gas bubbles on the electrodes when the capacitors discharge. These bubbles appear on the cathode for a lower voltage than is necessary to produce them at the anode and are probably the result of electrolysis. An inconclusive attempt was made to collect the gas from the cathode and test for hydrogen, but this is difficult since a very small quantity of gas is evolved.

The Effects of Obstacles

Fig. 15, 16, and 17 illustrate the effects produced by placing dielectric barriers between the electrodes. In Fig. 15 a $1\frac{1}{4}$ inch square of 1/16 inch thick polystyrene sheet was placed in the middle of the gap and was oriented edgewise to the camera. A much higher impulse potential is necessary to produce breakdown under these conditions, and the balls are much larger and considerably distorted. Although the actual delay time was not measured, the voltage across the capacitors dropped to about two-thirds of its original value before the gaseous conduction phase began. This indicated a relatively long formative period which would be expected with such large ball formations.

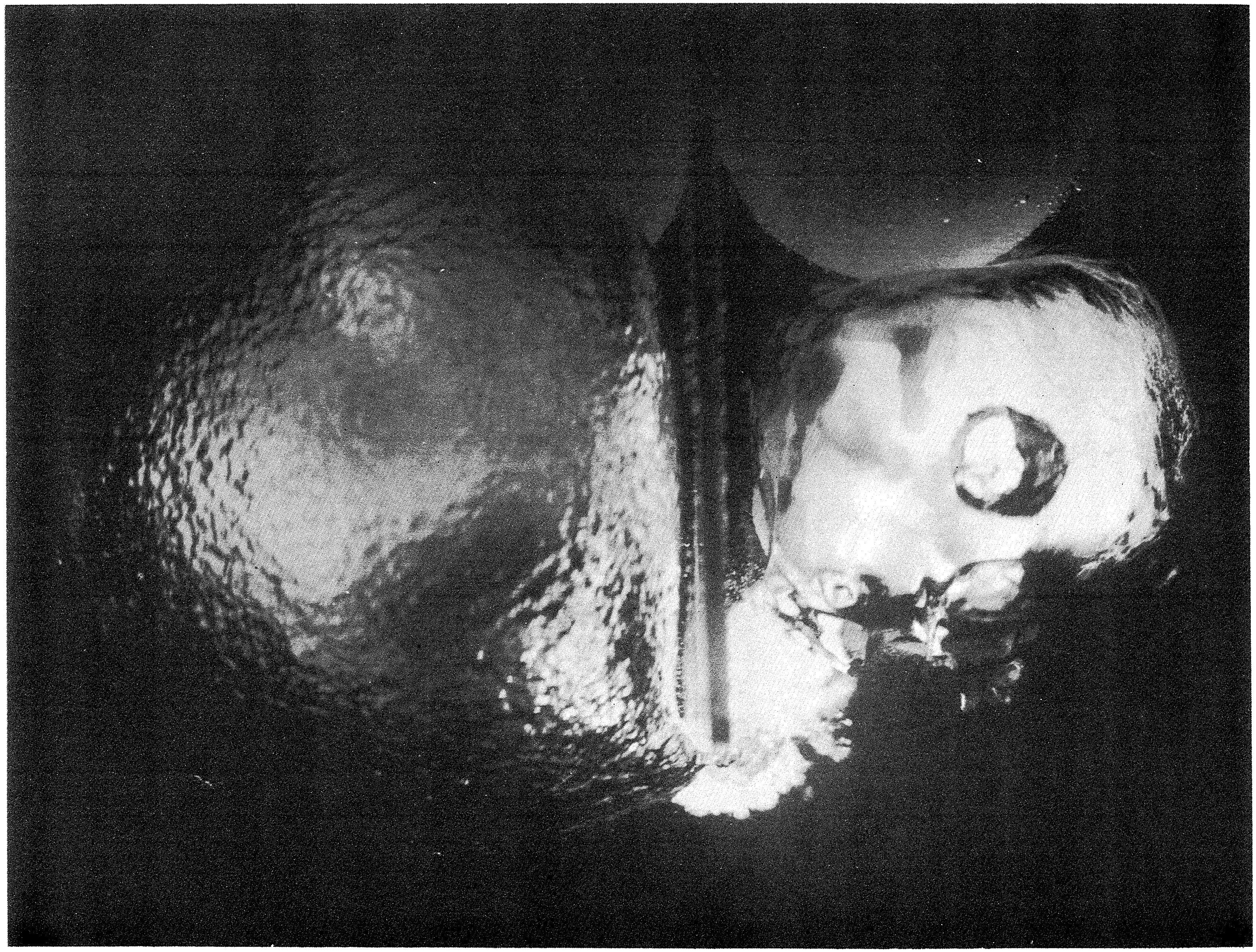


Fig. 15

Kerr Cell picture - 4 μ sec. delay; Impulse potential - 7 kv
Solid dielectric barrier between electrodes

The distorted shape of the structures surrounding the electrodes in Fig. 15 is quite interesting. The gaseous conduction channel apparently was not initiated until the spheres had grown around the end of the barrier. Another interesting feature is the apparent transparency of the right-hand, cathode, ball. The wire electrode can be seen fairly clearly, projecting into the center of the ball-like region and thus gives another indication of the insubstantial nature of these formations.

Fig. 16 and 17 were taken under identical conditions, except that in Fig. 16 the dielectric barrier was placed midway between the electrodes, while in Fig. 17 the obstacle was located close to the anode. The barrier for these tests was the same as used in Fig. 15 except that a small pinhole (0.040 inches in diameter) was drilled in the polystyrene sheet and located in line with the tips of the electrodes. In Fig. 16 the balls are larger than occur when no barriers are present (Fig. 5, 6, 7 and 8), while in Fig. 17 there are practically no spheres at all. At present no conclusive interpretation of the phenomena in these pictures is apparent, but they are probably the consequence of the gap-bridging mechanisms rather than the processes which produce the balls.

