

THE DESIGN AND OPERATION
OF A KERR CELL

by

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ADVANCE BOND
MILL BROWN

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THE DESIGN AND OPERATION OF A KERR CELL

INTRODUCTION

When suitable liquids are placed in a strong electrical field, they become double refracting and behave optically as a uniaxial crystal. This is true in that a plane polarized beam of light which passes through the liquid may be changed into an elliptically polarized one by introducing a phase difference between the two components of the beam parallel and perpendicular, respectively, to the electrical field. A glass cell filled with such a liquid and containing a pair of electrodes arranged as condenser plates constitutes a Kerr cell. While some conducting liquids show a greater Kerr effect than do nonconducting liquids, (5, p.150) it is impossible to maintain an electrical field for any length of time within a conducting liquid, therefore, in practice, only nonconducting liquids are used.

The Kerr cell was first used by Abraham and Lemoine (1, p.245-248) as an electro-optical shutter. This device consists of a polarizer and analyzer, set for extinction, with the Kerr cell placed between them. With a sufficient potential difference across the cell, light may pass through; when the voltage drops, the light is cut off. Since its initial application, it has been used in various investigations of light phenomena in which the interval of time is an important factor. J. W. Beams (4, p.474-480) used the electro-optical shutter in his investigation of the time interval

between the appearance of spectrum lines in spark discharges.

Lawrence and Beams (11, p.478-485) used it in a search for a time lag in the photoelectric effect.

Karolus and Mittelstaedt (10, p.698-702) used a pair of Kerr cells as a modulator in their measurement of the speed of light. More recently, 1937-1941, Anderson (2, p.239-247 and 3, p.187-197) measured the speed of light by the use of a circuit containing one cell.

By means of the electro-optical shutter, considerable knowledge has been gained regarding the time and nature of electric spark breakdown. Dunnington (6, p.1533-1546) and Lawrence and Dunnington (11, p.396-407) studied the early stages of the spark breakdown. They used various metals as electrodes; particularly zinc, cadmium, and magnesium. Also, H. J. White, using a Kerr cell, (13, p.99-106) studied the nature of spark discharges in various gases.

In all of the cases mentioned above, the Kerr cell was the most important part of the apparatus. It has become a very successful tool for dealing with extremely short intervals of time. Therefore, it becomes highly desirable that the design and operation of the Kerr cell should be better understood. The purpose of this paper is to describe its design and operation.

The cell was designed to permit the use of any suitable liquid; however, because nitrobenzene has such a large Kerr constant, it is the liquid chosen for this study.

THE PURIFICATION OF NITROBENZENE

The nitrobenzene that is to be used in the Kerr cell must be as nearly pure as possible. Experiments have shown (13, p.100-104) that with impure nitrobenzene there is a time lag in the closing of the electro-optical shutter and that a background of extraneous light may be transmitted. These effects are closely related to the conductivity of the cell and are practically nil for sufficiently pure nitrobenzene.

Because nitrobenzene is an excellent solvent, it is important that all apparatus with which the nitrobenzene is to come in contact be thoroughly cleaned and dried. Therefore, in this experiment, after cleaning and drying, all containers were rinsed out from three to five times with the purest nitrobenzene available. The Kerr cell itself was washed out five times with the finished product before it was finally filled for use in the electro-optical shutter.

The procedure in the purification of the nitrobenzene was carried out very closely to that recommended by White (14, p.22-26). The four steps in the procedure and the order in which they were performed are as follows:

1. Treatment with a weak basic solution to remove traces of acid. A normal solution of potassium carbonate was used as the basic solution. It was added to the nitrobenzene in equal proportions and the two were mixed by passing air through them. At the conclusion of a two-hour mixing period, the mixture was allowed to

stand. After the nitrobenzene settled to the bottom, the solution was washed by running water through it for about an hour. Then, as much of the water as possible was removed by using a separatory funnel.

2. Treatment with a drying agent to remove as much water as possible. One hundred grams of calcium chloride were used per liter of nitrobenzene. The mixture was shaken occasionally for about 24 hours and then the calcium chloride was removed by filtering.

3. Fractional distillation. The design of the still is shown in Figure 1. It was made of Pyrex glass except for the bubble plates, P, which were made of nickel-plated copper. The boiler, S, was made of a liter flask; a ground joint was inserted between the boiler and the column to aid in filling and cleaning the still. The column was made of glass tubing one inch inside diameter. The bubble plates were slightly smaller in diameter than the column and were drilled with a No. 60 drill with 25 holes in each plate. These holes allow the rising vapor to bubble through the liquid collected on the plates. The air-cooled condenser, C, consists of a glass tube about 12 inches long and $\frac{1}{2}$ inch in diameter. A drying tube, DT, containing calcium chloride, is used to prevent contamination of the nitrobenzene by moisture from the air. A standard ground joint was placed at the top of the column and a thermometer having a ground joint was used to measure the vapor temperature.

The flow from the still was regulated by the stop cock, SC, and was measured by counting the drops from the drop counter, D.

