AN INVESTIGATION INTO PHOSPHOR-PHOTOCATHODE CASCADE SCREENS FOR USE IN IMAGE INTENSIFIERS.

by

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ABSTRACT.

The process of making cascade image intensifiers is fairly well-known, but the poor performance of the existing devices had limited their use as an aid to the scientific research. The performance can be improved by the improvement in phosphor screens and photocathodes..

Techniques for mounting very thin and fragile mica discs have been developed so that they can undergo the process of phosphor deposition and aluminization on one side without bringing any material in contact with the other side on which a photocathode is to be formed subsequently. The methods of screen deposition have been improved and a new method of phosphor deposition has been used to give very thin phosphor layers (0.5 mg/cm^2 in thickness) with about 99% coverage of the substrate.

Simple calculations have been made to show the dependence of the image resolution on the thickness of a transparent phosphor layer and the thickness of the mica substrate. The results of image resolution thus obtained are compared with the results of the image resolution of the experimental granular screens. Thus the effect of "graininess" of the phosphor screens on the image resolution is determined. The effect due to the electron scattering in the screens is also determined. Optical and electron-optical techniques have been developed and used for the measurement of the image resolution of the tubes.

A novel technique of aluminization ("Floated Backing") has been developed. Anti-reflection backings were also prepared and applied to the phosphor screens and their effect on the efficiency and the image resolution of the screens has been determined.

Other parameters of the phosphor screens such as the thickness measurement, coverage of the substrate, the effect of baking temperature and ageing on the efficiency of the screens have also been determined and discussed.

The performance of such screens in the cascade image intensifiers is summarized and three stage image intensifiers having a blue light gain $\sim$ 50,000 and an image resolution of 50 lp/mm., with a very low background can be prepared.

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CHAPTER I . Introduction.

I Photon Detectors.- Image Intensifiers.

The superiority of the photoemissive surfaces as photon detectors over other photon detectors such as eye or photographic emulsion has been pointed out by McGee[1]. A number of instruments employing photoemissive surfaces have been developed for photon detection. However, a particular class of these instruments in which the intensity of the original image is enhanced and its image quality preserved is known as image intensifier. A number of image intensification methods have been developed and notable amongst them are:-

an/

(A) Lallemand's Electronographic Camera.

Lallemand and his collaborators[2-9] have developed a tube in which both the photocathode and the electronographic emulsion are in the same vacuum compartment, electrostatic focusing is used for focusing the electrons. With such a device gains up to 100 in exposure time over unaided photography and a resolution of 70 lp/mm has been claimed. One of the problems in this system is that the photocathode is poisoned by vapours from the emulsion. In the later versions of the tube refrigeration of the photocathode and photographic plates and titanium ion pumps have been employed to lessen the effect of harmful vapours from the emulsion on the photocathode.

Kron[10] modified Lallemand's camera by putting a gating valve in between the photocathode and the emulsion. The gating valve could be opened when the tube is in operation and the valve could be closed when the electronographic emulsion was to be changed. In this way a photocathode could survive for two or three weeks.

(B) Hiltner's Camera[11,12]

Lallemand's camera was also modified by Hiltner by putting a thin membrane in between the photocathode and the electronographic emulsion. Thus the two were in separate compartments and so, in principle the photocathode should not be poisoned. In general this device has not proved to be so successful as to compete with the original version.

(C) The Spectracon - An Electronographic Image Tube.

McGee and his co-workers[13-15] have developed a sealed off device, so that it can be used any number of times during its life. It is magnetically focused single stage image tube with a thin mica window (~4 microns thick) sealed on the output end of the tube. Contact prints can be taken by pressing a nuclear emulsion against the mica window. Image resolution of 90 lp/mm has been achieved using this tube and a gain factor of 10-20 over unaided photography.

(D) Channelled Image Intensifiers[16-22]

This type of device was proposed by McGee in 1953. The basic idea is to divide the image into a number of picture points, and the photoelectrons produced from each picture point are multiplied in separate multiplying channels. The multiplied output electron currents from the multiplying channels are then combined to produce a flourescent image or a picture signal. An electron gain of 2×10^4 and a resolution of 2 lp/mm has been achieved. To obtain good resolution is the main problem in this device.

(E) Transmission Secondary Emission (T.S.E.) Image Intensifiers[23-28]

In this device photoelectrons from the photocathode are accelerated and focused onto a thin multiplying screen or dynode, primary electrons entering one side of the dynode eject secondary electrons from the other side which can be again focused onto another dynode and so on, until adequate multiplication is achieved. Then these electrons are accelerated and focused onto the output phosphor screen.

Blue light gains ~10^5 and a resolution of 30 lp/mm have been achieved, under the best focusing conditions a resolution of 60 lp/mm has been reported by Livingstone[29]. The signal to noise ratio of this device is worse than that of a cascade image intensifier due to greater fluctuations in the electron multiplication and transmitted primary electrons. However, the work is still in progress to improve the performance of the T.S.E. tube.

(F) The Cascade Image Intensifiers.

In order to achieve higher gain a number of single stage image tubes could be cascaded in series. The assembly of such sections in a single envelope was first suggested by scientists at Philips Gloeilampenfabrieken[30] in 1928. The phosphor of one stage being deposited on one side of a thin membrane, usually glass or mica, and the photocathode of the next stage being deposited on the other side. To ensure the highest possible gain in each stage the spectral distribution of the luminescent light from the phosphor and the wavelength response of the photocathode must be matched as closely as possible. The most efficient combination appears to be that of the trialkali photocathode matched with ZnS:Ag phosphor.

The cascade image intensifiers were first experimentally produced in Germany during world war 11, and the work was reported by Krizek and Vand[31]. Schaffernicht[32] described a two stage electrostatically focused cascade image tube in which glass membrane of 100 microns thickness was used at the interstage. At an overall voltage of 40 kV a light gain of 20 and a resolution of 10 lp/mm was recorded. In 1948 Morton et al[33] published an article discussing the use of an image intensifier for enhanced vision at low light levels. In 1954, Eckart[34] published a paper describing a two-stage tube in which the two stages were separated by a mica sheet of 30 microns thick. Morton[35] and Zavoiskii[36] et al published details of their respective works.

In 1956 Zavoiskii[37] reported a gain comparable to that of a photomultiplier and a resolution of 0.1 mm (10 lines/mm or 5 lp/mm) on the output screen. Stoudenheimer[38] published a paper on a two stage electrostatically focused image tube with S-20 primary photocathode and S-11 interstage photocathode. A blue light gain of 800 and a resolution of 18 lp/mm at the centre of the field which fell to 2 lp/mm only 12mm off the centre, has been reported.

E. J. Davis[39] reported in his work, at Imperial College, London, on the development of magnetically focused two stage image tubes that a blue light gain of 55 and a resolution of 14 lp/mm was achieved when an accelerating voltage of 10 kV per stage was employed to accelerate the photoelectrons. His tubes had "turnover photocathodes"[40] to suppress background but the tube background was even then quite high.

In 1962 Gildemeister and Giese[41] described a four-stage device which had a light gain of ~ 10^5 at 38 kV overall voltage, the interstage cascade screens being formed on glass diaphragms 10 microns thick. The tube was magnetically focused. Davis[42] described a four-stage magnetically focused image tube incorporating rotating cascade screen supports designed to protect the phosphor screens from alkali contamination during the activation of the Sb-K-Na photocathode. The blue light gain of such a tube was reported to be ~ 10^5 with a resolution of 15-18 lp/mm at 40 kV overall voltage.

The work on three-stage magnetically focused cascade tubes was started at Imperial College in 1962. Catchpole[43] and the author made three stage cascade tubes with a blue light gain of ~ 10^5 and a resolution of 23 lp/mm Cascade image tube work is still in progress, with improved phosphor screens a resolution of 35 lp/mm has been achieved in three-stage tubes. The author has made a two-stage image tube with a resolution of 65 lp/mm and a blue light gain of 900 at 30 kV overall voltage.

II Phosphor-Photocathode Phosphor Screens.

The performance of a cascade image tube is mainly dependent on the phosphor screens, photocathodes and to some extent on the substrates for the phosphors at the interstages. Higher light gains can be achieved by matching the spectral response of the photocathode to the spectral distribution of the luminescent light from the phosphor, this has been a common feature of all the cascade image tubes made upto date. Higher resolution can be achieved by improving the phosphor screens and by making the phosphor supports at the interstages very thin.

The composite assembly at the interstage consists of a mica or glass diaphragm, one side of which is coated with a phosphor and a photocathode is formed on the other side. This composite assembly will be called a "Phosphor-photocathode cascade screen" or for brevity a "cascade screen". Efforts have been directed towards reducing the thickness of the phosphor support at the interstage to improve the image resolution of the tubes by various workers in the field. Schaffernicht[32] used a 100 microns thick glass membrane while Eckart[34] used 30 microns thick mica disc at the interstage phosphor screen. Davis[39] used 15 microns thick mica while Stoudenheimer[38] used 10 microns thick mica at the interstage. It was felt that the thickness of the mica membrane could further be decreased so the effort was directed to reducing the thickness of the mica diaphragm and to preparing high quality thin phosphor screens on mica and glass. It is very difficult to handle a very thin mica due to its fragility so special techniques had to be devloped for carrying a mica disc through all the stages of phosphor deposition etc.

This thesis is devoted to the preparation of the phosphor screens on very thin mica sheets and their use in cascade image intensifiers. It should be emphasized that one side of the mica disc should be protected from any contamination while the phosphor is being deposited on the other side because a photocathode has to be formed on that side.

Mica diaphragms of 3.5 microns thickness have been used in our cascade tubes as interstage phosphor supports, thinner micas could not be used due to non-availability of the thin mica discs but it is felt that mica discs of ~1 micron thickness could be used as phosphor supports at the interstages if they could be obtained, or other films such as transparent aluminium oxide films of ~1 micron thickness might also be used.

The deposition of a good phosphor layer having optimum thickness and a very good coverage of the substrate calls for special fine grain phosphors and special phosphor deposition methods. It is well-known fact that as the particle size of the phosphor decreases the efficiency also tends to decrease but the resolution goes up, so efficiency and resolution are opposing requirements for a phosphor screen. Generally a compromise is sought to produce very good screens. Recently it has been possible to manufacture fine grain phosphors with approximately the same efficiency as that of the coarse grain phosphors, for example, EMI type 214 is a fine grain phosphor (particle size ~1 micron) and is nearly as efficient as the G.E. phosphor (particle size 3-5 micron). In this way it is possible to prepare phosphor screens with high resolution and high efficiency.

111 Requirements of Phosphor Screens.

A good phosphor for image tube work should have the following qualities:-

(i) The phosphor should be an efficient convertor of electron energy into light energy.

(ii) It should be stable under electron bombardment and it should have a very low vapour pressure.

(iii) In the cascade image tubes the spectral response of the photocathode should match the spectral distribution of the luminescent light from the phosphor. Probably the most efficient combination is ZnS: Ag (P-11) phosphor with S-9 (Sb-Cs) or S-11 (SbCs:O) or S-20 (SbKNa Cs) photocathode as their emission and response curves respectively have maxima at about 4500 A^o and both are efficient. The Sb-K-Cs photocathode[44] has been known to have 30% quantum efficiency in the blue as compared with 15% quantum efficiency of S-9, so a combination of P-11 phosphor and Sb-K-Cs photocathode will be a very efficient combination. However, it is possible that the trialkali (S-20) photocathode combined with ZnSCdS:Ag (P-20) phosphor might give a more efficient intensifier combination[1]. The output phosphor screen should have a blue luminescence for efficient recording on a photographic emulsions as most of the emulsions have a maximum response to blue light or a green luminescence for visual observations. In our work P-11 phosphor and S-9 photocathodes were used because of the ease of preparation of the S-9 photocathodes.

A finished phosphor screen should have following properties:-

(i) It should be able to produce images of very good definition.

(ii) The texture of the phosphor surface should be very uniform so that under electron bombardment different points on the screen are equally bright, that is a good signal to noise ratio.

(iii) The coverage of the substrate by phosphor should be as near complete as possible so that there are no pin-holes and hence there is no loss of information due to electrons falling into pin-holes in the phosphor.

(iv) It should be capable of producing high contrast images.

(v) For cascade screens the support diaphragm should be very thin to avoid loss of image resolution.

IV Phosphor Deposition Methods.

A number of screen formation methods have been used for the preparation of cathode ray tube screens and the outstanding ones are:-

(i) Dusting or Air Settling.

The substrate is made tacky by the application of a binder and dry phosphor is allowed to fall onto or roll over the surface and adhere. The binder then may be baked off. Kohl[45] deposited sulphur from burning CS_2 onto a substrate, sprayed dry phosphor onto the sulphur, then removed the sulphur by heating.

Leverenz[46] used 1% P_2O_5 in acetone containing 0.3% acetyle alcohol (first dissolved in ether) to wet the substrate and dried until tackiness was obtained. Dry phosphor powder was blown onto the binder and the excess of the powder was removed and the binder could be baked off. Other binders such as K_2SiO_3 could also be used. The phosphor used should be a free flowing phosphor and different parameters such as temperature, air currents, humidity, etc. should be carefully controlled for accurate work. The adhesion of phosphor deposited in this way is poor.

(2) Dry Spraying

This is a variation of the above process. A binder is applied (25% solution of pot. silicate or 10% aqueous solution of sodium carbonate) to the substrate and allowed to dry to tackiness, and a fine spray of dry powder is blown from a spray gun onto the surface[47]. The screen is then dried and baked. The adhesion is poor.

3. Electrostatic Application[48].

In this process the substrate and the phosphor are oppositely charged. The phosphor particles are charged to several thousand volts by blowing them gently past a charged tungsten point or rod. The phosphor deposits on the substrate giving up its charge. The adhesion of such phosphor screens is poor.

4. Wet Spraying.

A phosphor suspension in an organic binder and alcohol is prepared, a few drops of acetic acid may be added for deaggregation. The suspension is kept well-stirred during pressure spray onto the substrate. The screen is dried and the binder baked off. Actual screen thickness and uniformity are difficult to control and such screens show relatively poor contrast in cathode ray tubes[49].

5. "Flow on", Swirling, flush or "dip coat" method[50].

A thin paste of the phosphor in a binder and diluent is introduced onto the substrate and distributed by flowing or swirling it around the surface until a fairly even coating is obtained. The surface is then tilted and excess is drained off and the surface is dried. Binder can be removed by baking it off. The use of camphor[51] has also been advocated for making up the paste or slurry. It is very difficult to make screens of accurate thickness by this process.

6. Sublimation.

The phosphor powder is sublimed onto a cold or moderately hot ($\sim 400^{\circ}C$) substrate. The screen is now heated to $1000^{\circ}C$ for reactivation of the phosphor. Evidently the substrate must have a melting point higher than $1000^{\circ}C$. The efficiency of such screens is very low[52,53]

Koller and Coghill[54] evaporated ZnS:Ag onto a substrate at room temperature and heated the screen up to 700°C in the atmosphere of H_2S + HCl after deposition. A luminescent screen could also be prepared by heating the substrate to 600°C, when deposition is taking place in the presence of HCl gas flow, this method needs the whole chamber to be at 600°C so that there is no sink for ZnS. King[55] also describes a similar method of preparation of luminescent screens. Feldman and others have also made phosphor screens by vacuum evaporation[56-58].

Another method of making luminescent screens is the vapour phase deposition method in which the constituents of the phosphor react in vapour phase condition to form luminescent films, activators are introduced by different methods[59-68].

In general the efficiency of the evaporated phosphor layers is about 30% of the efficiency of the settled screens from the same phosphor but they have the advantage of being free from granular structure and hence the image resolution can be very high.

7. Electrophoresis.[79]

In this process a suspension of phosphor in a suitable electrolyte~~s~~ is prepared and current is passed through the suspension by making the cathode, the substrate to be coated. This is why this process is sometimes called cataphoresis.

Conducting metal oxide (Tin oxide, etc.) was used to make the glass surface conducting and then phosphor was deposited onto it. During the electrophoretic process some of the tin oxide reduces to tin which causes a reduction in the electron energy conversion efficiency of the phosphor by poisoning it. This also makes the conductivity of the substrate non-uniform and gives rise to non-uniform deposits.

Recently the process has been modified to give excellent phosphor screens. A conducting metal coating is applied to the glass disc by evaporation and phosphor is deposited onto it, the metal film is subsequently removed by sublimation or chemical means[70-72]. The process will be described in detail in Chapter II. Gutierrez et al[73] also describe electrophoretic process onto conducting substrates.

8. Raft Method.

A free flowing phosphor powder is floated onto water and compressed onto the surface of water by sliding barriers and put onto glass substrates under water by slowly siphoning the water[74]. Beesely et al[75] have improved the method by controlling the various parameters. This method can give monolayer screens but the coverage of the substrates is rather poor.

9. Sedimentation Method.

A phosphor suspension in a binder such as pot. silicate and a coagulator such as barium nitrate is allowed to settle for a known time, the clear liquid is siphoned off and the screen is dried and baked. This method will be discussed in detail in the next chapter.

10. Centrifuging.

This technique is described by Batchelder[76] and Sadowsky[77]. This is a special case of liquid settling process. The gravitational force in the actual settling process is greatly enhanced by centrifugal force, resulting in a more adhesive and more tightly packed screen and the settling time is also reduced. This technique has aslo been mentioned by Leverenz[78] and more recently Pakswer[79] has used this technique to get excellent phosphor screens. This method is particularly useful in the case of fine grain phosphors.

Apart from the above methods of coating screens, there are other methods such as embedding, painting, chalk settling etc. but these are not sophisticated enough for the preparation of the screens for cathode ray tubes or image tubes.

V. Choice of the Deposition Technique.

Out of the above methods, sedimentation, centrifuging electrophoresis and evaporation of phosphors look attrative for the preparation of the screens for image tubes. Sadowsky[77] has compared different methods and concluded that the settling and centrifuging processes produce similar screens, so this is why we selected sedimentation process for screen formation. The preparation of the screens by phosphor evaporation or vapour phase methods gives less efficient phosphor screens with high image definition but as it involves a lot of technical knowledge so this technique was not used for the preparation of the screens.

Later on in the work a new technique (to be described in Chapter II) for electrophoretic deposition was used for the preparation of high quality screens.

CHAPTER II Preparation of Phosphor Screens.

For the deposition of phosphor screens, glass and mica substrates were used, which were prepared as detailed below:-

I Preparation of Substrates.

(A) Glass discs.

Circular glass discs of 44 mm diameter were cut from Kodak 2" x 2" x 1/25" cover slides. As the finished screen is to be mounted into two stainless steel rings so four slots of 2mm x 2mm are ground at the ends of two perpendicular diameters near the edges. The glass discs are cleaned and platinum point is applied on both sides of the glass discs leaving a central circular space of clear glass of 40 mm in diameter. The painted discs are baked at a temperature of 520°C for half an hour. The discs are now thoroughly cleaned in preparation for phosphor settling. It has been found that painting of glass discs with platinum paint is not necessary as the conducting aluminium backing on a finished screen provides an electrical contact between the phosphor and the stainless steel rings. When the glass discs are prepared for deposition of phosphor by electrophoresis then after cleaning the plates an aluminium layer of $\sim$ 400 A^0 thick is evaporated onto them.

The cleaning of the substrates is a very important step in the process of deposition of phosphors. The glass discs may be dipped into 50% hydrochloric acid or aqua regia (20% hydrochloric acid and 20% Nitric acid) or chromic acid for 10 minutes followed by a wash in running water. The glass discs are now scrubbed with a dilute Teepol solution after which the discs are rinsed in running water for 15 - 20 minutes followed by two changes in analar water and drying. This process cleans the glass discs and preserves the polished surface. If a thorough cleaning is required then the glass discs should be dipped in 3% hydroflouric acid for 5 minutes during which the surface layer of the glass disc is removed by hydroflouric acid and therefore a clean surface is produced, but this process produces rather a rough surface. The process can be made less chemically active by preparing a solution of:-

Hydroflouric acid	5%
Nitric acid	33%
Teepol	a few drops.

This solution has been known to give cleaner surfaces[80]. Other cleaning processes such as scrubbing the glass discs with very fine grain ceric oxide and Teepol followed by the usual rinsing and drying etc were also tried.

The cleaning process now in use is to dip the glass discs in Teepol solution for 5 minutes, scrub them with cotton wool soaked in Teepol solution and ultrasonically agitate them in a dilute Teepol solution, then the glass discs are given a thorough rinse in running water ($\sim \frac{1}{2}$ hour). The glass discs are now given three changes of analar water and then dried in isopropyl alcohol vapour bath. This process does not affect the finish of the surface. More recently R.B.S 25 is being used as a detergent in place of Teepol, but if R.B.S 25 is used then the glass discs must be soaked in 2% solution of the detergent for 24 hours or 5 minutes in ultrasonic cleaner, followed by a thorough rinse in water (about one hour duration) to remove all traces of the detergent.

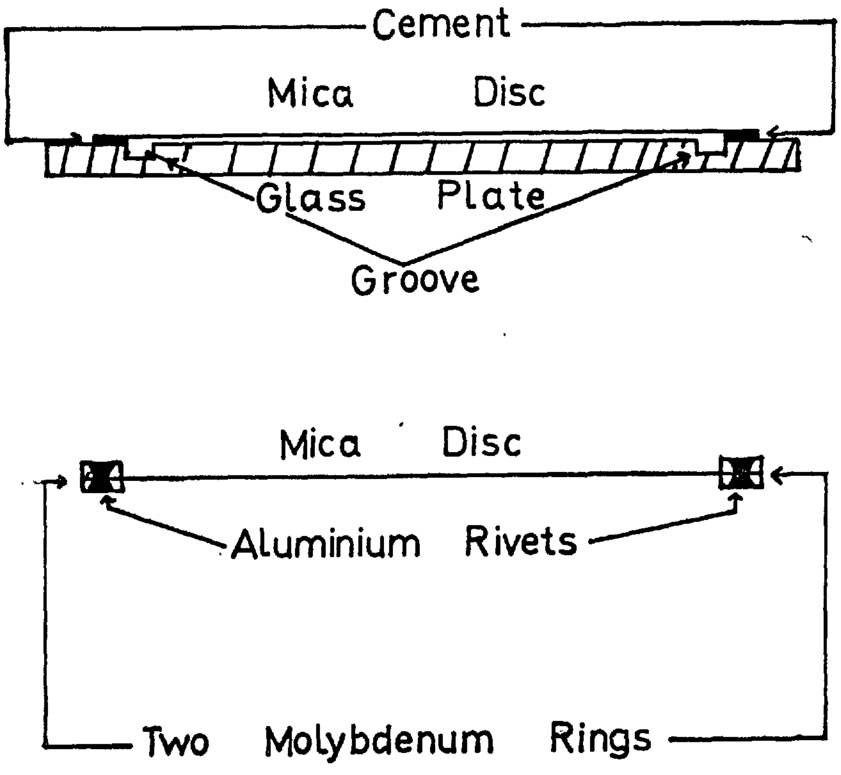
(B) Preparation of Mica Substrates.