Aspects of Ball and Discharge Column Appearance

The ball-like structures (in Fig. 5, 11, and 15) appear to be almost transparent and to consist of a surface effect only, rather than a disturbance existing throughout the volumn. Also, the luminous discharge column does not seem to penetrate the balls but

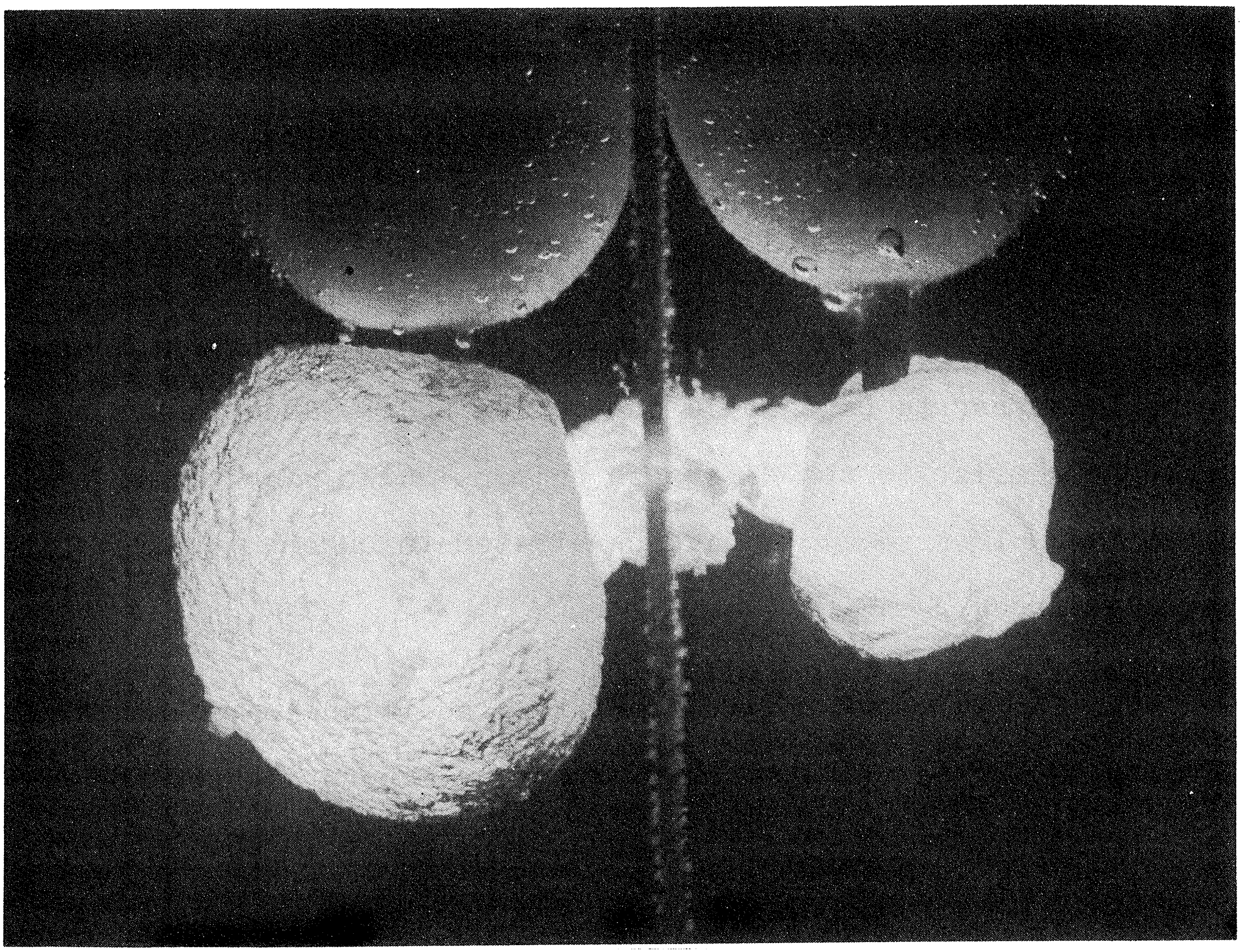


Fig. 16
Kerr Cell picture - 6 μ sec. delay; Impulse potential - 6 kv
0.040" diameter hole in dielectric barrier