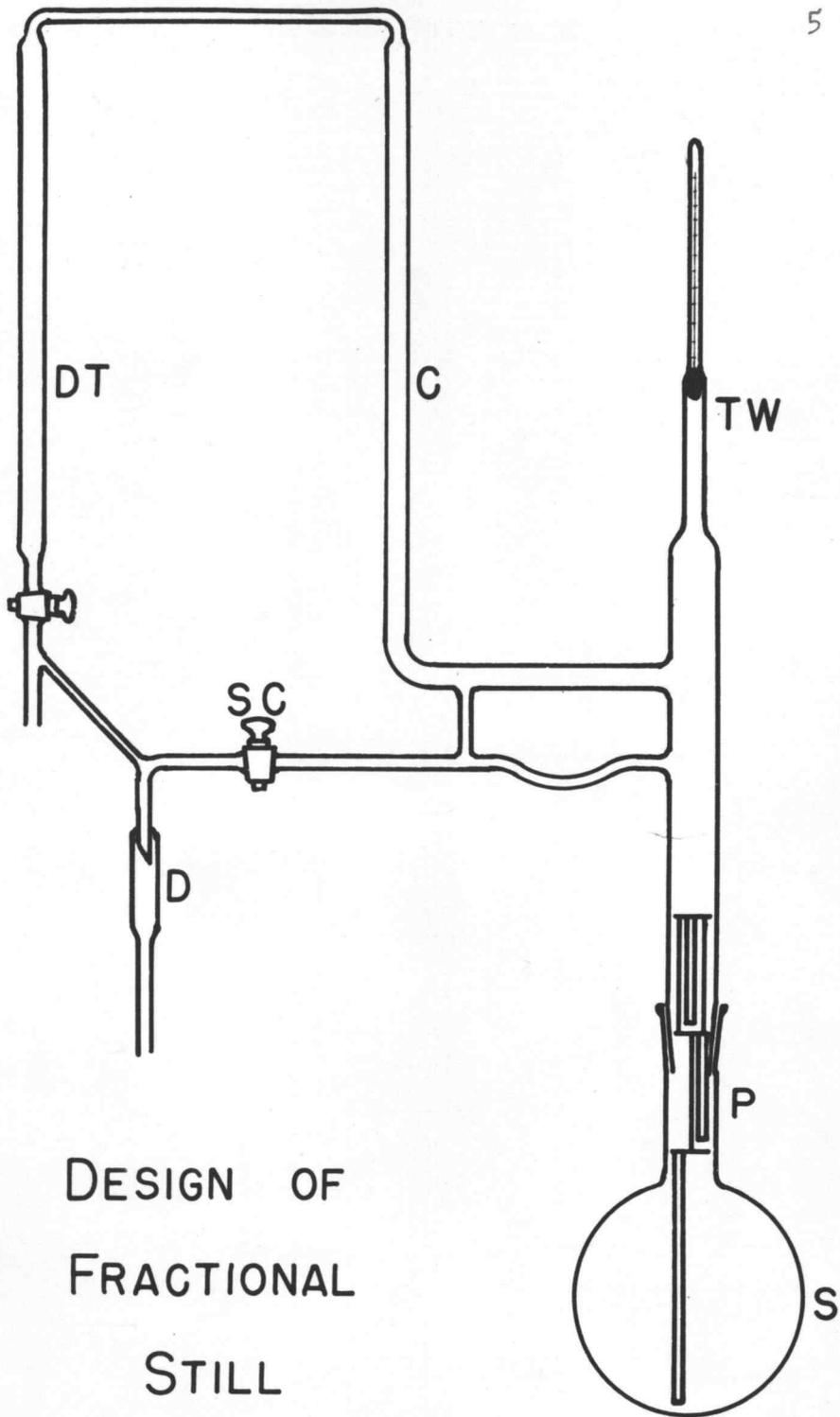


Figure 1

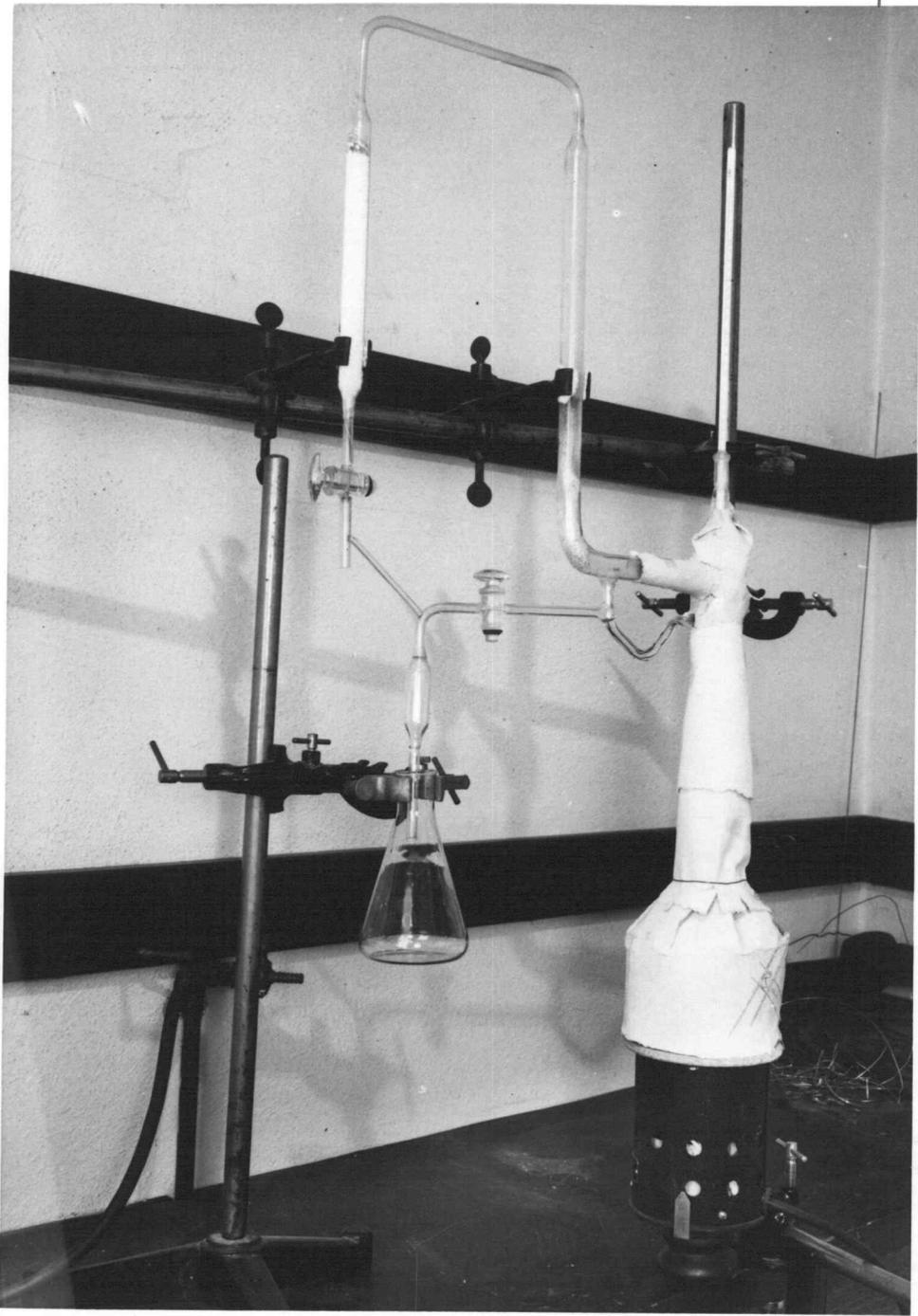
The boiler and column, wrapped with asbestos, were heated by mounting them above an electric plate. Figure 2 shows the still as it was used.

It required from an hour and a half to two hours to bring the still to the operating temperature. Too rapid heating will cause the column to flood and, therefore, should be avoided. The boiler was heated sufficiently so that the output was about forty drops per minute with a reflux ratio of one to four. Since the boiling temperature of nitrobenzene is 210 degrees centigrade, any water returning to the column from the condenser causes considerable agitation and is likely to damage the still. It is, therefore, advisable to leave the stop cock, SC, open until all the nitrobenzene containing moisture has been exhausted. The nitrobenzene that contains moisture appears milky.

The first third of the distillate was discarded and about one-third of the nitrobenzene was left in the still. The still was then cleaned and the middle third redistilled.

4. Fractional freezing. The freezing apparatus consisted of a 500 ml. Erlenmeyer flask with a standard taper ground-stopper immersed in an ice bath.

A stopper was made of a standard ground-joint tube by sealing inside a small glass tube just large enough for the stirring rod to pass through. This made the flask as nearly air tight as possible and permitted the nitrobenzene to be stirred continuously during the freezing process. A stirrer was made of a glass propeller



THE STILL IN OPERATION

