UNDERWATER TURBIDITY MEASUREMENTS

BY

ATHELSTAN F. SPILHAUS JR.

S.B. Massachusetts Institute of Technology

(1959)

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May, 1960

Signature of Author ______________________

Department of Geology and Geophysics
May 21, 1960

Certified by ______________________

Thesis Supervisor

Accepted by ______________________

Chairman, Departmental Committee on

Graduate Students

Abstract

Underwater Turbidity Measurements

by Athelstan F. Spilhaus Jr.

Submitted to the Department of Geology and Geophysics in partial fulfillment of the requirements for the degree of Master of Science.

The purpose of this study was to propose a design for an underwater light scattering photometer that will make measurements of certain potentially useful optical variables in sea water. A very simple bathyphotometer was constructed and used to obtain first hand knowledge of some of the problems of underwater instrumentation. A design and method of calibration are proposed for a new photometer. This instrument will yield values of the extinction coefficient for a number of discrete wavelengths and the percent of polarization of the light scattered at 90°. Some of the possible interpretations of these data are indicated.

Thesis Supervisor: Columbus O'Donnell Iselin
Professor of Oceanography

TABLE OF CONTENTS

TABLE OF FIGURES

I. INTRODUCTION

During the infancy of oceanography batches of sea water were classified using simple thermometers and some elementary chemical analyses. There were no techniques for obtaining samples from depth and in order to measure the temperature at a given location and to obtain a water sample the ship had to heave to. As time progressed the instrumentation improved. Temperatures and water samples can now be obtained from great depths; however, this is a tedious job and very little space can be covered by a single ship that is hove to most of the time. Further improvement has resulted in continuously recording instruments for some variables as a function of either depth or time. Extention of this to greater depths and more variables is one of the major problems facing oceanographers today.

Sea water is generally classified by its temperature and salinity. Sometimes variables such as dissolved oxygen are used. Only an overall picture of the steady state can be obtained from such measurements because small scale features are washed out by the movement of the sea during the time required to retrieve the sample collectors. For obtaining a view of small scale, rapidly changing features, continuous measurements are imperative.

Temperature and salinity can both be measured continuously to moderate depths. Unfortunately these often will not yield sufficient detail, especially where there is little variation in them.

A further possibility for classifying sea water is using some of its optical properties. The extinction coefficient, the absorbtion at various wavelengths and others could prove valuable for labelling a parcel of water. The coefficient, also called the turbidity, is defined for a unit length of a given medium by: $\gamma = \log \frac{I_o}{I}$, where I_o is the intensity of the light before it enters the medium and I the intensity as it leaves.

The objective of the study was to propose a design for an instrument to measure some of the useful optical variables.

Previous work on this problem is confined mainly to measurements of the extinction in the surface layer and measurements of illumination at depth. The Secchi disk is the oceanographer's primordial device for measuring turbidity. As a matter of historical record, this was the first turbidimeter (13). An improvement on this technique has been made by Clarke. He has devised a bathyphotometer capable of measuring illumination continuously at great depths (2). Prior to this attempts to use photographic methods were made by Koczy and Jerlov (5). Jerlov has designed a transparency-meter; however this would supply only information regarding relative turbidities and is subject to numerous errors arising from the complicated optical system employed (4).

The name of Tyler is also a prominent one in the field of underwater light transmission and scattering. He has devised instruments for making individual measurements; however, his work has been more closely related to how light behaves in various media than what use can be made of it (8, 9, 10, 11, 12).

Much work has been done on samples brought onto the deck and further processed or analyzed immediately (1). This is certainly less satisfactory than "in situ" records if one desires a detailed picture. Measurements of spectral absorbtion have been made by Hubbard using natural light and an underwater spectrometer (3). Here again only relative values were obtained. No information regarding the amount or the size of the absorbing matter could be gathered from these experiments.

Light-scattering measurements were made by Ketchum and he attempted a correlation with Secchi disk readings (6). Unfortunately the data obtained on one lowering could not even be satisfactorily compared with the next because there was no assurance that the geometry of the light path or the intensity of the source remained constant.

In designing an instrument for use in measuring optical variables the problem was to try to eliminate the errors inherent in the devices of others and yet maintain a device simple enough that the inevitable shipboard mishaps would not affect the data. Furthermore, only measurements of actual physical quantities such as the extinction coefficient that are independent of the instrument were permitted.

II EXPERIMENTAL PROCEDURE AND RESULTS

After a survey of the literature and discussions with some of the individuals who have worked with underwater photometers, a very simple one was built. It consisted of two pressure cases one of which contained a light source and the other a photomultiplier dectector.

The light source was a three volt tungsten filament bulb placed at the focal point of a lens so designed that a columnated beam emanated from the pressure case through a plexiglass window. Dry cells supplied the necessary current.

The pressure cases were 4 inch aluminum tubes. The ends were flat plates fitted tightly with O-rings. One end held the plexiglass window and the other had a spark plug that served as a electrical feed-in. The cases were attached to a 6 foot piece of aluminum T by connecting devices that allowed sliding along the T and complete rotation about themselves. With this arrangement it was possible to obtain any angle between the detector and the source. In direct line separations up to one meter were achieved.