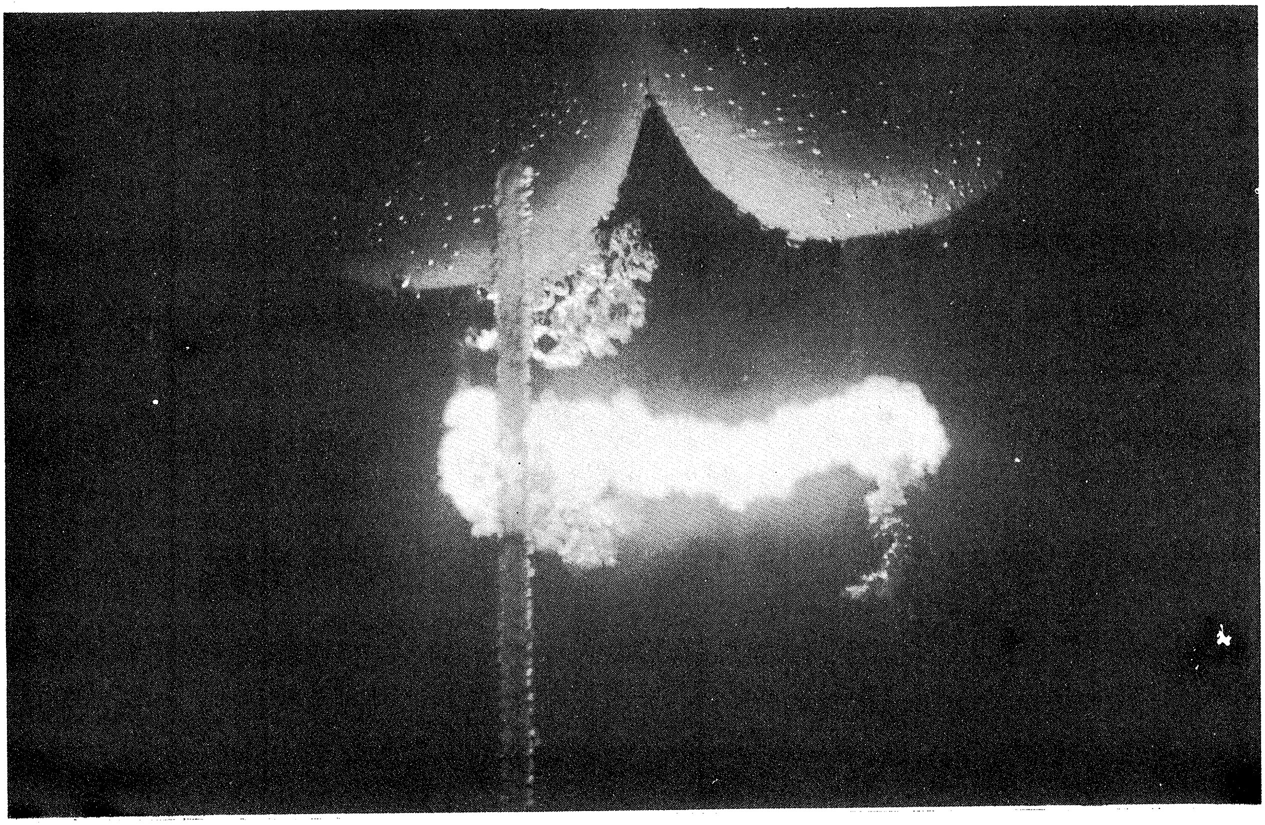


Fig. 17
Kerr Cell picture - 2 μ sec. delay; Impulse potential - 6 kv
0.040" diemeter hole in dielectric barrier

to terminate on their surfaces, leaving their interiors fairly dark. These aspects, however, appear only during the first part of the gaseous conducting phase. In Fig. 7, 8, and 16 which were all taken at later times during the course of the high-current stage, the balls appear to be a solid orb of luminosity and to have a structure similar to the discharge column. Also, for these later stages the column seems to have penetrated through the ball to the wire electrode.

Fig. 16 and 17 furnish interesting additional evidence about the size of the actual discharge column. In both figures the current-carrying channel passes through the pinhole in the polystyrene without any noticeable difficulty. The diameter of the apparent luminous column is about three to four times larger than the holes. Even if the pinhole in Fig. 16, which was taken at the time of maximum current, was enlarged by the spark, the apparent column is still much larger. (The polystyrene was destroyed by the spark so that any erosion of the pinhole could not be determined.) The billowy structure which is seen in all of the Kerr Cell pictures is probably a cloud of minute streamers and gas bubbles which surrounds a small current-carrying core.

A determination of the size of the active current-carrying channel was one of the original objectives of this research. This information would be very valuable as it would permit a calculation of current density, pinch-effect, percentage ionization, and many other important properties of the discharge. It is obviously not available from the simple Kerr Cell pictures taken so far because of the billowy casing which always masks the interior structure. A consideration of experimental methods for determining the actual size of the current-carrying channel is receiving considerable attention.

VI - PRE-BREAKDOWN LUMINOSITY

The luminosity which occurs in the vicinity of the electrodes just prior to breakdown, and also for the case of incomplete breakdown, was investigated with the oscilloscope and a photocell. A type 1P42 photocell which has a 0.19 inch diameter window was used to observe the light coming from a small selected region in the vicinity of the electrodes. This was done by forming the image of the spark gap on the ground glass back of the camera and placing the photocell window over the desired portion of the image. Because of the very weak light intensity and the low output of the photocell, a great deal of amplification was required in order to see the photo currents on the oscilloscope.

Fig. 18, 19 and 20 show a relatively slow growth in luminosity at the cathode, mid-gap, and anode, respectively, just prior to the initiation of the gaseous conducting channel. The apparent end of the trace in the middle of each figure is the instant at which the brilliant light from the complete breakdown occurs. The intensity of this flash is many orders of magnitude larger than the pre-breakdown luminosity and the resulting large signal saturates the scope amplifier so that it does not recover until the trace is over.

These figures indicate that when the conditions are such that there is a long formative period, the pre-breakdown luminosity in the cathode region is greater and starts sooner than elsewhere in the gap, while at the anode it is barely perceptible. Further, there is a dark interval of several milliseconds after the application of the impulse voltage before any luminosity appears. Oscillograms taken for the case of incomplete breakdown also show these same general features. These facts suggest that for long formative periods a luminous streamer growing slowly from the cathode is responsible for bridging the gap and initiating the gaseous conducting channel, and that a certain time lag is involved in starting the streamer. As yet no study has been made of the pre-breakdown luminosity for conditions which result in a short formative time lag.