attached to a bent glass rod so that it was free to rotate. Since the freezing temperature of nitrobenzene is 5.7 degrees centigrade, ice was used as a freezing agent. About two-thirds of the liquid was frozen and the rest discarded. The frozen portion of the nitrobenzene constitutes the final product.

CONSTRUCTION OF THE KERR CELL

Because the Kerr cell is a part of both the electrical and the optical systems (Figure 6), the characteristics of both systems must be considered in the design. In the optical system, the cell is placed between two crossed Polaroids so as to permit the light to pass through it when a sufficiently high potential difference is applied. Therefore, it is important that the cell be free from optical distortions.

The cell is of the high potential and low capacity type. It is designed to operate on potentials from 3 to 15 kilovolts. Therefore, the leads to the electrodes were taken out on opposite sides of the cell. The construction is shown in the photograph (Figure 4).

The body of the cell was made of Pyrex glass tubing about three and one-half centimeters in diameter. The windows were made of Pyrex plate glass carefully selected to obtain pieces that were as nearly optically perfect as possible. These were cut into circular disks having a diameter such that they would just slip into the tubing from which the body of the cell was made. The windows were sealed in place by applying sufficient heat to insure a good weld after which the cell was cooled slowly to prevent undue strain on the windows. It is very important that the windows be placed parallel to each other and perpendicular to the electrodes of the cell. It is also essential that the distance between the electrodes