The photomultiplier detector was an RCA 931-A which was wired as shown in figure 1. This circuit is a modification of that employed by Ketchum (6). In order to draw as little current as possible from the batteries 10 megohm resistors were placed between stages. When this was done the light-activated current becomes an appreciable

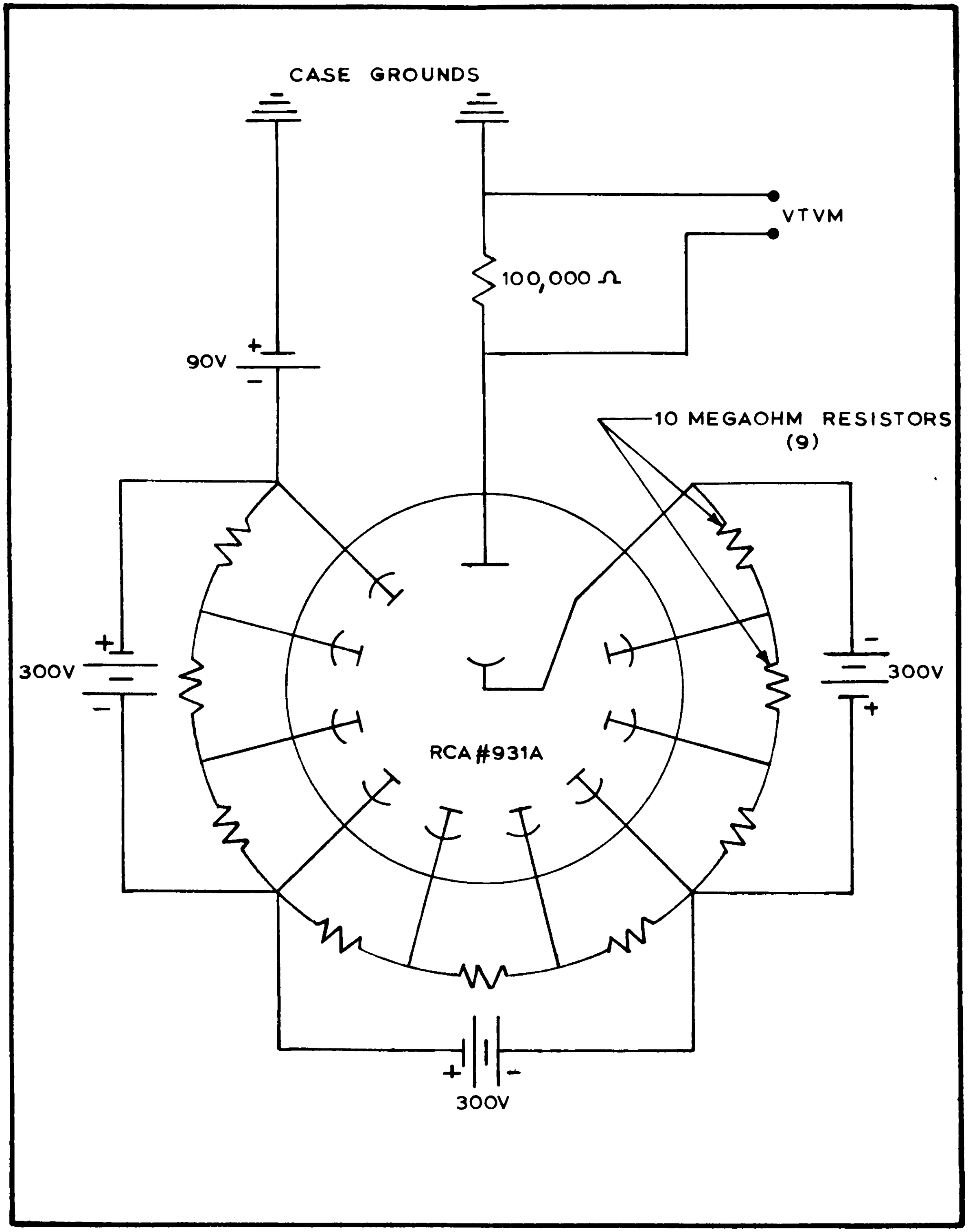

FIGURE 1

CIRCUIT FOR PHOTOMULTIPLIER RCA #931A

fraction of that drawn from the batteries. To maintain an equal potential drop across each stage the batteries must be connected individually instead of simply using the whole 900 volts between the anode and the cathode. A 90 volt battery was placed between the last stage and the cathode to ensure a constant potential drop at this point. Such a bias extends the range of linearity of the device. This range was checked by using an optical bench and a point source of light and comparing the inverse square law with the experimental results. Further experimentation with the photomulitplier tube revealed that the resistance between stages did not affect the response of the device as long as the potential across each stage was the same.

The signal was the voltage drop across a 100,000 ohm resistor that was kept on deck. It was read out with a vacuum tube voltmeter and was between 0.1 and 2.5 volts.

In the detection unit interference filters could be situated in front of the photomultiplier tube. The wavelengths available were 466,546 and 669 millimicrons. A polarizing filter was also available.

Several important design considerations were pointed up by the experiments. The most important of these was the steadiness of the light beam and optical components that must be maintained in order to obtain consistent readings. Slight misallignments can result in drastic errors, especially if either the beam ar the receiving aperture is small and there is variation in light intensity through the beam.

Three wavelengths were not enough to make possible a distinction between colour absorbtion and the change in turbidity with wavelength that is due to the particle size.

A third problem was that of the disturbance of the water at the windows. This was caused by the fact that the window protruded from the face of the pressure casing.

III RECOMMENDED INSTRUMENTATION

A. General: The instrument recommended is a photometer consisting of two detectors and a light source mounted on a rigid frame. The detectors are at right angles to each other and one measures the incident beam and the other the light scattered at 90^{o}. There is a depth sensing potentiometer which is battery operated attached to the frame. The instrument is connected with the surface by a four conductor cable and data is obtained from the records of three high input impedance recording potentiometers.

