A Study of High Intensity Light Sources for Use in the Photography of Effects Observable in an Expansion Chamber.

by

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SUMMARY

The light sources chosen for special study were arc tubes through which a condenser was discharged. The discharge was initiated by an external control electrode. Tubes were made of Pyrex or quartz and had cathodes of mercury or nickel. Work was first done with mercury tubes at low pressures. Later, tubes were made having nickel cathodes and filled with argon. Tubes were tested to see at what voltage they discharged spontaneously and hence if they could be used with the 20,000 V power supply available. A 2500 V power supply was obtained for use with low voltage tubes.

An integrating light output meter was constructed for measuring the light output of the tubes. Using this meter relative readings of the light output of tubes used under different conditions were obtained. Fine fibres were set up and illuminated in a manner reproducing conditions of cloud tracks in an expansion chamber. The fibres were then photographed to get an indication of whether the light sources would be practically useful, and of their effects on a photographic emulsion.

Experimental results indicate that low pressure arc tubes are not a practical means of obtaining high voltage operation. Mercury cathodes were shown to be little better than nickel ones in all types of tubes studied; and have the disadvantage of becoming dirty. In gas filled tubes having pressures of the order of a few centimeters of mercury, the light output is greatest when the bore of the tube is small. A good line source for cloud chamber work was made out of ordinary Pyrex capillary and had a life of over 100 flashes.

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CONTENTS.

INTRODUCTION.

PURPOSE OF RESEARCH For many years cloud chamber workers have had trouble in ~~acquiring~~ obtaining enough light to photograph their cloud tracks. Few have devoted much attention to this problem . Most researchers seem to have been satisfied with something that barely answered to their minimum requirements. This was often a constant source of trouble.

It was proposed, therefore, to investigate the characteristics of light sources commonly used with a view to their adoption for cloud chamber technique. Further investigation was to be conducted into methods of concentrating the light. What was desired was a source that could be made and used in any moderately well equipped laboratory.

The intensity of a continuous source was the characteristic of chief interest. For an "instantaneous" source the total light output had to be known, and it was necessary to be sure that the duration of the flash was short enough to provide sharp photographic images without the use of a shutter. Of course, the flash of any condenser discharge arc is likely to be short enough for this purpose.

Since the exposure had to be made at just the right time, the control of the light source was of prime importance. Only a very slight delay was allowable for the control of switching mechanism to start the light source.

The geometrical form of the source had to be such that it simplified the focussing problem. A line source represents the ideal shape by this criterion, although point sources may also be readily focussed and several may be used to get a flat beam.

Due attention had to be paid to the spectral characteristic of the source. However, any source that was not photographically inefficient on this account was perfectly acceptable. Lastly, reliability was required, and long life was highly desirable because of the large number of pictures taken in work with an automatic cloud chamber.

<u>HISTORICAL BACKGROUND</u> Most papers on cloud chamber technique deal only very briefly with the type of light source used. Workers in this field have used a great variety of devices to provide light for their photographs. However, the most usual source used by early workers was some form of the mercury arc. This type of source was used by Wilson in 1912 (1)# and many other workers up to the present day. Wilson's procedure was typical of many mercury sources. His tube was of quartz, filled with mercury, and nearly surrounded by a silver shell. The mercury was vapourized by heat from a burner, conducted by the silver shell. A group of Leyden jars charged to a high potential was discharged through the mercury vapour so formed. Sources similar to this one were used up until about 1930. For example, Blackett (2) discharged a 1/30 mfd. condenser charged to 35 KV through a 3mm. quartz capillary containing mercury. He observed that a 1 mm. capillary had a shorter life but used more of the available energy.

The numbers in brackets refer to the Bibliography.

Skobelzyn (3) in 1927 used a continuous arc at 100 amp. for a short period. Exposures were made with shutters on both the lamp and camera. Curtiss (4) described in 1929 a design for a Pyrex tube filled with mercury. The whole tube was sealed off from the atmosphere. Tungsten electrodes were used and a short vertical column of air was left above one end of the mercury to act as a cushion. The mercury was vapourized by a heating coil of tungsten wire wound about the capillary section.

In 1933 Dahl and his colleagues (5) reported a mercury arc in a Pyrex envelope which was used with a 0.3 mfd. condenser at 30 KV. Dahl used two lamps in parallel connected to a magnetically controlled. spark-gap switch. He succeeded in making his tubes last up to 4000 flashes, after which he noted that they either became inefficient because of fine cracks on the inner Pyrex wall or blew up.

Bearden tested a Pyrex capillary and mercury source and in his paper (6) gives some information about its characteristics. He discussed the effects of different gases in the tube, particularly with reference to the voltage at which this type explodes.

In all sources using quartz capillary tubes the vapour was used at, or near, atmospheric pressure. This was because electrodes cannot be sealed directly into quartz and a special method (such as graded seals) was expensive when the tubes had such a short life. Each of the sources already mentioned required some kind of switching device for their operation. This created a difficult problem when dealing with potentials of many thousands of volts. An ordinary mechanical switch wasted much energy from sparking at high voltages.

Vacuum insulated mechanical switches had been proposed and one such design is given by Vaudet (7). In a long article on light sources he describes a vacuum switch worked by external magnets. However, he did not retain this design as practical and instead used a similar one in air. In some cases where a transformer was used to supply high voltage a switch in the primary circumvented this difficulty. Blackett and Occhialini (8) used a large transient current from a 4 KV transformer through a quartz mercury capillary source. In a more recent paper Blackett (9) reports a 8KV transformer used at 100 amp. primary current.

The switching problem has been met in a number of ways. Some auxiliary switching tube such as a thyratron or ignitron might be used in series with the source. However, energy losses in the switching device are important, and so it is preferable to have the control in the light emitting tube itself. Discharge in electronic tubes has been controlled by an igniter electrode, an auxiliary cathode or anode, by a grid, or by a magnetic field which affects the mean length of the path of the particles. A simple method due to Edgerton (10) is that of the external control electrode. This type of control uses an electrode in contact with the outside wall of the discharge tube. Now if the spontaneous striking voltage is but slightly above the applied voltage, a discharge may be initiated by applying one or more sharp pulses to the external electrode. The action of this pulse is to start a flow of electricity to the glass or quartz wall, producing a great many ions as in the technique often used for finding leaks in vacuum apparatus.

External electrode control was first used by Edgerton (10) in a mercury stroboscope tube. Later he applied it with much success to other gas filled arc tubes. The principal advantage of the external system is the rapidity and efficiency with which the tube may be "triggered". This was originally accomplished by discharging a condenser through the primary of a spark coil in series with a thyratron. The positive pulse released at the secondary of the transformer by the thyratron was applied to the control electrode. Extensive investigation into flash tubes of different kinds was carried out by Edgerton (11). He measured the integrated light output of his tubes with a phototube which was allowed to charge up a condenser. The condenser voltage was then found with a vacuum tube voltmeter. This method (11) forms the basis of the meter described in this report under the heading "Experimental Work".

Street and Stevenson (12) experimented with a quartz tube filled with mercury, mounted vertically, and water cooled. It was operated for short periods from a 5 KW, 220 to 22000 V transformer. They state that a Tesla coil was used to ensure starting but do not say how this was done. The coil was not used for complete control, however, as the power was controlled by a circuit breaker in the transformer primary which was adjusted to open after 2 or 3 cycles.

There are now on the market several commercial lamps for high speed photography developed from Edgerton's work. The General Electric FT-14 and the Sylvania R4330 and R4340 are examples. Sylvania Electric's R4330 is an extremely efficient and reliable light source. It is eminently suitable for cloud chamber work except where a line source is desired. The form of this tube is that of a helix about one inch in diameter and two and a half inches long, enclosed in a cylindrical glass envelope.

No account of cloud chamber sources would be complete without mention of the exploding wire type. A source of this kind has been described by Klemperer (13). A fine piece of tungsten wire (5 cm. long and 0.1 mm. in diameter) carried current from a 1/3 mfd. condenser charged to 50 KV. This large current immediately heated the wire to incandescence, vapourizing it in the process and giving a great flash of light. Difficulties in high tension switching (not mentioned in Klemperer's article) are met with here. The need for replacing the wire for each flash makes the exploding wire inconvenient for use with automatic cloud chambers. In 1928 an extremely complicated apparatus was constructed by Nimmo & Feather at the Cavendish Laboratory for automatically replacing tungsten wire in this type of source. This device was discarded shortly after its completion and was not regarded as practical.

A few sources other than those already mentioned have been used with varying degrees of success. 2000 W motion picture flood lamps (14), projection lamps (15), arc lamps (16, 17), and incandescent wires (18) have been used for continuously operated sources. Overloading photoflood or ordinary tungsten bulbs, for example, putting 200 volts on a 110 volt filament, is a method once in use in this field. These types of sources are clumsy and cannot be focussed in the ordinary way. This limits their use considerably. Another kind of instantaneous source has been provided by calcium-magnesium sparks(19).

THEORY Unfortunately most modern theories of arc and spark discharges are too complicated to enable one to interpret experimental results in terms of them. The transient nature of a condenser discharge arc complicates the problem so that while considerable work may be found on continuous discharge, much less is known about the theory of those of short duration. Much work has been done in the field of the high pressure mercury arc due to its present commercial importance. W. Elenblaas (22) and Adams & Barnes (25) have attacked this subject.

More useful are the simple theories developed by J.S. Townsend and Sir J.J. Thomson. Townsend based his theory on the assumption of ionization by collision. His well known equation is of the form:

$$i = \frac{i_0 (\beta_n - \beta_p) e^{(\beta_n - \beta_p)d}}{\beta_n - \beta_p\, e^{(\beta_n - \beta_p)d}} \qquad (1)$$

where i = current $\qquad i_0$ = constant

d = distance between electrodes

β_n = number of ion pairs produced per centimeter of advance of a negative ion

β_p = number of ion pairs produced per centimeter of advance of a positive ion

Thomson's equation, which is based on the assumption that cathode bombardment by positive ions ejects negative ions, is:

$$i = \frac{i_0\, e^{\beta_n d}}{1 - \gamma (e^{\beta_n d} - 1)} \qquad (2)$$

where γ = number of electrons ejected from the cathode per positive ion, and other quantities as already defined.

In each of these equations, if we put the denominator of the right hand side equal to zero, we get a condition for sparking.

This is an important result of these equations. Although each theory is based on a different assumption, it has not been possible to state which is correct. Probably both processes take place. It has been shown, however, that the sparking phenomenon may be represented by Thomson's equation alone. The condition for sparking gives:

$$Y = \frac{1}{\left(e^{\frac{P_n V_s}{F}} - 1\right)} \qquad (3)$$

where V_s is the sparking potential and F is the electric field. Unfortunately Y, which depends on the nature of gas and cathode, is seldom known and not at all constant, especially when much power is being dissipated by the cathode. For this reason it is usually not possible to calculate the sparking potential for a given tube directly from theory.

Mention should also be made here of Paschen's law: that for a given value of (pressure x electrode distance) the sparking voltage remains the same. This is sometimes useful for getting a tube of given size to have a required striking voltage, if this quantity is known for a similar tube of different size.

<u>METER CALIBRATION</u> A capacitor integrating circuit (described under "Experimental Work") has been used to measure integrated light output. If we let F represent the light flux at any point then the integrated light say, L, is given by $L = \int F\,dt$. Now in a phototube the current that flows is proportional to the incident light flux and we may write:

$$i = kF \quad (4)$$ where *i* is the current and *k* is a constant.