Fig. 18
Luminosity at cathode prior to breakdown;
Impulse potential - 5.5 kv

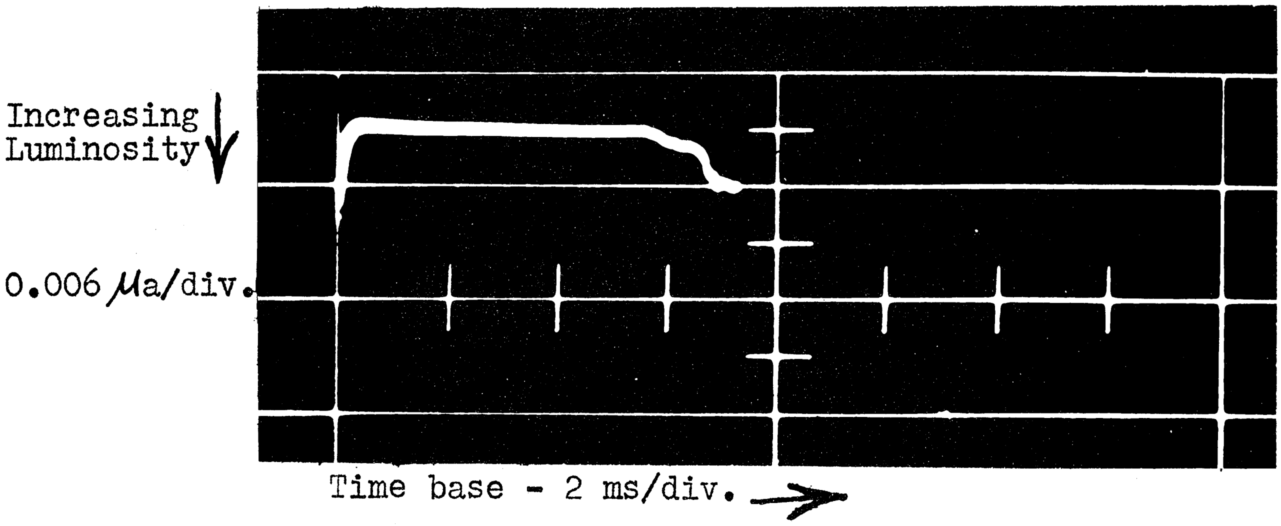


Fig. 19
Luminosity at mid-gap prior to breakdown;
Impulse potential - 5.5 kv

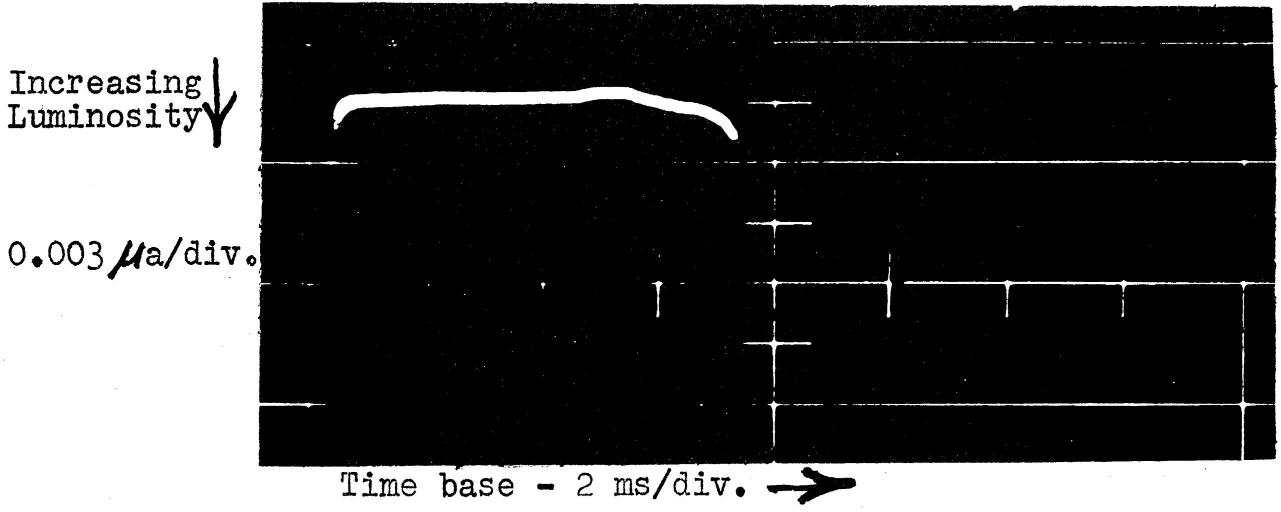
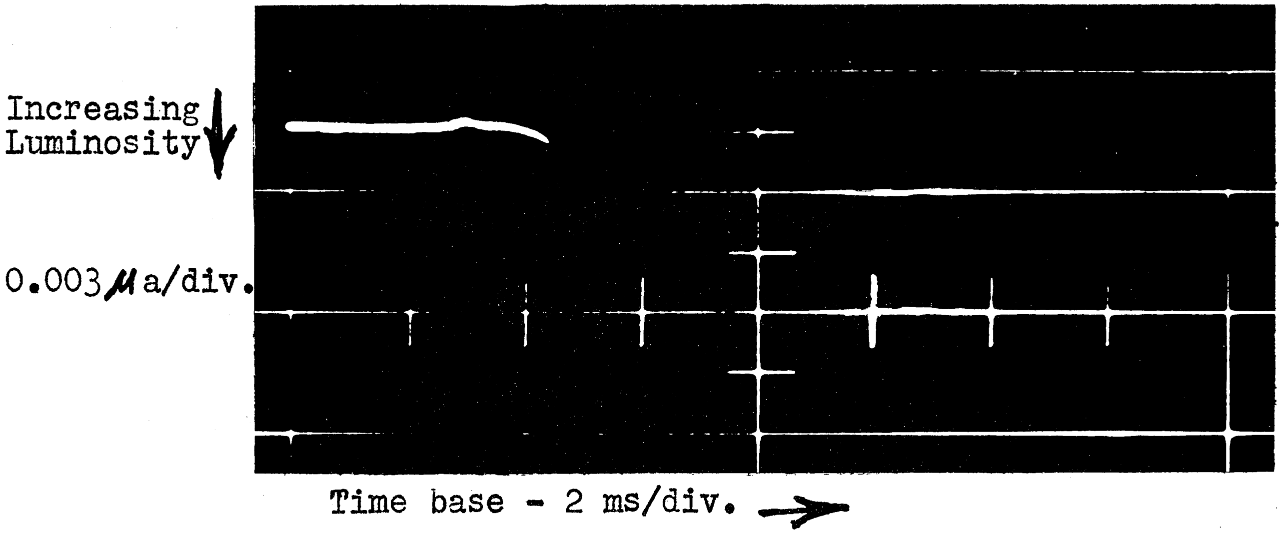