B. The Frame and Pressure Casings: The operating components must be attached to a single rigid frame. This frame, as shown in figure 2, consists of two rectangular shaped pieces that are linked at three points by disks that serve as the faces for the pressure cases that enclose the circuitry. It is for this reason that the outer sides of these disks are raised and slotted for O-rings. The cases are attached by screws through holes drilled in the flange-like surface of the disk. The cases must have an inside diameter of 8 inches in order to contain the filter changing mechanism. The thickness of the walls depends entirely on the depth range desired. In the back of each casing there should be an appropriate number of electrical feed-in components. The Joy Manufacturing Company produces a plug that screws in and employs an O-ring pressure seal that has been found quite

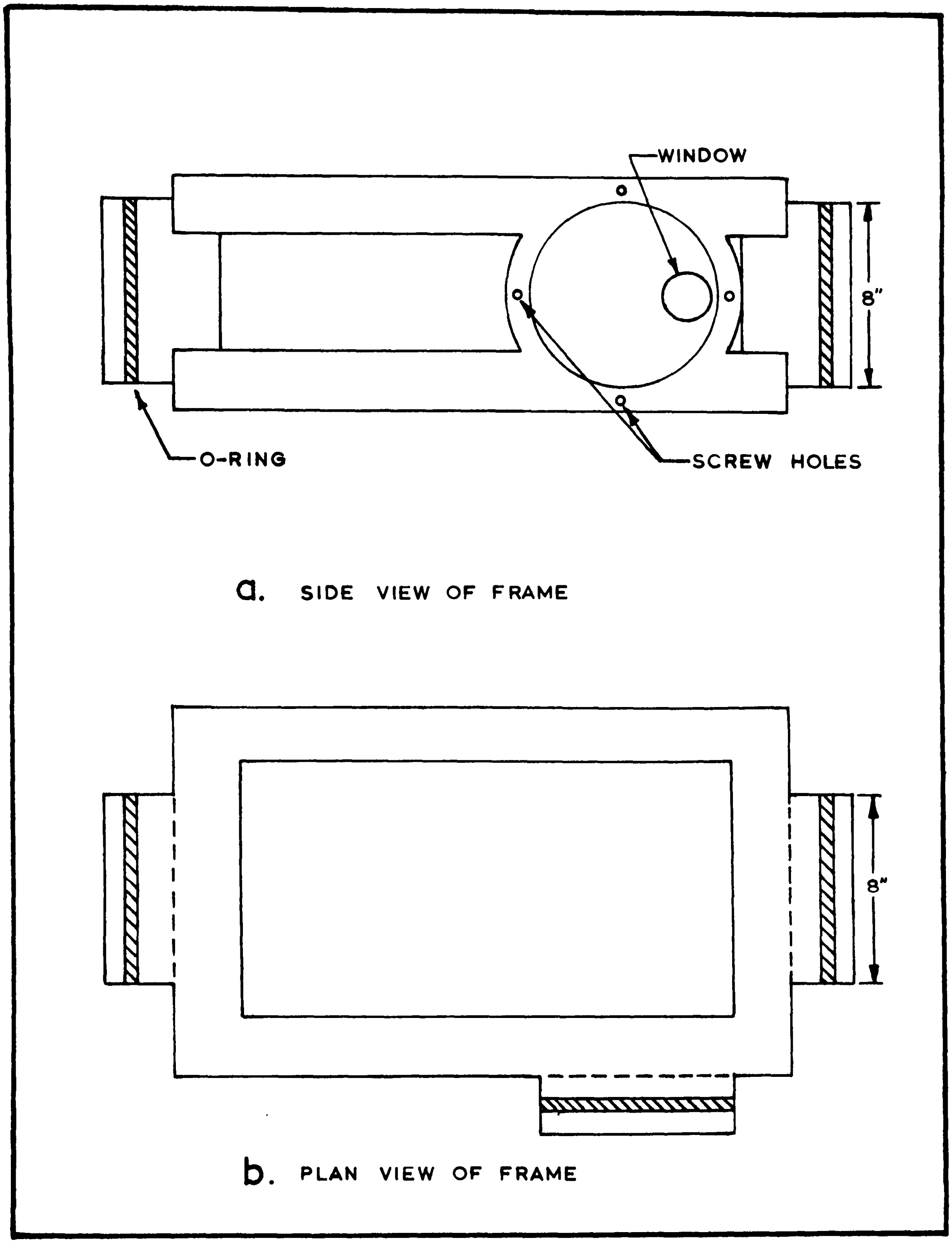
WINDOW
8"
O-RING
SCREW HOLES
a. SIDE VIEW OF FRAME
8"
b. PLAN VIEW OF FRAME

FIGURE 2

satisfactory in these applications. The feed-in itself is a male fixture and the connector is a rubberized female plug that prevents electrical leakage through the sea water to ground.

The faces must each have a plexiglass window set into them. These windows should be located halfway between the two frame members as indicated in figure 2. This minimizes the error introduced by reflections off the frame into the detectors. The windows should be set into a hole in the face in such a way that the front is flush. This cuts down the turbulence. O-rings are necessary to ensure a watertight seal.

C. The Light Source: The light source must contain a tungsten filament bulb. Such a bulb has a spectral output that increases toward the infrared. This partially compensates for the decreasing response of the photomultiplier tube in that direction.