The charge then,

$$Q = \int i\,dt = k\int F\,dt = kL \qquad (5)$$

Thus, the voltage across a condenser of capacitance, C, will be:

$$E = Q/C = kL/C \tag{6}$$

Now, for a continuous standard source, the voltage drop across a resistance, R, will be:

$$E_s = iR = kF_sR \tag{7}$$

E_s and F_s refer to the voltage drop and light flux respectively of the standard source. Eliminating <u>k</u> between these equations gives us the formula for <u>L</u>, the integrated light:

$$L = \frac{E}{E_s} CRF_s \tag{8}$$

EXPERIMENTAL WORK.

POWER SUPPLIES Two power supplies were used in this work. A power supply giving up to 20 KV was used to charge a 1 mfd. condenser. Another smaller power supply, using one 2X2 rectifier, gave 2500 V from a 32 mfd. condenser.

The circuit of the 20 KV power supply was that of a full wave voltage doubler using two 8013 half-wave rectifiers. The output voltage could be adjusted to any value between 0 and 20 KV by means of a Variac in the primary of the high tension transformer. The output voltage was measured by a meter, with suitable multiplier, directly across the terminals of the main condenser. Thus, any energy up to 200 joules could be used in a single flash.

The smaller power supply was usually run near 2500 V. It, too, was connected to a Variac, but this was used only for small adjustments as the filament transformer was also affected by it. A 1 mfd. condenser was found necessary directly across the rectifier output, in order to get the full voltage output of the transformer. Final charged voltage was read by a meter connected to a voltage divider across the output. This power supply could give a maximum of 100 joules per flash. The power supply was designed by Mr. D.M. Hunten and assembled by Mrs. R. Clarke.

VACUUM SYSTEM The vacuum system used to evacuate and fill the tubes is shown in diagram 3 and accompanying photographs. It consisted of a Hyvac pump connected through a mercury trap to a small mercury diffusion pump which in turn was connected to the tube. A small separate discharge tube was connected to the system for getting a quick indication of the pressure. The system was fitted with a mercury manometer and a McLeod guage reading down to 0.0005 mm. of mercury. A flask of argon was attached to introduce gas to the system. The whole system was made of Pyrex tubing; principally of 8 mm. diameter, but with sections of 6 mm. diameter. All joints were glass-sealed, except those connecting ~~in~~ the backing pump and the argon flask, which were of rubber vacuum tubing. Pressures less than 0.01 mm. of mercury were easily obtainable with the backing pump alone and pressures below 0.005 mm. of mercury could be had with the diffusion pump working. I am very much indebted to Mr. D.M. Hunten, whose skill in glass blowing was mainly responsible for the construction of a successful vacuum system.

<u>TUBES</u> Flash tubes that were tested were of four main types. The Pyrex tubes were made with either nickel or mercury pool cathodes. Those with mercury cathodes consisted of a vertical piece of Pyrex tubing containing a pool of mercury at the bottom and a horizontal piece of Pyrex capillary sealed on just above the mercury. Electrical connections were made to pieces of tungsten wire sealed in the Pyrex. Those with cylindrical nickel cathodes simply had a section of capillary with two large diameter ends and a side tube for sealing-off. Quartz capillary was used in some tubes with large diameter Pyrex ends. One type was sealed with DeKhotinsky cement and the other type was completely enclosed in a Pyrex envelope.

<u>MERCURY</u> The mercury used in these tubes was purified by filtering it through a cleaning tower which contained a solution of 10% concentrated nitric acid in water. After cleaning, the mercury was distilled two or three times, and finally distilled into the tube on the vacuum system.

<u>TRIGGERING</u> The Edgerton system, viz. external electrode in contact with the glass, of initiating an arc was used in all tubes. Current was obtained from a spark coil. Where the term "triggering" is used in this report it refers to starting an arc intentionally by the Edgerton method. Arcing from other causes is referred to as "striking" or "spontaneous flashing".

<u>OUTGASSING</u> In order to remove gases from the walls of the tubes they were baked for between one and two hours in a specially made oven. The oven was made of porcelain tubing and a moulded mixture of asbestos and cement. Heat was provided by nichrome wire giving a temperature of over 400°C. Metal parts were made of tungsten or nickel which had been treated for vacuum work. Nickel cathodes were heated to incandescence by positive ion bombardment in some cases. All mercury was boiled carefully to remove air.

<u>EVACUATION</u> Procedure in evacuating the tubes was to pump them down at first with the fore pump, flush out the system with argon, and then sweep out residual gases with the diffusion pump. The outgassing procedure already described was then carried out. By

this procedure low pressure tubes could be evacuated to below 0.0005 mm. of mercury. If the tube was to be filled with argon this was done after the outgassing.

The desired striking voltage was found by applying this voltage to the tube from the power supply and pumping out the argon slowly until the tube flashed spontaneously. Small corrections could be made until the tube was pronounced satisfactory by testing it with the power supply.

LIGHT METER.

It was mentioned in the Introduction that Edgerton has used a phototube with condenser and vacuum tube voltmeter to measure light output. A meter was built on these lines incorporating a 922 vacuum type phototube and a balanced bridge type of V.T. voltmeter.

VOLTMETER The voltmeter circuit is substantially that described by McMurdo Silver (31). Two 6SN7GT twin triodes are used in a balanced circuit. A very high input resistance had been achieved with cathode follower input. Sensitivity, range, and zero adjustment were provided. The grid of the input tube could be grounded by a pushbutton switch. Zero adjustment could then be made by the 5 kilohm potentiometer connected across the plate of the second 6SN7GT. Another 5 kilohm potentiometer regulated the sensitivity of a 1 milliampere meter which read 50 full scale. Power was obtained from a centre grounded power supply. This very symmetrical circuit gave stable and consistent action at all times.

PHOTOTUBE The 922 is a vacuum type phototube particularly recommended for measurement work owing to its excellent stability. It is small and of the cartridge type with a maximum plate voltage of 500 V. The spectral characteristic has greatest response near the red end of the spectrum and considerable infra-red sensitivity. No attempt was made to correct this for the response of a photographic emulsion. A coating of polystyrene was applied to the tube to cut down surface leakage and help to diffuse light. The 922 phototube takes its anode supply from the same 275 V supply as the V.T. voltmeter. It is generally desirable to have the anode voltage as high as possible to cut down space charge effects. Saturation curves that were made with an R4330 flash tube and variable voltage supply show that this is sufficiently near saturation for the order of accuracy required. The departure from saturation was only about 3%.

HOUSING The phototube was kept in a shielded housing. This was made from two pieces of telescoping brass tubing; one with a hole in it to admit light and the other acting as a cover. The phototube was mounted between two brass clips insulated from the housing by a bakelite disc and bar. Opal glass could be mounted in front of the opening with a circular clip. Insulated leads passed out of the housing through a piece of grounded shielding braid.

GENERAL The whole instrument was mounted on a 10" x 7" x 2" chassis connected to the phototube by shielded wires. The grid of the first 6SN7GT may be connected to different capacitors or resistors by a multiple selection switch. The capacitors provide different integrating ranges while the resistors give continuous ranges for use with a standard source of light. The meter could be calibrated using the formula $L = \frac{E}{E_s} RCF$ as explained in the Introduction (Theory -- page 9). The light output of the R4330 obtained in this way was very nearly 119 candle seconds at 100 joules energy.

<u>MEASUREMENT</u> It is of advantage to note briefly what quantities are measured by the integrating light meter. The window of the phototube housing passes a certain flux of light, the unit of which is the lumen. The meter, then,measures the integrated amount of light which passes the window. The meter reading would be in lumen-seconds if calibrated. However, since the area of the window is kept constant for a group of experiments, we may take it that the meter might equally well measure the integrated flux density or illumination in lumen-seconds per square centimeter. If we are dealing with a point source, we may state the result directly in candle seconds. This is so because the window subtends a definite solid angle (usually very small) at the source, and one lumen per unit solid angle indicates a source intensity of one candle power.

For sources of extended area the question is more complicated. Measurements might have been made of the source brightness (candles per cm^2.) but it was necessary here to deal with line sources. The corresponding quantity (candles per cm.) was not very useful and it was the illumination which was really desired. Since other sources that were being dealt with could be considered point sources at moderate distances, it was decided to select a standard distance and express all results in equivalent candle power seconds. In other words, the results indicated the integrated candle power of a point source required to produce the same integrated illumination as the trial source at the standard distance of 61.4 cms.

FIBRES.

In order to check up qualitative results of the light meter some fine fibres were prepared to represent cloud tracks in an expansion chamber. These fibres were of drawn Pyrex or of spider web. The Pyrex fibres were etched with hydrogen fluoride to give a better scattering surface. The spider web fibres were 0.002 to 0.005 mm. in diameter whereas the coarser Pyrex fibres were between 0.03 and 0.08 mm. These fibres were put in a light trap to obtain a black background and photographed by the light of a test source.

CAMERA The camera was made to take a standard 35 mm. Leica magazine. The film was advanced one frame at a time by means of a ratchet and lever projecting outside the camera. Provision was made for cutting off any number of frames for development . The lens was an f/8 Kodak rapid rectilinear. This aperture was sufficient to obtain results and is frequently used in cloud chamber work to get good depth of field.

LIGHT TRAP The light trap was made of cardboard painted inside with a glossy black enamel. An arm curving away from the direction of the light prevented any from being scattered or reflected back, and an arm below the fibre kept light from being sent upwards. The glossy black surface reflected light at grazing incidence but absorbed it at angles near the normal. A dull black was not found to be as good as the glossy surface in the light trap. This apparatus was very successful and no trouble was experienced from stray light.

<u>FOCUSSING</u> The photographic method was used to see how much the focussing contributed to the illumination from the source. This was in doubt owing to absorption and other losses encountered in the very simple optical system. A reflector was made from a piece of 4 cm. Pyrex tubing silvered on the inside except for a longitudinal strip about 2 cm. wide.

The line source was put at the centre of the cylindrical reflector thus throwing an image of the source on itself. Another piece of 4 cm. Pyrex tubing was filled with water and used to make a lens of focal length about 2 cms. A slightly diverging beam was produced with the lens arranged to touch the clear portion of the reflector.

RESULTS

The first measurements undertaken were of the striking potentials of mercury cathode tubes at low pressure. These measurements were taken with the tubes on the vacuum system. In order to get pressures as low as possible, all argon was pumped out with the diffusion pump until there remained just mercury vapour. Two striking potentials were characteristic of these tubes. The first time a tube was put into operation the striking potential was quite high. After one flash the tube materials were disturbed in some way and successive striking potentials were much lower. If the tube were allowed to cool for some time and regain its former state, the higher striking potential was observed. These two striking potentials were referred to as "maximum" and "minimum" striking potentials respectively.

Results for five different tubes are given in Table I below. In this table "length" means the length of the capillary section of the tube. This is very nearly equal to the distance between the two electrodes. The 20 KV power supply was used in all these measurements.

Table I.

Low Pressure Mercury Tubes on the Vacuum System.