Fig. 20
Luminosity at anode prior to breakdown;
Impulse potential - 5.5 kv



VII - ELECTRICAL PROBE MEASUREMENTS

The variation in potential of a "floating probe" placed in the vicinity of the discharge was observed on the oscilloscope. A 1/16 inch diameter copper wire projecting 1/16 inch from the end of a piece of glass tubing was used as the probe. For this experiment, the probe was located 3/16 inches from the grounded electrode on the side away from the path of the discharge. The polarity of the grounded electrode could be reversed so that probe voltages were measured with respect to both the anode and the cathode. The probe was connected to ground through a resistance of approximately five megohms so as to draw negligible current.

Fig. 21 and 22 are oscillograms of the probe potential for a relatively long formative phase. In Fig. 21 the probe potential, with respect to the anode, is given for a case of incomplete breakdown, while Fig. 22 shows the probe to anode voltage when a gaseous channel does form. These two figures illustrate the essential features which were observed for all oscillograms made in this preliminary experiment.

Inspection of Fig. 21 and 22 shows that at the instant the voltage is applied to the electrodes, the probe potential jumps to high value (about 1/3 to 1/2 of the applied potential). This evidence implies that initially the voltage gradient adjacent to the electrodes is quite large. The voltage then drops fairly rapidly

Fig. 21

Probe potential re anode for incomplete breakdown;
Impulse potential - 7.5 kv

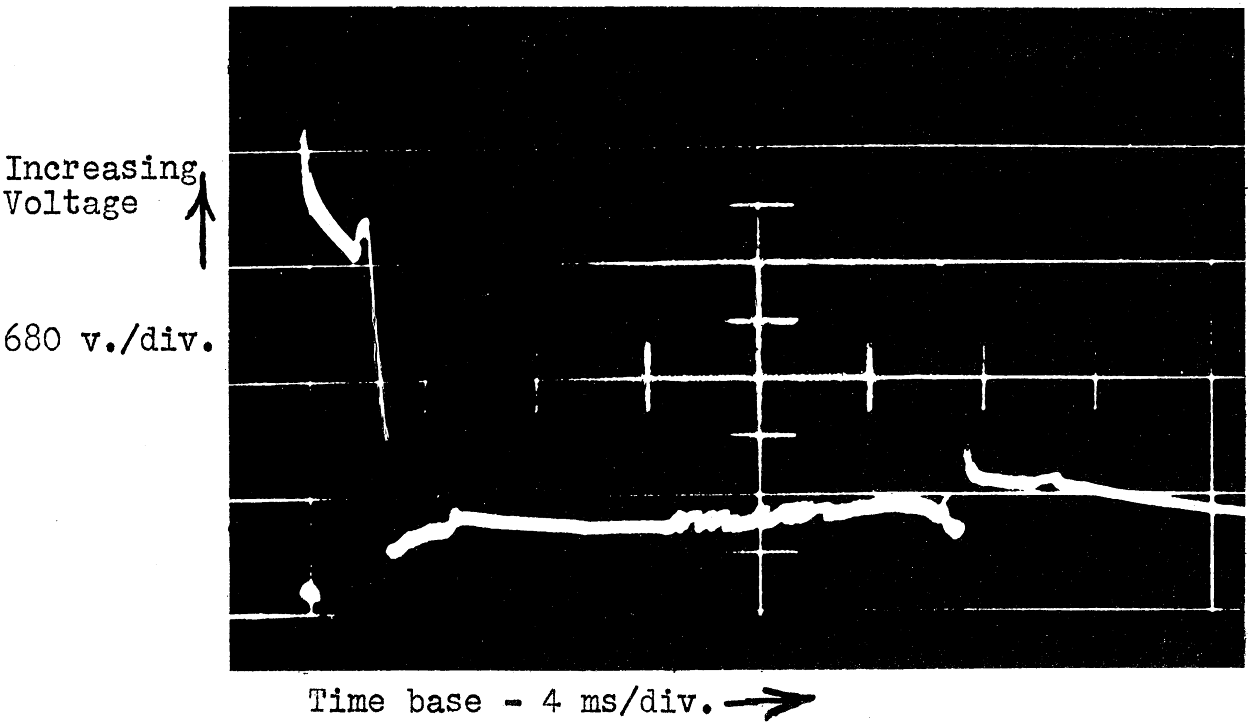
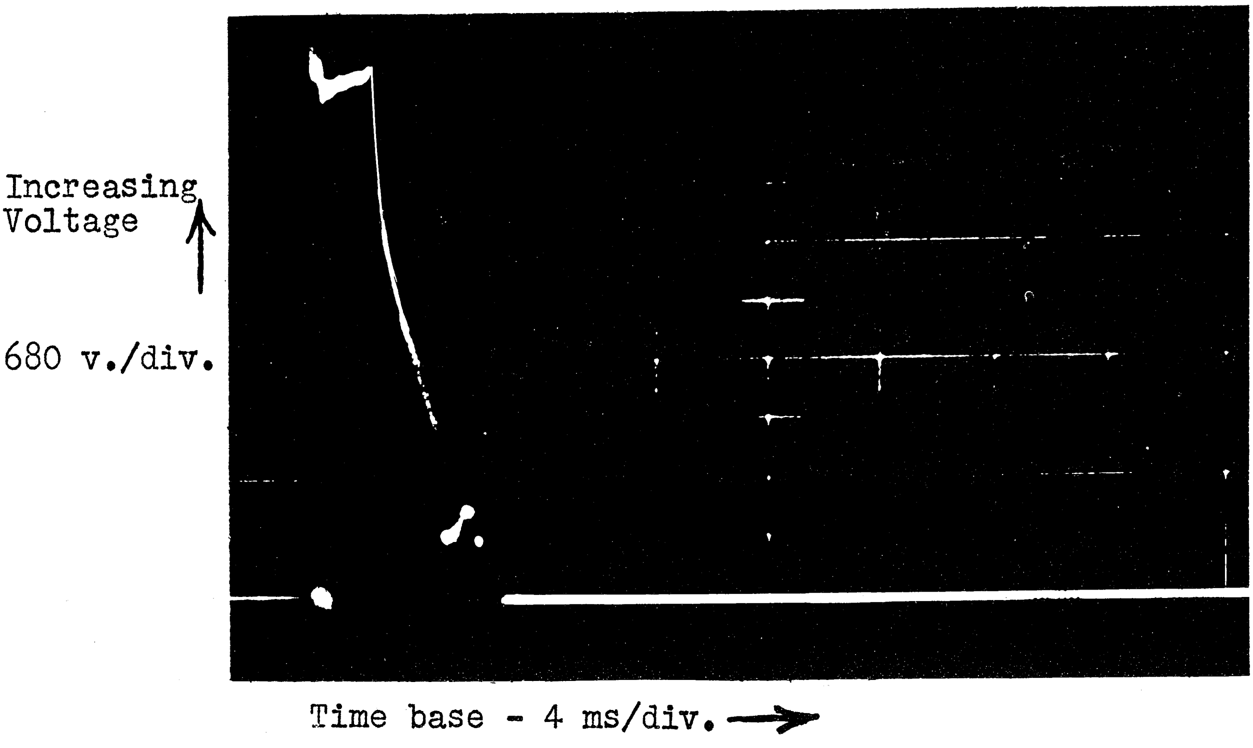