The spectral output of a tungsten filament bulb is largely dependent on the voltage across it. In order to maintain a constant voltage the circuit shown in figure 3 is used. A resistor is placed in series, and a zener diode in paralell with the bulb. The diode should have a nominal zener breakdown voltage equal to the voltage to be maintained across the bulb. The resistance is determined by the formula:

$$R = \left(E_{IN} - E_Z\right) / I_R$$

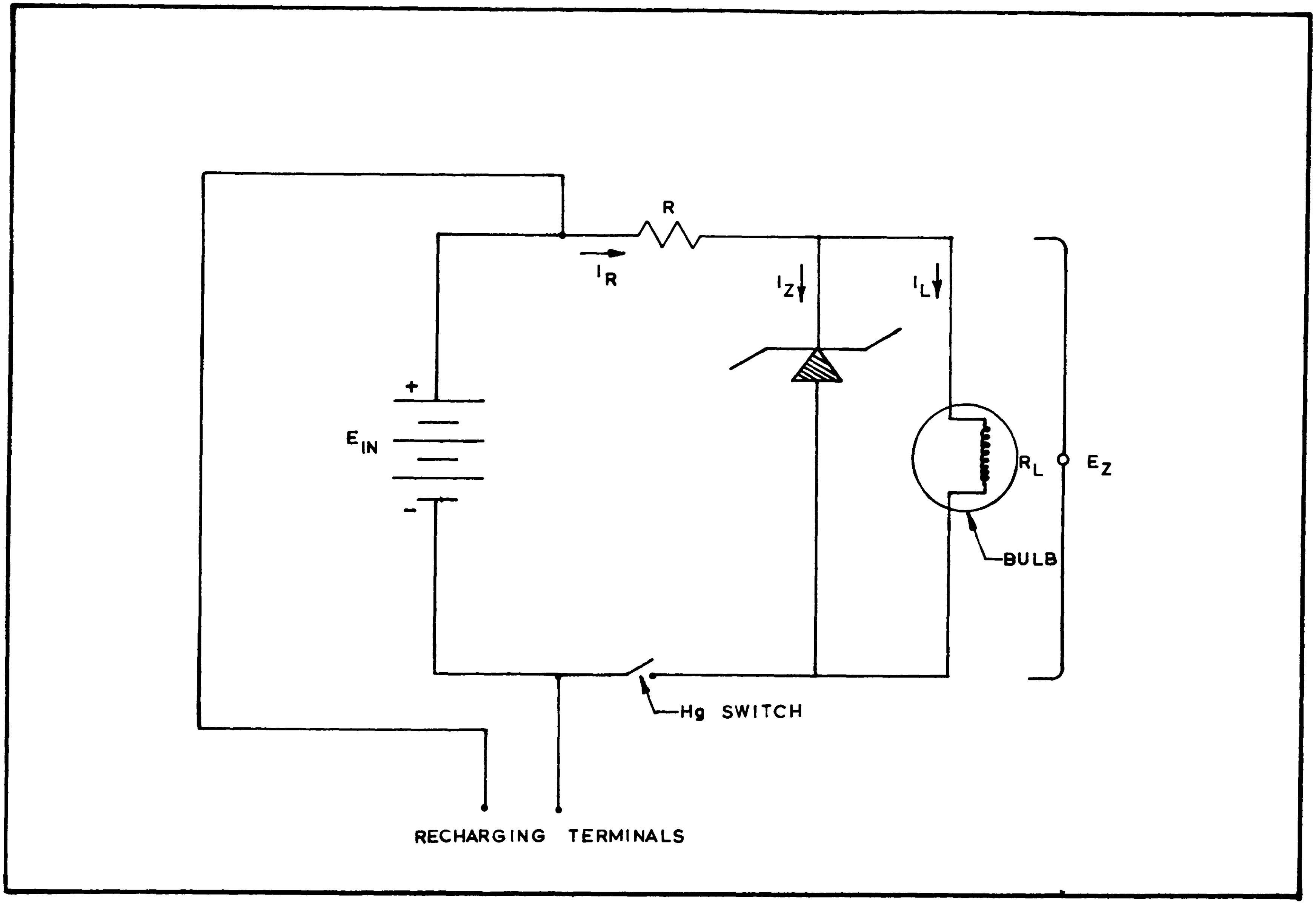

FIGURE 3

CIRCUITRY OF THE LIGHT SOURCE

I_R is determined from: $I_R = I_Z + I_L$, where $I_L = \frac{E_Z}{R_L}$ and I_Z is a characteristic of the diode chosen. The power rating of the diode must be above that of the bulb to protect it in the event of a burnout.

A mercury switch is provided so that the source may be turned off without opening the case. A rechargable battery should be used and there must be two Joy plugs on the light source pressure case for recharging purposes. An excellent battery for this application is the Yardney silver-cell. This battery has a 20 ampere-hour life and is a rechargable wet cell that can be used in any orientation.

The bulb should be firmly mounted behind a lense in such a way that a reasonably columnate beam issues from the window. A diaphram should be used in combination with the lense to give a beam that is approximately 1/2 inch in diameter. A beam of this size will more than cover the whole filter in the detector and slight motions of the frame due to tensions will not affect the results materially.

A device must be included for chopping the light beam. Between the bulb and lense a light tight disk is placed. This disk has one hole for the light to shine through. A disk with a semicircular slot in it is then rotated past the hole by an electric motor. The speed of this motor should be such that the light goes on and off at least once for every filter change. The slot coincides with the hole half of the time; therefore, the motor should revolve once in a time equal to the sum of the charging and discharging time of the capacitor in the pulsing circuit of the filter changing mechanism. There must be felt around the hole to insure no light leakage.