Tube #	Length Cm.	Bore Mm.	Max. Striking Pot. Kilovolts	Min. Striking Pot. Kilovolts
2	11	2	14	7.5
3	11	2	13	7.5
4	11	2	12	10
5	23	2	13	9.0
6	15	4	15	10

Because the minimum striking voltage of a tube used with the 2500 V power supply need only be above 2500 V these tubes were easily made. The striking potential of the tube on the pump was not a factor in limiting the use of the tube. Instead, it was of more interest to find how long a given tube could maintain the striking voltage that was initially above 2500 V after it was sealed off.

In all cases the tubes failed in some manner. Usually this was because the tube either refused to trigger or flashed spontaneously. Reasons for this behaviour are discussed in a later section.

The data in Table II were compiled with the tubes evacuated as described in "Experimental Work" (page 12), and then sealed off. Each one was originally flashed at 2500 V, using the external control electrode, except in the case of tube #12. The 2500 V 32 mfd. power supply was used throughout. The light outputs are in arbitrary units and not related to other values in this report.

Table II.

Low Pressure Mercury Tubes Used with 32 mfd. 2500 V Supply.

Tube #	Length Cm.	Bore Mm.	Times Flashed #	Remarks
8	15	1	3	Flashed spontaneously at 2400 V.
9	13	2.2	11	Refused to trigger.
10	14	0.8	3	Refused to trigger.
11	18	6	6	Flashed spontaneously at 2400 V.
12	30	6	3	@ 2000 V light output 45
13	46	6	-	Blew up; light output 38
14	27	2.2	4	Refused to trigger; light output 14.

The light output of many different tubes operated at higher pressures of gas was found. This was done by filling the tube with a known pressure of argon and then triggering it in front of the light output meter. A series of readings was taken for each tube, the pressure being increased slightly each time. The trial ceased when a pressure was reached at which the tube would not trigger at 20 KV. All these trials were made with the 20 KV power supply.

For each separate tube a table was made noting the pressures of argon, the flashing voltage, and the light output. From the voltage at which the tube was flashed the total energy was calculated. Using this energy the ratio of light output to total energy was found. The L/E ratio, as it was called, gave a measure of the efficiency of the source. These tables enabled one to find the variation of efficiency with pressure and energy for any particular tube. The number of readings which may be taken at constant energy and different pressures is limited because change of pressure affects the voltage at which the tube may be triggered.

<u>EFFICIENCY</u> The variation of efficiency with energy released may be described by saying that the efficiency increases gradually with energy and then decreases again as the energy is still further increased. This was true for all those tubes for which a table of this nature could be made. A sample table for tube #29 is given below.

Data on the variation of efficiency with pressure were more difficult to obtain for the reasons already noted. Tube #30 provides a representative table of these quantities. Tubes were usually more efficient at the higher pressures of argon, although the efficiency decreased rapidly just before the point was reached where the pressure was too high for the triggering electrode to work.

Tables on variation of efficiency were all very much alike for different tubes. Results are given for two tubes to show how readings were taken. Similar trials were performed on over 30 tubes, but including them all would add little to the value of this report. All trials were made with the 20 KV power supply.

Table III.

Sample Table of Efficiency, Pressure, & Energy.

Tube #29.				Tube #30.			
Pressure Cm. of Hg	Energy Joules	Light Arb. Units	L/E 100	Pressure Cm. of Hg	Energy Joules	Light Arb. Units	L/E 100
7.1	60	12	20.0	8.2	128	17	16.0
7.1	72	15.5	21.5	8.2	162	20.5	15.5
7.1	85	18	21.2	9.7	128	21.5	16.8
7.1	98	22	22.5	9.7	162	27.5	17.0
7.1	112	25.5	22.8	10.7	128	19	14.8
7.1	128	27	21.1	10.7	162	26	16.0
7.1	145	29	20.1				

The results obtained from the data on the separate tubes has been summarized in Table IV. The readings given in this table are for the highest energy that the tube would stand and at pressures giving greatest efficiency. The maximum energy is usually 200 joules, but where a tube blew up at a smaller energy the last recorded value is given. The symbol Ni(b) signifies that the cathode has been heated by positive ion bombardment. In Table IV the light is expressed in arbitrary units but a calibration factor was calculated and this may be used to express the results in candle seconds. If the light reading in tables III and IV be multiplied by 1.13, the result will then be given in candle seconds.

Table IV.

Summary of Results Obtained with Argon Filled Tubes Used with 20 KV Supply.

Tube	Pressure	Cathode	Length	Bore	Energy	Light	L/E
#	Cms. of Hg		Cms.	Mm.	Joules	Arb. Units	100
11	14.3	Hg	18	6.0	200	24	12.0
12	8.9	Hg	30	6.0	200	21	11.5
13	3.8	Hg	46	6.0	98	13	13.3
15	7.0	Ni	30	6.0	200	20	10.0
15	11.3	Ni(b)	30	6.0	200	20	10.0
22	9.2	Ni(b)	34	6.0	200	19	9.5
23	12.6	Hg	19	2.2	145	26	17.9
24	5.8	Hg	28	2.2	200	33.5	16.7
25	7.1	Hg	28	1.5	162	35	21.5
26	7.0	Hg	28	0.8	72	28	39.0
27	7.8	Hg	19	4.0	200	30	15.0
28	5.8	Ni	30	0.8	112	23	20.5
29	7.1	Ni	30	1.5	145	29	20.5
30	9.7	Ni	28	2.2	200	31	15.5
31	14.8	Ni	18	4.0	200	31	15.5
32	10.5	Ni	26	2.2	200	28	14.0
33	10.2	Ni	32	2.2	200	35	17.5

CRAZING After one or more flashes at high energy, Pyrex tubes showed evidence of many very fine cracks on the inner wall of the capillary tube. These cracks have been observed by Dahl and by Edgerton who called the phenomenon "crazing". Crazing did not appear as long as tubes were used at low energies. Also, it was usually visible only in the capillary section of the tube. Fine bore capillaries were much more prone to become crazed than those of larger bore. Some large bore (4 - 6 mm.) thin walled tubing was used in a few tubes and also exhibited crazing after many flashes. If the inside wall was not badly cracked, then the performance of the tube was hardly impaired. When the interior became cracked enough to have the appearance of ground glass the light output of the tube was reduced. This reduction was seldom more than about 10%. The final result of crazing was to weaken the tube wall until it shattered and the tube exploded. A tube usually became crazed during the flash, but not always. Some tubes were seen to be quite clear shortly after a flash, but then suddenly fine cracks spread from one end to the other with an audible click. For this reason, crazing is thought to be due to sudden local heating by the discharge and cooling afterwards with consequent strains in the glass.

Crazing may be reduced by annealing capillary tubing in an oxygen-gas flame for one to two hours. This was shown by a tube which had one end only annealed. This end produced much fewer cracks than the unannealed end. Some tubes were totally annealed for two hours and showed less crazing than unannealed tubes after the same amount of use. Because of the more favourable properties of quartz, the difficulty was not present with that material, at least for energies of 200 joules and below.

QUARTZ Three quartz tubes were made according to designs shown in the diagram. #1. Two which had waxed joints were about 30 cm. long and had bores of 2.0 and 1.5 mm. The tubes were pumped down, filled with argon, and sealed off. The light output of these tubes was about the same as for Pyrex tubes of the same size. Both of them took the full 200 joules and showed none of the fine cracks or "crazing" which ruins Pyrex tubes. The quartz tubes did not last but became gassy. This was put down to failure of the wax seals. A third tube was made of quartz capillary completely sealed in Pyrex (Diag. 1, No. 4). This tube had a bore of 2.0 mm. and a length of 18 cm. The discharge was seen to go mainly outside the quartz capillary and through the small space between it and the Pyrex wall. The tube was not successful and exploded at 20 KV.

PHOTOGRAPHS OF FIBRES

Table V.

Results of Photographs of Fibres Taken at f/8 on Kodak Plus-X Film.

Picture #	Tube #	Condition	Remarks
1	22	Lens & reflector	Good lines -- quite dense
2	22	Reflector only	Fainter than (1)
3	22	Unfocussed	Faint but visible
4	22	Lens only	Denser than (3); like (2)
5	31	Lens only	Better than (1) of tube #22
6	31	Unfocussed	Less dense than (5)
7	R4330		Dense lines broad but sharp
8	R4330 (twice)		Very dense -- some background
9	Std. lamp 53 cps.		Visible line -- no background
10	Std. lamp 106 cps.		Very nearly as dense as (7)
11	Std. lamp 159 cps.		Denser than (7)

Table V gives the results of photographs taken of the spider web and Pyrex fibres with different focussing arrangements. A specimen photograph of spider web fibres is included among photographs of apparatus. In pictures (1) to (6) fibres were spider web of about 0.002 to 0.005 mm. in diameter. The order of density of lines, from densest to thinnest was (5), (1), (6), (4), (2), (3). In pictures (7) to (11) the fibres were etched Pyrex having diameters of from 0.03 to 0.08 mm. The order of density, from densest to thinnest, was (8), (11), (7), (10), and (9).

DISCUSSION OF RESULTS.

Referring to Table I it may be seen that while the maximum striking potentials achieved are well above 10 KV, the minimum striking potentials are low. With improved technique the maximum striking potential might have been (indeed was in some cases) raised above 20 KV. Unfortunately the tubes would still strike sometimes at low potentials, making them useless for control with an Edgerton external electrode. In fact, when tubes were sealed off under these conditions, the second or third and subsequent flashes all took place near the minimum striking potential. Many hours then elapsed before the tube regained its previous state and often this condition was never again realised. It must be emphasized here that in tubes like these, having small volume and dissipating large amounts of energy, the internal conditions are disturbed to a great extent by each discharge. This is evidenced by the appearance of crazing on the walls of the tubes, as already mentioned. For this reason, tubes tend to become "gassy" explaining the changes in their characteristics. Initially the tubes were highly evacuated and had high striking potentials. After the first discharge, the tube evidently became gassy and the striking potential dropped to its low value. As the tubes were on the pump in Table I the former state was regained when this gas was removed.

Most careful outgassing was carried out on the tubes in Table II as explained on page 12 above. This did not prevent them from becoming gassy like the previous tubes. The appearance of gas in the tube was probably due to momentary heating of the glass wall to a high temperature at which devitrification came into account. Comparatively large areas of new glass surface produced by the crazing would facilitate this process. Decomposition like this could not be reduced except by reducing the energy of discharge. Refusal to trigger and spontaneous flashing may both be explained by the appearance of gas in the tubes. Of course, "clean-up" with consequent reduction of pressure might explain the refusal to trigger. This is considered unlikely because whenever tubes suspected of being gassy were tried with a spark coil the appearance of the discharge was that of a pressure of several millimeters.

The data given for tube #29 in Table III show how small the change of efficiency is with different energies. In this case, the variation is under 15%. A maximum efficiency is shown to occur at an energy of 112 joules. Because the efficiencies changed so little, this point was not pursued any further. Interest was mainly directed towards obtaining a large amount of light regardless of the energy used. In the second part of Table III a maximum efficienc is found between 8.7 and 10.7 cm. pressure of argon. Again, the amount gained by realizing this maximum is small.

Results of more interest are contained in Table III. The most noticeable factor effecting efficiency of a tube is its bore. Referring to Table III we see that the efficiencies of the tubes with small bores greatly exceed those of larger bore. So pronounced is this effect that, ignoring effect of gas pressure, length, etc., the order of the efficiencies almost corresponds inversely to the order of size of tube bore. The highest efficiency recorded (39.0) was that of a tube having the smallest size of bore.