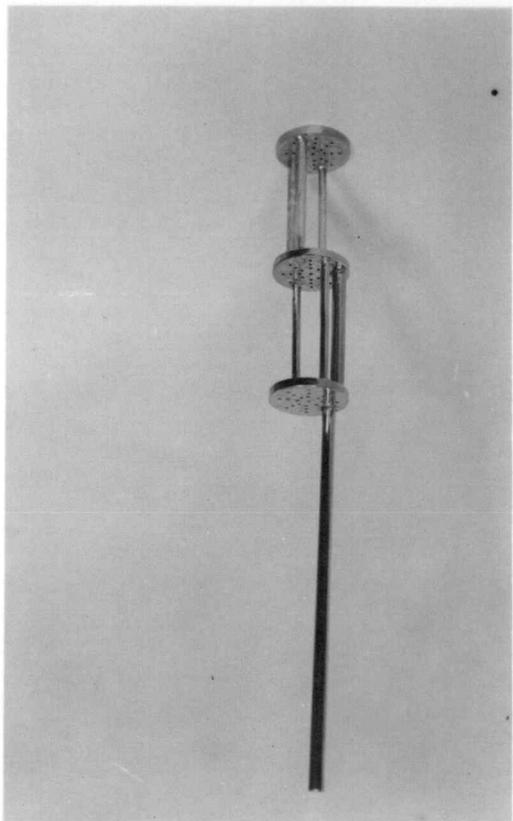


FIGURE 3

BUBBLE PLATES OF THE STILL

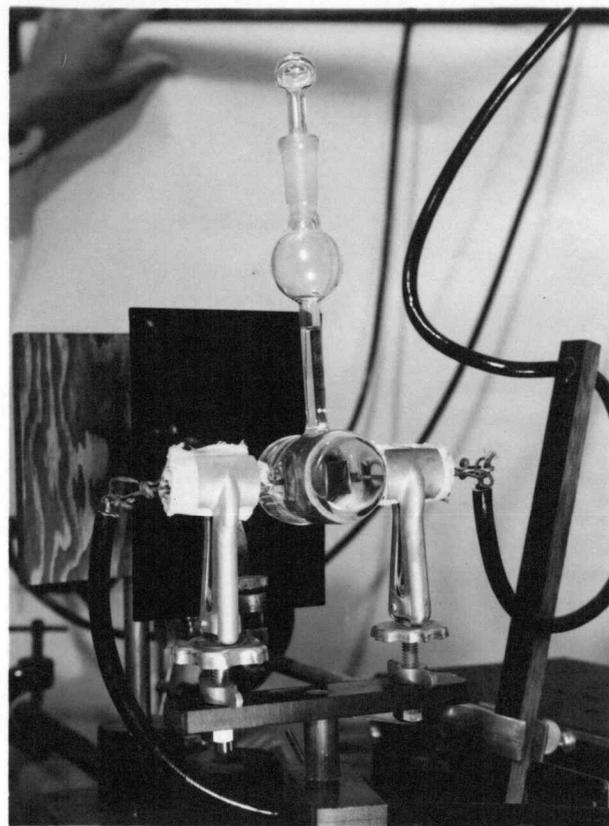


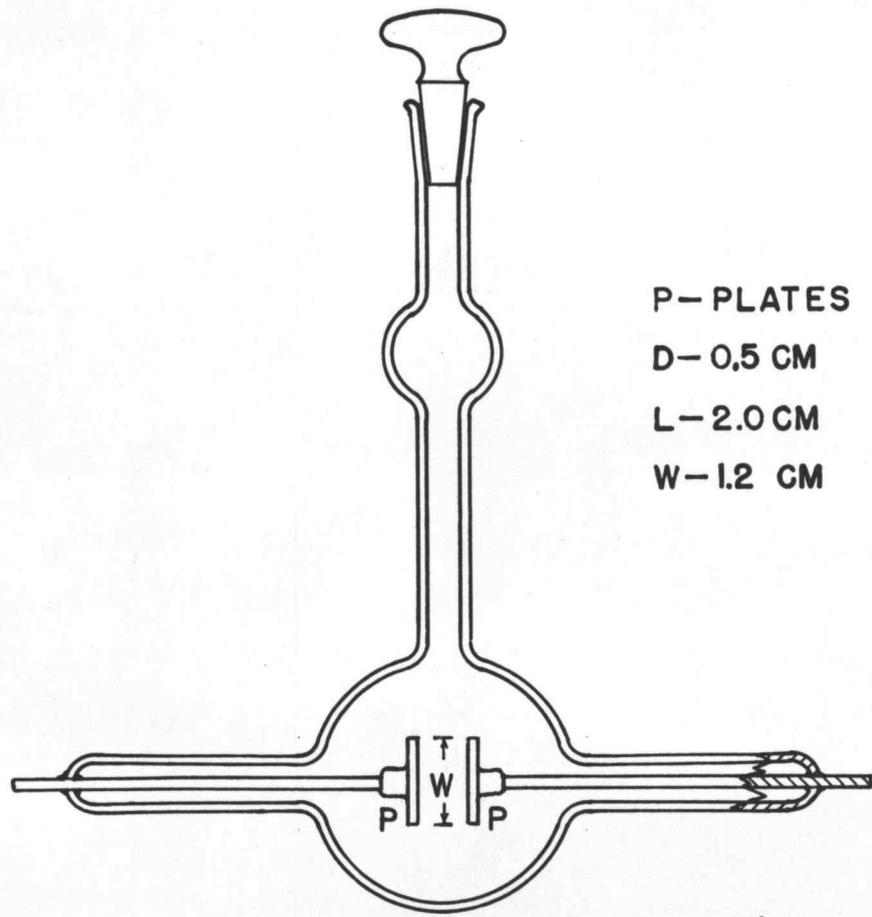
FIGURE 4

THE KERR CELL

be accurately measured for any quantitative work on the Kerr effect.