The present work was started with commercially available circular discs of 44 mm diameter and having a thickness of 7-10 microns, the thickness of each mica disc is measured with an interference microscope. The thickness of mica discs used was gradually reduced to 3.5 microns. Platinum paint is applied around the periphery on both sides of each disc leaving a central clear space of 40mm diameter. The mica disc is heated on a glass plate till the liquid paint gives a metallic appearance. Later on it was found that painting one side is enough as this side will provide a good electrical contact with the photocathode surface and the mounting ring while on the other side the conducting aluminium backing provides an electrical contact between the phosphor and the mounting ring.

No cleaning procedure was used for the mica discs prior to settling phosphor screens because it was difficult to handle such thin mica sheets. Mica discs supplied , freshly split, by the manufacturers were assumed to be clean and since good Sb-Cs photocathodes were made on them, our assumption seemed to be correct. However, for the actual deposition of the phosphor the fragile mica disc should be on a solid support so that it can go through the stages of phosphor deposition, aluminization, etc., without rupture. Moreover, the support must be such that it protects the other side of the mica disc from any contamination during these processes since a photocathode is to be formed on it subsequently.

A number of experiments were performed to achieve the desired objective and the successful design for such a device is shown in Fig. I. A circular groove is ground into a cover slide of 2" x 2" size having an outer diameter of 40 mm and inner diameter of 36 mm and a depth of 0.5 mm. A mica disc is placed onto such a plate so that 2 mm of the mica disc projects outside the groove all around the circumference. This projecting portion is sealed onto the glass plate with cellulose solution, which forms a water tight seal and hence protects the mica surface facing the glass plate when it is in the phosphor settling solution, and the excess of the cementing solution goes into the groove. With this method, the mica disc can have the phosphor screen deposited and the aluminium backing

Fig.–1


Cement
Mica Disc
Glass Plate
Groove
Mica Disc
Aluminium Rivets
Two Molybdenum Rings

applied without damage and without contamination of the surface on which photocathode is to be formed subsequently.

For the electrophoretic process the above device could not be used because the cellulose cement is soluble in isopropyl alcohol which is the most suitable liquid for the suspension of the phosphor for the electrophoretic process. For this the following new technique had to be developed. First the mica disc was sealed between two titanium rings of 45 mm. outer diameter and 40 mm. inner diameter, using a suitable low melting point solder glass (G.E.C. X -88). The coefficients of expansion for mica, titanium and solder glass are nearly the same. The titanium rings are prepared in the departmental workshop and are vacuum stoved at 700°C. The rings are then dipped in 3% hydroflouric acid to etch them, after which they are rinsed in water and dried. Now the titanium rings are glazed on one side with the solder glass. A mica disc is sandwiched between two glazed titanium rings by heating the assembly up to the melting point of the solder glass ~ 500°C. Mounted in this way the mica discs can be handled very safely. The mica disc so mounted is taut and strong enough to resist rupture by a reasonable force but the contact between the mica disc and any sharp point should be avoided.

As the mica disc has gone through the process of mounting, etc., so the cleaning may be advantageous. The mica discs are cleaned by heating them in hydrogen peroxide solution up to 60°C, this probably oxidises the organic impurities on the mica surface, then the mica disc is dipped in a dilute Teepol solution for about 5 - 10 minutes. It is given a thorough rinse in water followed by two changes of analar water and drying in isopropyl alcohol (IPA) bath. The mica discs can not be cleaned in an ultrasonic cleaning bath because they are shattered by this treatment. Also the mica discs should not be taken out of the hot hydrogen peroxide or I.P.A bath until they are cold because the very thin mica does not stand a sudden temperature change; probably the mounting rings cool too quickly.

In order to provide an electrical contact between the mica surface and the titanium rings, liquid platinum paint is painted near the periphery and the mica discs are heated to 350°C which turns the platinum paint into a bright metallic coating. The mica discs are then given another cleaning after which they are placed in a vacuum chamber and heated to 200 - 250°C and aluminium is evaporated onto them in order to provide a conducting substrate for electrophoresis. This heating is necessary for the aluminization of the mica discs otherwise the aluminium film does not adhere well and peels off at some points when the electrophoresis is taking place. An alternative technique was also tried, an aluminium film was "floated" onto a mica disc and after drying, the phosphor was cataphorized onto it, this technique also works but it is not reliably reproducible because sometimes the aluminium film peels off at some points during electrophoresis due to the lack of adhesion.

In order to protect one side of the mica sheet, the mounted mica disc was sealed onto a ground glass disc of 45 mm diameter with paraffin wax, which forms water-tight and alcohol tight seal so the mica disc can now be carried through the process of phosphor deposition and aluminization.

II <u>Deposition of Phosphor</u>.

The phosphor was deposited onto the substrates by the sedimentation and electrophoretic processes. The following three types of phosphor were used for the two deposition processes.

	Phosphor	Grain Size
1.	G. E.(P-11)	3 - 5 microns
2.	EMI type 214 (P-11)	~1 micron
3.	Derby Luminescents type A/259	~1 micron

The two processes will now be discussed in detail.

(A) The Sedimentation Process.

This method consists of making a phosphor suspension in one or more than one liquids and allow it to settle on a substrate in an aqueous medium. The chemical agents which bond the phosphor particles to the substrate are known as binders; and the chemical agents which promote this adhesion are known as electrolytes which are in general acidic salts. Four methods have been employed for phosphor settling.

1. Where no binder or electrolyte is used in the suspension.
2. Binder only is used.
3. Electrolyte only is used
4. Binder and Electrolyte are used.

In general the adhesion of phosphor screens prepared by the first three methods is very poor and aggregations of particles take place at different points. Though for some applications any one of these methods may be advantageous[77,81] ~~but~~ such screens are definitely not good enough for cathode ray tubes or image tubes as the screens have to undergo processes of aluminisation, etc.

The fourth process is most commonly used for the preparation of phosphor screens for cathode ray tubes or image tubes, though the choice of electrolyte varies according to the requirements. The binders used are potassium silicate, ~~or~~ sodium silicate or ethyle silicate while the electrolytes used are sodium or magnesium sulphates or strontium or Barium nitrates. Sometimes weak acids are also used to promote adhesion, the acids are phosphoric acid, acetic acid etc. For the preparation of the phosphor screens a combination of potassium silicate and barium nitrate was employed.

The sedimentation of a suspension of solid particles in a liquid is determined by Stoke's Law. According to this law the speed v of a spherical grain under the influence of an external force F and the resistance to the movement of the grain in a given liquid is given by.

$$F = 6 \pi \eta r v$$

where η is the coefficient of viscosity (poises)
r is the radius of the grain.

If the force is gravity diminished by buoyancy then

$$F = \frac{4}{3} \pi r^3 (P-P_o) g$$

where g is constant of gravitation
P is density of the solid particle
P_o is density of the liquid.

$$F = \frac{4}{3} \pi r^3 (P-P_o) g = 6 \pi \eta r v$$

$$v = \frac{2(P-P_o) g r^2}{9 \eta} = \frac{h}{t}$$

where

h is height of the column (cm)
t is settling time (secs)

$$t = \frac{18 \eta h}{(P-Po) g D^2}$$

where D is the diameter of the particle.

The above relation is valid only for spherical particles which are large enough for the Brownian movement to be negligible. Huber and Freytag[82] have calculated the settling time for cubic crystals to be

$$t = \frac{7\eta h}{(P-P_o)e\,a\,g}$$

where

e = thickness

a = length of each side of the crystal.

Neglecting the effect of Brownian movement of particles the settling time can be calculated for spherical and cubical particles of phosphor of 1 micron diameter and 1 micron each side respectively under the following conditions:-

η = 0.01 poise gm/cm sec.
h = 3 cms.
P = 4.1 gm/cm^3 (For ZnS)
P_o = 1 " (For water)
D = 1 micron
e = 1 micron
a = 1 micron

Although the phosphor settling suspension contains some pot. silicate ($\sim$ 2.5%) and some barium nitrate (0.4 gm/litre) but for calculations values of η, P_o used are that of water and hence the results will be approximate.

Calculations show

$t \sim 5$ hours for spherical particles
$t \sim 2$ hours for cubic particles.

Sullivan and Jacobson[83] have shown that the effect due to Brownian movement of particles can not be neglected for particles of size $\lesssim$ 2 microns.

As zinc sulphide phosphor of particle size 1-2 microns was used for settling process, so the Brownian movement would tend to keep the particles in the suspension for much longer time than expected from the above formulae. As calculated above cubic ZnS would settle in approximately two hours but experimentally a settling time of about three hours was found to be necessary, which is in accordance with the above theory.

The role of the binder and the electrolyte in the mechanism of adhesion of the phosphor to the substrate is a subject of a number of papers by Hazel and his co-workers[84,85,86]. The composition of the potassium silicate is shown in Fig. 2(a) and when it is introduced into the suspension then the silicate imparts negative charges to both the substrate and the phosphor particles as shown in Fig. 2(b).

When an electrolyte is added then its role is:-

(a) to decrease the negative potentials due to the imparted charges from the silicate ions.

(b) to promote the formation of oxygen bridge by intermolecular dehydration as shown in Fig. 2(c).

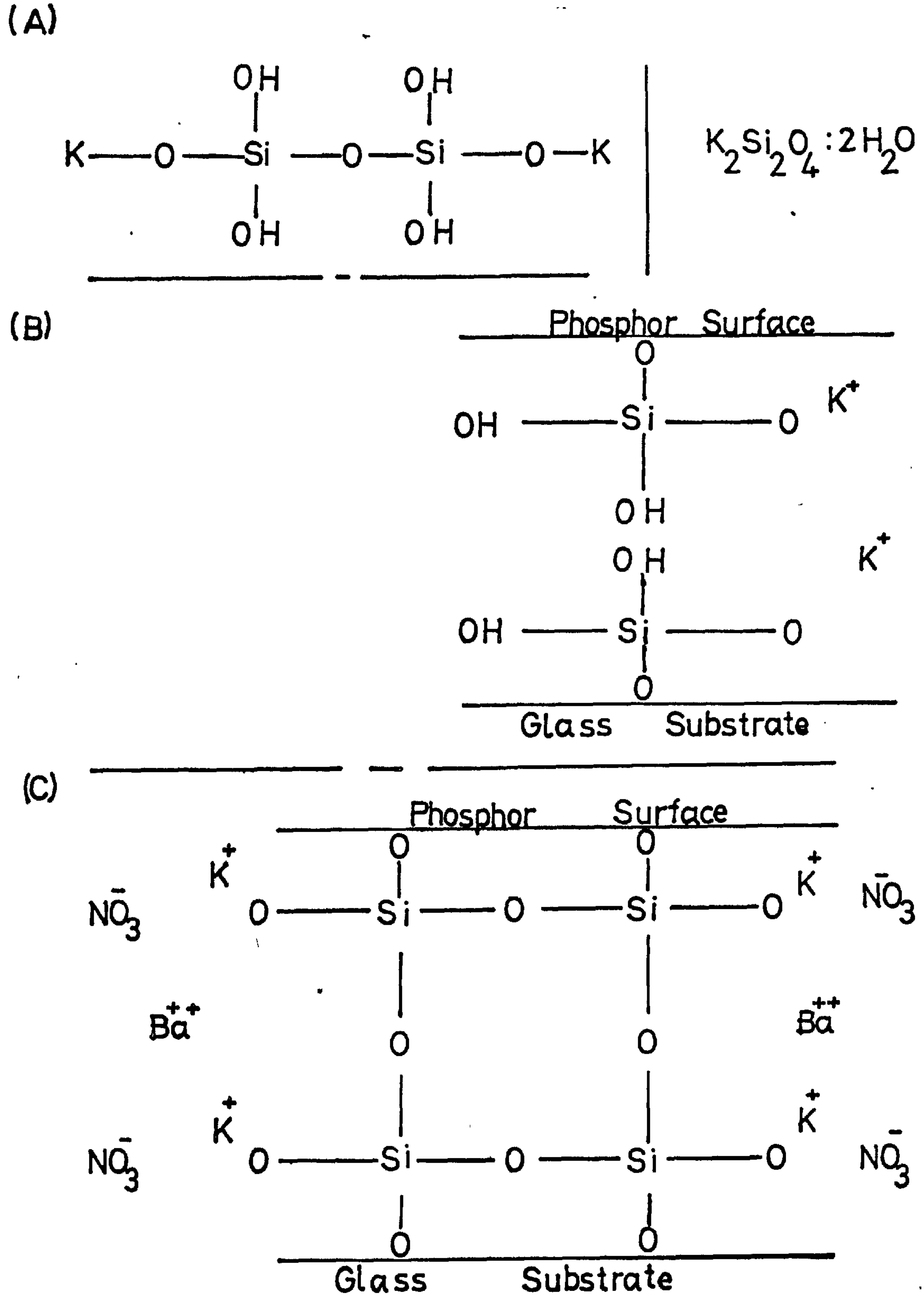
(c) Since the silicate is concentrated by adsorption on the solid surfaces, the loci of polymerisation are predominatly there as shown in Fig. 2b & c.

The polymerisation of the silicate or "gelling" is the cause of the adhesion of the phosphor to the substrate and it is brought about by an electrolyte.

The polymerisation of the silicate can also be obtained by lowering the pH of the concentrated potassium silicate by dilution - a very slow process, but the process can be expedited by the addition of alkali metal or ammonium salts[86,87].

de Boer and Emmens[88] in 1955 proved that the use of the barium or calcium salts as electrolytes was more effective because "gelling" can be achieved in much shorter time as compared with the "gelling" due to the "sulphates" of magnesium and sodium. Later on Saminskii[89] performed experiments to determine the relative merits of doubly charged metal ions as "gelling" agents for settling process.

Figure -- 2


(A)
OH
Si
K
O
$K_2Si_2O_4:2H_2O$
(B)
Phosphor Surface
K^+
OH
Si
O
Glass Substrate
(C)
Phosphor Surface
K^+
NO_3^-
Ba^{++}
Si
O
Glass Substrate

He found that the rate of the development of the turbidity or "gelling" of the potassium silicate depended upon the cations of the added electrolytes in the following ratio.

$$Ba^{++} : Sr^{++} : Ca^{++} : Mg^{++} :: 100 : 60 : 6 : 3$$

Since Ba salts produce "gelling" more quickly therefore barium nitrate was used as an electrolyte.

Saminskii also found that the electrostatic effects do not primarily determine the adhesion of the phosphor to the substrate, the adhesion is primarily determined by the degree and conditions of polymerisation of the silicic acid.

The adhesion of the settled screens depends upon the composition of the phosphor suspension. In the case of the sulphate electrolytes the purpose of the electrolyte is only to promote adhesion but it does not build itself into the phosphor layer; while in the case of barium nitrate the barium ions probably occur in the completed gel but the amount is small as compared with the amount of the silicate in the phosphor layer[88].

The amount of the binder in the phosphor layer affects the surface brightness of the phosphor due to the loss of electron energy in the binder layers (scattering and absorption). Hangos et al[90,91] made investigations into this effect and found that the surface brightness depends upon three factors.

(i) Composition of the settling liquids.
(ii) Settling time
(iii) particle size of the phosphor.

Evidently the surface brightness (light output) would depend upon the amount of silicate and barium oxide embedded into the layer; the decrease in surface brightness (output light) is quite marked at lower voltages ($\sim$ 5 keV) but it is negligible at higher voltages ($\sim$ 15 KeV,or more).

The decrease in surface brightness with increase in settling time is due to the landing of colloidal particles of ($BaO-SiO_2$) on the phosphor screen. The efficiency loss due to decrease in particle size of the phosphor is quite well-known[92], but with refined techniques efficient fine grain phosphors have been manufactured.

Preparation of Suspension.

A known amount of phosphor is ball-milled in a flask after adding a few drops of potassium silicate. Water or barium nitrate solution could also be used for ball-milling but potassium silicate seems to be a better disperser. It has been found that if 10-20 cc. of dilute pot.silicate solution is added to phosphor and then ball-milled for about 15 minutes on a rotor, then it does help in breaking aggregations of phosphor particles more effectively. The ball-milling should not be too long as it might crush some of the phosphor crystals which will result in electron energy conversion loss[93].

The liquids etc. used for the settling process should be of analar quality. The potassium silicate used for the settling process was manufactured by Messrs Levy West, having a specific gravity of 1.225 and a molar ratio 2:1. High purity barium nitrate was used. The water used for the settling process was doubly distilled water prepared in the laboratory, known amounts of potassium permanganate and caustic soda being added to singly distilled water in order to get a good quality double-distilled water[94].

The present work was started with G.E. p-11 phosphor, a workable solution for the settling of this phosphor is

Total vol. 250 c.c.
Pot. silicate 20-25 c.c of 10% solution in water.
Barium Nitrate 225-230 c.c of solution in water having a strength 0.22 gm/l

It is recommended that a dilute solution of pot.silicate should be freshly prepared as it tends to polymerise and hence loses its binding power if kept at room temperature for more than four days. The dilute solution of barium nitrate can be prepared in any volume as it is very stable at room temperature.

The substrates are placed in a glass dish and covered with double-distilled water which serves as the so called "cushion layer". It may be mentioned that the cushion layer could be of pot. silicate or barium nitrate solutions keeping the concentrations constant as described earlier. The phosphor suspension is added to this cushion layer and allowed to settle for one hour. After the process of settling, the excess liquid is siphoned off, the phosphor screens are dried, and aluminized by the floated aluminium backing technique described in chapter III.

The above type of phosphor screens were used in three stage image intensifiers with a very good blue light gain and a resolution of 15 lp/mm. The resolution of the cascade tubes is mainly limited by the thickness of mica discs and phosphor screens. The coverage of the substrates by the phosphor was not very good.

In order to improve the resolution of the image tube, the mica thickness was reduced from 7-10 microns to 3-4 microns subsequently. A fine grain phosphor EMI type 214 was used which also served to improve the coverage of the substrates and hence minimized the loss of information and the thickness of the phosphor layer was also reduced. Another P-11 phosphor prepared by Messrs. Derby Luminescents Ltd. (type A/259) was also used but the electron energy conversion efficiency was found to be half that of the EMI type 214 value. Mostly EMI phosphor has been used for the preparation of phosphor screens for the image tubes.

The EMI type 214 phosphor was settled in the same way as the G.E phosphor but this was a failure as the adhesion of phosphor onto the substrate was very poor. Different concentrations of potassium silicate and barium nitrate were tried out, and good settled screens are obtained if the following formula is used

Total Volume 250 c.c
Pot. Silicate conc. solution 6-7 c.c
Barium Nitrate (0.4 g/l) 243 c.c.

Good quality phosphor screens were prepared in this way with improved coverage and bettwr image definition.

In order to further improve the coverage of the substrate double layer phosphor screens were prepared. In this method the amount of the phosphor is divided into two halves and settled onto the same substrate one after the other. It has been found that the second layer needs a lesser amount of potassium silicate as compared with the first layer, namely 7 c.c for the first layer and 5 c.c for the second layer. A similar result was obtained in floating aluminium films on settled and electrophorized phosphor screens (see chapter III).

The double layer screens have almost no pin-holes but the image definition and output light are worse than a single layer screen of the same thickness, probably due to the scattering of electrons in the increased layer of binders embedded into the phosphor layer.

B. Electrophoresis.

Electrophoresis of insulating powders has been known to give very uniform deposits on conducting substrates[69] and luminescent materials have also been applied in this way[73]. In general the method employed to coat a glass or mica surface with a luminescent material is to render the glass surface conductive by a conducting layer of nesa (Sn_2O) which is a transparent layer. During the electrophoresis of ZnS:Ag onto such a substrate some of the tin oxide turns into metallic tin which reduces the transparency of the substrate, makes the resistance of the substrate non-uniform giving rise to non-uniform coating and poisons the phosphor thus reducing its electron energy conversion efficiency.

Airey[70] discovered a new technique in which the substrate is temporarily rendered conducting by evaporating a layer of aluminium or silver or copper and cataphorizing phosphor onto it; the conducting layer is then removed by chemical means. The author found that some other materials such as magnesium, cadmium and Zinc could also be used with their appropriate solvents to remove them after electrophoresis of the phosphor.

Another technique is to render the substrate conducting by the evaporation of zinc and then to sublime it in vacuum after the electrophoresis[72]. The author feels that the process could be carried out more effectively by using magnesium or cadmium because it is possible to get very thin uniform layers of Mg or Cd onto glass substrates more easily than Zn and the sublimation temperatures of all these substances are similar. Camp and Pulleston[71] have also employed a similar technique of rendering the substrate conducting temporarily for the electrophoresis of the phosphor.

Preparation of the Phosphor Suspension.

Two stock solutions were prepared:-

A. Thorium nitrate (0.6 gm) of analar quality was dissolved in 100 c.c of analar isopropyl alcohol.

B. Another solution consisting of 50-50 isopropyl alcohol and pure glycerol was prepared. All the chemicals used were of analar quality.

The glass-ware is cleaned as described earlier. 500 mgms of phosphor powder are poured into a clean flask with glass balls in it, 2 c.c. of solution B and 10 drops of solution A are added to the phosphor. The mixture is agitated for about 10 minutes to disperse the powder; continuous rotation of the flask accompanied by intermittent shaking is employed until visible lumps of phosphor disappear. Then 95 c.c of isopropyl alcohol and 5 c.c of analar water are added to the phosphor, the mixture is shaken thoroughly and 3-3.5 c.c of solution A is added. The mixture is now ultrasonically agitated by immersing the flask in water in an ultrasonic cleaning unit for about 5 minutes.

Such a suspension is stable and it can be used a number of times. The main purpose of adding thorium nitrate in the suspension is to reduce the resistivity of the suspension. Powell[95] found that in a high gain (blue light gain $\sim 10^6$) three stage cascade tube, employing phosphor screens prepared by the above-mentioned electrophoretic process, some very bright flashes could be observed. The existence of these flashes was attributed to the emission of α-particles by atoms of thorium, a small residue of which must remain in the phosphor layers after the electrophoretic process.