The bore, therefore, is of most importance in designing a tube for high light output.

It is apparent, also, that making the bore of a tube small adversely affects the amount of energy per discharge that it can stand. No tubes of 1.5 mm. bore or 0.8 mm. bore could stand the whole 200 joules. The life of tubes with these bores was small at the lower energies. A bore of 2.2 mm. represents the smallest that can be used with 200 joules and still retain a reasonably useful life. Tubes having this bore met these two conditions and gave a life of one to two hundred flashes.

The length of a tube was not shown to have any large effect on the light output or efficiency. Among the 6mm. tubes (#11 to #22) the shorter one gave slightly more light output. In other parts of the table this trend is not followed. Probably the best length of tube is the one that will just provide the width of beam desired.

The type of cathode is not critical as far as light output is concerned. Mercury cathodes gave about the same light output as nickel ones in tubes of the same size. Nickel which has been bombarded was not superior to ordinary nickel from the point of view of light output.

Pictures taken of fibres show that the focussing system, simple as it was, contributed to the efficient use of light available. The reflector alone gave great increase of light. The lens alone gave results comparable to a tube used with the reflector alone. Pictures #7 to #11 in Table V enable us to check the result of 119 candle seconds found for the R 4330 with the light meter. The photographic effect of the 106 candle seconds from the standard lamp was nearly as great as that from the R4330. The greater effectiveness of the R4330 was due to its more effective colour as well as its greater light output than the standard lamp.

CONCLUSIONS.

References to papers on cloud chamber work were consulted and the light sources used were noted. Of the many types of light sources used, arc tubes were chosen for special study. Thirty-six arc tubes were made and their properties investigated. These arc tubes had mercury or nickel cathodes and were filled with argon. The discharge was controlled by a wire or clip in contact with the glass acting as an external control electrode. An integrating light output meter was made. The light outputs of tubes of different compositions and contents were measured with this meter. Results of the meter were checked and the value of focussed sources determined by a method of photographing fine fibres.

Five mercury-type tubes were made and their striking potentials at low pressures measured. It was not found possible to produce a tube which maintained a striking potential above 20 KV. Seven tubes were made and used with a 32 mfd. condenser charged to 2500 V. All these tubes failed to function after a few flashes. It is not practical therefore to use tubes with very low pressures as a means of providing a permanent high striking potential for use with an external electrode.

The efficiency of a tube, as determined by the light meter, varies slightly with the energy of discharge. There is a certain maximum point at which the tube is most efficient. The amount of variation is so slight that it is always of advantage to increase the energy of discharge and sacrifice a small amount of efficiency.

The light output of a tube is also affected by the pressure of argon in the tube. The amount of gas necessary for good light output is not critical, although it seems better to have the pressure high rather than low within the workable range.

The light output of twenty-two tubes operated at higher pressures of argon was taken. Small bore tubes emit much more energy in the form of light than large bore tubes. The small bore causes tubes to explode at lower energies. When tubes are operated under conditions of high argon pressures (5 to 15 cm. of Hg) the type of cathode is not important in determining the light output. The illumination of a source is not greatly affected by the length of the tube. If the light is being used in the form of a beam the length of the tube should not be longer than necessary. No dependence of the light output on tube volume could be found.

Crazing is encountered in tubes used at high energies. It appears earliest and most densely in fine bore capillary. Crazing is responsible for some loss of light but it is of more consequence in shortening the life of a tube. Annealing reduces crazing in Pyrex indicating that strains may be present in Pyrex capillary stock. Quartz tubes of 1.5 mm. bore do not craze at energies up to 200 joules. No successful method was found for using this property of quartz.

A Pyrex tube with a bore of 2.2 mm. gives good light output but does not craze unduly at an energy of 200 joules. A length of 20 to 30 centimeters should serve for most purposes. These dimensions were shown to be the best for a tube of the kind desired. Annealed tubes like this had a life of one to two hundred flashes.

The photographs of the fibres showed that the kind of sources made gives ample light to photograph small objects of the size of cloud droplets. It was shown that a simple focussing device consisting of a cylindrical reflector and lens gives sufficient improvement in illumination to justify its use.

By referring to the results just summarized, a description of an ideal light source for cloud chamber work may be arrived at. If the application for which the source is used does not require it to be focussed, then the best light source is the R4330 or an equivalent type. This tube is remarkably efficient and gives more light than laboratory made sources even when the latter are used at much higher energies.

When a source must be focussed to stop scattering of light from walls or floor, a very successful source may be made without elaborate equipment from Pyrex stock. The tube should have a section of Pyrex capillary with a bore of about 2 mm. The length should be about 20 to 30 cms. A pressure of about 10 cm. of argon in the tube will enable it to be used with a 20 KV power supply. The life of the tube will be extended if the whole tube is carefully annealed after being assembled.

Control over the discharge is had by using an external control electrode. If an automatic circuit is timing the cloud chamber and ~~auxilliary~~ auxiliary apparatus, then this may be used to control the discharge of a condenser through the primary of a spark-coil. The secondary will then produce the necessary controlling pulse.

The source should be focussed into a beam confined between two horizontal planes by a cylindrical lens and a cylindrical reflector. Better focussing could be had from a reflector in the form of a parabolic cylinder, if such could be made or purchased.

A tube with a quartz capillary of the same dimensions as recommended for Pyrex would prove much more satisfactory. If not prohibited by the expense involved, it is suggested that graded seals be used in a quartz tube with Pyrex ends. Failing this, some other method might be devised for using quartz capillary without graded seals.

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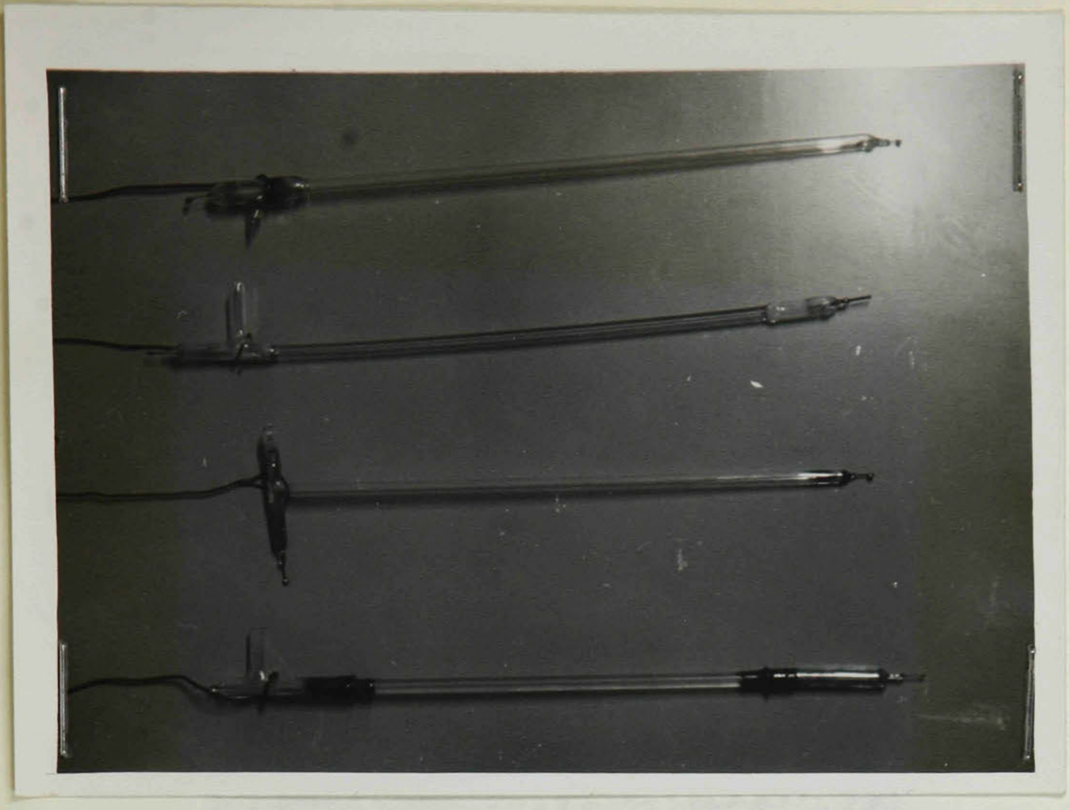

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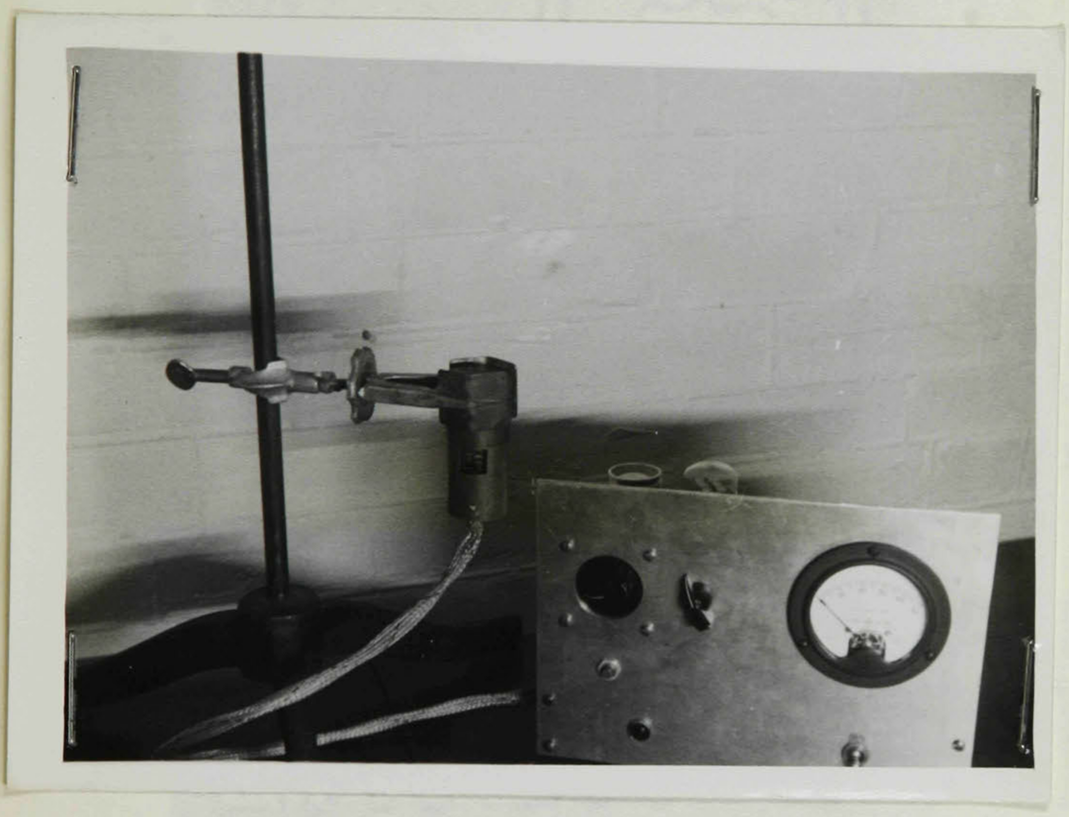