Figure 5 shows a diagram of the cell. The length of the electrodes, l , is 2 cm., the width, w , 1.2 cm., and the space between the electrodes, d , 0.5 cm. The electrodes, P , were made of nickle plates silver soldered to nickle stems which in turn were soldered to tungsten leads. The electrodes were then gold plated.

DESIGN OF THE KERR CELL



P- PLATES
D- 0.5 CM
L- 2.0 CM
W- 1.2 CM

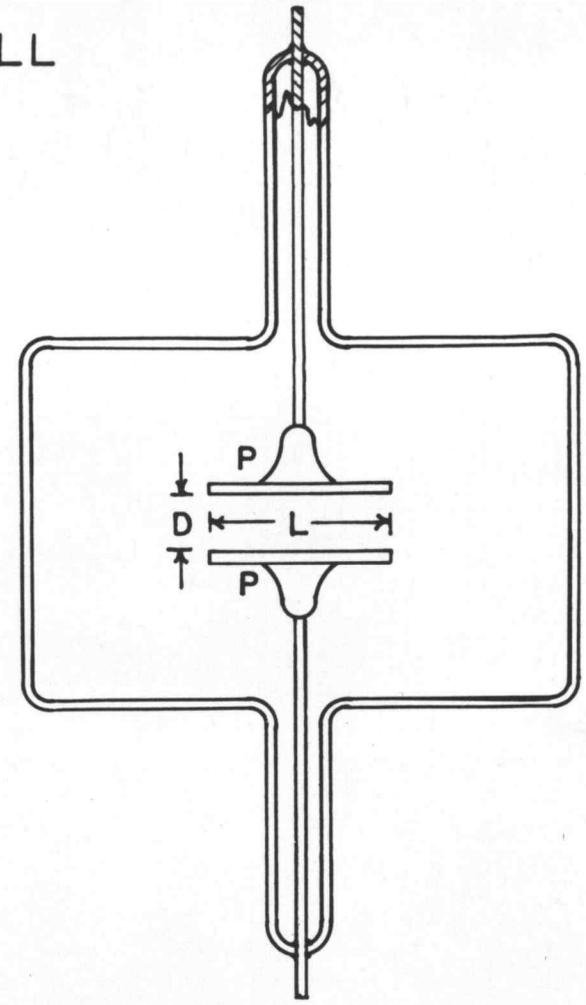


Figure 5

NOT TO SCALE

THE OPTICAL SYSTEM

The optical system (Figure 6) consisted of a light source, SG, a mirror, m, two Polaroids, N_1 and N_2 , a collimator, C, and the Kerr cell, K. The light source was a spark from a gap of 2.5 mm between zinc electrodes. The spark gap was placed slightly off the axis of the optical system so that the light which travels first to the mirror, M, is reflected back past the gap along the optical axis into the Polaroid, N_1 . The Kerr cell was placed between the two Polaroids N_1 and N_2 which were set for extinction. The light was collimated by means of a rectangular hole 1.2 cm. by 0.5 cm. cut from a piece of sheet metal which was placed between the polaroid N_1 and the Kerr cell. The light passing through the system was viewed through the analyzer N_2 .

Figure 7 shows a general view of the electro-optical shutter and its accessories.