D. The Detection units: Both detectors are identical except that the pulsing circuit for changing filters is common to them. Working in from the windows the first thing that one comes to is the filter changing mechanism. This consists of a disk 7 inches in diameter whose outer edge has gear teeth. This disk holds the filters in a symetrical array around it leaving 1/4 inch between each. There is one blank spot so that the dark current of the photomultiplier tube can be determined. One spot is clear and one has a polaroid filter. There are fourteen other positions and each one is occupied by a 1/2 inch interference filter. Each one of these filters has associated with it a diaphram that makes the order of magnitude of all the signals the same.

The hole through which the light is transmitted from the window should not be much larger than the filter and there should be felt between it and the filter disk as shown in figure 4.

The filter is changed by a single rotation of the motor. This acts through the gear train shown in figure 4 and is made possible by cutting the gears correctly.

The filters must be moved at intervals that allow the device to come to equilibrium after each change and yet

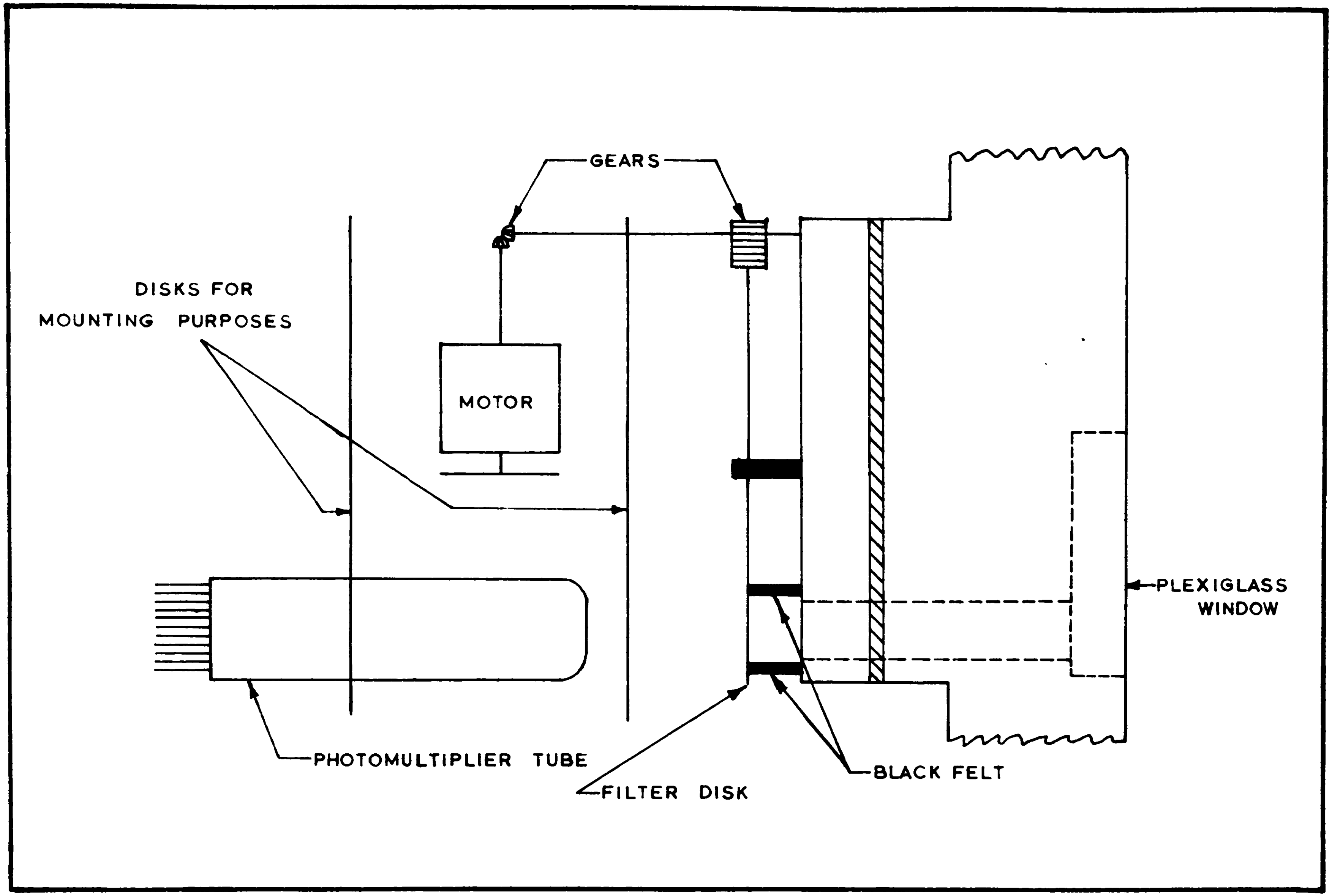

FIGURE 4
FILTER CHANGING MECHANISM

not so slowly as to incur the disadvantages attendant with batch sampling. Each filter should remain in front of the photomultiplier window for a few seconds. The time necessary will be primarily dependent on the instrument used for recording the data.

The motors driving the filter disks are required to start and stop at definite intervals. There is a cam on the shaft of the motor which is slotted at one place. This cam holds a microswitch closed except when the arm falls into the slot. A cycle of the motor is given as follows, starting with the microswitch arm in the slot, that is the switch in position A as shown on figure 5b. The controlled rectifier, 2N1595, is given a pulse from the pulsing circuit that is described later. This allows a current flow I_{CR} which starts the motor. As the cam turns the switch arm moves to position B. The motor is now on and current ceases to flow in the rectifier. The motor continues for one full revolution at the end of which time the switch arm falls back in the slot and position A is resumed. The 15 ohm resistor serves as a brake for the motor and the 0.1 microfarad capacitor cuts down the transients across the rectifier that might start it before the next pulse is delivered. There is one of these driving circuits in each of the detection units.