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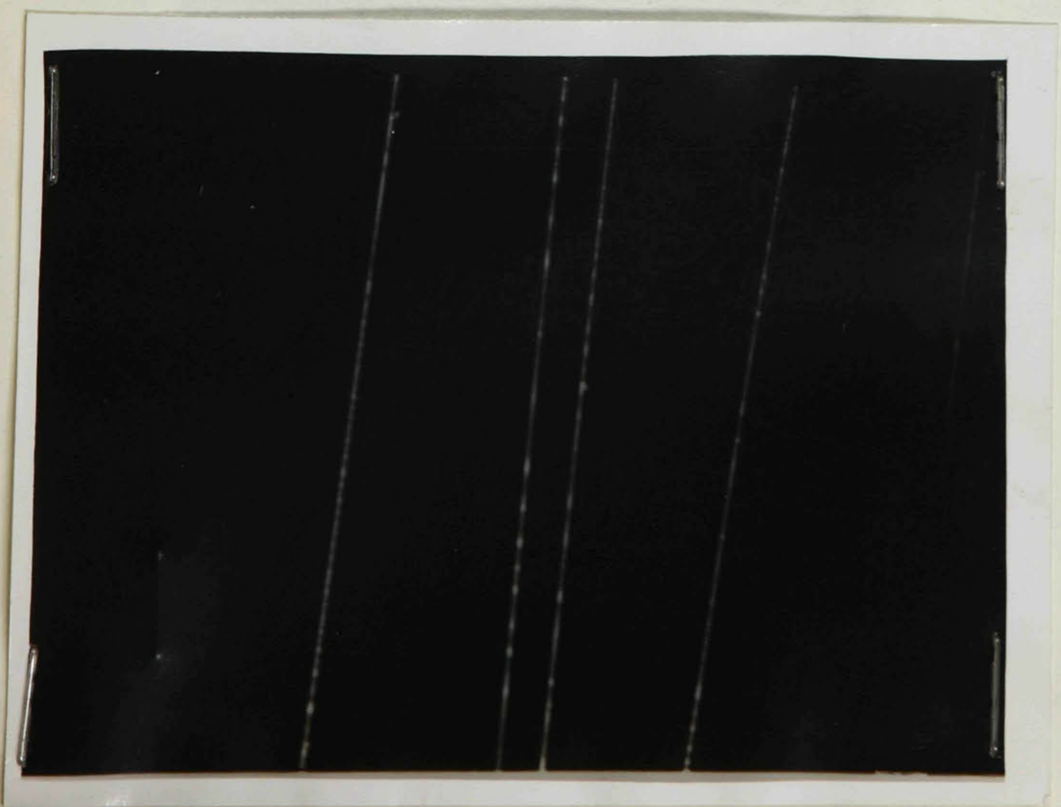

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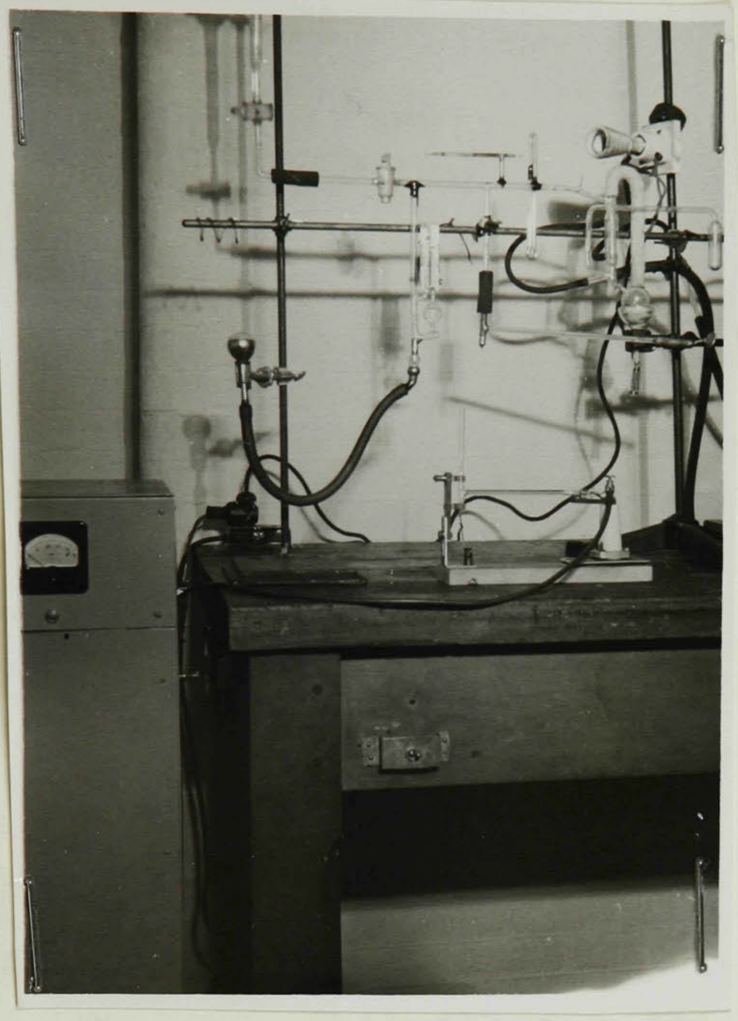

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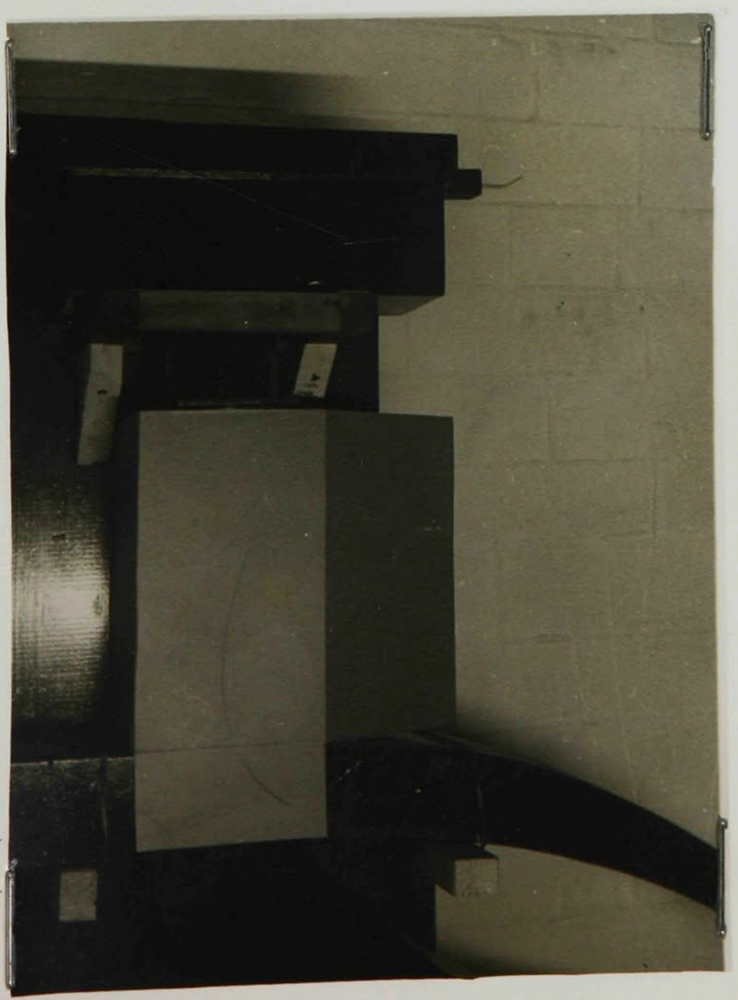