A DIAGRAM OF THE ELECTROOPTICAL SHUTTER

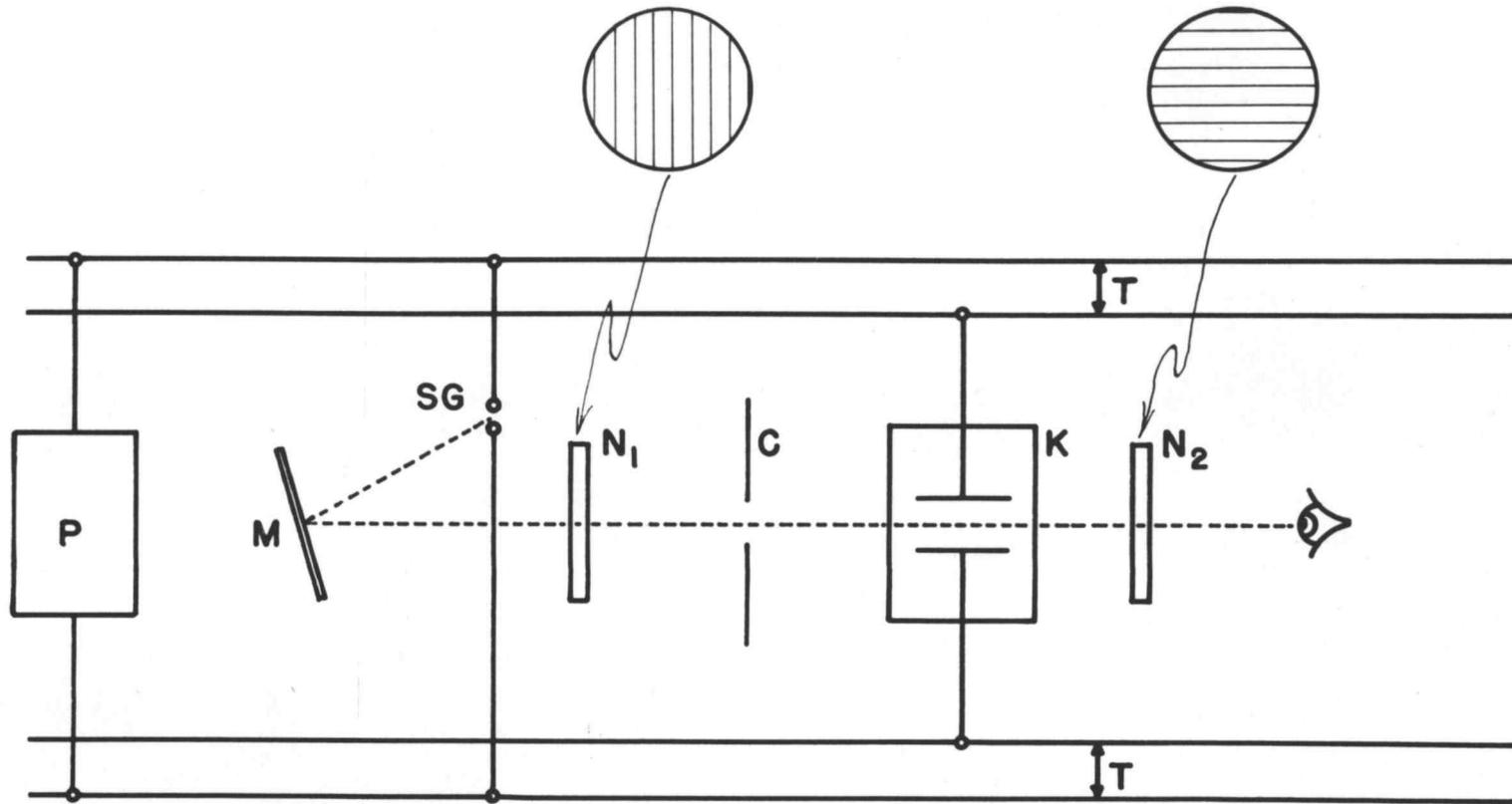


Figure 6

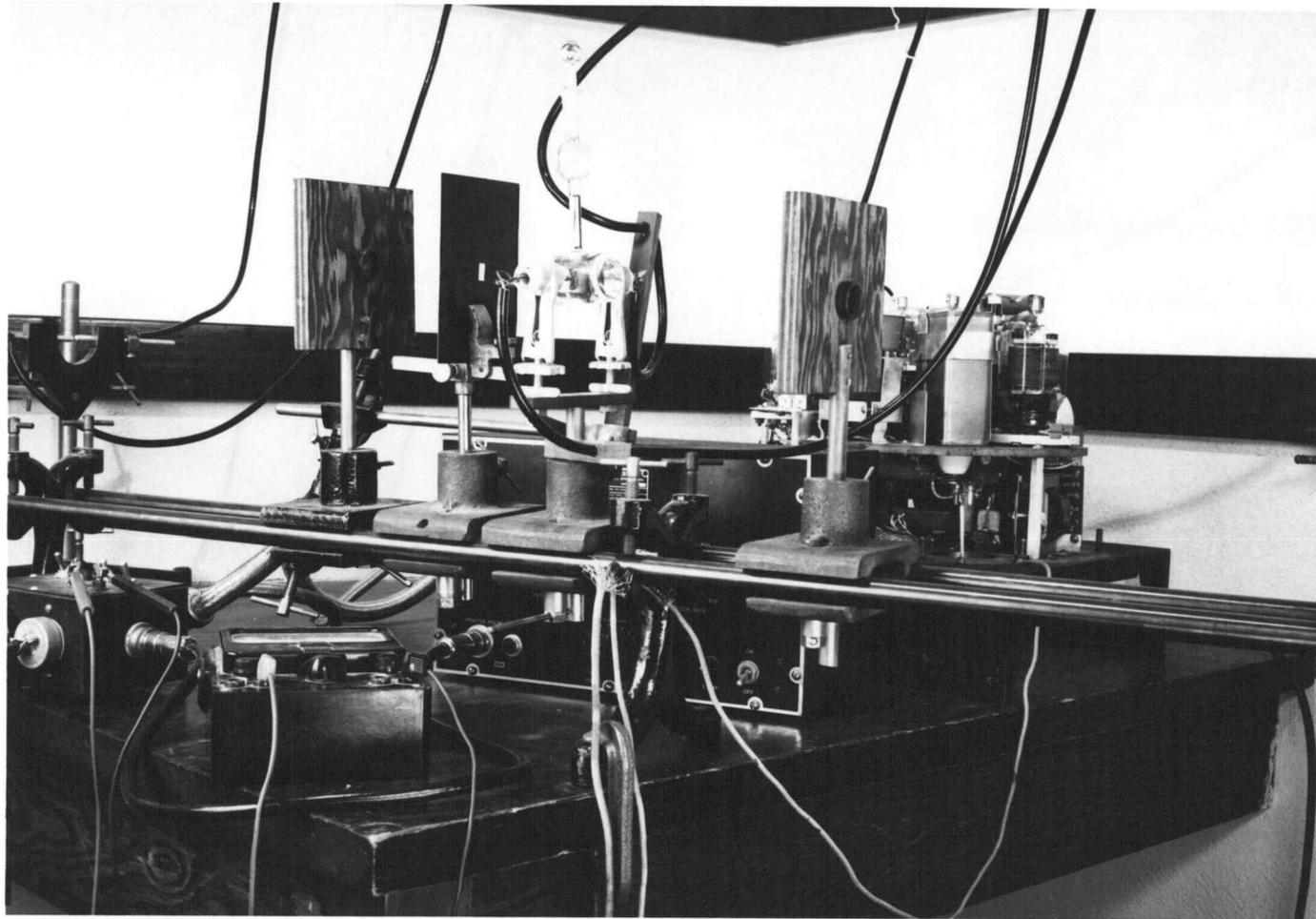


FIGURE 7
GENERAL VIEW OF THE ELECTROOPTICAL SHUTTER

THE ELECTRICAL CIRCUIT

The high voltage for both the Kerr cell and the spark gap was supplied by a pulse generator. This pulser was manufactured by the Derola Corporation, Detroit, Michigan, for the Navy Department Bureau of Aeronautics for use in the APS-2 and other radar sets. The pulser was adjusted to give 450 pulses per second with a pulse duration of one-half microsecond at a ten kilovolt peak. This short pulse duration eliminated overheating of the Kerr cell such as might occur with other sources of high voltage current.

Four number 14 bare copper wires, each 24 feet long, were stretched across the room. These were placed 4 inches apart; that is, on the corners of a four-inch square, and were insulated at their ends from the room walls with four-inch strain insulators. A turnbuckle at one end of each wire was placed so that sufficient stress could be put on the wire to prevent sagging and any difference in tension could be adjusted. The four wires made up the track of the trolley system. Sash pulleys were placed between the wires at each end and a cord was threaded through the pulleys and tied to the ends of the trolley. The cord was used to move the trolley back and forth along the track.

The trolley was made of two pieces of bakelite $4\frac{1}{2}$ by $5\frac{1}{2}$ inches fastened together in the center by a piece of heavy bakelite rod 4 inches long. Plastic strips with holes in them were fastened to one end-piece so that two brass tubes could be inserted. These

tubes, which made electrical connections between the wires, were free to rotate as the trolley was moved along the track. This trolley system made it easy to change the length of the electrical circuit to the Kerr cell. The leads from the trolley track to the pulser, spark gap, and the Kerr cell were each one meter in length. These leads were carefully measured so that when computing, the lengths of the electrical circuits were known.

One side of the high voltage circuit was grounded to the frame of the pulser; the pulser frame and optical bench were grounded to a water pipe. The grounded side of the high voltage circuit was attached to the lower wires of the track thus eliminating any danger due to accidental touching of the high voltage wires of the trolley system. Wires insulated for high voltages were used for all connections.

CONCLUSION AND DISCUSSION