To eliminate the necessity for synchronization, there is one pulsing circuit for both of the driving ones.

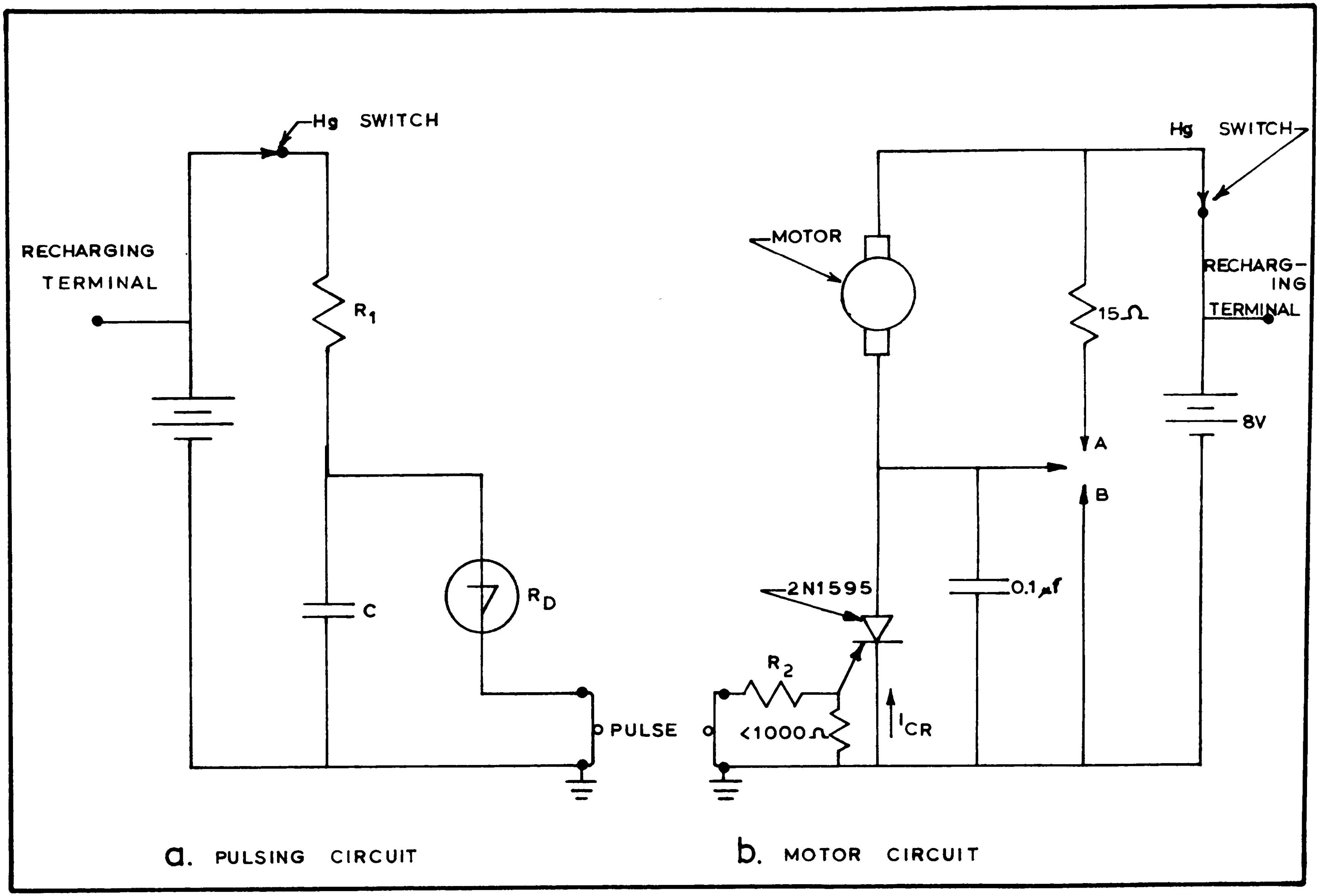
Hg SWITCH
RECHARGING
TERMINAL
R1
C
RD
PULSE
a. PULSING CIRCUIT
MOTOR
Hg SWITCH
RECHARG-
ING
TERMINAL
15Ω
8V
A
B
2N1595
0.1μf
R2
<1000Ω
ICR
b. MOTOR CIRCUIT

FIGURE 5

the pulsing circuit is shown in figure 5a. It is an RC circuit with the following modification. A four layer transistor diode is placed in parallel with the capacitor through the gates and cathodes of the controlled rectifiers. Until the voltage across the diode reaches a certain level it acts like a very high resistance and allows the capacitor to charge. After this point it switches to a low resistance and the capacitor discharges through it delivering a pulse to the gate of the rectifier. The diode switches back to a high resistance element when the current through it reaches a sufficiently low level.

The parameters of this circuit can be calculated as follows:

$$\tau_1 = \text{charging time constant} = R_{eq} C$$

where $R_{eq} = [R_1 (R_D + R_2)] / (R_1 + R_D + R_2)$

$$\tau_2 = \text{discharging time constant} = R_2 C$$

One fact that must be born in mind when calculating these parameters is that I_D must start above 20 milliamperes to guarantee triggering both rectifiers.

During charging the voltage across the capacitor is given as a function of time by:

$$E_c = E_{max} \left(1 - e^{-t/R_{eq}C}\right)$$

The charging ends when E_c reaches the switching voltage of the diode and does not begin again until I_D falls below the value for the holding current which is a characteristic of the component selected. This current may vary between 1.0 and 5.0 milliamperes.