Camera &
Light Trap

DIAGRAM 1

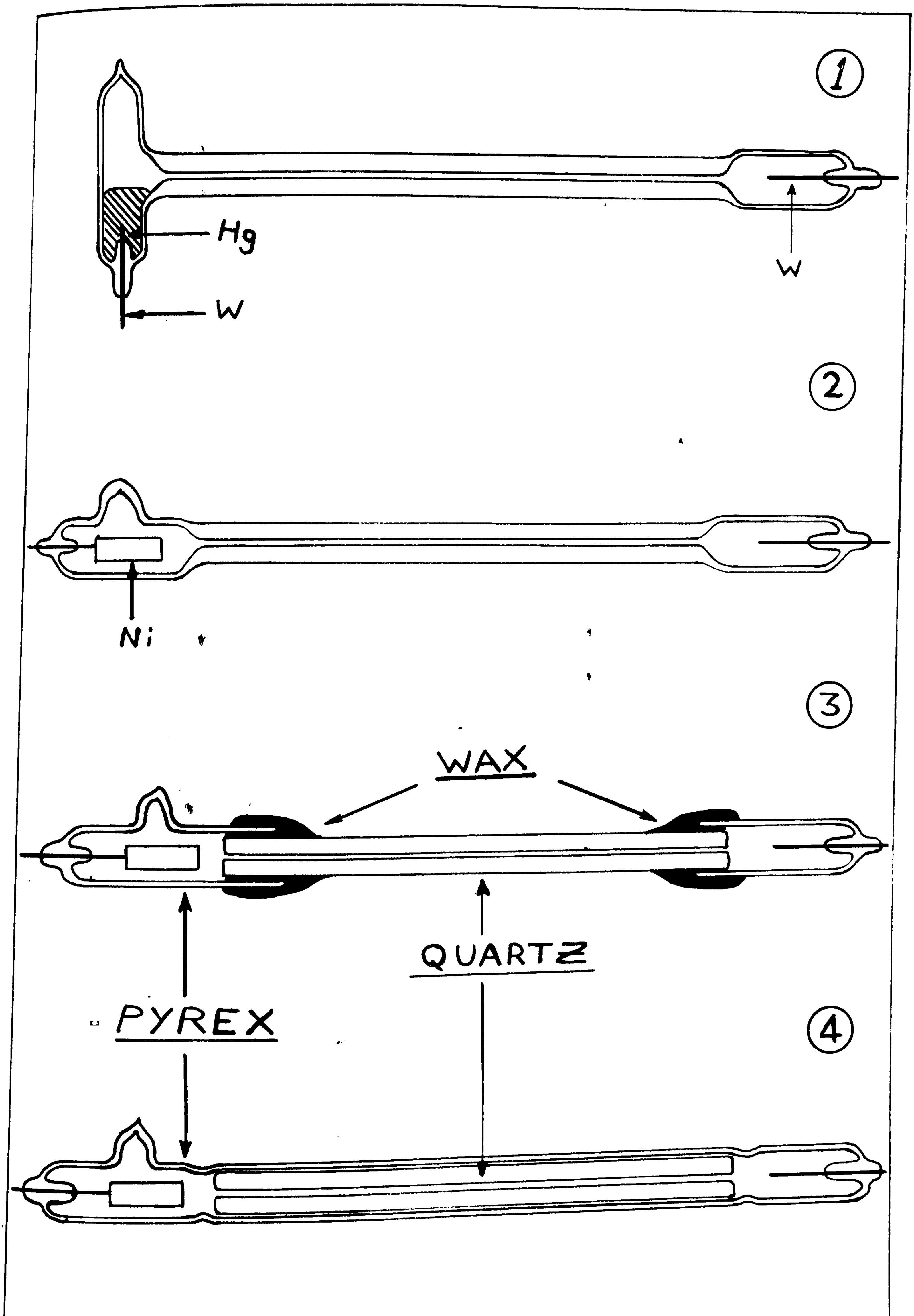

DIAGRAM 2

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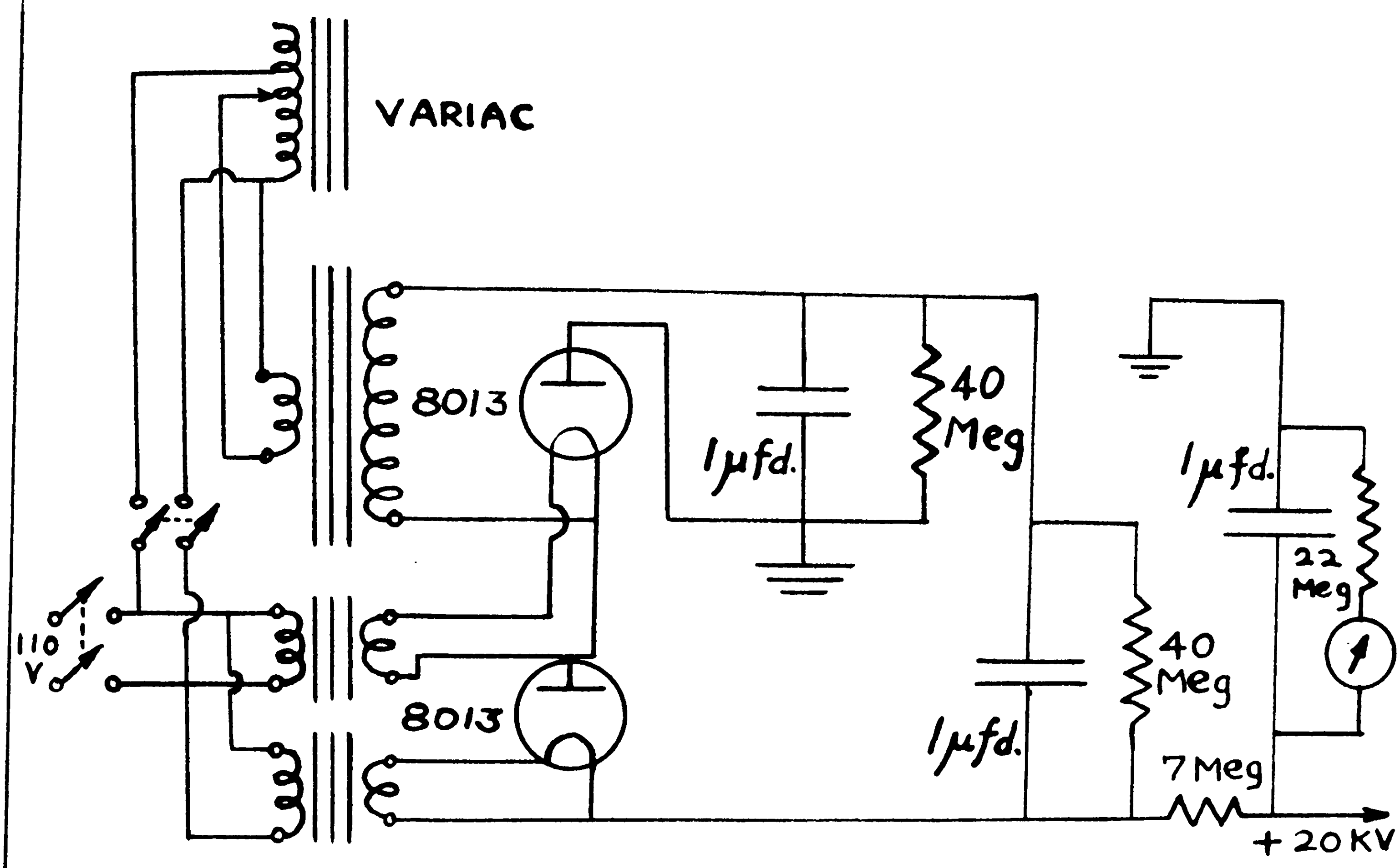
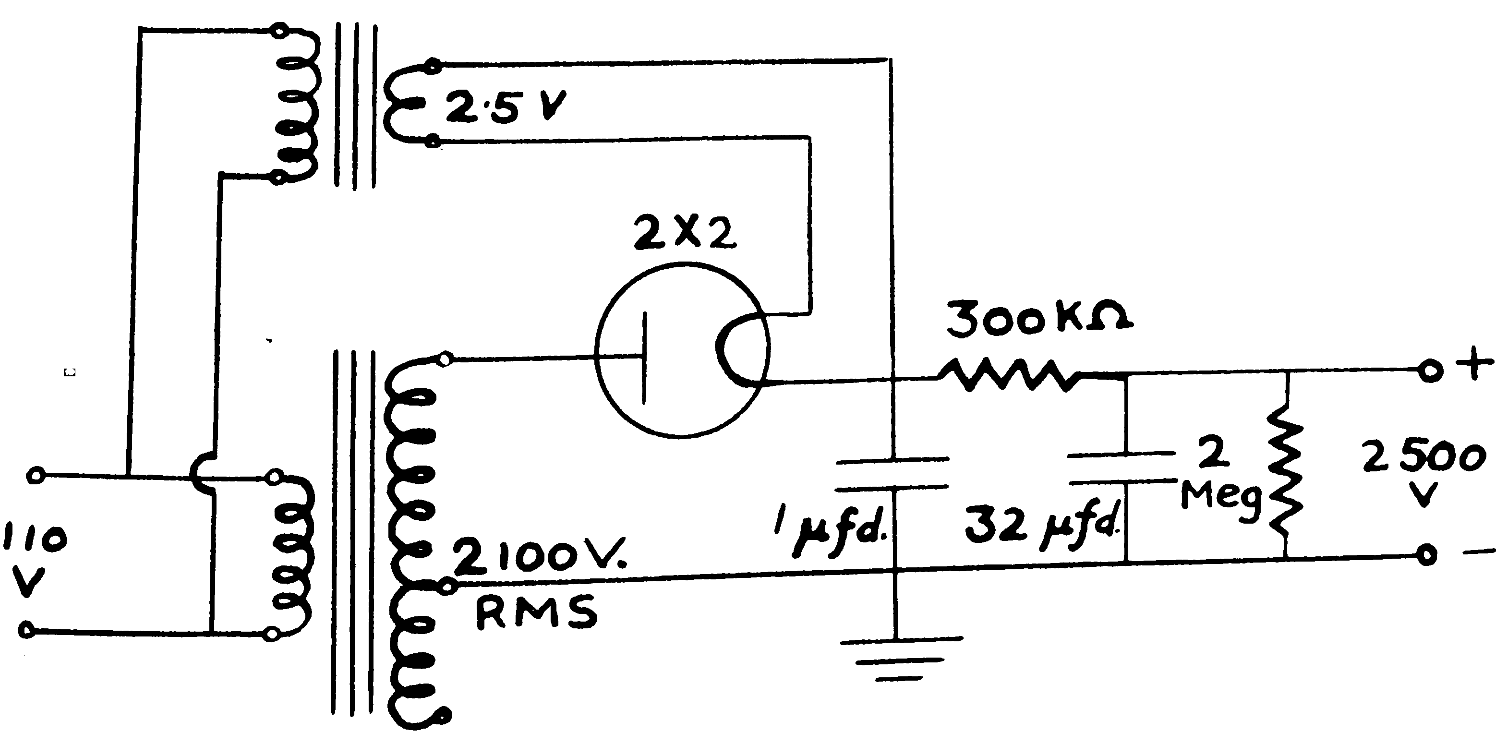