The Kerr cell was tested for operation by placing a direct current voltage of 4250 across it. It was placed between two Polaroids and the optical system was focused upon the filament of a clear 40 watt lamp. When the Polaroids were set for extinction, the light appeared only when the electrical field was imposed upon the cell. For maximum effect, the Kerr cell (6, p.169 and 2, p.240) must be placed at an angle of 45 degrees to that of the Nicol polarizer. With the Polaroids used, this angle was not so apparent because their plane of transmission was not marked, but it was observed that by rotating the polarizer to a particular angle with respect to the Kerr cell, a maximum of the Kerr effect could be observed.

There was some distortion of the light due to strain on the windows of the cell, but not enough to cause any trouble in observing the effect. This distortion could doubtless be eliminated if greater care was given to the construction of the cell.

The conductivity of the nitrobenzene was tested by placing the 4250 direct current voltage across the electrodes of the cell and measuring the current by means of a microammeter. The conductivity of the nitrobenzene was found to be as low as 5×10^{-11} mhos per centimeter cube. This value compares favorably with that given by White (16, p.24) for nitrobenzene sufficiently pure for satisfactory operation of an electro-optical shutter. The quality of the

nitrobenzene might be improved by further distillation. No trouble, however, was encountered since the degree of purification was sufficient so that no noticeable heating of the cell occurred.

In operation, the Kerr cell was arranged as in Figure 6. The voltage was supplied to both the spark gap and the Kerr cell by the pulser. When the spark crosses the gap, there is a rapid collapse of the voltage and emission of light in the gap. Following this breakdown, an electric wave is propagated out along the wires toward the Kerr cell. The electric wave reaches the cell at a time after the beginning of the breakdown equal to the length of wire path between the gap and cell divided by the wave velocity, while the light reaches it after a time equal to the path traveled divided by the speed of light. Light arriving at the cell before the voltage wave, passes on through; that arriving after, is rejected due to the collapse of voltage which closes the electro-optical shutter. As the voltage wave path was increased by moving the trolley along the track, the light first appeared very faint and then increased in intensity as the path was lengthened; the maximum intensity being reached at a distance of 400 cm. plus or minus 10 cm. from the minimum point.