The recommended photomultiplier tube is RCA 6217. This is an end on sensitive tube with a spectral response of greater than ninty percent of its peak between 3600°A and 5700°A, and greater than ten percent at 7000°A. A circuit for this tube is shown in figure 6. Batteries are used across each stage instead of a voltage divider. This ensures equidivision of the potential and in such a low drain situation the life of the battery approximates its shelf life the battery recommended is Burgess type XX69 which is 103 1/2 volts. Two of these are required between the anode and the first stage and one more for each succeeding stage. Between the last stage and the cathode there is a resistor in series with the battery. The voltage drop across this resistor is a measure of the output of the tube and is the signal which is read on deck.

The tube should be wrapped with mu-metal for magnetic shielding.

The batteries used for the pulsing circuit and for running the motors should be rechargable. Provision must be made for recharging without opening the pressure case.

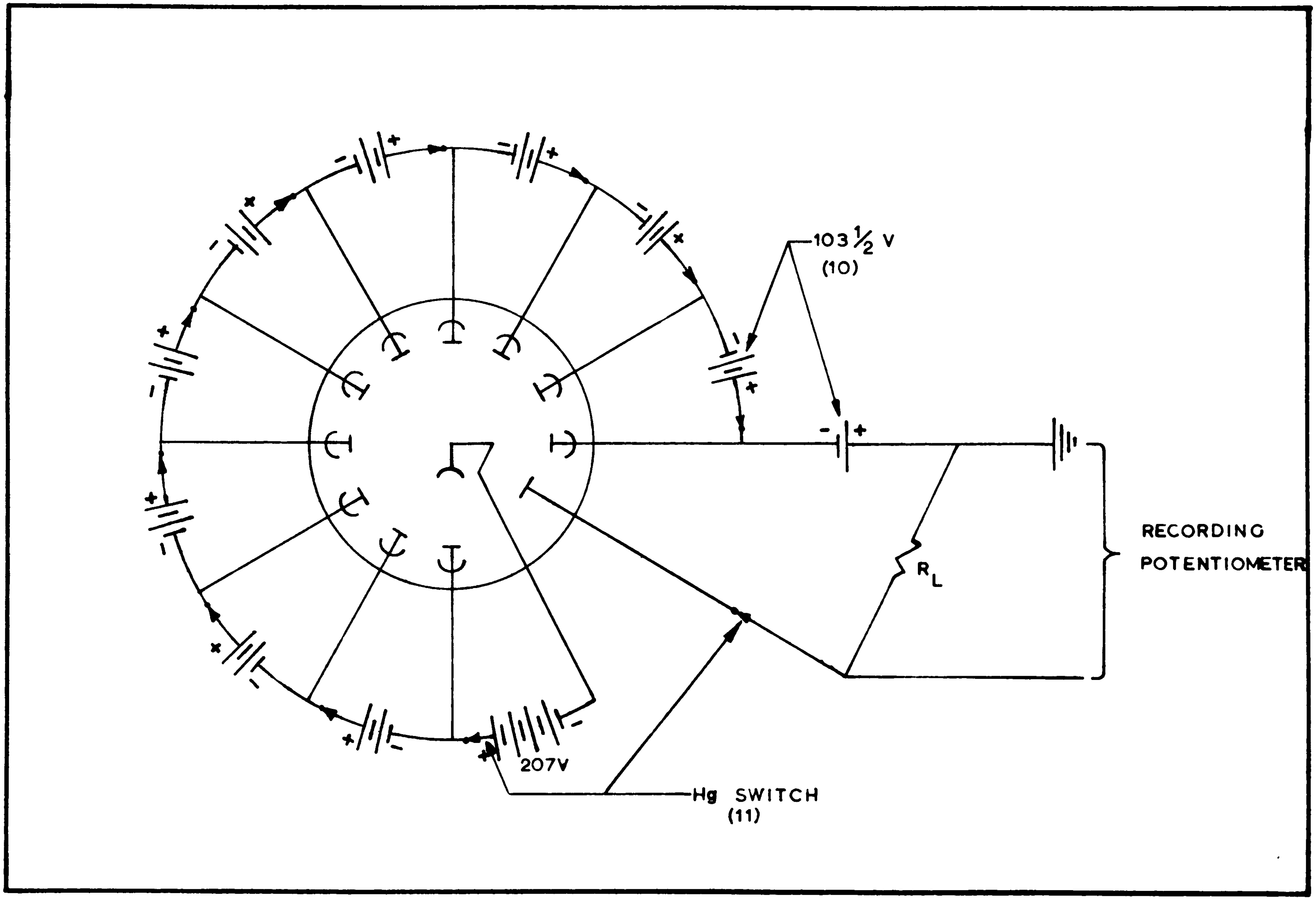

FIGURE 6
CIRCUIT FOR PHOTOMULTIPLIER RCA # 6217

IV DATA PROCESSING

The data are recorded on three potentiometers. They appear as a record of voltage versus time so they can be compared on a time basis. The lowest reading is that of the blank place on the filter changing disk and this gives the dark current which must be subtracted from all the readings. For each filter setting except the blank there will be two voltage levels. One of these is while the beam is on and the other while the beam is off. The latter must be subtracted from the former since it represents the contribution of ambient light to the readings.

Having deducted the contributions of the dark current and ambient light to the readings the calibration factors must be applied to find the turbidity and the percent of polarization of the scattered light.