2500V. POWER SUPPLY



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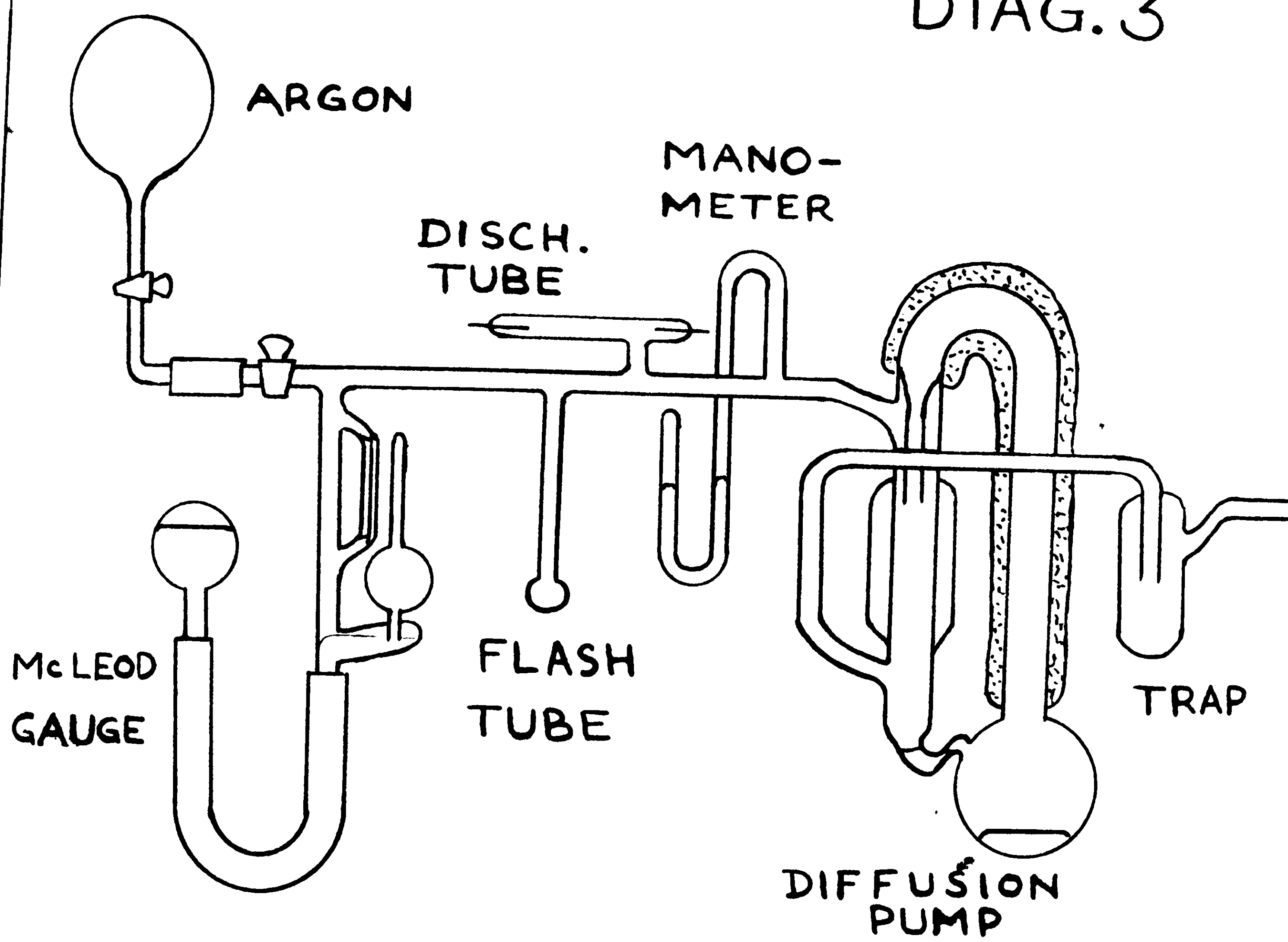
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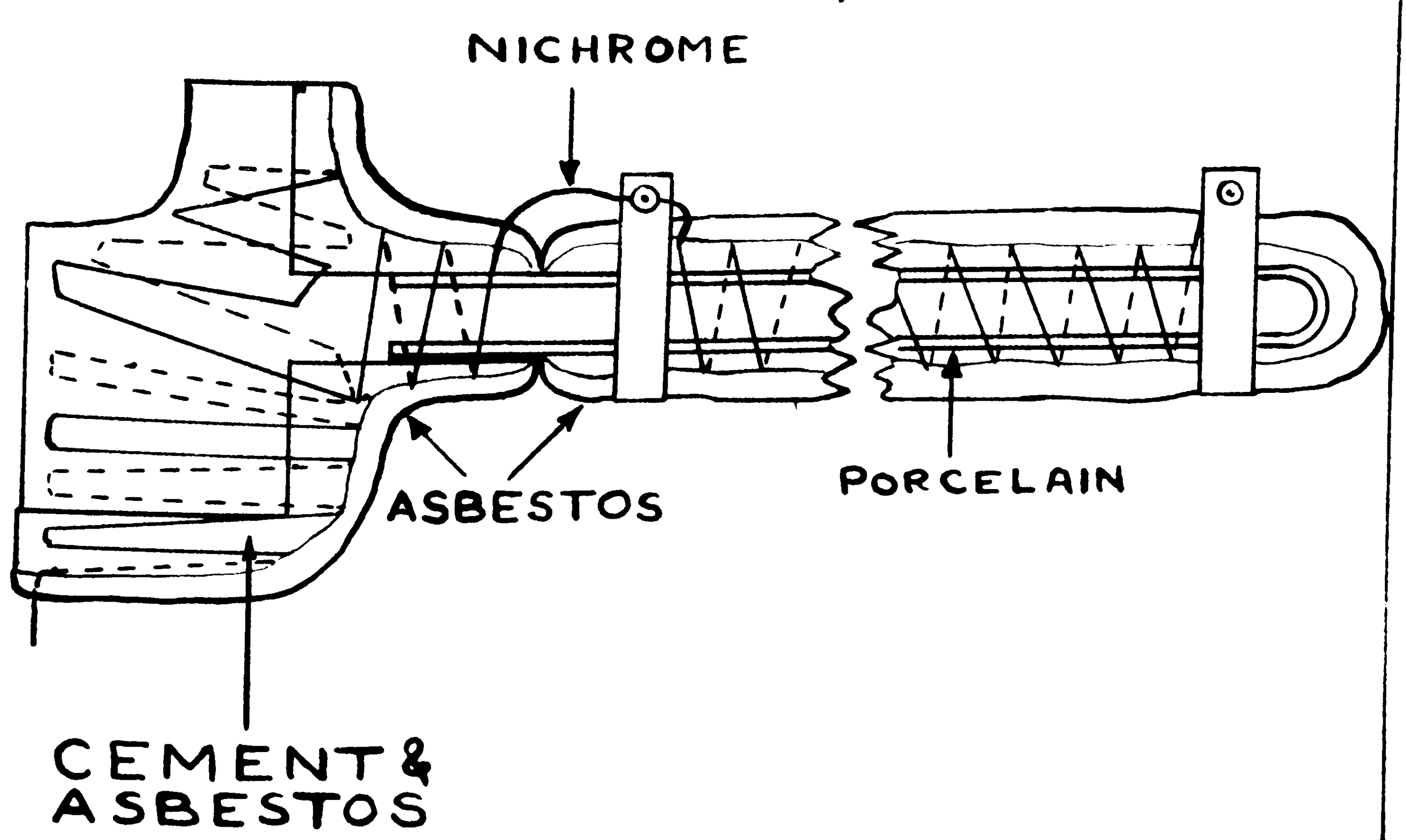
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CEMENT &
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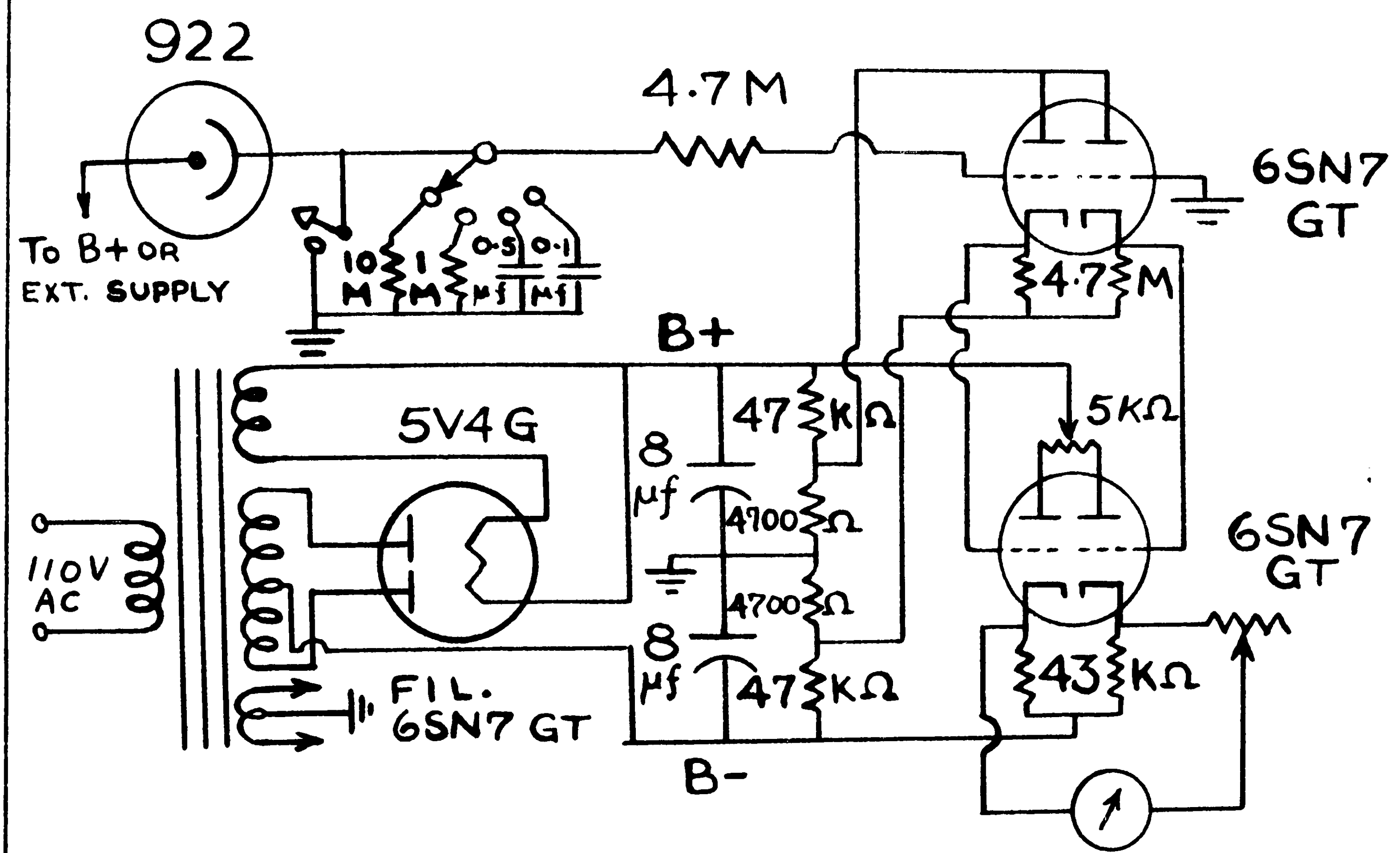
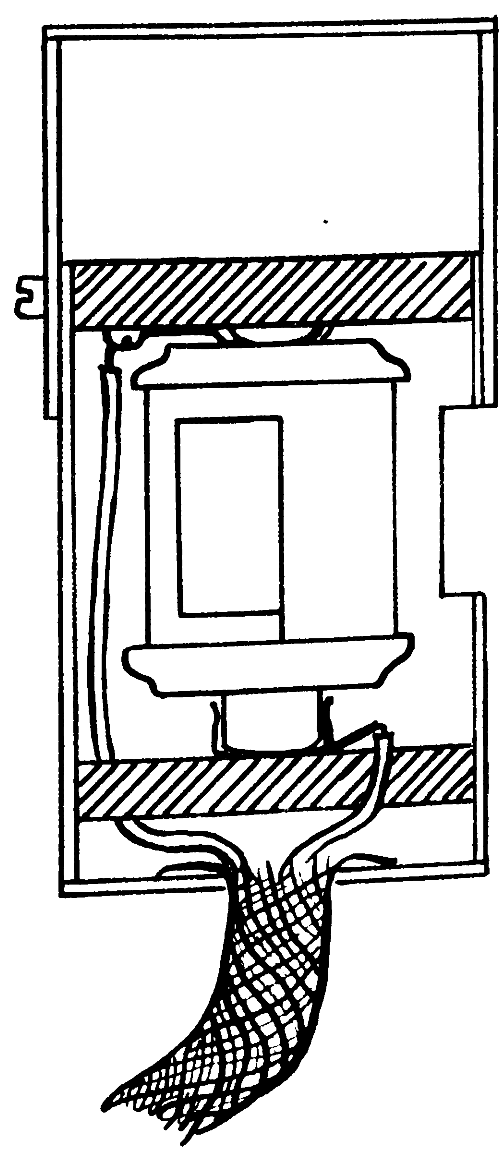
DIAGRAM 4