This suspected origin of these flashes was shown to be true conclusively by the following experiment. Two phosphor screens, one deposited by electrophoresis using thorium nitrate as an additive, the other without it and prepared by settling technique, were brought successively into close proximity to the input photocathode of a cascade intensifier tube in operation. On the output phosphor screen of the tube bright flashes were seen when the thorium containing phosphor screen was pressed against the input photocathode of the tube, no bright flashes could be observed in the case of the settled screen. Thorium is a radioactive element which decays into its daughter element by emitting an α-particle which in turn produces luminescence in the phosphor and this luminescent light is amplified by the image tube thus giving rise to bright flashes.

Lanthanum nitrate was used in place of thorium nitrate but after the electrophoretic process the phosphor layer came off when phosphor screen was dipped in the etching solution; aluminium nitrate was tried instead and this gives satisfactory screens but the suspension is not stable. In order to make a stable suspension a mixture of lanthanum nitrate and aluminium nitrate (1:2) is being used but even then the phosphor suspension becomes useless after two days.

Electrophoretic Deposition.

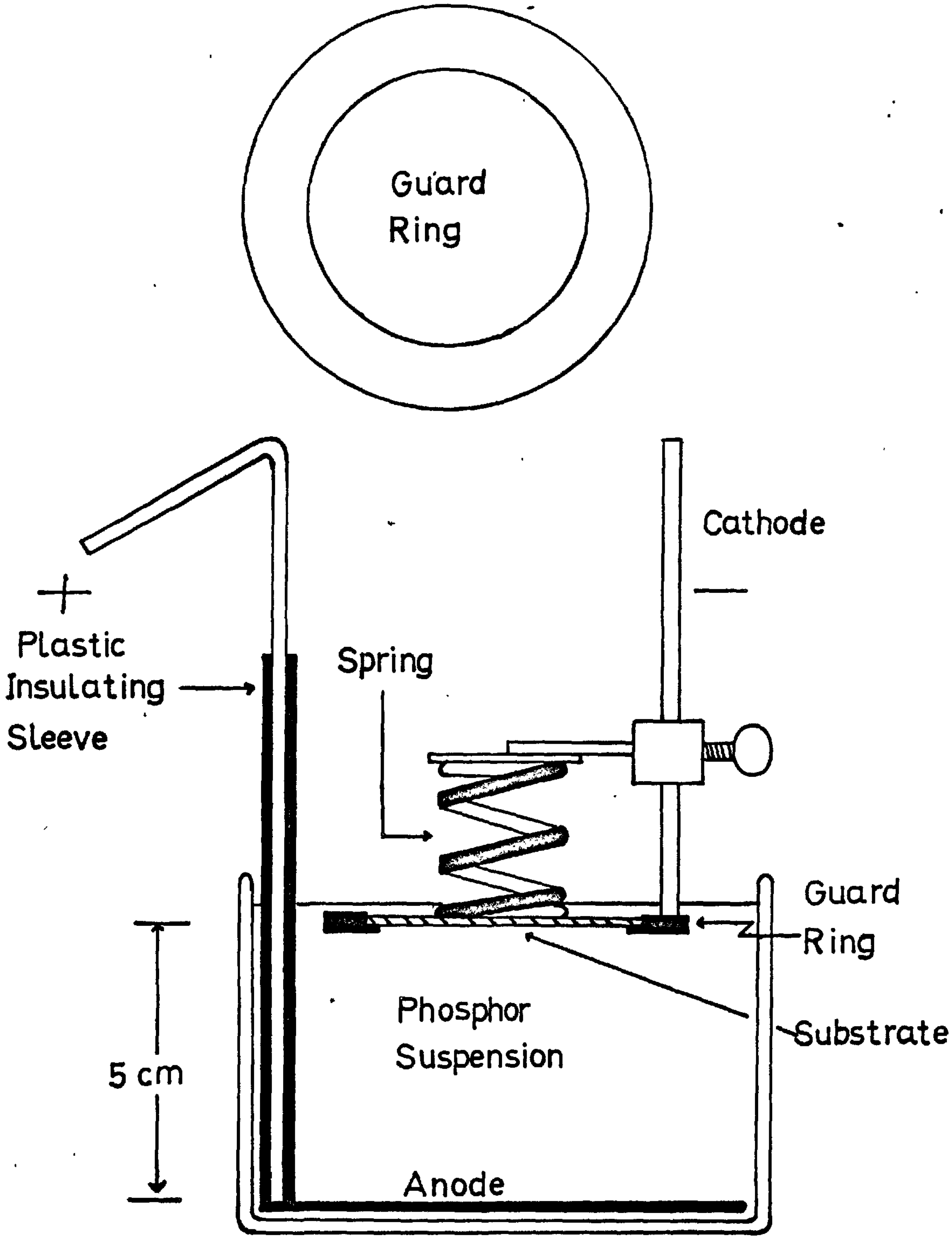
The substrate to be coated is mounted in a stainless steel guard ring (shown in Fig.3) to provide a good contact between the aluminium layer and the guard ring at many points, to provide a uniform field in between the substrate and the anode and thus to obtain a more uniform deposit. The phosphor suspension is poured into a glass dish containing a stainless steel plate which is to serve as an anode in the electrophoretic process. The guard ring containing the substrate to be coated is dipped into the phosphor suspension and a known current is passed through the suspension by making the substrate as the cathode. The phosphor particles having adsorbed positive ions of lanthanum or aluminium are attracted towards the substrate under the influence of electrostatic forces.

The rate of phosphor deposition will depend on the following factors.

1. Composition of phosphor suspension especially the amount of thorium or lanthanum nitrate added to it.
2. the distance between the electrodes.
3. Voltage applied.
4. Current passing through the electrolyte.
5. Temperature of the suspension.

If all the above factors are kept constant then the

Fig. —3



Electrophoretic Deposition

thickness of the deposited phosphor layer can be calibrated with time. Experiments were performed to find out the relationship between the deposited thickness and the deposition time; the relationship is linear if the amount of phosphor taken out of the phosphor suspension is small as compared to the amount of phosphor still remaining in the phosphor. With the continuation of the electrophoretic process the thickness comes to a maximum and then falls with time, the curves are shown in (Fig.4&5). The details of the conditions under which the electrophoresis was performed to obtain the two curves are as follows:-

Phosphor	Derby Luminescents type A/259 (Fig.4)	EMI type 214 (Fig.5)
Distance between electrodes	1 cm	2.5 cm
	55 volts	150 volts
Current through the electrolyte	30 mA	30 mA
Temperature	20°C	20°C

Composition of the suspension was the same in both the cases except for the change of the phosphor powder. The substrates were weighed before and after deposition of the phosphor and in this way the thickness of the phosphor layer in mg/cm^2 was determined.

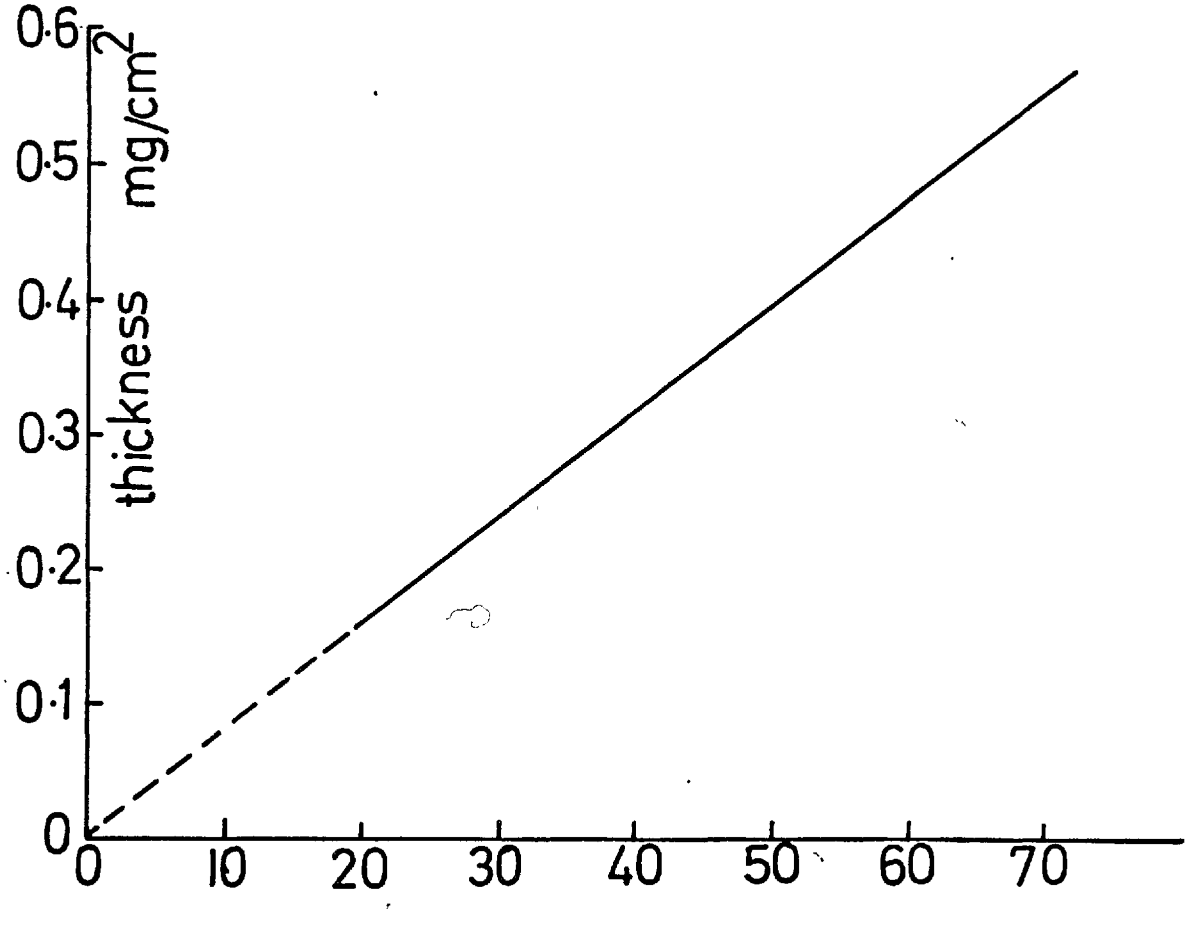
In Fig. 4 the actual amount of phosphor deposited in fact is $\sim$ o.5 mg/cm^2 and hence only the first part of the curve of Fig.5 is significant.

<u>Etching of the conducting layer.</u>

To etch away aluminium layer under phosphor layer the following chemical etch is being used:-

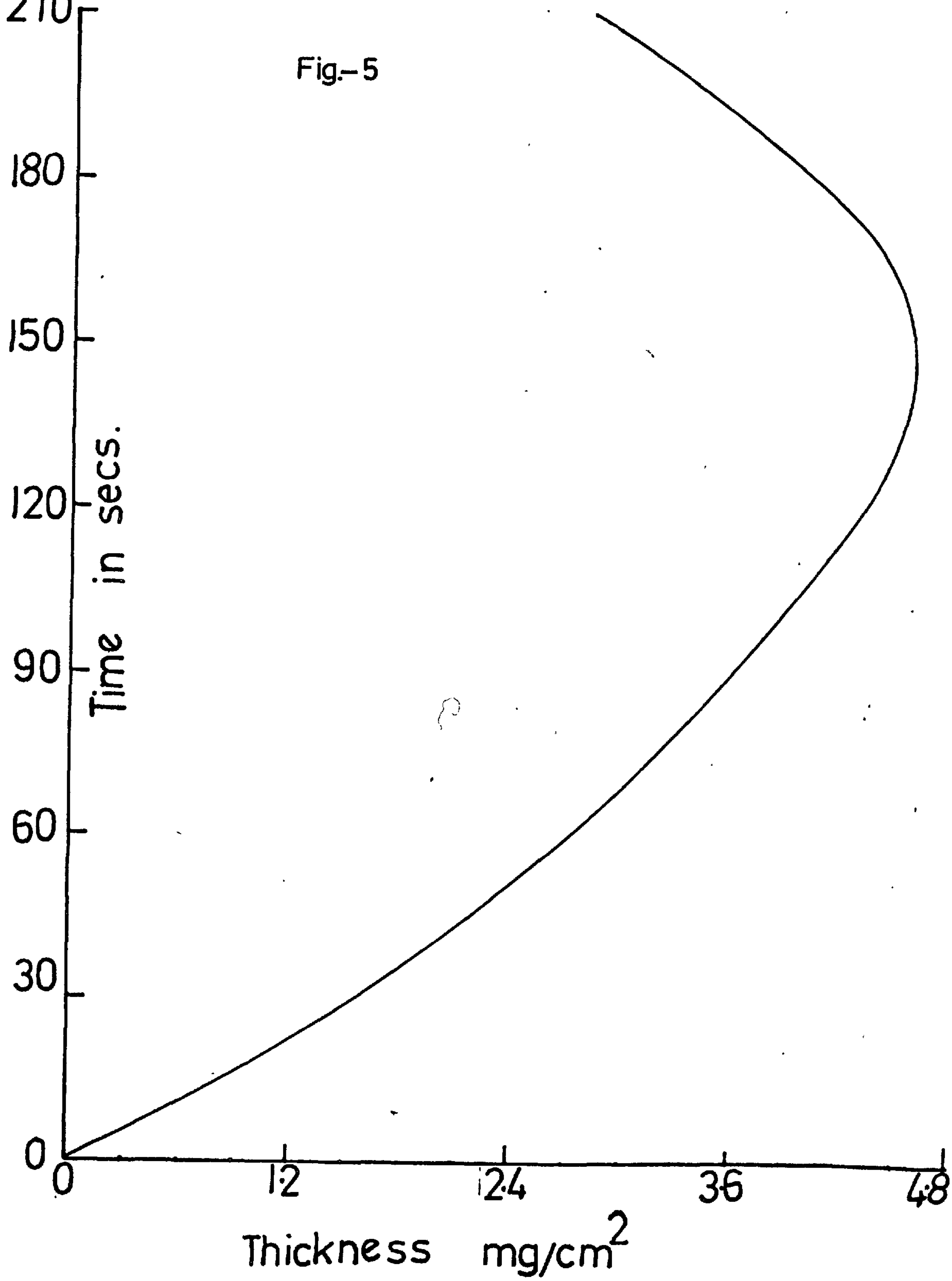
Ammonium persulphate	8 gms
Ammonia solution	40 c.c
Double distilled water	200 c.c.

Fig—4


0·6
0·5
0·4
0·3
0·2
0·1
0
thickness mg/cm^2
0
10
20
30
40
50
60
70

time in secs.

Fig.-5


210
180
150
120
90
60
30
0
Time in secs.
0
1·2
2·4
3·6
4·8
Thickness mg/cm^2

The phosphor screens are placed in the solution for about 10-15 minutes during which the aluminium layer is etched away.

The phosphor screens are thoroughly washed in double-distilled water and aluminized as described in Chapter III.

Fig. 6 & 7 show the different stages through which a mica disc goes through for phosphor deposition. The details are:-

Fig. 6 Settling Process.

A. Mica holding substrate (a grooved glass plate)
B. Mica disc cemented onto the glass plate A.
C. Sedimented phosphor onto the mica.
D. Aluminized phosphor on mica.
E. Mica mounted in two molydenum rings.
F. A completed cascade screen with a black layer of aluminium on top of the aluminised screen.

Fig. 7 Electrophoretic Process.

A. A mounted mica disc in between two titanium rings.
B. Platinized version of A.
C. Aluminized B.
D. Phosphor deposited onto C and aluminium dissolved away by chemical means.
E. Aluminized D.
F. An aluminium black layer applied to E.

Fig. 6

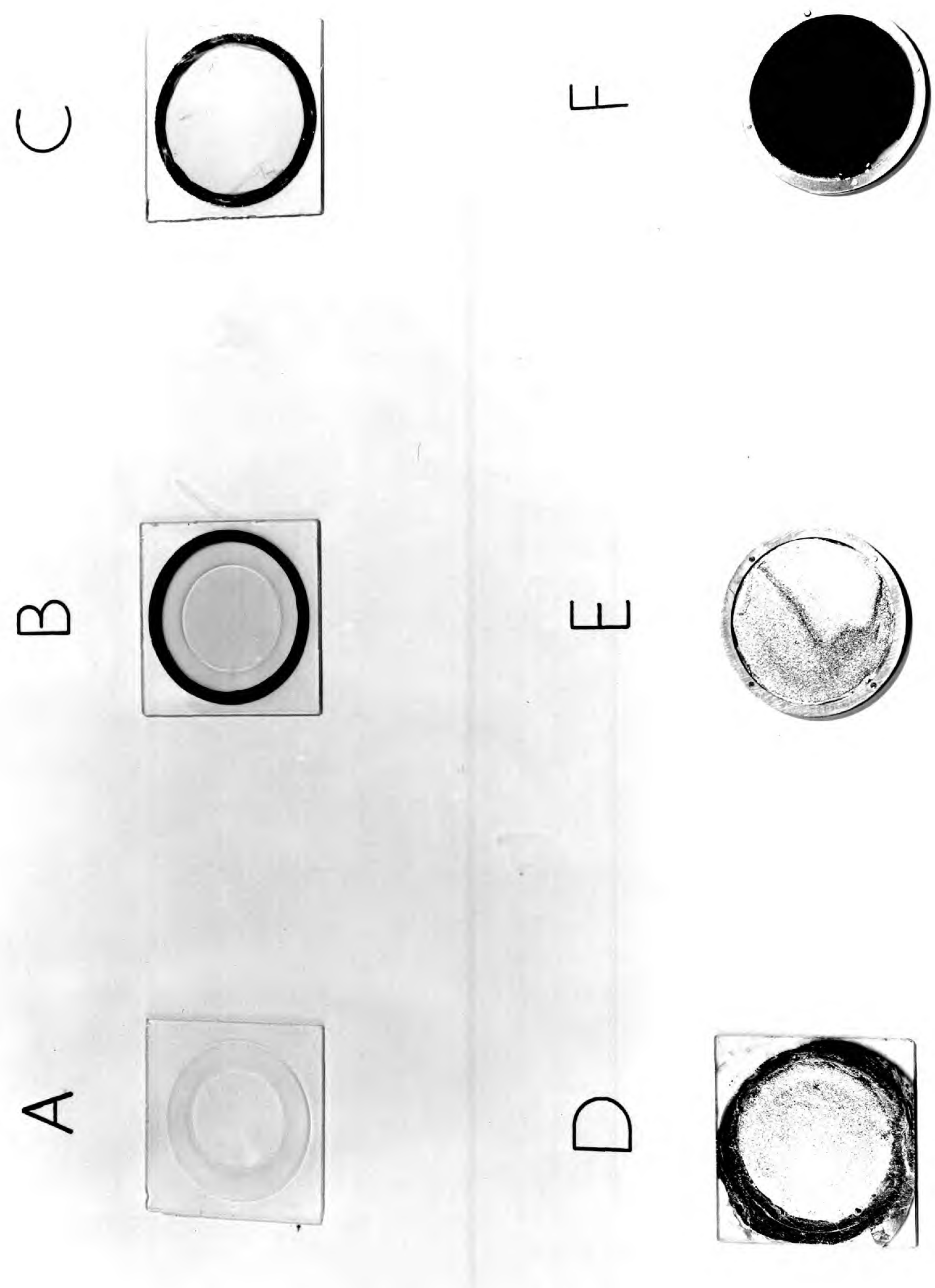
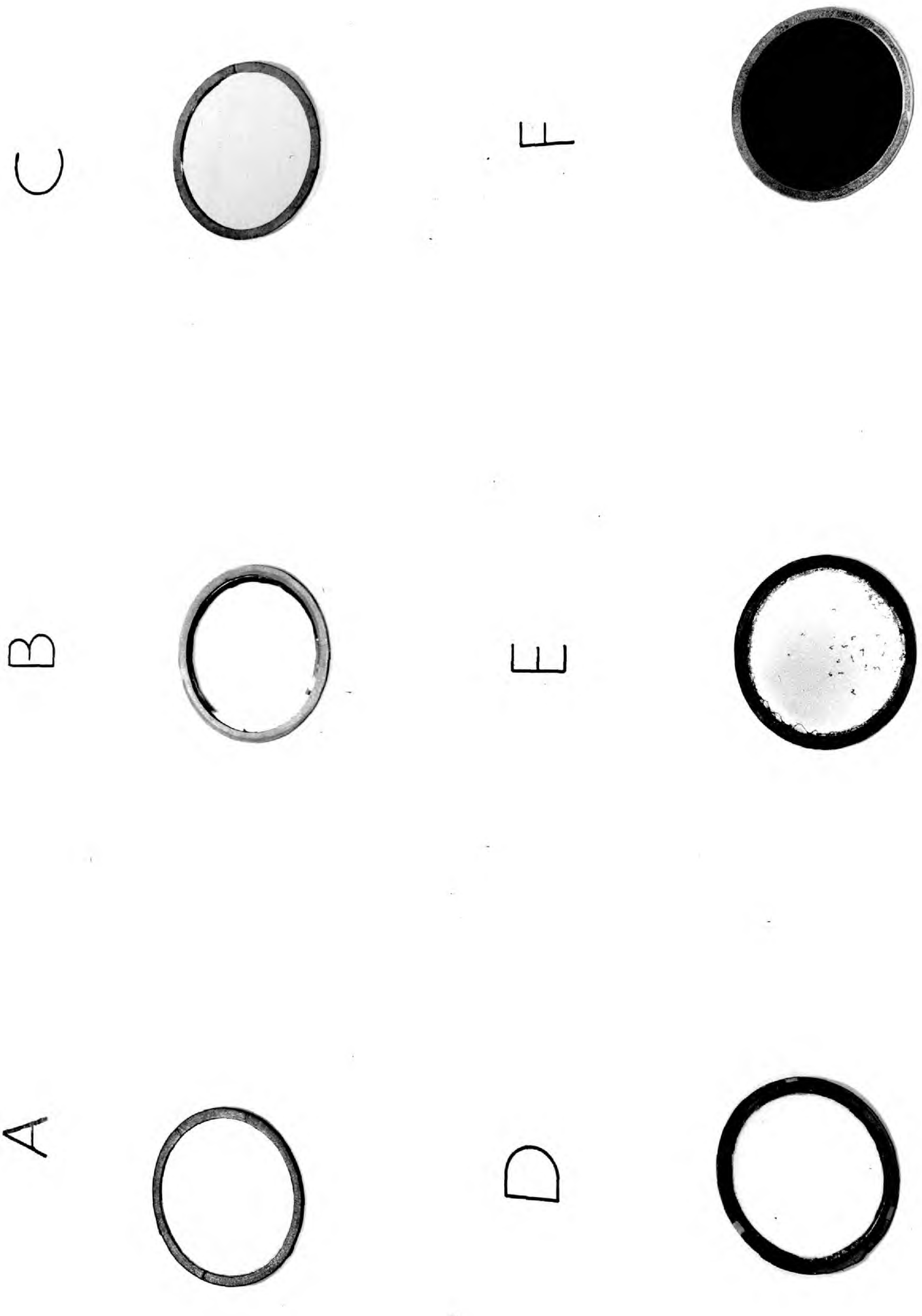


Fig. 7



CHAPTER III Preparation and Application of Backings onto the Screens.