Fig. 22

Probe potential re anode for complete breakdown;
Impulse potential - 8 kv



for 1 to 2 milliseconds and subsequently rises again. This subsequent rise is observed most often when measurements are made with respect to the anode and seems to be correlated with the fact that luminosity appears around the cathode before appearing at the anode. After this, there is a relatively rapid fall in the probe potential which probably corresponds to the growth of luminosity at both electrodes. For the case of incomplete breakdown (Fig. 21) the probe potential does not drop to zero but remains at a fairly constant value until the stored energy has been dissipated and the current from the capacitors is no longer able to support the luminosity.

There seems to be an approximate correlation between these "floating probe" measurements and observations of the pre-breakdown luminosity. However, a clear interpretation of all the information contained in these oscillograms would require an extensive program of investigation and correlating experiments.

VIII - DISCUSSIONS OF PICTURES FOR A SHORT FORMATIVE PHASE

Fig. 23 and 24 are Kerr Cell photographs of an underwater spark for conditions which produce a short formative period and consequently no ball structure. Fig. 23 was taken for an impulse potential of 5 kv and a water temperature of 48°C, and Fig. 24 shows the initial stages of the discharge for 4.5 kv and 25°C. These pictures illustrate some unusual formations which appear to be "dead" or non-luminous channels that stopped growing when the gap was bridged In Fig. 23 a dark, streamer-like formation can be seen silhouetted against the active luminous discharge column. In Fig. 24 there is one such formation branching off from the main discharge column at a point about three-fourths of the distance from the cathode, left-hand electrode, to the anode. The tip of the cathode is also surrounded by what appears at first glance to be a ball, but which on closer inspection seems to be a dark dendrytic structure growing downward.

The appearance of these "dead" streamer channels strongly suggests that they are a result of the mechanism responsible for bridging the gap and initiating the gaseous conduction phase. An explanation of the double discharge column in Fig. 6 is suggested by a comparison with Fig. 23. In both cases two main streamer structures probably started across the gap. In Fig. 23 the back channel matured faster than the front one resulting in just one