LIGHT METER

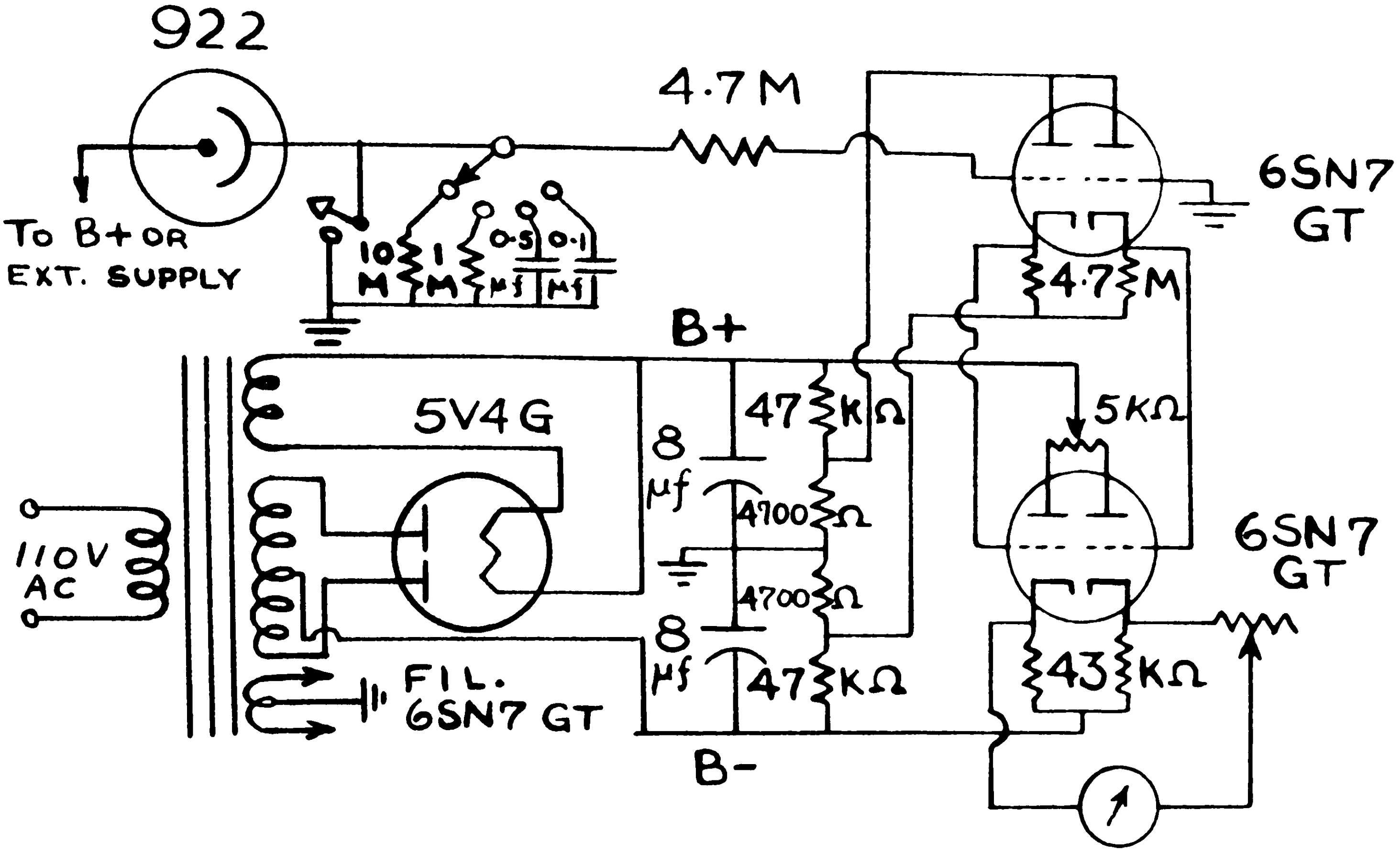


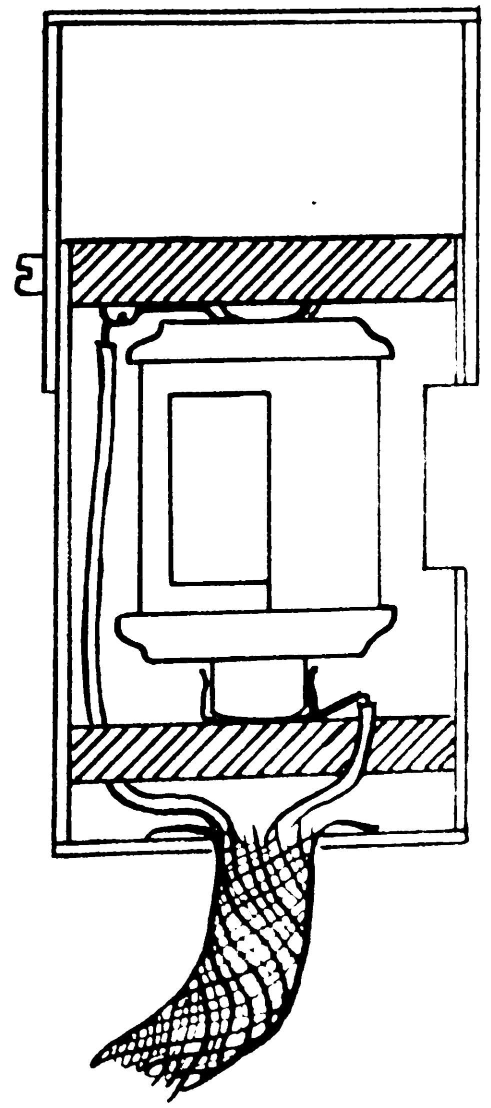


PHOTOTUBE HOUSING

DIAGRAM 4

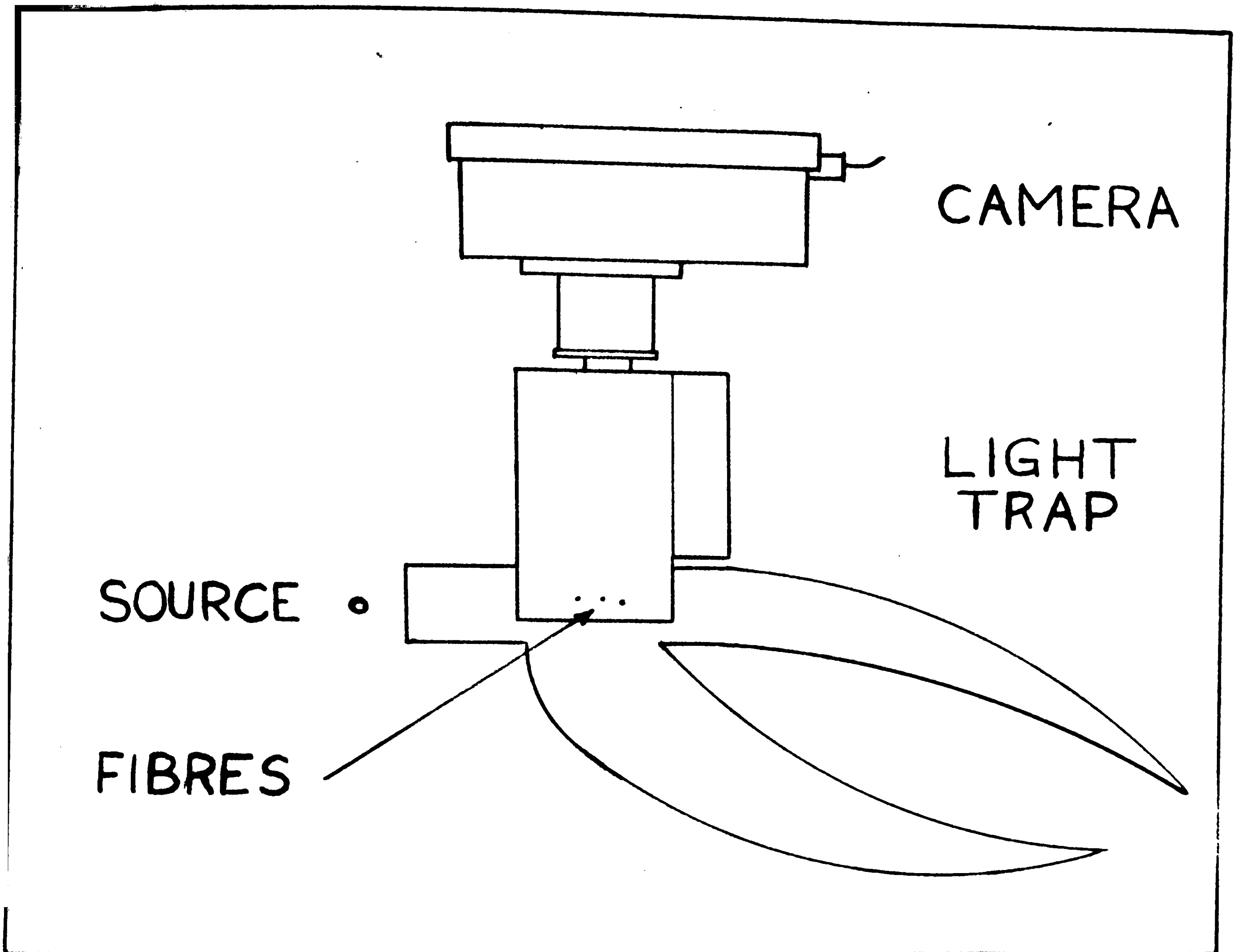
LIGHT METER





PHOTOTUBE
HOUSING

DIAGRAM 5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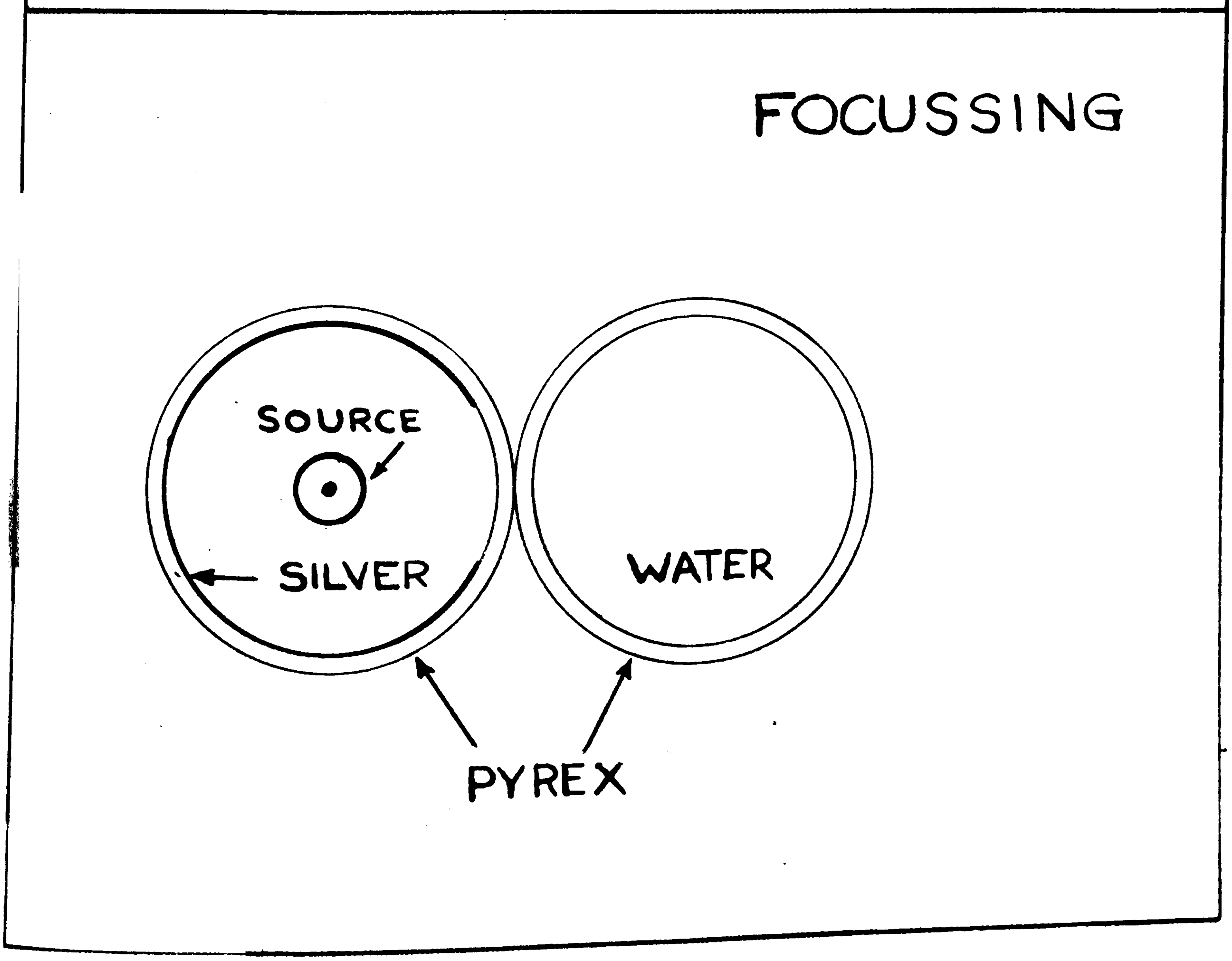
SOURCE
FIBRES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