I Reasons for the application of Aluminium backings.

In any practical photoelectric device involving the use of phosphor screens or in cathode ray tubes, the phosphor screens should have aluminium backings for the following reasons:-

(i) For enhancing the amount of light in the forward direction. Bril and Klasen's[96] experiments on willemite phosphor screens showed that a light output of 30 to 40 per cent of the total light emitted by the phosphor could be recorded on the glass side in the case of unbacked phosphor screens. If the phosphor be backed by an aluminium layer of 100 per cent reflection and if no electron energy was lost in the aluminium layer then the light output would be increased by a factor of 2.5 to 3. They found an enhancement factor of 2.2 by aluminizing the willemite phosphor screens. In the case of sulphide phosphors similar results are expected and we have consistently observed a gain factor of 2 for p-11 (Zinc Sulphide silver activated) phosphor screens.

(ii) In image intensifiers, the aluminium backings prevent the light emitted from the phosphor from going back to the photocathode and in this way help to prevent light feedback. The loss of image contrast due to the light going back to the photocathode is also reduced.

(iii) For stabilizing the potential of phosphor screens.

(iv) In tubes in which a photocathode must be activated in the presence of a flourescent screen which is easily damaged by alkali vapour the aluminium backing helps to protect the phosphor and preserves its efficiency.

II. Choice of the material for backing phosphor screens.

Aluminium has long been chosen as a backing material for the following reasons.

(i) Reflectivity.

The reflectivity of the aluminium films in the visible region of spectrum is very high. Holland[97] reported a reflectivity of 93% for a freshly prepared aluminium film which falls off to 88% after one weeks exposure to air. These data are for the aluminium films made from high purity aluminium (99.99% pure) such as is used for the preparation of the aluminium backings for our phosphor screens.

Silver (Ag) films have even higher reflectivity in the visible region of spectrum but the application of the silver films to phosphor screens is not advisable because of higher stopping power of silver for electrons and the growth of a gray layer on the film after exposure to air.

(ii) Loss of electron energy due to penetration.

The loss of electron energy while passing through a medium is given by the Thomson-Whiddington law

$$v_0^4 - v^4 = b\rho x$$

where

v_0 is the velocity of electrons entering the film.

v is the most probable velocity at a depth x

ρ is the density of the film material.

b is a constant. It is clear from the above expression that the stopping power of a material depends on its density or atomic weight. Longini[98] calculated the loss of electron energy for the aluminium films of various thicknesses. The energy loss for 15 KeV electrons in penetrating a thickness of 500 A° of the aluminium film is of the order of 2 per cent which is negligible.

(iii) On exposure to air a fresh aluminium surface is oxidised to a depth $\sim$ 35 A° (Ref 99). This transparent inert layer of aluminium oxide protects the metal from further oxidation.

(iv) An aluminium film is a good conductor so it stabilises the phosphor potential.

(v) An aluminium film does not react chemically with the phosphor material and it is stable under electron impact.

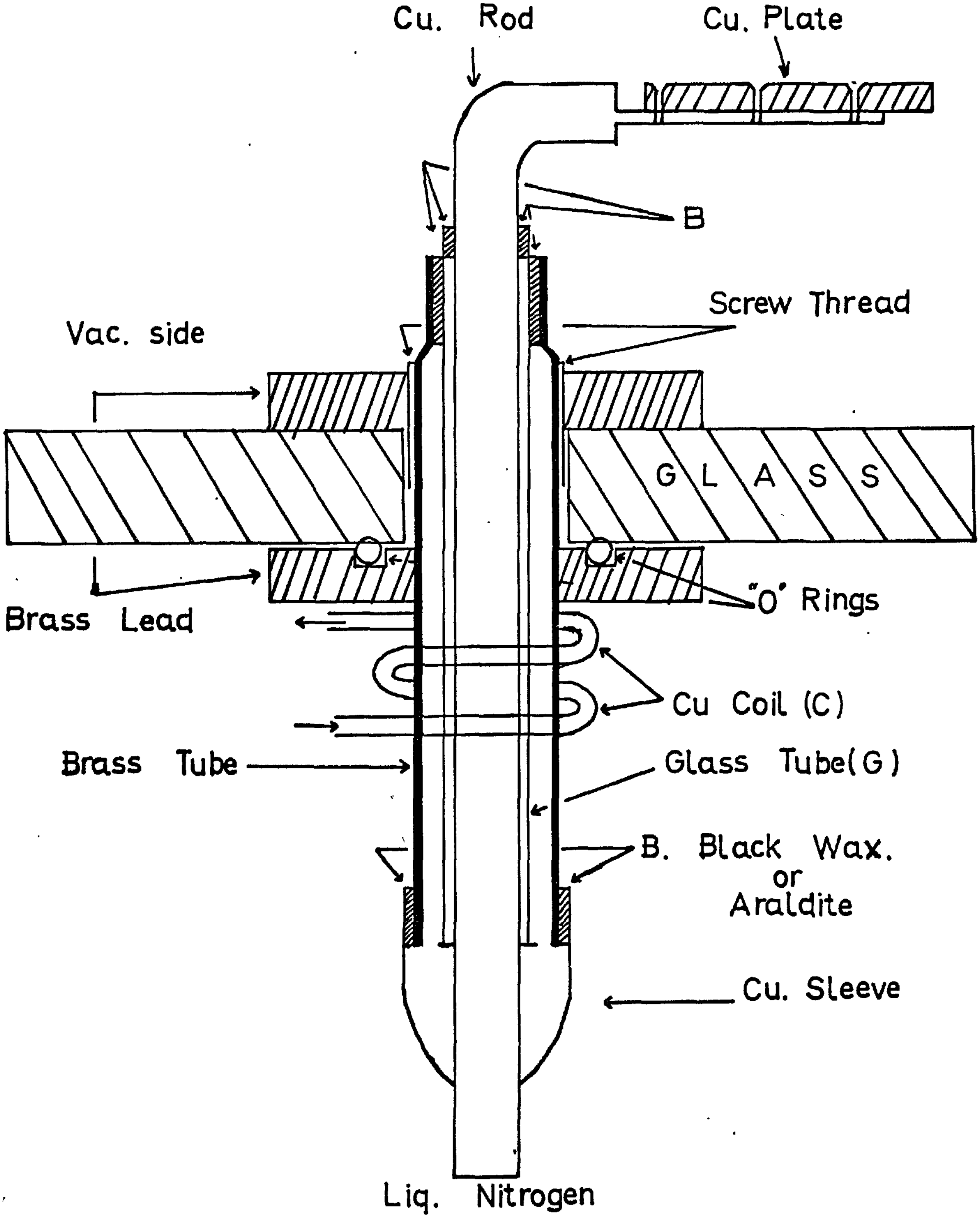
III Techniques of application of the aluminium backings.

(i) Direct Evaporation.

A direct evaporation of aluminium onto a phosphor layer will produce a discontinuous layer unless the phosphor layer is very smooth, which is possible only in the case of evaporated phosphor screens. The main disadvantage of direct evaporation is that the incident aluminium atoms are scattered round the phosphor grains. This causes a considerable loss in the amount of light in the forward direction. Anyway this technique was adopted to study the effect of such a backing on the efficiency and resolution of phosphor screens. It was invariably found that the amount of light in the forward direction was reduced by a factor of 2 or 3 as compared with an unbacked phosphor screen. The aluminium layer was also applied by evaporating aluminium at grazing angles but similar results were obtained.

In order to investigate whether the loss of light in the forward direction was caused by the scattered aluminium atoms, as argued above, an apparatus was designed in which the phosphor substrate could be cooled before the evaporation of aluminium. A diagram of the apparatus is shown in Fig. III-1. Essentially, it consists of a vacuum chamber with a copper rod passing from the inside to the outside of the vacuum system. The end of the rod inside the vacuum chamber carries a copper plate and the other end of the copper rod dips into liquid nitrogen. A glass tube "g" insulates the copper rod from the copper coil C. Warm water runs through the coil C in order to reduce the

Fig. III—1


Cu. Rod
Cu. Plate
B
Screw Thread
Vac. side
GLASS
Brass Lead
"O" Rings
Cu Coil (C)
Brass Tube
Glass Tube(G)
B. Black Wax. or Araldite
Cu. Sleeve
Liq. Nitrogen

temperature difference of the glass plate of the vacuum chamber and its surroundings.

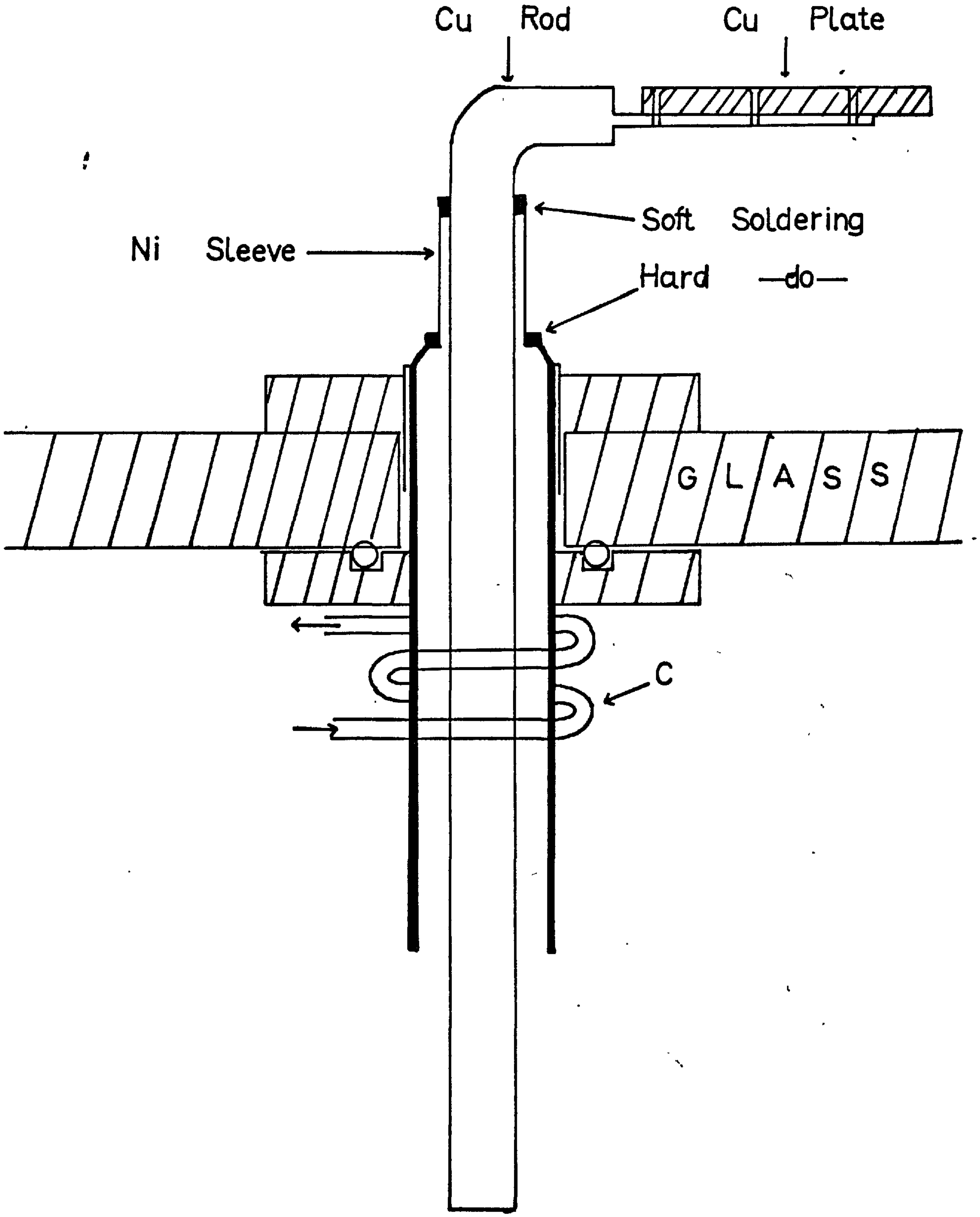
Black wax was used to make the apparatus leak-tight at room temperature but as the copper rod was cooled a leak developed. Araldite was then used in place of black wax but similar results were obtained. The most effective seal made use of hard and soft solder. The modification of the apparatus is shown in Fig. III-2, the different parts are also labelled. The temperature of the copper plate inside the vacuum chamber was measured with a thermocouple. The temperature was of the order of -120°C.

A glass plate carrying the phosphor screen onto which the aluminium layer was to be evaporated was placed on the copper plate. A vacuum was created in the chamber enclosing the screen and the screen was cooled to -120°C as detailed above. Sufficient time was allowed for the phosphor screen to assume the temperature of the copper plate before the aluminium was evaporated onto the phosphor. Such phosphor screens were tested for efficiency. Some improvement in the amount of light in the forward direction was found as compared with a similar screen with an aluminium backing evaporated at room temperature, but still it was less than an unbacked screen. These experiments proved that this particular technique is not useful from the view point of enhancement of the amount of light in the forward direction.

(ii) Conventional Backings.

Conventional backings were first applied by Germans during second world war. Epstein and Pensak[100] published the method at the end of the war. In this technique an organic film is put onto a phosphor screen so that it stretches across the surface of the screen as a blanket. An aluminium layer is evaporated onto this "blanketed" screen. The organic film is removed by baking the phosphor

Fig III-2



screen at 350°C for one hour. This method is widely used in industry and the technique of applying an organic film onto the phosphor screens has been perfected by different workers but the published data is lacking. are

In order to assess the relative merits of this type of aluminium backing a number of phosphor screens were prepared and aluminized in the following manner. A phosphor screen was placed in a glass dish just covered with analar water and a droplet of the filming solution was put onto the surface of water. The droplet spread itself on the surface of water due to surface tension forces and was allowed to dry. The water was then siphoned off carefully causing the organic film to settle on the phosphor screen. The screen was dried and an aluminium layer was evaporated onto it. The screen was first baked at 100°C for half an hour to get rid of trapped water vapours followed by a baking at 350°C for one hour to bake off the organic film.

It is difficult to estimate the thickness of the organic film on the surface of water but experience shows that if the organic film is just visible by reflected light then it is of the right thickness. The different parameters such as the dilution of the filming solution, the size of the droplet and the area onto which organic film is to be spread can be worked out by careful experimentation. As the monitoring of the thickness of the organic film was done by eye so the thickness of the organic film was likely to vary. In practice differences in the amounts of light in the forward direction by as much as 20% were observed for the phosphor screens from the same settling batch. The results obviously indicated a variation in thickness of the organic film.

Our experiments indicated that the thickness of the organic film is a very important factor. If the organic film is very thin then it may break at different points in following the contours of the phosphor surface and thus impair the reflectivity of the aluminium film. If, on the other hand, the organic film is too thick then it may leave some residue on baking off which again will affect the reflectivity of the film.

The filming solution is a nitrocellulose solution to which some plasticisers such as dibutyl phthalate and some solvents like amylacetate, ethyle lactate, ethyle acetate, acetone and cyclohexanone are added. Concentrated solution is available and it can be diluted by any one of the solvents but mostly amylacetate is prefered for diluting the solution. Some people use Toluene to dilute the solution. It is generally recommended to bake off the organic film in an atmosphere of air or oxygen.

A number of phosphor screens with conventional backings were prepared and tested for efficiency and it was found the amount of light in the forward direction was always smaller than for a phosphor screen having a floated backing as described below.

(iii) Floated backings.

In this technique an aluminium film is evaporated onto a thin layer of sodium chloride which itself had been evaporated onto a polished glass disc. The sodium chloride film is then dissolved out in analar water leaving the aluminium film floating onto the surface of water from where it can be transferred or "floated" onto a phosphor screen. The aluminium film is then cemented to the phosphor with a solution of potassium silicate. The details of the process will be given in subsequent pages.

IV Comparison of Aluminization Techniques.

(i) Output Light.

If all other variables are kept constant the amount of light emitted in the forward direction will depend upon the aluminization technique.

It is clear from the previous section that a direct evaporation of aluminium is not practicable. The amount of light in the forward direction will depend upon the reflectivity of the aluminium film. The maximum reflectivity of an aluminium backing when a screen is conventionally backed has been reported to be ~ 80%[96,101]. On the other hand the reflectivity of a freshly prepared aluminium film can be as high as 93%, one would expect, therefore a gain of 8% in the amount of light emitted in the forward direction if a floated backing were used on a phosphor screen instead of a conventional backing. In actual practice gains ~ 20% or more have been observed which indicate that our technique of applying the organic film was not perfect.

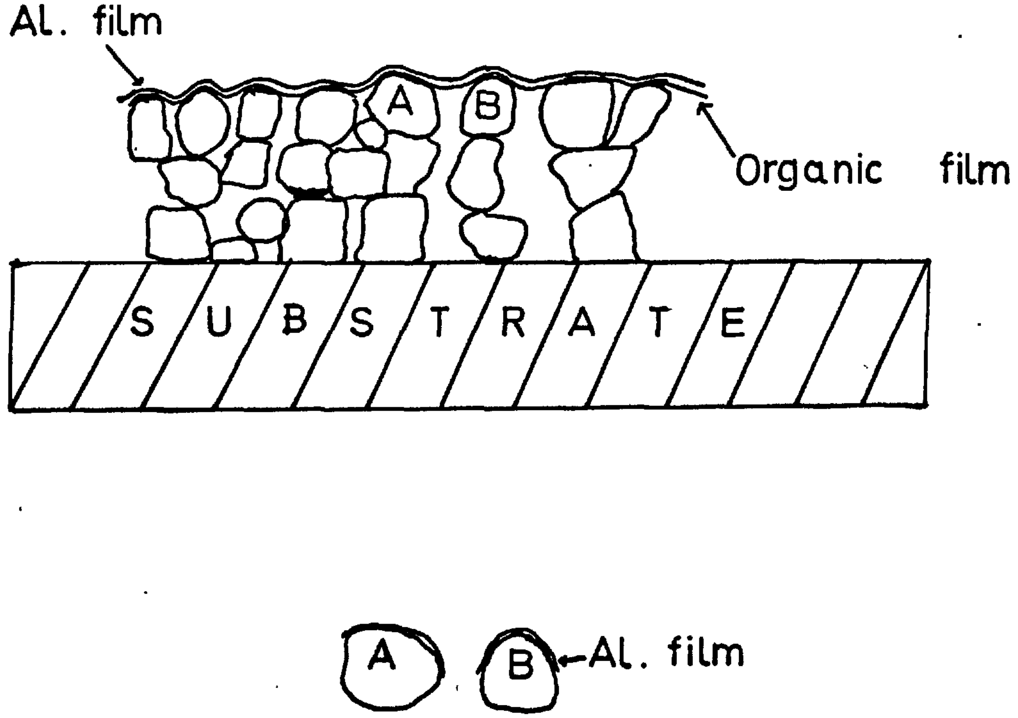
(ii) Reproducibility.

As pointed out earlier that the light gain in the case of conventionally backed screens varies even if the screens are from the same settling batch, presumably due to the imperfection of the application technique of conventional backings, while in the case of the screens with floated backings have nearly the same output light if they are from the same settling batch. So from this point of view the screens with floated backings are more reliably reproducible than the conventionally backed ones.

(iii) Pin-holes.

The number of pin-holes (gaps) in a backed screen depends upon the number of pin-holes in the unbacked phosphor screen and the number of pin-holes in the aluminium film applied to it. A suggested mechanism for the number of gaps a / in the conventionally backed screens is diagrammetically shown in Fig. III-3. If two grains A & B are separated by a small gap then in the case of conventional backing the initial organic film "blankets" the gap and then aluminium is evaporated onto it. When the organic film is baked off

Fig. III— 3



then the support for the aluminium layer is gone, the pin-hole in the original screen is reproduced in the backed screen. A settled phosphor screen of 1 mg/cm^2 thickness prepared from EMI type 214 P-11 phosphor we found by counting visible pin-holes under high magnification to have ~ 4000 pin-holes/mm^2. A conventional aluminium backing of 500 A^o thick was applied to it and the number of the pin-holes in the finished screen was found to be ~ 4000 pin-holes/mm^2, If the thickness of the aluminium is increased then the number of pin-holes decreases but increase in the aluminium film thickness results in the loss of image definition due to scattering of electrons and loss of light in the forward direction due to loss of energy of incident electrons while penetrating through the aluminium film. On the other hand a floated backing of 500 A^o thickness on a similar phosphor would have ~ 10 pin-holes/mm^2 because it was a self supporting film before application to phosphor screen. Thus in a cascade image intensifier, the conventionally backed screens are more likely to be attacked by caesium vapour than screens with floated backings when the photocathodes are being processed.

It was decided to develop the floated backing technique. An investigation was made into the preparation of highly reflecting aluminium films and their application to phosphor screens. The techniques developed are described here:

V Preparation of the Aluminium Films.

In principle the aluminium should be evaporated onto a substrate from which the aluminium film could easily be floated off onto the surface of water. Three methods have been tried and these are discussed below.

(i) Teepol Technique.

Six glass plates were taken, cleaned as described in chapter II and dipped into a concentrated solution of clean Teepol. The glass plates were dried and aluminium was evaporated onto them in a vacuum chamber. The aluminium films were highly reflecting but the drying pattern of Teepol was reproduced on them. In a number of subsequent experiments the Teepol solution was diluted but the drying pattern was always reproduced. These films could be easily floated onto water. In another experiment the glass plates were polished with soft cloth after dipping them in Teepol solution. Aluminium was evaporated onto these glass plates, the resulting aluminium films were highly reflecting but it took 15 minutes to float off one aluminium film. Due to this difficulty of floating off the aluminium film this technique was not used for the preparation of the aluminium films for backing the phosphor screens.

(ii) Evaporation onto Single Crystals of Sodium Chloride.

Single crystals of sodium chloride of size 2" x 2" x $\frac{1}{2}$" were obtained[102]. The crystals were polished on a very flat surface so that the irregularities of the crystal surface were removed. Aluminium was evaporated onto these polished crystals in a vacuum chamber, highly reflecting aluminium films were obtained and could be very easily floated onto the surface of water. This method of preparing aluminium films is expensive and more time-consuming as the polishing of the crystals is not easy. Further work on this technique was stopped because of the reasons mentioned above.