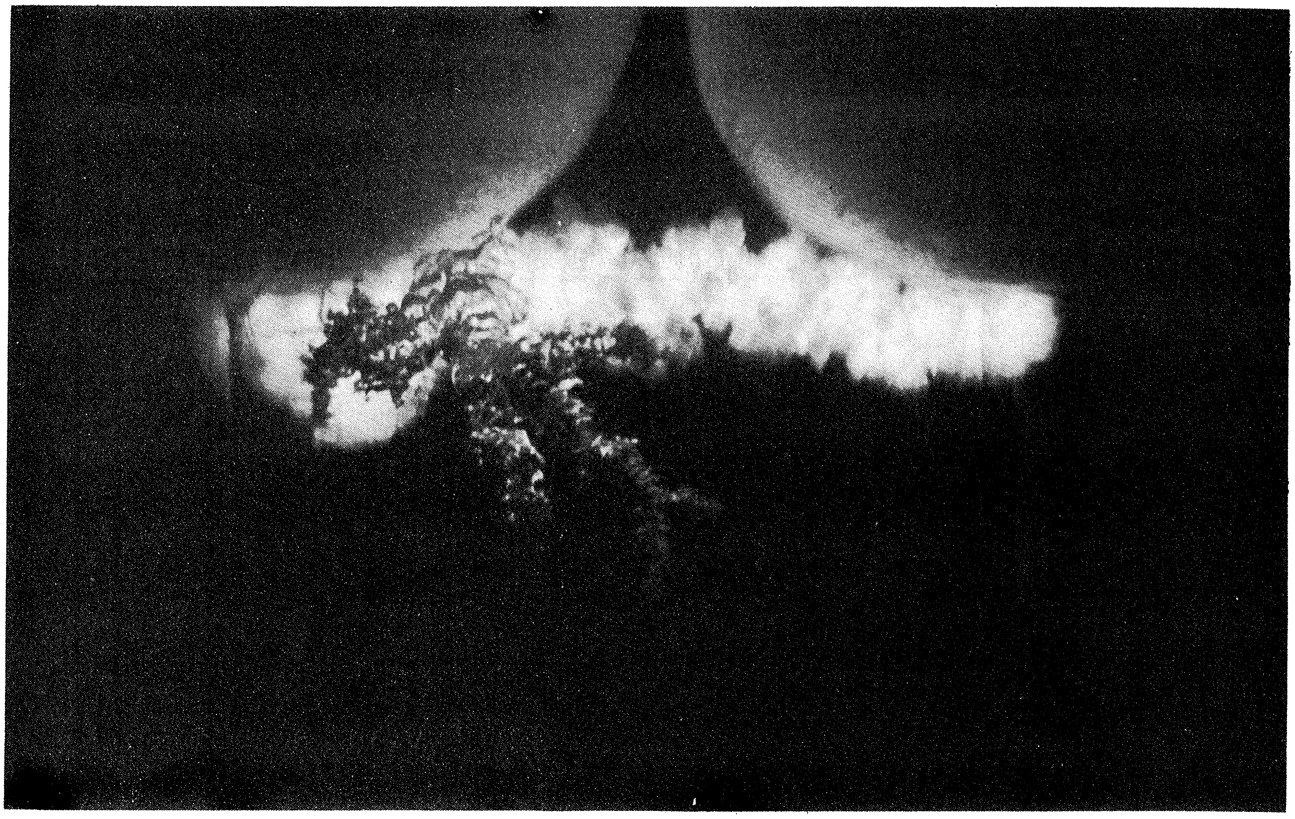


Fig. 23
Kerr Cell picture - 1 μ sec. delay; Impulse potential - 5 kv
Short formative time lag

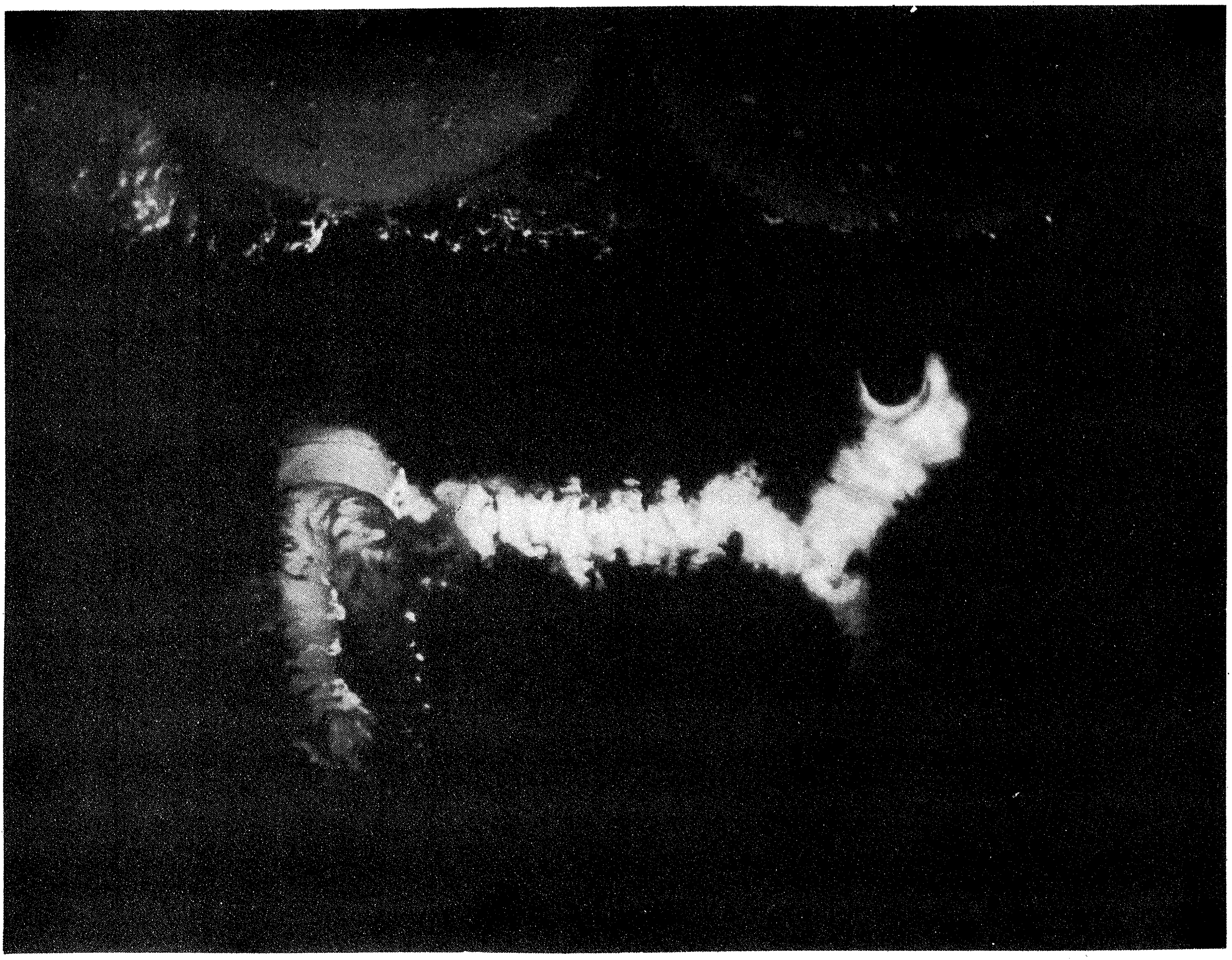


Fig. 24
Kerr Cell picture - 1 μ sec. delay; Impulse potential - 4.5 kv
Short formative time lag