The turbidity is found from the equation:

$$\gamma_\lambda = \frac{A_\lambda \, I_{90}}{B_\lambda \, I_0}$$

, where A and B are constants determined for a given wavelength during calibration. I_{90} and I_0 are the voltages recorded from the two detectors.

The percent of polarization is obtained from:

$$\% = \frac{I_{90}\,(\text{white}) \times \text{transmittivity of the polaroid}}{I_{90}\,(\text{polarized})}$$

where the transmittivity is determined during calibration.

V CALIBRATION TECHNIQUE

The spectral response of the system as a whole must be found and a relation between the extinction coefficient and the recorded intensities established.

The first step is to hang the instrument in its operating position in a dark place where the atmosphere is relatively free from scatterers. The intensity is then read on the voltmeter for each wavelength. Since there are essentially no scatterers on absorbers, the intensity should be equal at each wavelength. If it is not, find the factors, B_{λ} ; that will perform this function. Applying these factors places the readings on the same basis so they can be compared.

To determine the response of the scattering detector a bath in which the instrument can be immersed must be prepared. This bath should contain distilled water and duPont Ludox. Ludox is a colloidal silica suspension that obeys the fourth power law of scattering. This means that the turbidity varies with the inverse of the fourth power of the wavelength of the light used according to the theory of Lord Rayliegh.

The instrument should be immersed in the bath and the turbidity determined from the equation:

$$I_{Bath} = I_{air} e^{-\gamma \ell}$$

where ℓ is the length of solution between the source and the detector. At the same time I_{90} must be measured. This intensity is then related to the turbity by:

$$\gamma_\lambda = \frac{16\pi r^2}{3v} \frac{I_{90}}{B_\lambda I_0}$$

under the assumption that the sum of the lengths from the centre of the scattering volume to the detector windows divided by 2.303 and multiplied by γ is small in relation to $\log \frac{16\pi r^2}{3v I_0}$ (7). For this reason the concentration of the bath should be kept as low as possible. Since γ and I_0 and I_{90} are known, $\frac{16\pi r^2}{3v}$, a constant previously called A_λ can be calculated.

To determine the transmittivity of the polaroid filter the white intensity is measured in the Ludox solution and then the intensity using the polaroid. Since the Ludox particles are small, all the light scattered at 90° is polarized, and, therefore, the ratio of the filtered to the unfiltered light is the transmittivity of the polaroid filter.

VI INTERPRETATION OF RESULTS

The results obtained from the device are in the form of turbidities and percent of to scattered light polarized.

The turbidity is obtained at fourteen wavelengths. If these turbidities are plotted on log graph paper versus the wavelengths, a straight line is obtained in the absence of absorbtion. If a straight line is drawn through as many of these points as possible, bearing in mind that no points may fall below this line, the slope is a measure of the average particle size. The range is from minus four for particles.smaller than the wavelength of light to zero for very large particles. Points that fall above this line indicate absorbtion increases at those wavelengths. Particular points to look for are 675 and 750 millimicrons which are characteristic of chlorophyll and 475 millimicrons which represents the yellow and blue matter in plants.

The percent of the scattered light that is polarized gives the ratio of the Rayliegh to the Mie scattering. This coupled with the turbidity measurements gives a qualitative idea of the size distribution of the particles.

Use of such an instrument provides the means of measuring parameters which have not previously been available to describe sea water.

VII LITERATURE CITATIONS

(1) Clarke, G.L. and H.R. James, "Laboratory Analysis of the Selective absorbtion of light by Sea Water", J.O.S.A., 29, 43-55 (1939)

(2) Clarke, G.L. and Wertheim, "Measurements of Illumination at Great Depths and at Night in the Atlantic Ocean by means of a New Bathyphotometer", Deep Sea Research, 3, no. 3, P 189 (1956)

(3) Hubbard, C.J. and W.S. Richardson, "Measurement of the Spectrum of Underwater Light", Wood Hole Oceanographic Institution, Unpublished Manuscript, Ref. #59-30, (June 1959)

(4) Jerlov, N.G. "A Transparency-Meter for Ocean Water", Tellus, 9, P 229 (1957)

(5) Jerlov, N.G. and F. Koczy, "Photographic Measurements of Daylight in Deep Water", Reports of the Swedish Deep Sea Expedition, Vol. 3, Physics and Chemistry No. 2, P 63-9.

(6) Ketchum, B.H. and D.H. Shonting, "Optical Studies of Particulate Matter in the Sea", Woods Hole Oceanographic Institution, Unpublished Manuscript, Ref. #58-15 (Feb. 1958)

(7) Maron S.H. and Lou R.L.H., "Calibration of Light Scattering Photometers with Ludox", Journal of Polymer Science, 14, 26-36, (1954)

(8) Tyler, J.E., "Underwater Photometer," J.O.S.A., 45 904A (1955)

(9) Tyler, J.E., "Monochromatic Measurement of the Volume scattering of Natural Waters" J.O.S.A., 47, 745-747 (1957)

(10) Tyler, J.E., "A Nephelometer for Underwater Measurements" J.O.S.A., 47, 346A (1957)

(11) Tyler, J.E., "Nephelometer for the Measurement of Volume Scattering Function in Situ", J.O.S.A. 48, 354-357 (1958)

(12) Tyler, J.E., "Comparison of Light Distribution Above and Below Water, Jour. of Mar. Research, August 1958.

(13) Willard, H.H., L.L. Merritt and J.A. Dean, "Instrumental Methods of Analysis", Princeton, D. Van Nostrand, Company, Inc. P 90 (1958)