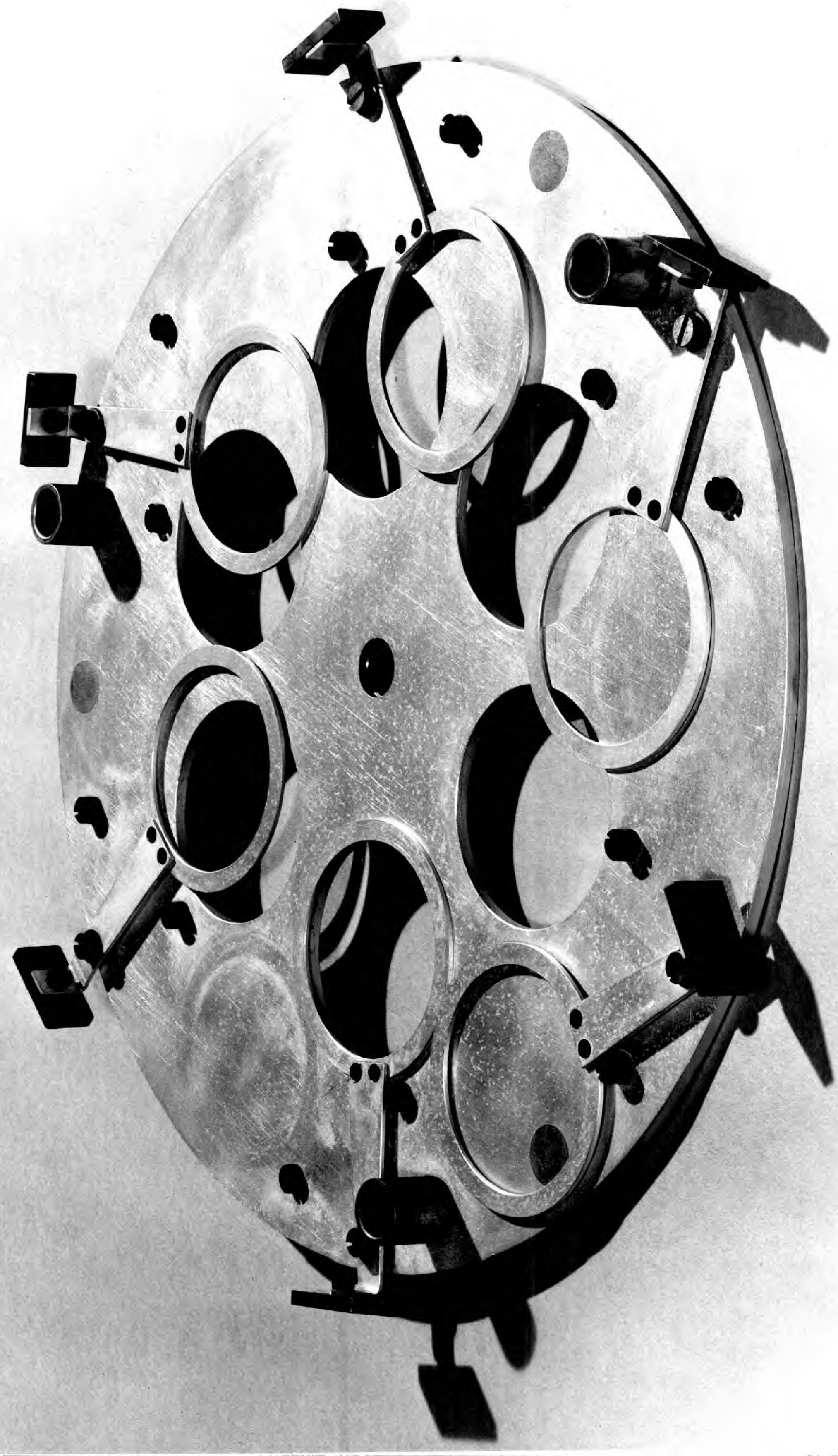
(iii) Evaporation onto Amorphous Salt Substrate.

A metallic plate having six holes (each with a diameter of 52 mm), the centres of which lie on a circle, was supported in a vacuum chamber. These six holes were covered with clean glass plates. Analar sodium chloride was evaporated onto these glass plates from a Molybdenum boat at a pressure of 10^{-5}mm Hg. The thickness of the salt layer is quite critical, if the salt layer is very thin then the aluminium film will not float off; on the other hand if the salt layer is too thick then the aluminium film assumes a golden yellow colour. The right amount of salt was evaporated (see next section) which was followed by aluminium evaporation at a pressure of 10^{-5}mm Hg.

It was found that if the areas onto which the salt and the aluminium have been evaporated were approximately the same, the aluminium films did not float off easily presumably due to adhesion of aluminium where it comes directly in contact with the glass. To overcome this difficulty the salt was evaporated onto a larger area than the aluminium. In the first experiments the salt was evaporated as described above, the vacuum chamber was let down to atmospheric pressure and a new metal plate having six holes of slightly smaller diameter (48mm) was put underneath the metal plate having bigger holes. The chamber was again pumped down and the aluminium was evaporated. In this way the salt layer is 52mm in diameter while the aluminium film is 48mm in diameter. When the glass plate having the salt and the aluminium layer on it is lowered into water the salt is dissolved and the aluminium film floats off.

To bring the vacuum chamber to atmospheric pressure after salt evaporation is not desirable because the salt may absorb some moisture which is likely to change the surface texture of the salt layer and hence the growth of the aluminium layer may be affected. Secondly if this operation is eliminated then the production of the aluminium films will be quicker and easier. In order to make up this defect a mechanism was designed and made which could be operated from outside the chamber. This device is shown in Fig. 4. It consists of a metal plate having six holes (hole diameter 52mm), each hole

Fig. 4



is provided with a metallic ring of 54 mm outer diameter and 48 mm inner diameter. These rings can be brought into line with the holes by means of a lever system. The lever system has a metal ring on one end and an iron slug on the other end. The iron slug can be operated from outside the vacuum chamber with the help of a magnet and so every ring can be brought into line with the hole or swung clear of it. After the evaporation of the salt layer, the rings are brought into line with the holes by operating the iron slugs with a magnet and aluminium is evaporated. Thus it was no longer necessary to bring down the vacuum chamber to atmospheric pressure after the salt evaporation.

VI Monitoring the thickness of the films.

(A) The salt layer.

It was mentioned in the previous section, the thickness of the salt layer is very important for the reflectivity of the aluminium films. In order to evaporate the optimum amount of salt, attempts were made to monitor the thickness of the salt layer. The following two methods were tried.

(i) As a very thin salt layer is transparent so the thickness of the salt cannot be monitored by measuring the amount of transmitted light passing through the salt layer.

In order to evaporate the exact amount of the salt required, a thin semi-transparent layer of aluminium ($\sim$ 100 or 200 A^{o}) was evaporated onto the glass plates to be used, and then the salt was evaporated while watching for the interference fringes produced by the sodium chloride layer on the aluminium layer. The interference fringes could be watched either from the glass plates or on a glass shield encircling the evaporators. Experience showed that if the fringes start with a blue fringe then the salt layer is of optimum thickness, so the salt was evaporated until the starting blue fringe was visible. If the fringes start with green or any other colour, then too much salt has been evaporated. This method of monitoring the salt layer was used successfully for the production of highly reflecting aluminium films.

(ii) In the above technique experience plays quite an important role so another technique was adopted for evaporating the exact amount of salt. In this technique the thickness of the salt layer was monitored by collecting reflected light from one of the glass plates with the help of a selenium cell. The selenium cell was connected to a galvanometer which gave a measure of the reflected light. It was found that the reflectivity of the salt layer falls as the thickness inceases to a certain value. The amount of the reflected light goes through a minimum and begins to rise again as the thickness of the salt layer increases. This minimum of the reflectivity corresponds to a thickness of $\lambda/4$ where λ is the wavelength of the light used for monitoring or precisely the same amount where interference fringes should be visible. From our experience of watching blue fringes for the right amount of the salt layer we concluded that blue light should be used for monitoring the thickness of the salt layer, a Wratten 47B filter was used in the path of white light. The glass plate which was being monitored for the salt layer thickness was ground on the back surface in order to stop reflection of light from the back surface. It was found that the aluminium films were more reflecting if the evaporation of the salt was stopped just before the minimum of the reflectivity, so the thickness of the salt layer should be of the order of 1000 A^{o}.

(B) Thickness of Aluminium Films.

The thickness of the aluminium film was monitored by measuring the amount of light transmitted through it. A light source was so arranged that a beam of light could pass through one of the glass plates into a photovoltaic cell placed on the top of the vacuum chamber, so that it could receive the amount of light transmitted through the glass plate and the aluminium film. The amount of light was adjusted by varying the input of the light source so as to cause full-scale deflection of a galvanometer connected with the photovoltaic cell. When the aluminium was evaporated the transmission of the light fell and the reading on the galvanometer also fell. In this way the thickness of the aluminium film was monitored.

At low transmissions of light ~ 5% the photovoltaic cell begins to pick up light from the aluminium evaporating filament. In order to overcome this difficulty a chopper-amplifier can be used coupled with the photovoltaic cell. Aluminium films of various thicknesses expressed in percentage of light transmission were prepared for experimental phosphor screens.

VII Reflectivity of the aluminium films.

Some aluminium films were prepared in this way in order to compare their reflectivity with the value of 93% quoted in the literature[97]. The aluminium films were floated on clean glass plates. A narrow beam of white light from a tungsten filament lamp held at a temperature 2850°K was transmitted through the clear portion of aluminized glass plate. The amount of transmitted light was measured with a photovoltaic cell connected to a galvanometer. The amount of transmitted light was 98%. Then the same narrow beam of light was reflected from the aluminium layer facing the glass plate and the reflected light was fully collected by the same photovoltaic cell and was found to be 97%. As the glass plate was very thin (~ 1 mm) so the light absorption in the glass is negligibly small. Substracting the contribution due to reflected ray A Fig. III-4 (~ 2%) the reflectivity comes out to be 95% which is in good agreement with precise measurements published in literature[97].

VIII Evaporators.

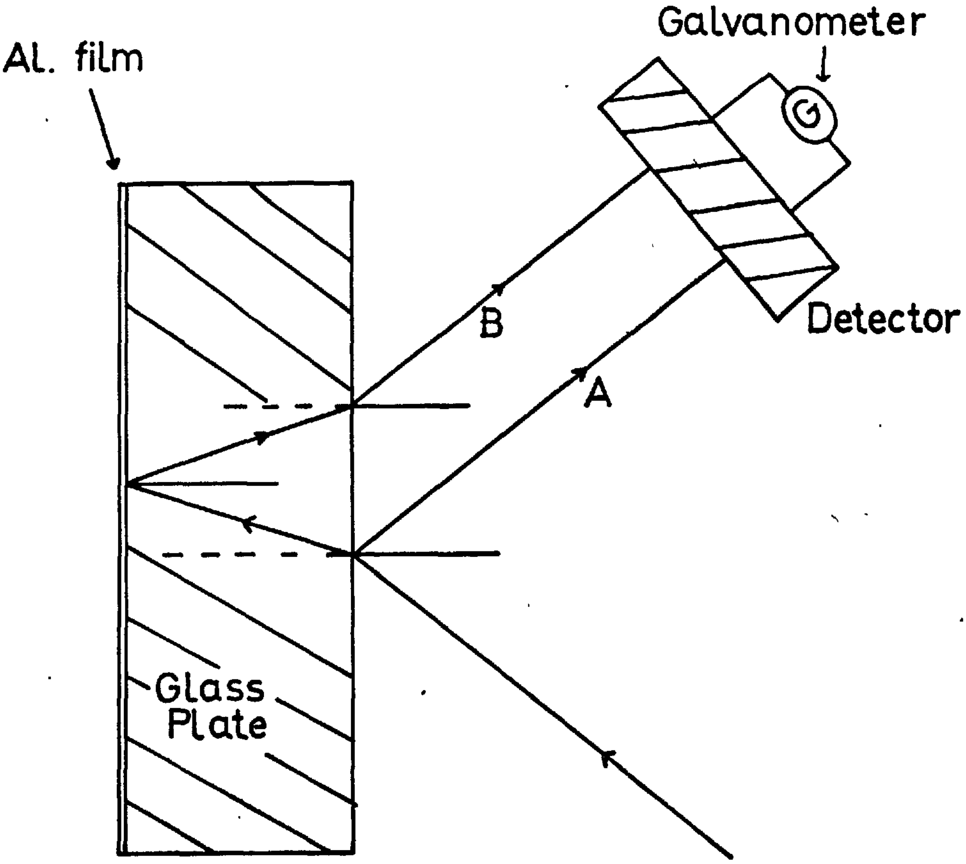
(i) Salt Evaporator.

The analar sodium chloride was evaporated from a molybdenum boat, a tantalum boat could also be used for the salt evaporation. The melting point of the salt is $801^{\circ}C$ and it evaporates at a temperature of $1413^{\circ}C$[103]. In order to prepare a charge of sodium chloride for evaporation, the powdered salt is put into a molybdenum boat and heated on a gas-air flame until the salt melts, when the heating is stopped, the salt solidifies. Now the salt is ready for evaporation. This operation is necessary because it avoids the "spitting" of the salt in the cavuum chamber on evaporation. The salt is evaporated by heating the molybdenum boat by passing a current through it. The boat is heated slowly to reach the temperature at which the salt begins to evaporate.

(ii) Aluminium Evaporator.

Aluminium melts at $660^{\circ}C$ and evaporates at $1100^{\circ}C$. The molten aluminium is highly chemically reactive and forms alloys with most of the refractory materials, these alloys have generally a low evaporation temperature[104]. Molybdenum and tantalum boats were employed to evaporate aluminium but the molten aluminium reacted with boat materials and so the aluminium could not be evaporated. Alumina lined carbon boats have been used for the evaporation of aluminium[105]. A molybdenum boat lined with alumina (Al_2O_3) was tried for the evaporation of aluminium. It takes quite a long time to melt the aluminium charge and when the aluminium starts evaporating, the evaporation continues even after the input current to the molybdenum boat is switched off. We

Fig. III–4



also tried a silica tube as an evaporating source but the molten aluminium reacts with silica.

Tungsten seems to be the only refractory metal which is little affected by aluminium and hence aluminium can be evaporated from tungsten filaments. Holland[106] states, "During the evaporation of aluminium from tungsten the dissolved tungsten in the aluminium charge is precipitated back onto the tungsten wire forming a porous sintered layer". Furthermore the tungsten filament becomes brittle due to the repetition of this process so the filament design was investigated in order that the filament could last 3 or 4 evaporation. Tripple-strand tungsten wire was used for making filaments which were cleaned by electrolysis in a dilute solution of sodium hydroxide and then degassed in a vacuum chamber before putting an aluminium charge onto them. Different designs of filaments such as single loop, multiple loop, helical etc were tried out from the view point of making the filament last for several evaporations. The best solution was found to be two single loop filaments close together side by side.

Variation in the thickness of individual aluminium films could result if the evaporating sources of aluminium and salt were not properly positioned. The evaporators for aluminium and salt were put very close to each other and a shield was put in between them to avoid contamination of one by the other. The sources were mounted near the axis of the system and the glass plates onto which salt and aluminium were to be evaporated were put at a suitable distance from the sources so that the glass plates could receive equal amounts of the salt and aluminium irrespective of their position.

IX Application of Aluminium Backings.

An aluminium film prepared on a salt subtrate was lowered gently into water in a glass dish. The salt underneath the aluminium film dissolved and the aluminium film floated off on the surface of the water. A phosphor screen was brought underneath the aluminium film and positioned so as to catch the aluminium film and lift it out of the water at a slight angle. The phosphor screen was dried and baked in an oven at 350°C for one hour. When such a backed screen was put into a vacuum tube and baked then the aluminium film tended to come off the phosphor screen. A number of similarly backed screens were tried and in most of the cases the aluminium film peeled off.

The preparation of a good photocathode phosphor cascade screen is a difficult process and if the screen loses its aluminium backing in a cascade image tube then it will render the device useless. An investigation was made into the problem of cementing the aluminium film onto phosphor screens.

When an aluminium film is floated onto a phosphor screen the Van der Waal's forces are enough to stick it onto a phosphor screen in air at room temperature. When the same screen is baked the Van der Waal's forces are weakened due to large difference in the coefficients of expansion of the materials in contact. The coefficients of expansion of the materials[103,107] are:-

van der Waals'

Material	Coefficients of expansion
Mica	9×10^{-6}
Glass (lime soda)	9×10^{-6}
Aluminium	19×10^{-6}

As the phosphor (ZnS:Ag) is firmly held onto the substrate so its coefficient of expansion along the substrate may be taken to be the same as that of the substrate.

It appeared that the Van der Waal's forces were insufficient to make the aluminium film adhere to the phosphor under vacuum and baking conditions and hence an investigation was made of potassium silicate to cement the film to the screen. An aluminium film was floated onto the surface of 100 c.c of analar water in a glass dish and 5 c.c of concentrated potassium silicate solution was then added to the water. A phosphor screen was then brought underneath the floating film, the film was floated onto the phosphor screen and after drying was baked in an oven at 350°C for one hour. However, when these screens were baked in vacuum, the aluminium films peeled off from some of the phosphor screens and it was clear that the process was not satisfactory.

In order to test if a greater concentration of potassium silicate would improve adhesion a pilot experiment was performed in which a number of phosphors with floated backings for which different concentrations of potassium silicate solution had been used, were put in a glass envelope. The envelope was pumped down to a pressure of 10^{-6} mm.Hg. All the phosphor screens were arranged on a glass stand in the envelope so that the aluminium side faced downwards. The envelope was given a bake at 350°C for two hours. During the bake the aluminium films did not come off but when the envelope was cooled, it was observed that the backings started peeling off from some of the screens. This effect was more pronounced on mica than on glass and it was further observed that the peeling of the aluminium films did take place even from those phosphor screens having a higher percentage of potassium silicate as a cement.

The flaking of the aluminium could be due to two factors: (i) mismatch of the coefficients of expansion of the materials in contact (ii) the cementing agent may not have been properly used. It is clear that (i) can not be remedied but a more effective use of the cementing agent can be envisaged. Flaking of the aluminium films near the periphery of phosphor screens was remedied by allowing the Al film to overlap the phosphor layer and so provide a direct contact between the aluminium film and the substrate.

As the water can not be stirred after the addition of potassium silicate in the above process due to the fragile aluminium film floating on the surface of the water so it would be reasonable to conclude that the adhesive was not used properly owing to the inadequate mixing.

Experiments were performed to determine the most effective way of making use of the adhesive to cement the aluminium films to phosphor screens. Attempts were made to float off aluminium films onto the surface of dilute solution of potassium silicate, but the aluminium film crumpled due to insufficient surface tension of the liquid. Different dilutions of pot. silicate were tried but similar results were obtained. Failure of this method lead to the following successful technique. A phosphor screen was first soaked in a 5% pot. silicate solution for a few minutes, removed and allowed to drain, and then brought underneath the aluminium film floating on distilled water from which it was lifted out in the usual way. The phosphor screens backed in the above way were baked at 350°C for one hour in an oven. Such screens have been used in cascade image intensifiers and the backings did not peel off on any one of them. Efficiency tests showed that the phosphor screen was not damaged by this additional silicate used in this process. So this technique was adopted as standard for the application of the aluminium backings to the phosphor screens.

The above technique worked very well for floating the aluminium backings onto phosphor screens prepared by the sedimentation process. When the same technique was applied for backing cataphorized phosphor screens, it was not really successful as the aluminium backings peeled off from some of the screens. It was suspected that this was because the settled phosphor screens had had a certain amount of pot. silicate embedded into phosphor layers during the settling process and an extra 5% pot. silicate was enough to cement the aluminium backing onto them. However, in the case of cataphorized phosphor screens no adhesive had been used to bond the phosphor grains to the substrate so it seemed reasonable to expect that a higher percentage of pot. silicate would be necessary to cement the aluminium films to the phosphor screens. In fact an 8% solution of pot. silicate in analar water was successfully used to cement the aluminium backings to cataphorized screens.

An alternative technique is to dip the phosphor screen in 5% pot. silicate and let the screen dry. The screen is again dipped into the same solution before floating the aluminium film onto it. This is also effectively an increase in the amount of pot. silicate used as an adhesive.

After the process of application of the aluminium backings the substrate of the phosphor screen often has drying marks on the uncoated side. These drying marks are characteristics of pot. silicate and can be removed by wiping the uncoated side of the substrate with a filter paper before drying the phosphor screen.

X Use of aluminium oxide film in place of an organic film in the case of conventionally backed screens.

The possibility of using a thin transparent aluminium oxide film instead of an organic film in the case of conventional backings was considered. This method of backing phosphor screens would be very attractive if it did not degrade the image definition of the screen. Aluminium oxide films have good vacuum properties and it will stay as a buffer layer in between the aluminium film and phosphor screen. The aluminium oxide film does not bake off as did the organic film so no undesirable residue is expected.

Some aluminium oxide films were prepared, having a thickness ~ 365 A^{o}, by anodic oxidation in a suitable electrolyte. The desired thickness can be achieved by carefully controlling the parameters[108,109,110]. An unbaked aluminium oxide film was carefully laid on a phosphor screen already wetted with a few drops of analar water. When the aluminium oxide film was drying on the phosphor screen the film developed creases and it was no longer a continuous film so aluminium evaporated on to it will penetrate into the phosphor layer. In order to avoid this defect a baked aluminium oxide film was applied to another phosphor screen using 1% potassium silicate solution as a cement. Aluminium was evaporated on to the screen and viewing through a microscope discontinuities in the aluminium oxide layers could not be observed. Similar samples were tested for efficiency and resolution and the results are discussed in chapter V.

XI Antireflection Backings.

For some applications of imaging devices a moderate gain and a very high image resolution can be main requirements. From the experience with EMI type 214 (P-11) phosphor screens it is known that floated aluminium backings increased the amount of light in the forward direction by ~ 100% compared with no backing at all, so if instead of an aluminium backing a light-absorbing backing is applied then the amount of light in the forward direction from the phosphor screen should fall to 0.5 as compared with an aluminium backed screen. However, the image definition should be higher since some loss of resolution is due to scattering of electrons in the film and scattering of reflected light from the film, also a light absorbing film appeared essential to prevent light from the phosphor returning to the previous photocathode and producing a more or less uniform rain of photo electrons over the whole image. This could at least reduce image contrast and at worst cause instability of the image tube. To achieve this a carbon film appeared a possible substitute for the aluminium film.