Assuming that the electric wave travels with the speed of light, the length of time, t_s , during which the shutter remains completely open after the breakdown, is given by the formula

$$t_s = \frac{L_w - L_l}{3 \times 10^{10}}$$

where L_w and L_1 are respectively the lengths of the wire path and light path from gap to cell in centimeters. When L_w is less than L_1 no light is transmitted through the shutter and the shutter is considered closed. When L_w is greater than L_1 the light passes through the analyzer and the shutter is considered open. When L_w is sufficiently long, the shutter will remain open for the complete breakdown of the spark. If the point on the track where the trolley must be placed to first obtain the maximum of light through the shutter, be denoted as P_1 and the point where the light just comes through with a minimum detectable intensity as P_2 , then the total time for the spark breakdown t_p is

$$t_p = \frac{2(P_1 - P_2)}{3 \times 10^{10}} \quad \text{second.}$$

It was found that $(P_1 - P_2)$ equals 400 cm., therefore, t_p is equal to 27×10^{-9} seconds. The time it takes a spark to break down to 25 per cent of its intensity with a potential difference of 9 kilovolts, at atmospheric pressure, and a 2.5 mm. gap as obtained by Rogowski and Klemper (6, p.1545), is 25×10^{-9} seconds. This agrees very closely with the observed time for t_p .

The strength of the Kerr effect in any substance is expressed by its Kerr constant, B . This may be stated by the relation

$$B = \frac{\delta d^2}{2\pi l E^2}$$

where E is the potential difference between the plates in

electrostatic units, l the length of the plates, d the distance between them and ϕ the phase angle in radians between the components of the elliptical vibration of the light parallel and perpendicular, respectively, to the electrical field.

In this experiment, we have the following values: l equals 2 cm., d equals 0.5 cm., E equals 33 1/3 electrostatic volts and B equals 2.55×10^{-5}

$$\text{Then } 2.55 \times 10^{-5} = \frac{0.25\phi}{2 \times 1111.11 \times 2 \times 3.14}$$

$$\text{And } 0.785\phi = 1.10$$

$$\text{And } \phi = 1.40 \text{ Radians}$$

$$\text{Or } 80^{\circ} 46'$$

Table I gives the Kerr constant B for a number of the more common liquids for which it has been determined. These values are given by Raman and Krishnan (13, p.725-728) and are doubtless the best that are available. There is, however, some disagreement with those given by Jenkins and White (9, p.437) as listed in Table II.

Nitrobenzene is the liquid most often used in the electro-optical shutter. It has one disadvantage, however, in that it is not colorless and it is therefore not as transparent as some other liquids. Anderson (2, p.240) found that orthodichlorobenzene is more suitable for use in cells that are to be used

TABLE I
 VALUES OF THE KERR CONSTANT AS GIVEN BY
 RAMAN AND KRISHMAN

<u>Liquid</u>	<u>Symbol</u>	<u>B x 10⁷</u>
Acetone	CH ₃ COCH ₃	16.30
Acetic Acid	CH ₃ COOH	4.18
Aniline	C ₆ H ₅ NH ₂	-1.21
Benzene	C ₆ H ₆	.60
Bromobenzene	C ₆ H ₅ Br	9.03
Carbon Disulphide	CS ₂	3.22
Carbon Tetrachloride	CCl ₄	.07
Chloroform	CHCl ₃	-3.32
Ethyl Ether	C ₂ H ₅ OC ₂ H ₅	-.62
Ethyl Chloride	CH ₃ CH ₂ Cl	4.81
Methylene Chloride	CH ₂ Cl ₂	-1.06
Nitrobenzene	C ₆ H ₅ NO ₂	254.85
Nitrotoluene	NO ₂ C ₆ H ₄ CH ₃	174.20
Toluene	C ₆ H ₅ CH ₃	.75
Water	H ₂ O	3.96

TABLE II
VALUES OF THE KERR CONSTANT AS GIVEN BY
JENKINS AND WHITE

<u>Liquid</u>	<u>Symbol</u>	<u>B x 10⁷</u>
Benzene	C_6H_6	.60
Carbon Disulphide	CS_2	3.21
Water	H_2O	4.70
Nitrotolune	$NO_2C_6H_4CH_3$	123.00
Nitrobenzene	$C_6H_5NO_2$	220.00

with ultra high frequencies. He also found it easier to handle.

Because it is impossible to buy nitrobenzene in a form sufficiently pure for use in the Kerr cell, it is necessary to purify it in the laboratory.

There is no allowance made for a time lag in the Kerr cell, but as Beams and Lawrence (5, p.170) pointed out, "There is at the present time no experimental evidence for the existence of a lag of the Kerr effect behind rapidly changing electric fields." It is possible, therefore, to deal with intervals of time as short as 10^{-9} seconds with an accuracy depending upon the ability to measure the length of the electrical circuit to the Kerr cell.

The Kerr cell is a very effective device for the measuring of short intervals of time and for studying various phenomena. It is not too difficult to construct or operate and can be used in the laboratory for study and demonstration purposes as well as for research.

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