active column, while in Fig. 6 they both bridged the gap at the same time resulting in a unique situation of two seemingly equally active channels. The random manner in which the streamers appear to grow is probably the explanation for the zigzag appearance of the discharge column in all of the Kerr Cell photographs.

Another interesting feature of Fig. 23 and 24 is that the streamers appear to go from the cathode to the anode. This observation agrees with the information obtained in measurements of the pre-breakdown luminosity in which the light appeared brighter and for a longer period of time at the cathode, as illustrated in Fig. 18, 19 and 20.

The growth of streamers in electrolytic solutions is mentioned in the literature.[1,2,3] The velocity of propagation of anode streamers was measured with a rotating mirror,[1] and by an electrical method;[3] the reported velocities being of the order of 10^4 to 10^5 cm/sec. Copper sulphate was used as the electrolyte and the streamers were observed to grow from the anode to the cathode, whereas in the present experiments with water, the streamer growth seems to be in the opposite direction. No ball formations or long formative time lags are mentioned; however, the copper sulphate solutions used had a much higher conductivity than the water employed for

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1. L. B. Snoddy and J. W. Beams, "Progressive Breakdown in a Conducting Liquid," Phys. Rev., 55, 879 (1939).
2. L. B. Snoddy and J. W. Beams, "Spark Discharge on Surfaces," Phys. Rev., 55, 663 (1939).
3. H. F. Henry, "Velocity of the Anode Spark in Copper Sulphate Solution under Application of Impulse Potentials," J. of Appl. Phys., 19, 988 (1948).

most of the present tests. Also higher voltage gradients and considerably less stored energy were involved than is currently being used.

Another aspect of the ball structures observed in the present work is the appearance of mushroom or tree-like formations on some of the balls. These can be seen on the left-hand, anode, ball in Fig. 5. They appear to be present only during the initial stages of the gaseous conduction phase and to die out fairly rapidly, as in Fig. 6 where the last vestige of them can just be seen. At first glance these formations appear to be the same as the streamers seen in Fig. 23 and 24; however, they are attached to the anode ball instead of growing out from the cathode and they appear much blunter, instead of branching to fine points like the streamers in Fig. 23 and 24. A careful investigation of the streamers occurring for short formative time lags is a major concern of the present experimental program.

IX - MEASUREMENT OF THE SHOCK WAVE VELOCITY

A preliminary experiment was performed for determining the velocity of propagation of the shock wave produced by the discharge. A knowledge of this velocity can be used as the basis for determining the pressure generated by the expanding channel. The position of the wave front is indicated by its action in collapsing tiny air bubbles which collect on a fine thread passing through the discharge region. The white arrows in Fig. 6, 7 and 8 show the position of the boundary between the collapsed and un-collapsed air bubbles and thus the assumed position of the shock wave. The distance of this boundary from the center of the discharge channel is measured for a sequence of several pictures taken at accurately timed intervals of which Fig. 6, 7 and 8 are examples.

If a plot is made of the indicated position of the pressure wave versus the delay time for each picture, the slope of the resulting curve gives the velocity of the wave front. For a plot based upon the present pictures there is a considerable scatter in the points. This is probably due to errors in estimating the position of the center of the column, or origin of the disturbance. Further, the indicated velocity at large distances from the discharge column (one-half inch and greater) is only 1.1 mm per microsecond, whereas the normal accoustical velocity in water under these conditions is about 1.45 mm per microsecond. This low measured value is probably a result of the various errors involved in a preliminary experiment, although other effects may be present.

Very close to the discharge (at about one-quarter inch) the indicated velocity is 2.05 mm per microsecond. This value is reasonable since close to the source the magnitude of the compression is quite large and the velocity of a shock wave is greater than the velocity of a wave of low amplitude.

A modification of the present experiment is being considered in which the discharge is viewed "end on" instead of from the side as in the present pictures, and in which a curtain of tiny bubbles rising free through the water is substituted for the bubbles on the thread. If this method proves feasible, it should be possible to see the contour of the pressure wave as it progresses radially outward. By measuring several points on the contour it would be much easier to determine the distance that the wave front has traveled, and thus eliminate the present error in estimating the origin of the disturbance. Further, by using a larger amount of stored energy, or auxiliary flash illumination, it should be possible to record the position of the wave front at much greater distances from the discharge than can now be done. Schlieren techniques might be used for observing the position of the shock wave, but such a complex experimental setup would not be required if the present system proves workable.

It should be noted that the pressure wave expands more rapidly than the discharge column. This is clearly seen in Fig. 6, 7 and 8. The advancing shock front in the water is consequently associated with the first one or two microseconds of channel growth; however, a complex pressure pattern is undoubtedly present as a result of subsequent channel expansion. A study of the pressure pattern and the magnitude of the pressure variations by means of a strain gage or a piezoelectric type pressure-sensing element would require a fairly elaborate experimental program.