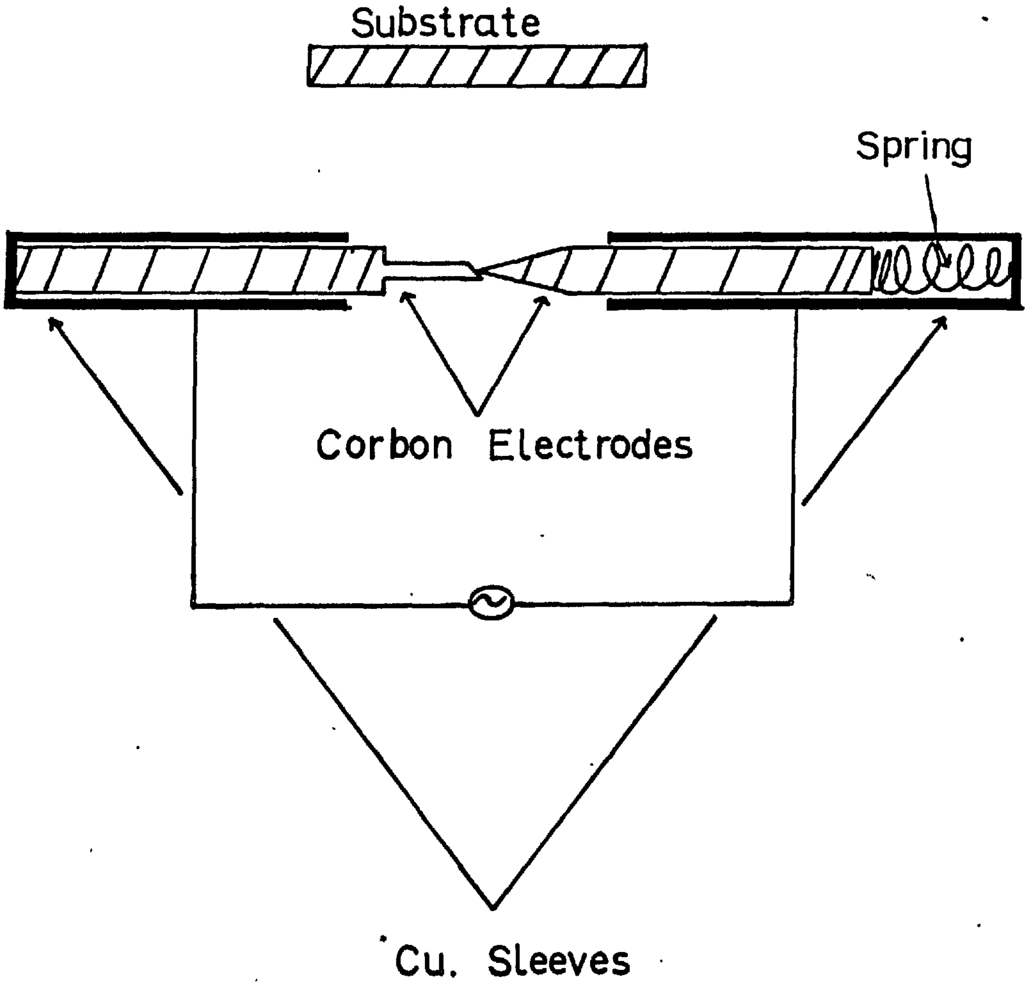
In order to evaluate the performance of carbon backed screens an investigation was made into the preparation and application of carbon backings. Carbon can be evaporated from a carbon arc produced between the tapered ends of two carbon rods, one of the rods being spring loaded. Suitable current and voltage can be applied for striking an arc. Bradley[111] recommended an alternating current between 20 and 50 Amperes, while Rhoad's et al[112] recommended an a.c. voltage of 40 volts at 11 amperes. The voltage required for striking an arc will depend upon the shape of the electrodes. We evaporated carbon from a carbon arc in short bursts with a 6 volts a.c. source at 60 amperes. If the carbon arc "spits" then the spitting can be reduced by decreasing the input current. A diagram of the evaporating source is shown in Fig. III-5.

Similar to aluminium backings three methods were used for making carbon backings:-

(i) direct evaporation of carbon on to the phosphor screen. The performance of such screens is similar to the screens with direct evaporation of aluminium.

(ii) Putting an intermediate organic film between the carbon backing and the phosphor. This process was not successful for two reasons: (a) Owing to the intense radiated heat from the carbon arc, the organic film is punctured. This could be remedied by cooling the phosphor

Fig. III-5



and evaporating sudden bursts of carbon at suitable intervals. (b) The organic film cannot be baked off because the carbon is oxidised during baking in air at 350°C. (iii) Self-supporting carbon films have been prepared on collodion film[113] or Teepol[114] substrates. We preferred to use salt substrates for the preparation of carbon films as it is easier to float off the film. There is no critical thickness of salt for the carbon backings but it should be enough so that the carbon film could be easily floated off.

The carbon backings were prepared on a salt substrate and floated on to phosphor screens using 10% pot. silicate solution as described in previous sections. The phosphor screens with carbon backings should not be baked in air because carbon is readily oxidised. The performance of such screens was studied and is discussed in chapter V.

B. Other Black Coatings.

(i) Lamp Black.

A phosphor screen was coated with a deposit of lamp black, which took the form of minute snow flakes consisting of very fine carbon particles. This phosphor screen was put in a demountable cathode ray tube (described in chapter V) for measuring relative efficiency. During the pumping the lamp black was pulled off the phosphor surface due to the poor adhesion between the phosphor layer and the lamp black. Hence this process was abandoned.

(ii) Electrophoresis of Carbon Particles.

A very fine suspension of carbon particles in alcohol was diluted with analar water and some thorium nitrate solution was added to it to increase conductivity. A cataphorized phosphor screen which had an aluminium conducting substrate underneath the phosphor was taken and Aquadag was cataphorized on to the phosphor layer. The conducting layer of aluminium was subsequently removed by chemical means. Such a screen was tested for performance and the results are described in chapter V.

(iii) Aluminium black.

If aluminium is evaporated from a tungsten filament at a residual pressure of air $\sim$ 200 microns, a black deposit of aluminium results. Direct evaporation of aluminium black was tried. An intermediate organic film between the phosphor layer and aluminium black deposit was also tried. The organic film was baked off. Such phosphor screens were tested for efficiency and the results will be described in chapter V.

XII Black layers on aluminized screens.

In image intensifiers, a certain amount of input light is transmitted through the semi-transparent photocathode. This transmitted light can be reflected from the highly reflecting surface of aluminium backing of the next phosphor screen, and hence it will cause signal induced background in an image tube. In order to minimize the undesirable effect some light absorbing layer should be put on the reflecting aluminium film. It is clear that an extra barrier is being put in the path of incident electrons so it is likely to cause some loss of image definition and some loss of output light from the phosphor screen for the same input electron energy.

Obvious possibilities were carbon and aluminium black layers. Carbon was evaporated on to aluminized screens in the form of a thin layer of carbon and an interference film resulted. So in the case of carbon layers; an opaque film of carbon should be used which is more than 1000 A^O thick which is quite a thick film. It also appeared that the carbon does not land on aluminized screens very well. Thus, aluminium black was chosen for treating aluminized phosphor screens in preference to carbon black.

Aluminium black was applied to the aluminium backing of the screens by evaporating aluminium at a pressure of air of 200 microns. The important parameters for the evaporation of aluminium black are the distance between source and the surface on to which the deposit is to be made, the position of the phosphor screen with respect to the source, and the pressure at which aluminium is to be evaporated. Best results were obtained by keeping the recipient phosphor screen at a distance of 12 cms from the filament and exactly above the filament, at a pressure of 200 microns.

The amount of aluminium black was monitored by measuring the amount of trnasmitted light through a glass plate kept very near the phosphor screen. Different amounts of aluminium black were deposited on a number of screens (from 84% to 10% transmission) and these were then tested for output light and image definition. No loss in output light was observed for 10% or more transmission while the image definition begins to show signs of impairment at 50% transmission. It was decided to apply aluminium black layers of 50% transmission. The aluminium black layer of 50% of the input light will reduce the light going back to the photocathode from the aluminized screens by a factor of 4 or more.

An attempt was made to measure the thickness of aluminium black layers of different transmissions but the thickness could not be reliably measured. Aluminium black deposit was viewed through a microscope and its surface texture was found to be composed of hills and dales.

CHAPTER IV Image Definition.

I. Definition of Resolution Limit.

The quality of the reproduced image in an imaging device is not as good as that of the original. When a very narrow line of light (a slit source) is projected on to the photocathode of an image intensifier, the intensity distribution of light in the reproduced image is different from that in the original. A certain spread of the original narrow line is noticeable in the reproduced image. This spread causes loss of image definition or resolution. The spread or the "width of confusion" is shown in Fig. IV-Ia

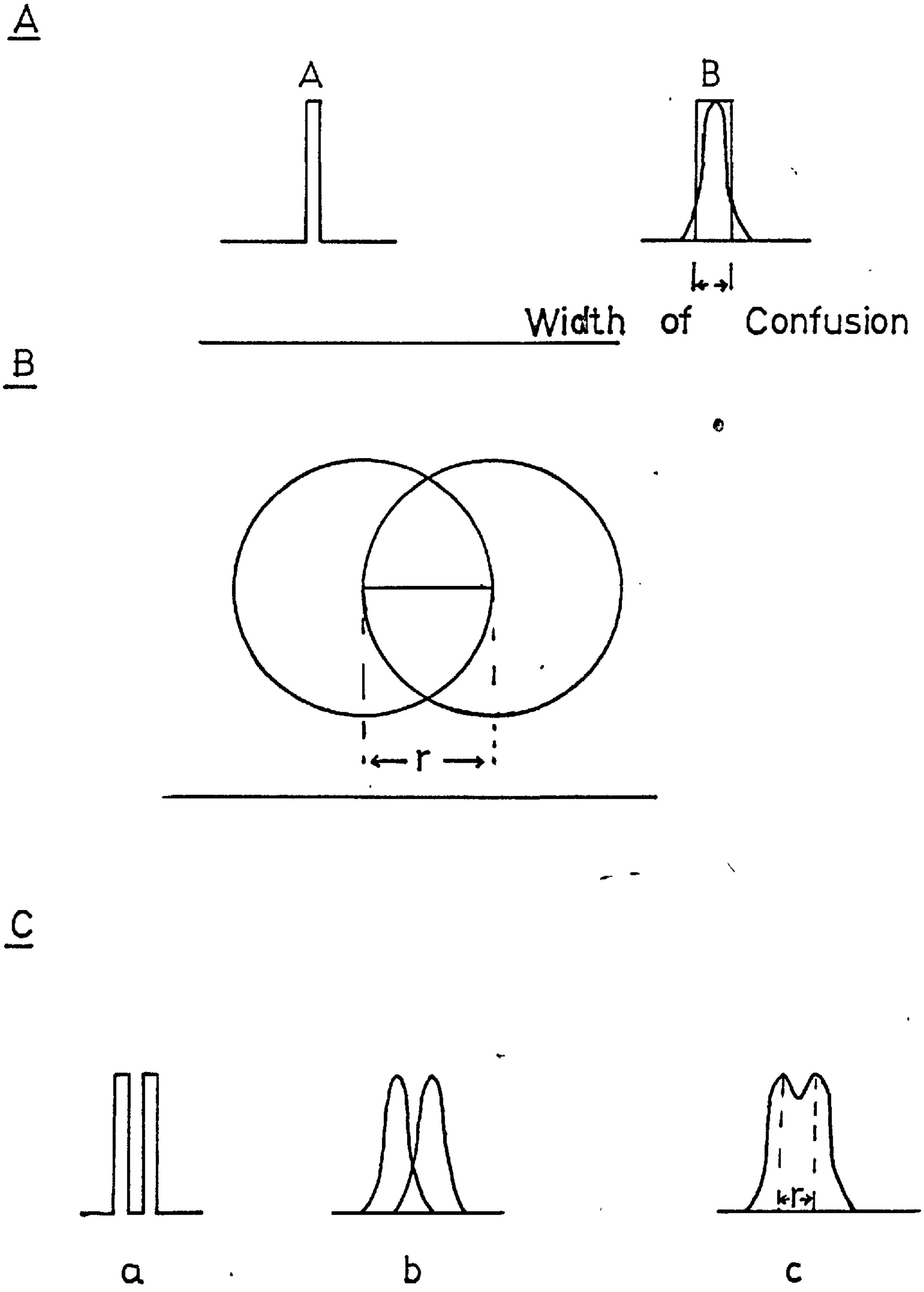
Ref 1

The narrow rectangular peak A is the distribution of the light in the original image. The curve B shows the intensity distribution in the reproduced image. If a rectangle super-imposed on the curve B is drawn such that the height and area of the curve is the same as that of the rectangle then the width of the rectangle will be known as the"width of confusion".

If two point sources being imaged by a circular aperture on to a screen are considered then each point source will give rise to circular diffraction patterns. Each circular diffraction pattern consists of a bright central disc known as "Airy disc" surrounded by a number of fainter rings. Two "Airy discs" from two point sources will be just recognizeable if their centres are separated by a distance equal to the radius of an Airy disc[115], as shown in Fig. IV-1(b). This distance gives the value of the limiting resolution.

Considering another case in which two point sources are imaged by a rectangular aperture on to a screen, then the profiles of the images (Ref.115) will be as shown in Fig. IV-I(c). As the point sources (a) move towards each other then the profiles of their images begin to overlap

Fig IV-1



(b) until the profiles are just distinguishable from each other as shown in (c). The curve C is the resultant profile of the images and it has a minimum at about four-fifths of the total intensity maximum of either of the sources, so the contribution due to each source is 0.4. The distance r shown in the curve c is the minimum distance which can just render two narrow slits recognizeable, and it is called the radius of the disc of confusion.

II Resolution of an Image Tube.

The resolution of an image tube is generally measured in line pairs per mm which can be just resolved on the final screen. A line pair consists of a black line and a white line of equal width, and having, it will be assumed, a 100% contrast on the primary photocathode. The resolution of a screen could also be expressed in terms of the spatial frequency response (number of cycles/cm) which can be converted into lp/mm.

The width of confusion in an image tube depends on a number of factors and their relative effects on the resolution of the image tube will be considered.

(i) Chromatic Aberration in an Electronic Image.

It will be assumed that a uniform electrostatic accelerating field and a uniform magnetic fields exist in an image tube. The photoelectrons leaving a point on the photocathode do not come to a point focus under the influence of the above fields due to the initial energies of photoelectrons, but they form a disc on the focal plane. The diameter of this disc of confusion will depend upon the spread of the initial energies and the directions of the photoelectrons. The width of confusion due to chromatic aberration can be taken as a measure of the contribution towards the total loss of resolution in an image tube.

Zworykin and Morton[116] calculated the width of confusion assuming the optimum focus position at the mid-point between the focal points of (a) photoelectrons with zero initial energies normal to the photocathode and (b) the photoelectrons with maximum initial energy normal to the cathode. The diameter of the disc of confusion (twice the width of confusion) was calculated to be

$$D = 2 \frac{V_t}{V} d \quad \text{where}$$

D is the diameter of the disc of confusion.

V_t is the potential corresponding to the maximum emission energy of a photoelectron from a photocathode.

V is the accelerating voltage applied between the photocathode and the target or phosphor screen.

d is the distance between the photocathode and the phosphor screen, in the same units as D.

Slark[117] calculated the diameter of the disc of confusion without making the above assumptions of the likely optimum focus position and got a result

$$D = \frac{1.56\, V_t}{V} d$$

Slark, while deriving the above formula, made a mistake of resolving the initial energy of an electron into two components, energy being a scalar quantity hence it can not be resolved.

Davis[39], discussing the subject, deduced the diameter of the disc of confusion to be

$$D = \frac{1.2\, V_t}{V} d$$

Davis further found that the optimum focus position is not midway between (a) and (b) but it is at three-tenths of the way between (a) and (b) and nearer to the photocathode.

By considering a Maxwellian distribution of the initial energies of the photoelectrons, Papp[118] deduced a formula for the minimum radius of the disc of confusion to be.

$$\delta = \overline{\Delta r}_{min} = 0.59 \frac{V_{ro}}{V} d$$

where V_{ro} is the potential corresponding to the initial radial velocity of the electron.

Beurle and Wreathall[119] assuming the angular distribution of photoelectrons to be Lambertian, have calculated the radius of the disc of confusion to be

$$r = 0.31 V_t \frac{\pi}{B} \sqrt{\frac{2m}{eV}}$$

Where B is the strength of the magnetic field, e and m are the charge and mass of an electron and the other symbols have the usual meaning.

For $B = 300$ G , $V = 15$ kV , $V_t = 0.9$ eV

$r \sim 8$ microns.

This result corresponds to a resolution of 125 lp/mm, which is rather a low value for electron-optic limiting resolution. Shalabutov et al[120] measured the initial energies of the photoelectrons from an S-9 photocathode and found that the initial energy ranged from 0 to 1.2 eV while 80% of the photoelectrons had energy between 0.4 eV to 0.9 eV.

Using Davis formula and substituting the values of $V = 15$ kV · $V_t = 0.9$ eV and $d = 10$ cms. ($d = 10$ cms length of the image section of one stage in the cascade tube while 15 kV is the applied voltage per stage) the radius of the disc of confusion comes out to be 3.6 microns which corresponds to 275 lp/mm which is a rather optimistic value.

The exact radius of the disc of confusion can not be worked out because the angular distribution is not known. However, for our calculations we shall use a value of the radius of the disc of confusion to be 5 microns which seems to be a reasonable value.

(2) Finite thickness of the mica substrate.

In the case of cascade image intensifiers the cascade screens are supported on thin discs of mica which introduce some spread of light when the luminescent light from the phosphor of the previous stage passes through the mica and thus causes an increase in the radius of the disc of confusion. Let us calculate the amount of the spread introduced by the mica disc. Considering a phosphor screen as a Lambertian radiator, it can be shown (Ref 121) that the illumination at a point A in a plane 1, distant t from plane 0, containing the source of area dS and brightness B (See Fig. IV - 2) is given by

$$E_1(R) = \frac{B\ \mathrm{Cos}^2\theta\ dS}{r^2}$$

$$= \frac{Bt^2 dS}{(R^2+t^2)^2}$$

Clearly $E_1(0) = B\frac{dS}{t^2}$

In order to obtain a realistic value of the radius of the disc of confusion a value which is nonzero should be chosen for this relation. Let us say that

$$\frac{E_1(R)}{E_1(0)} = 0.4$$

This value corresponds to Rayleigh criterion.

From the above relations

$$\frac{E_1(R)}{E_1(0)} = \frac{t^4}{(R^2+t^2)^2} = 0.4 \quad = \mathrm{Cos}^4\varepsilon$$

$$R_c = 0.76t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where R_c is the radius of the disc of confusion.

The above calculations have been made by assuming the

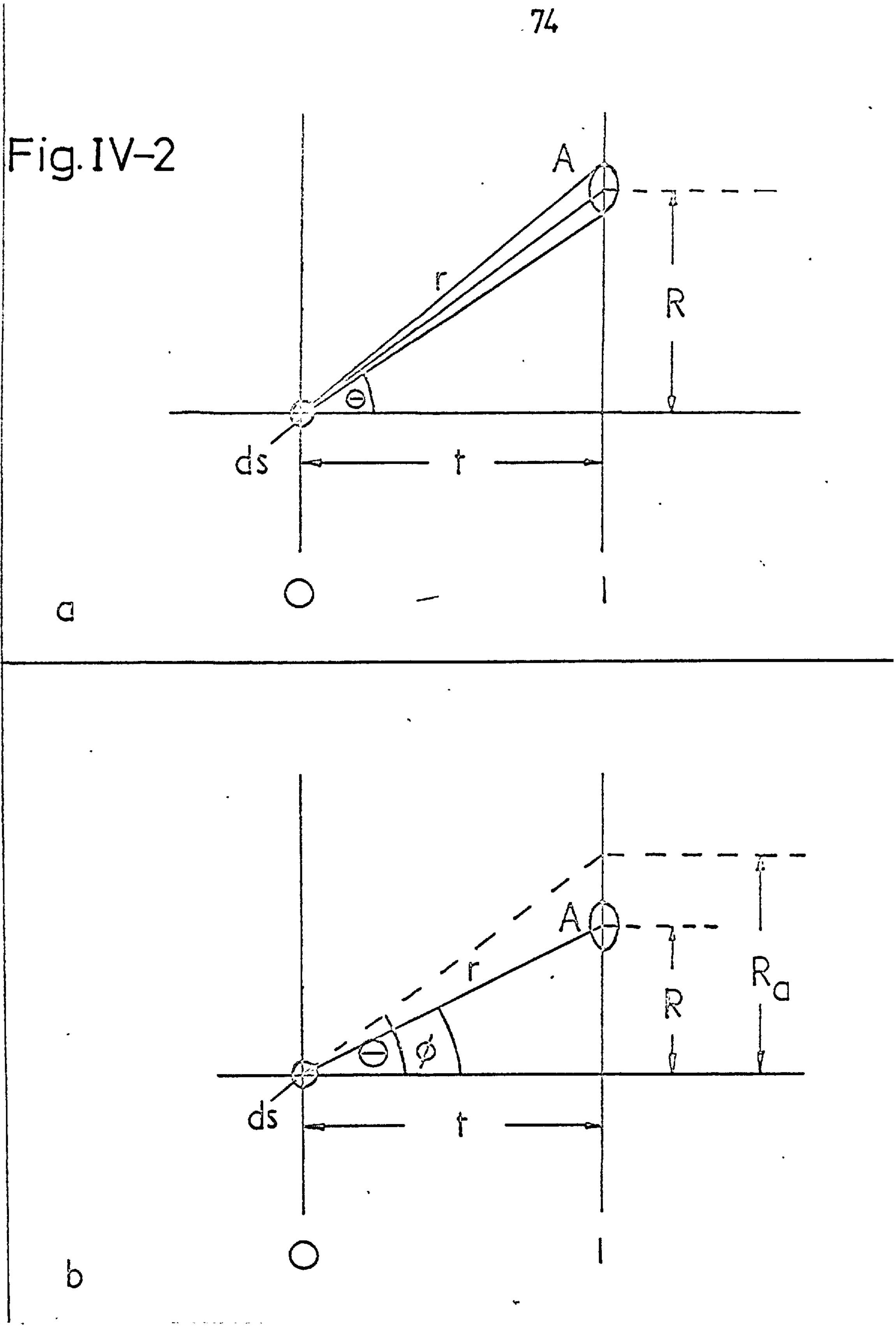


Fig. IV-2

source of light to be on one face of the mica disc or the luminescent phosphor grain in optical contact with the mica. This is not always the case because Zworykin and Morton[122] have reported that only 20% of the phosphor is in optical contact with the substrate in the case of settled screens. The electrophorized phosphor screens are more tightly packed than settled screens so one might in fact say that about 50% of the phosphor is in optical contact with the substrate.

Since the whole of the phosphor is not in optical contact with the substrate, one may repeat the above calculations. Considering the Fig. IV-2b, $E_1(R)$ will be given by

$$E_1(R) = \frac{B \operatorname{Cos}\theta \operatorname{Cos}\phi \, dS}{r^2}$$

where θ is the angle of incidence on mica and ϕ is the angle of refraction in mica. From the Fig. IV-2b

$$E_1(R) = \frac{B\, dS\, t^2}{(t^2+R^2)^{3/2}} = \frac{1}{(t^2+R_a^{\,2})^{1/2}}$$

$$E_1(0) = \frac{B\, dS}{t^2} \qquad \because R = 0 \qquad \therefore R_a = 0$$

$$\frac{E_1(R)}{E_1(0)} = \frac{t^4}{(t^2+R^2)^{3/2}(t^2+R_a^{\,2})^{1/2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

From Snell's law $\mu = \dfrac{\operatorname{Sin}\theta}{\operatorname{Sin}\phi} = \dfrac{R_a}{R}\left\{\dfrac{R^2+t^2}{R_a^{\,2}+t^2}\right\}^{1/2}$

where μ is the refractive index of mica. From the table of constants $\mu_{mica} = 1.58$.

(In fact : μ ranges from 1.56 to 1.60)

$$R_a^{\,2} = \frac{\mu^2 R^2 t^2}{t^2+R^2(1-\mu^2)}$$

Substituting $R_a^{\,2}$ and μ^2 in equation 3 and simplifying

$$\frac{E_1(R)}{E_1(0)} = \frac{1}{\left(1+\frac{R^2}{t^2}\right)^{3/2}\left(1+\frac{2.4\ R^2}{t^2-1.4\ R^2}\right)^{1/2}}$$

when $R = R_c$ then $\frac{E_1(R)}{E_1(0)} = 0.4$

$$R = 0.58\ t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Considering equations 2 and 4 and considering that in the case of settled screens only 20% of the phospher is in optical contact with the mica, then by weighting, the radius of the disc of confusion due to mica thickness can be calculated to be

$$R_c = 0.62\ t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

In the case of the electrophorized screens it has been assumed that 50% of the phosphor is in optical contact with the mica disc, therefore, the radius of the disc of confusion due to mica thickness for an electrophorized screen will be

$$R_c = 0.67\ t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

The above results can not be affected by total internal reflection because in a cascade tube a photocathode is formed on the clear face of the mica which has a higher refractive index than that of the mica.

In order to calculate the radius of the disc of confusion due to the thickness of the photocathode ($\sim$1000 A^o) the above calculations can be repeated and one obtains a result $R' = 0.25\ t'$ where R' is the radius of the disc of confusion due to the photocathode thickness and t' is the thickness of the photocathode. Comparing the above result with 3, 5, and 6 it can be concluded that R' is $\sim$1% of the results in

2, 5 and 6.

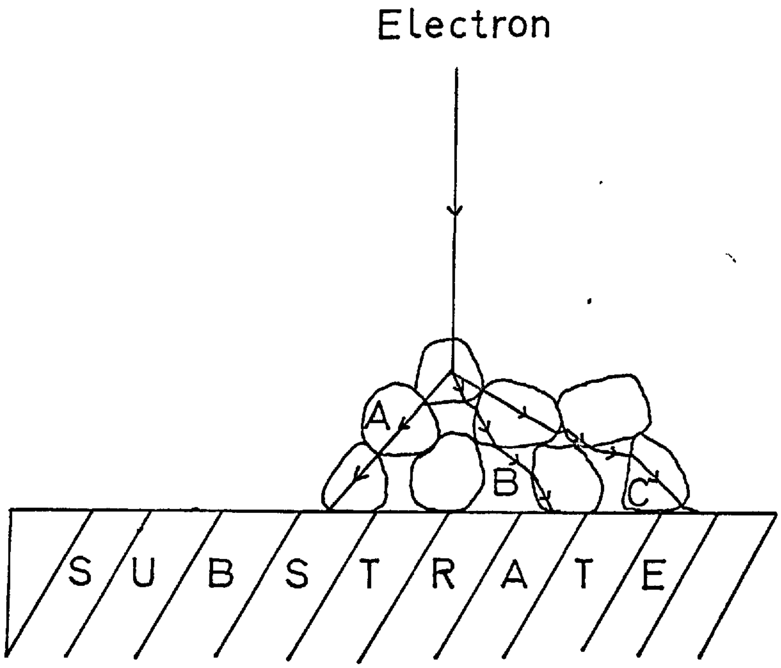
In the above analysis in the second case, it has been assumed that the points where the luminous grain is not in optical contact with mica, there is no intervening medium between the mica sheet and the luminous phosphor grain. This is not always true because the intervening medium can be phosphor layer and/or vacuum. It will be shown in chapter V that the average thickness of a phosphor layer measures 4 microns and weighs 0.7 mg/cm^2 when it is prepared by electrophoretic process. It has been established by a number of experimenters[55,123-26] that the range of a 15 keV electron in a phosphor layer is ~ 1.5 microns. Hence there will be an intervening medium having a thickness ~ 2.5 microns. It is very difficult to calculate the radius of the disc of confusion due to the spread of light in the phosphor layer due to the variable thickness of the intervening medium. Fig. IV-3 is a probable picture of the situation.

Bethe

In order to estimate the radius of the disc of confusion the average thickness of the phosphor layers will be considered. In the case of electrophorized screens using EMI type 214 phosphor, the average thickness of the phosphor layer ~ 4 microns and weighs 0.7 mg/cm^2 and for the settled screens the average thickness of the screens is ~ 8 microns and weighs 1mg/cm^2. According to Koller and Alden[127], nearly 90% of the electron energy is lost in a distance of the first half of the range of electrons in phosphor layers, so a 15 keV electron will presumably lose its whole energy in a distance of 1 micron in the case of a head-on collision or a typical grain of EMI type 214 phosphor is just enough to absorb the energy of a 15 keV electron. In fact a number of grains can become luminescent from one electron. The light from this luminous grain (luminous

Reconcile with Thompson Whiddington

Fig. IV-3



A, B, C are Light Rays

point) will have a Lambertian distribution.

From a consideration of the spread of light in the phosphor layers the image resolution of the screens can be calculated. Let t be the thickness of phosphor layer and for simplicity of calculation let it be a transparent thin sheet of phosphor having a refractive index n_1 on a substrate of refractive index n_2. If "O" be a luminous point then the radius of the circular spread of light will give the radius of the disc of confusion for the phosphor screen.

The spread of light at the interface will solely be governed by the critical angle for the interface. Considering Fig. IV-4A and applying Snell's law

$$n_1 \mathrm{Sin}\ C = n_2 \mathrm{Sin}\ 90^{\circ} \qquad \mathrm{Sin}\ C = {}^{n_2}/_{n_1}$$

n_1 = 2.4 for ZnS:Ag phosphor and n_2 = 1.5 for glass
= 1.6 for mica

$$\hat{C} \sim 39^{\circ}$$

$$R = t \tan C = 0.81\ t.$$

In this way the resolution of a phosphor layer at the phosphor-substrate interface can be calculated.

The phosphor screens were prepared by the sedimentation and electrophoretic processes and the resolution was measured by an optical technique to be described later. The following table shows the calculated, observed by a microscope and photo-micrographically recorded values of the image resolution of the screens. The difference between the calculated and measured values is due to the fact that an ideal phosphor layer was considered for the calculation while measurements were made on granular screens.

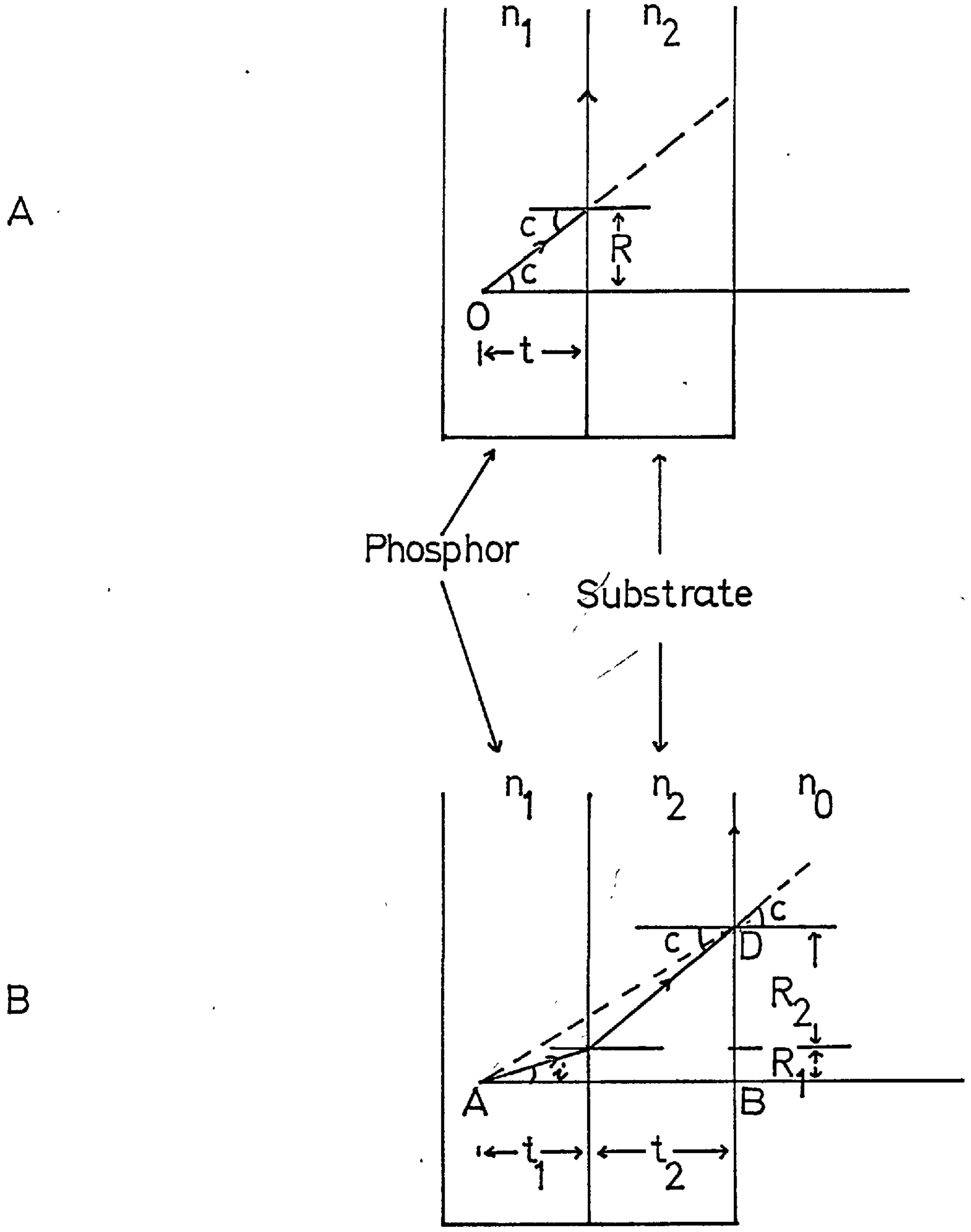


Fig. IV-4

Phosphor	Dep. Process	Thickness mg/cm^2	microns	Resolution in lp/mm. Calculated	Observed	Recorded
EMI type	Settling	1	8	150	120	120
214	Electrophoresis	0.7	4	250	250	250
D.L.A/259	"	0.45	2.7	460	305	305

For a D.L.A/259 phosphor screen the lenses used set the limit of the observed and recorded resolution. It may be noted that the difference between the observed and recorded values of the resolution is $\sim$ 20% and this is due to the granular nature of the screens on which the measurements were made.

In the case of a cascade screen the above resolution figures can not be taken into account because they are for the phosphor-substrate interface while in the case of a cascade screen the resolution at the mica-air interface is of interest. The resolution of a cascade screen will now be calculated.

Considering a continuous layer of phosphor of thickness t, for simplicity of calculation let it be a thin sheet of a large ZnS:Ag single crystal. Let n_1, n_2 and n_0 be the refractive indices of ZnS, mica and the air respectively. If there is a luminous point A in the phosphor layer then the spread of the light at the mica-air interface can be calculated. It will be further assumed that the phosphor layer is in optical contact with mica, then from Fig. IV-4B the spread of light can be calculated. Let C be the critical angle between the mica-air interface, then clearly from Fig. IV-4B, the radius of the circular spread of light or the radius of the disc of confusion will be

$$R = R_1 + R_2$$

Let the thickness of the phosphor layer be t_1 and the thickness of the mica substrate be t_2 then

$$R = t_1 \tan i + t_2 \tan C.$$

From Snell's law at the mica-air interface

$$n_2 \operatorname{Sin} C = n_o \operatorname{Sin} 90^o$$

$$\operatorname{Sin} C = n_o/n_2 \quad \text{and} \quad \tan C = \frac{n_o}{\sqrt{n_2^2 - n_o^2}}$$

The angle i can be caluated from Snell's law again, at the phosphor-mica interface.

$$n_1 \operatorname{Sin} i = n_2 \operatorname{Sin} C$$

$$\operatorname{Sin} i = n_o/n_1 \quad \text{and} \quad \tan i = \frac{n_o}{\sqrt{n_1^2 - n_o^2}}$$

$$R = t_1 \frac{n_o}{\sqrt{n_1^2 - n_o^2}} + t_2 \frac{n_o}{\sqrt{n_2^2 - n_o^2}}$$

As the refractive index of air = 1

$$R = \frac{t_1}{\sqrt{n_1^2 - 1}} + \frac{t_2}{\sqrt{n_2^2 - 1}} \quad \ldots\ldots\ldots\ldots(7)$$

The value of the angle DAB can be worked out to be

$$\tan DAB = \frac{R}{t_1 + t_2} = \frac{t_1/\sqrt{n_1^2 - 1} + t_2/\sqrt{n_2^2 - 1}}{t_1 + t_2} \quad \ldots\ldots(8)$$

for t_1 = 4 microns $\quad n_1 = 2.4$
and t_2 = 4 microns $\quad n_2 = 1.6$

$$R = 1.8 + 3.3 = 5.1 \text{ microns} \quad \ldots\ldots\ldots\ldots\ldots(9)$$

and $\tan DAB \approx 0.6375$
$\widehat{DAB} \approx 32^o$.

The angle DAB is less than the critical angle between the phosphor-mica interface ($\approx 34^o$) so the results are not affected by the total internal reflections in the phosphor layer from the above interface. The intensity of light at point D can be calculated from the consideration of the Lambertian distribution of the transmitted light and its value $\sim$ ~~75%~~ 49% of the value at B.

In the case of a cascade screen in an image tube a photocathode is formed on the clear side of mica substrate. Since the refractive index of the photocathode (Sb:Cs) is higher than that of the mica hence no total internal reflection will take place at the interface and hence the above simple theory will not be applicable. From the intensity of light considerations it has been shown previously that the consideration of the refractive index of the photocathode at the mica-photocathode interface would change the radius of the disc of confusion by about 1%. Moreover, as the experiments were done in air and Sb:Cs photocathode dies in air so the above theory is applicable to the cases studied.

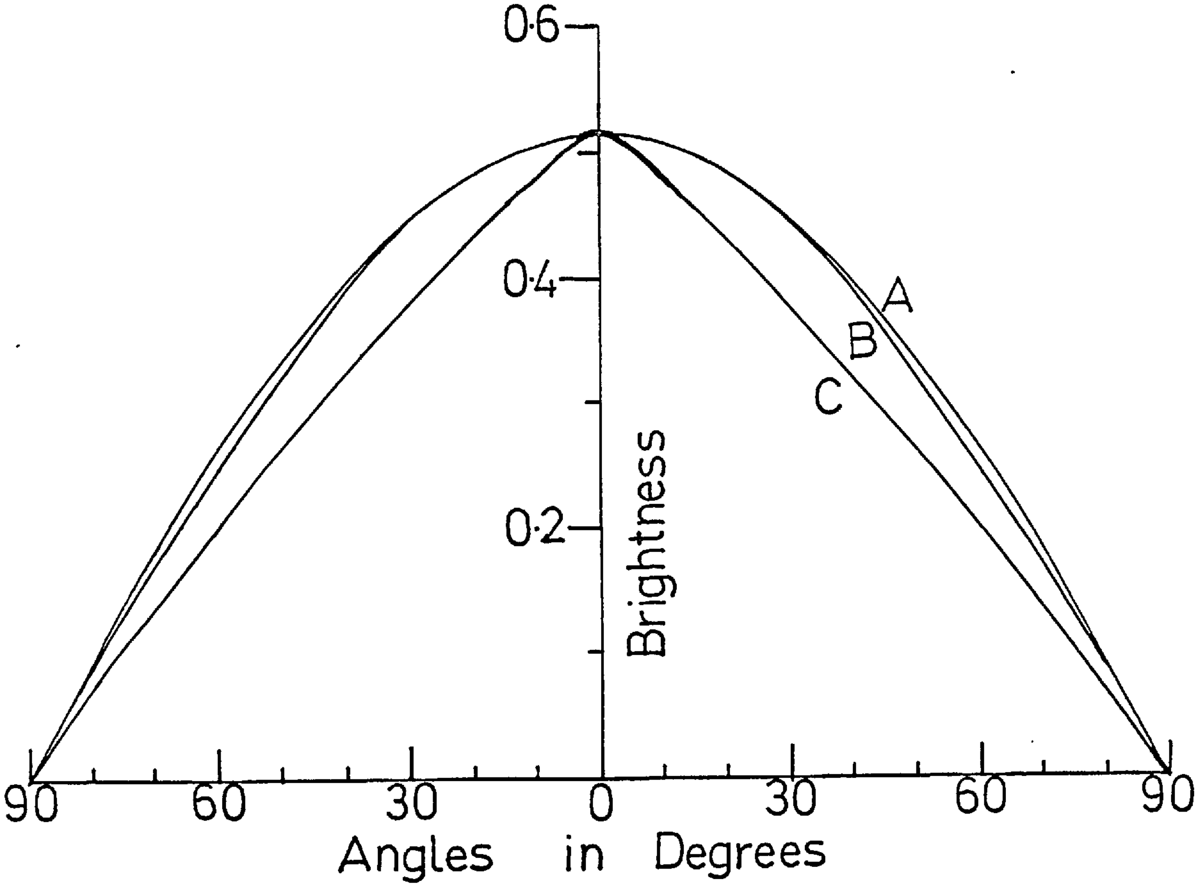
The distribution of the transmitted light was experimentally determined in the case of the granular phosphor screens. A white-light spot, 4 mm in diameter, was focused on to a phosphor surface. The amount of the transmitted light was measured by a photovoltaic cell which could be moved along a semi-circular scale in such a way that the distance between the light spot and the photovoltaic cell was always 8.9 cm. Fig. IV-5 shows a plot of the distribution of the transmitted light. The three curves are:-

A. The ideal Lambertian distribution.

B. The distribution of the transmitted light from an electrophorized screen of thickness 0.7 mg/cm^2 prepared from EMI typed 214 phosphor.

C. The distribution of the transmitted light from an electrophorized screen of thickness 0.4 mg/cm^2 prepared from Derby Luminescents type A/259 phosphor.

Fig. IV–5



It can be seen from the Fig. IV-3 that the distribution of the transmitted light is nearly Lambertian.

Equation (9) shows that the thickness of mica sheet contributes more than the phosphor layer towards the radius of the disc of confusion, so in order to increase the resolution limit of a cascade screen the thickness of the mica disc should be decreased until the thickness of the mica disc is $\sim$ 2 microns, the thickness of the phosphor layer being 4 microns. Then the phosphor layer and mica disc thickness should make equal contributions, but this will be true for the case of evaporated phosphors or nongranular screens. In the case of granular phosphor screens the observed and recorded value of resolution will be lower than the calculated values from the above theory.

The image resolution of a cascade screen was measured by an optical technique which is an optical equivalent of an image tube with a phosphor screen on a mica disc as the output screen and a light gain of the order of unity. In this technique a phosphor screen on mica is mounted on an optical bench and an optical test pattern is projected on to the phosphor layer by means of a Baum projector[128]. A white light source was used for the projection of the test pattern. A contact print of the diffused optical pattern was taken on G-5 emulsion by pressing it into close contact with the clear surface of the mica substrate.

In order to observe the resolution of a cascade screen on the clear side of the mica disc, the test pattern was projected onto the phosphor layer with a microscope objective of numerical aperture (N.A) 0.25 (depth of focus 2 microns) while a microscope was focused on to the mica surface with a microscopic objective of N.A 0.75 (depth of focus 1 micron) and in this way the resolution of a cascade screen was observed. This method is not very accurate due to the depth of focus problems of the projecting and observing lenses.

The following table shows the values of image resolution calculated, observed and recorded on a contact print for unbacked phosphor screens on 4 microns thick mica substrates.

Phosphor	Dep. Process	Thickness in mg/cm^2	in Microns	Resolution in lp/mm. Calculated	Observed	Recorded
EMI	Settling	1	8	140	-	65
type 214	Electrophoresis	0.7	4	190	-	85
D.L	"	0.8	4	190	-	95
A/259	"	0.45	2.7	220	150	95

The last two results suggest that the recorded resolution is probably limited by the resolution capability of the emulsion. Fig. IV-6 shows the contact print photographs Fig. IV-7 shows the recorded resolution of phosphor screens on glass substrates, the photographs were taken through a miscroscope.

A further experiment was performed to measure the loss of resolution resulting from the increase in the thickness of the mica disc. A number of phosphor samples of approximately the same thickness (0.8 mg/cm^2) of Derby Luminescents type A/259 phosphor on to mica discs of various thicknesses were prepared. The contact prints were taken and the results are shown in Fig. IV-8 indicating that 95 lp/mm can be recorded on a contact print for a mica disc of thickness 4 microns.

3. Phosphor Screens.

The phosphor screens contribute to the radius of the disc of confusion in a number of ways:-

(a) Scattering of Electrons.

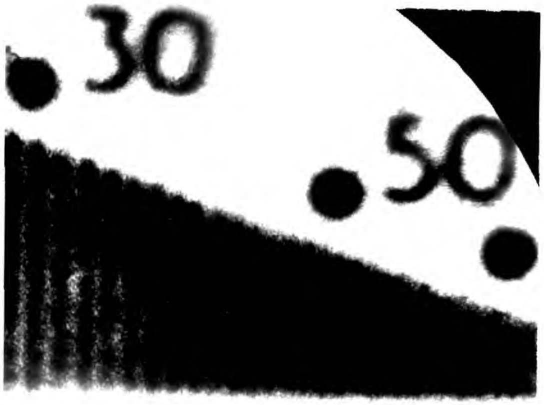
Scattering of electrons results in the spread of the

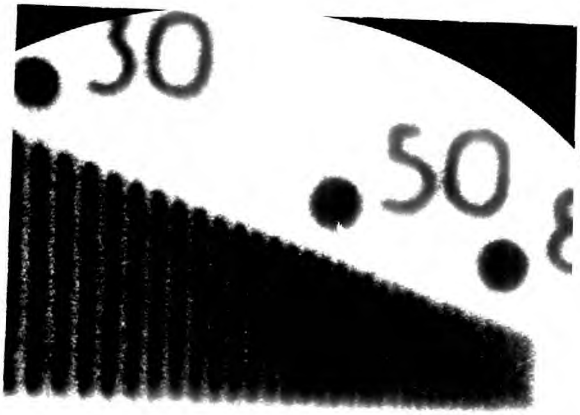
Fig. IV-6

Photomicrographs of 1:1 contact prints of the resolution pattern for different cascade screens.
magnification 50. Mica disc thickness = 4 microns.

(a) EMI type 214
settled phosphor screen
Thickness 1 mg/cm^2

(a)





(b) Electrophorized EMI type 214 phosphor screen. Thickness = 0.7 mg/cm^2.

(c) Electrophorized Derby Luminescents type A/259 phosphor screen. Thickness = 0.4 mg/cm^2

(c)

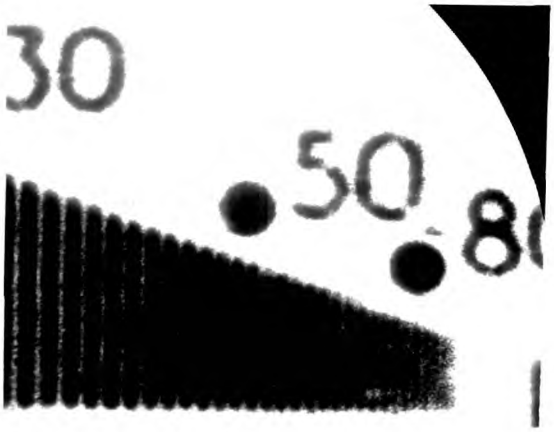
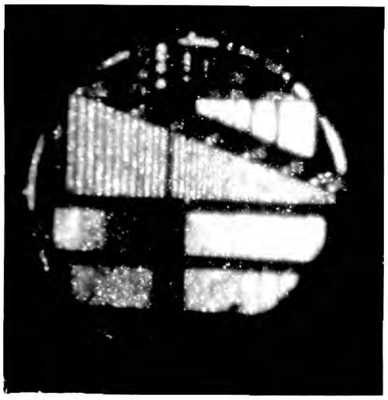


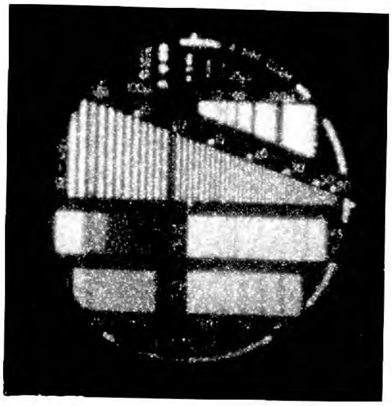
Fig. IV-7

Photomicrographs of four times demagnified resolution pattern projected onto different phosphor screens. The resolution pattern reads 96 lp/mm without magnification or demagnification.

(a) EMI type 214 settled phosphor screen of 1 mg/cm^2 in thickness.

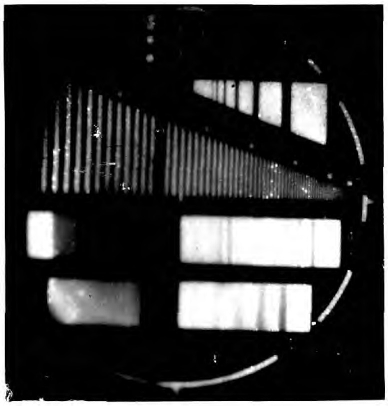


(a)



(b) Electrophorized EMI type 214 phosphor screen of 0.7 mg/cm^2 in thickness.

(c) Electrophorized Derby Luminescents type A/259 screen of 0.4 mg/cm^2 in thickness.



(c)

Fig. IV-8

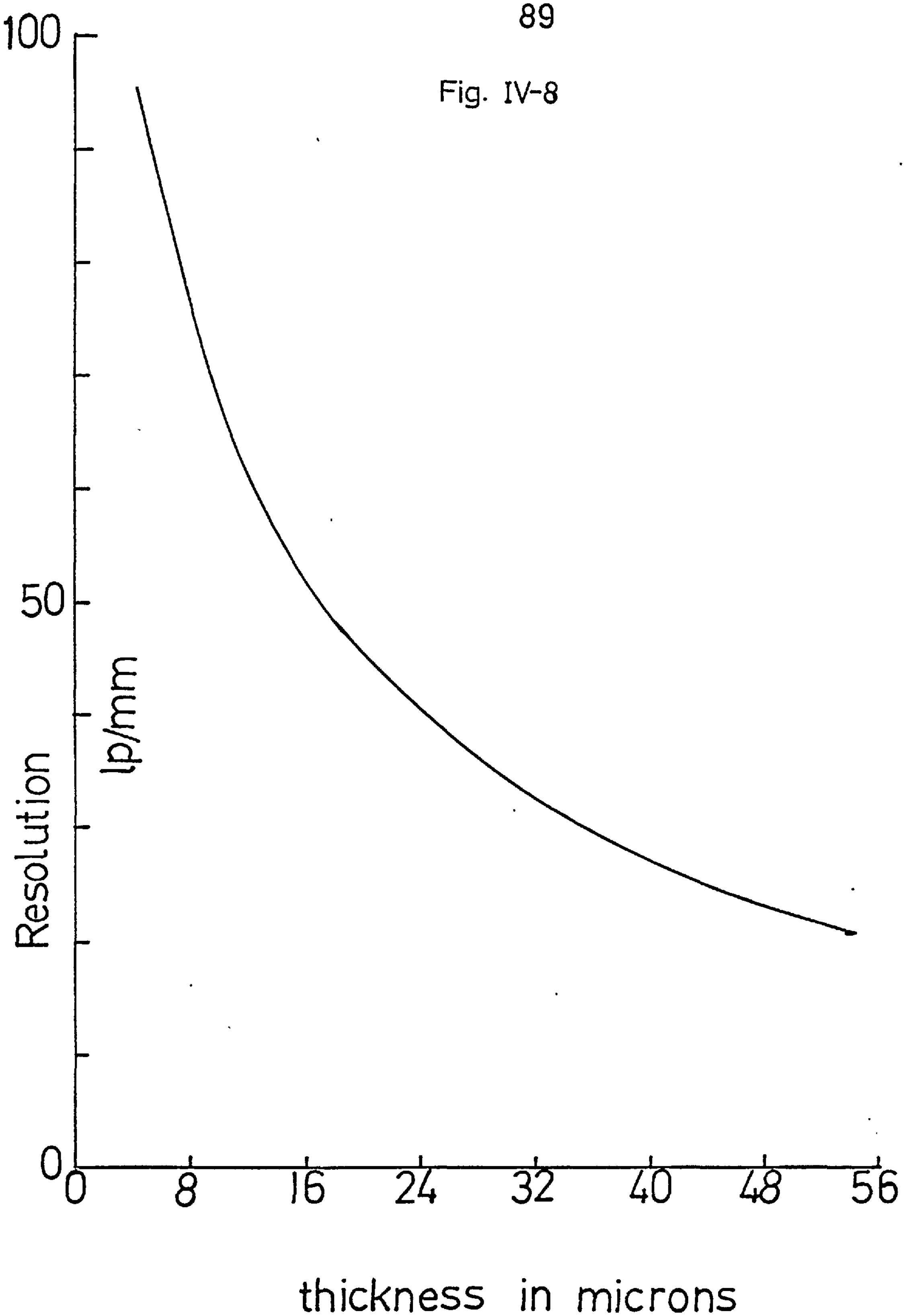

100
50
0
Resolution lp/mm
0
8
16
24
32
40
48
56
thickness in microns

image. The electrons can be scattered from the aluminium film, from the layer of potassium silicate cementing the aluminium backing to the phosphor layer, from the binder layers in the case of settled screens and from the phosphor grains.

An incident beam of electrons of 15 keV energy while penetrating through the aluminium backing of 500 A^o thick loses about 3% electrons and 2% of the energy and at the same time suffers a deviation of $\sim 3^o$ while passing through the film[98].

The uncovered area in an electrophorized phosphor screen of thickness 0.7 mg/cm^2 prepared from EMI type 214 phosphor is only 0.3%. So the slightly deviated beam of incident electrons is not likely to see any pin-holes in the phosphor screen; in this way almost every electron hits the phosphor and produces a luminescent point or "secondaries" or both or gets scattered. The "secondaries" are likely to have some lateral velocity so a further spread in the image is introduced.

It is very difficult to calculate the contribution to the radius of the disc of confusion due to scattering of electrons which probably is small.

(B) Scattering of light in the phosphor Screens.

From a luminescent point, in a thin phosphor screen with aluminium backing, 50% of the light goes in the forward direction and 50% in the backward direction which will be reflected by the aluminium backing towards the substrate side, in fact, there will be many multiple reflections and refractions before the emitted light works its way out of the screen. The absorption of the luminescent light in the screen may be neglected,[96,129] but the reflections from different interfaces can not be neglected.

The transmission of light through the phosphor layer introduces a spread of the image and the reflections reduce the contrast of the image and in this way the resolution is deteriorated. Approximate calculations were made in the previous section to determine the spread of luminescent light while passing through a phosphor layer. Assuming that the whole of the light going towards the aluminium backing is reflected back to the substrate side then it can be shown that the radius of the disc of the circular spread of light in the case of an aluminized screen is approximately double of that ~~one~~ for an unbacked phosphor screen of the same thickness, when the luminescent point is about 1 micron inside the phosphor layer from the aluminium backing side. The resolution of a settled screen of 1 mg/cm^2 in thickness can be calculated for an ideal layer having an aluminium backing to be $\sim$ 90 lp/mm. However, if the experimental value of the resolution of an unbacked phosphor screen is used (See Table I) then the aluminized phosphor screen will have a resolution $\sim$ 70 lp/mm.

In the case of an unbacked electrophorized screen of 0.7 mg/cm^2 in thickness, prepared from EMI type 214 phosphor, the observed value is $\sim$ 250 lp/mm (see table I) so for a backed screen the resolution should be $\sim$ 125 lp/mm.

From single stage image tube results, an image resolution of 50-60 lp/mm was recorded for the settled screens with floated aluminium backings and a resolution up to 80 lp/mm in the case of settled screens with conventional backings. In the case of backed electrophorized screens of 0.7 mg/cm^2 thickness a resolution $>$ 120 lp/mm has been recorded by casting an electronic shadow of a fine metallic mesh (the technique is described in a later section of this chapter).

Our results fairly agree with the theory proposed so it can be concluded that the loss of image resolution in phosphor screens is mainly due to the spread of light in the phosphor screen and mica substrates.

4. Halation

Multiple reflections in mica or glass and phosphor layer result in the loss of contrast in the image and hence there will be some loss of resolution.

5. Tube background.

The background in an image tube will decrease the contrast of the image and hence it may also result in the loss of resolution.

6. Curvature of the Image Field.

The curvature of the image field is important in electrostatically focused image tubes but it is not of much importance in magnetically focused image tubes. The cascade tubes, prepared at Imperial College, have uniform electrostatic accelerating field and uniform magnetic fields for focusing the electrons, so the resolution is not degraded on this account.

The relative contributions from 4, 5 and 6 are small, so the factors mainly responsible for the loss of resolution in image tubes are the factors 1, 2 and 3.

The calculated and experimentally observed values of the resolution in two and three stage cascade tubes will be discussed in chapter VII.

III Measurements of Resolution.

lp/mm (i) Resolution is generally expressed in lp~~s~~/mm or c/cm cyc~~le~~s/cm. There are a number of methods for measuring resolution. Pochtarev[130] et al describe an instrument in which the shadow of a fine metallic mesh is demagnified by an electrostatic lens and the resolution of a given specimen can be determined in lp/mm.

(ii) Woodley and Rogers[131] describe another method of measuring resolution in which the spot of a cathode ray tube under test is imaged by a microscope objective in the plane of a test pattern. The test pattern consists of opaque and transparent bars of equal width, increasing in frequency in seven discrete steps. A photomultiplier tube collects the light passing through the test pattern when the unmodulated spot is scanned across it, and displays the variations in light output on the vertical scale of an oscilloscope. At low grating (test pattern) frequencies, when the period of one cycle is long compared with the spot size, the contrast is maximum. As the grating spatial frequency increases, the contrast falls, so one can measure the spatial frequency response with the help of this device. This method has the advantage that resolution can be expressed at any contrast.

This method can not be used for high resolution screens because the spot size of an electron gun is too large and furthermore highly stabilised power supplies are required for this apparatus. Woodbridge[132] has measured 30 cycles/mm at 65% contrast dilution, but for the phosphor screens having a resolution of 100 lp/mm or more even at 20% contrast this method can not be used. This method was used to assess the resolution of electrophorised screens in C.B.S. laboratories but it ended in failure[133].

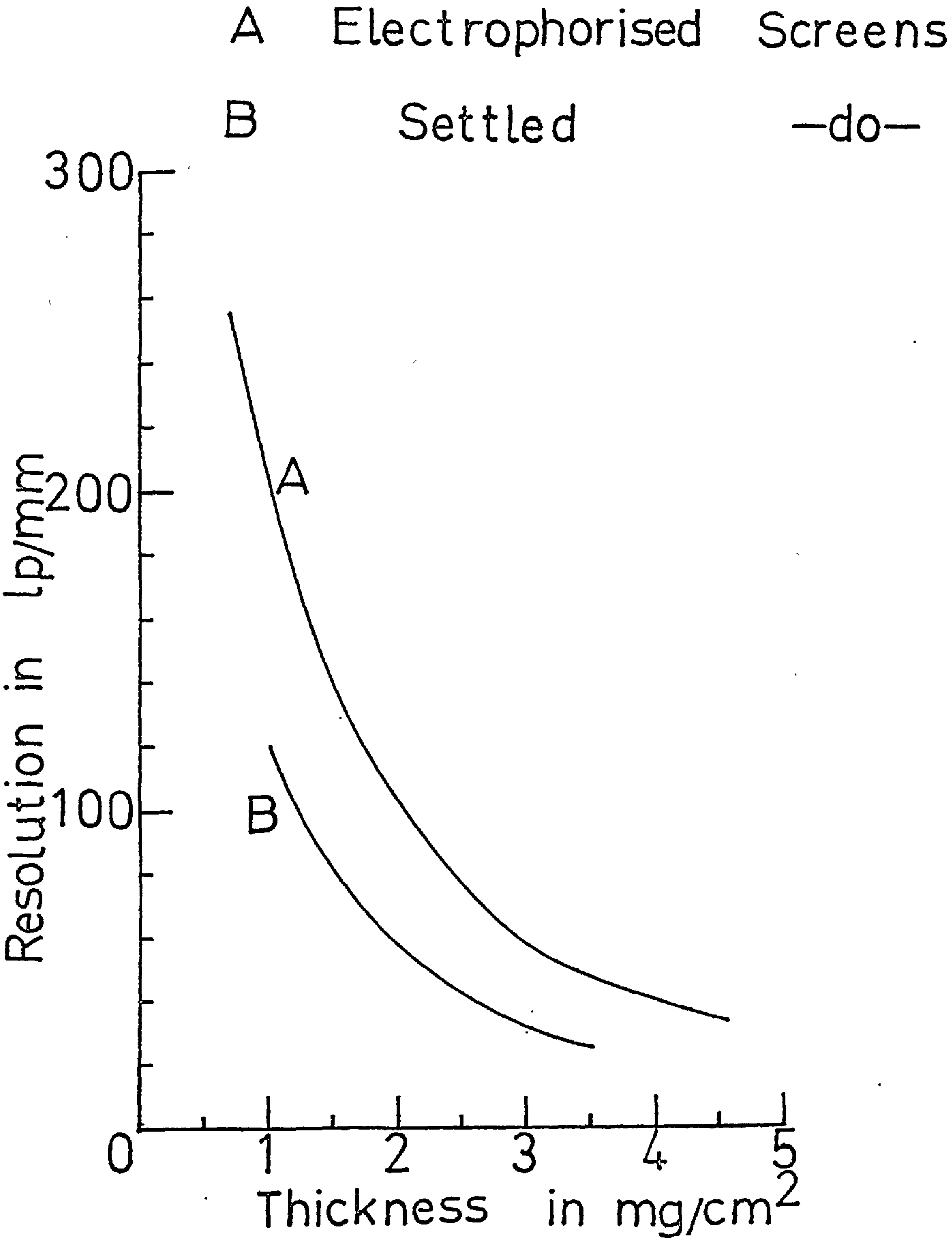
(iii) Cusano[134] describes a method in which a test pattern in ultra-violet light is projected on to a phosphor screen. The resolution of the screens can be measured visually with the help of a microscope. This method is only useful for unbacked phosphor screens.

A modification of Cusano's method in which a resolution test pattern (Baum Pattern) is projected onto a phosphor screen in white light was used to measure resolution. The distribution of the transmitted light is nearly Lambertian, so a U-V excitation of the phosphor is not needed. A number of phosphor screens of various thicknesses were prepared both by the sedimentation process and by the cataphoretic process. The resolution of these samples was measured visually and Fig. IV-9 shows a graph between the thickness of the phosphor screens and their respective visually observed resolution limits. This resolution will not necessarily be the same as the resolution of a screen on to which an electronic image is projected because the scattering of the electrons has not been taken into account. In the case of a settled screen of $1mg/cm^2$ thickness the resolution of an unbacked screen was observed to be ~ 120 lp/mm. While an unbacked screen of the same thickness was capable of resolving ~ 100 lp/mm in an image tube. So this method gives an optimistic value of the resolution of the unbacked screens.

None of the above methods could be employed for the assessment of the resolution of phosphor screens because it is difficult to set up the apparatus described by Pochterav; Woodley's apparatus is not capable of measuring the resolution of fine grain phosphor screens prepared by electrophoretic process and Cusano's method is only for unbacked phosphor screens.

(iv) Single stage image tubes were made to assess the resolution of the phosphor screens. The output phosphors consisted of a number of samples (4 to 6) mounted into two stainless steel rings. A resolution pattern was focused onto the photocathode and the image tube was focused to give the maximum resolution. The resolution of each sample was measured visually with the help of a microscope. A number of single stage image tubes were made to determine the loss of resolution with the increase in the thickness of the phosphor screens and also to investigate the effect of different backings on the resolution of phosphor screens. The results are discussed chapter V.

Fig. IV-9


A Electrophorised Screens
B Settled -do-
300
200
100
0
1
2
3
4
5
Resolution in lp/mm
Thickness in mg/cm^2
A
B

(V) As the above method of measuring resolution is very time consuming, an attempt was made to construct a demountable image tube. Three approaches to the problem were considered.

(a) A demountable image tube with a side arm which would have a gating valve (described in Ref. 10), this valve is such that it can maintain high vacuum on one side while the other side can be let down to air. A photocathode could be processed on the high vacuum side of valve and then the other side (image tube side) could be evacuated. The photocathode could be transported through the gating valve and resolution of the screen could be measured. After resolution measurements the photocathode could be pulled back and the gating valve closed. Now the image tube side could be let down to air and another phosphor screen could be introduced. This approach to the problem was not adopted because the construction of the gating valve is very difficult and also the photocathode surfaces are very sensitive to the traces of water vapour which are likely to be present on the image tube side.

(b) A demountable image tube could be made with a caesium iodide photocathode on a quartz plate. The image of a resolution pattern could be projected onto the photocathode with ultraviolet light. This approach to the problem was not put to practice because the CsI photocathodes are not very sensitive and moreover special test patterns and quartz lenses must be used for the projection of the image onto the photocathode. However, quartz lenses may not be needed as fine metallic meshes can be printed in aluminium onto the photocathode plate by masking technique before the formation of the photocathode.

(C) <u>A demountable image tube with theremionic cathode</u>.

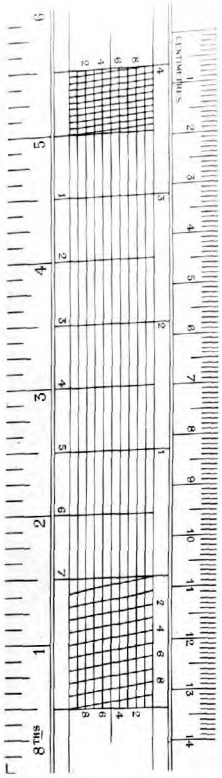
The principle of this device is that if a mesh of known resolution (number of meshes/mm) were kept at the first focus of the electrons in an image tube then it could be imaged on to the output phosphor. The apparatus is shown in Fig. IV-10. The image section of the tube was 10 cms long and the mesh was placed at a distance of 2.5 cms from the cathode and suitable magnetic field was applied so that two loop focusing could be achieved. The overall voltage applied to the tube was 15 kV. The thermionic cathode was an indirectly heated oxide coated button type filament.

A very good image of the mesh was obtained after overcoming initial difficulties. Since the source of electrons was an oxide-coated indirectly heated button type cathode, the emission of electrons decreased after successive exposures to the atmosphere, which were necessary for changing the phosphor screens. A cathode survived about two to three exposures to air and after that it had to be recoated and processed to obtain sufficient electron emission current. A tungsten mesh filament (1 cm^2) was used but the image of the filament mesh on the phosphor screen was masking the mesh image at the first focus.

An attempt was made to get electron emission by heating nickel disc by electronic bombardment, the arrangement is shown in Fig. IV-11A. The electrons from a hairpin filament bombarded a nickel disc with an energy of 3 keV, the nickel disc was not uniformly heated to dull red across its whole surface. The hairpin filament was replaced by a tungsten mesh filament and the process was repeated. In this case the nickel disc was more uniformly heated to dull red but the electron emission from the nickel disc was not enough. A successful cathode of this type could not be developed.

Thus it was necessary to investigate some other method of measuring resolution. A new method was discovered in which an electronic shadow of a fine metallic mesh is cast

Fig. IV-10

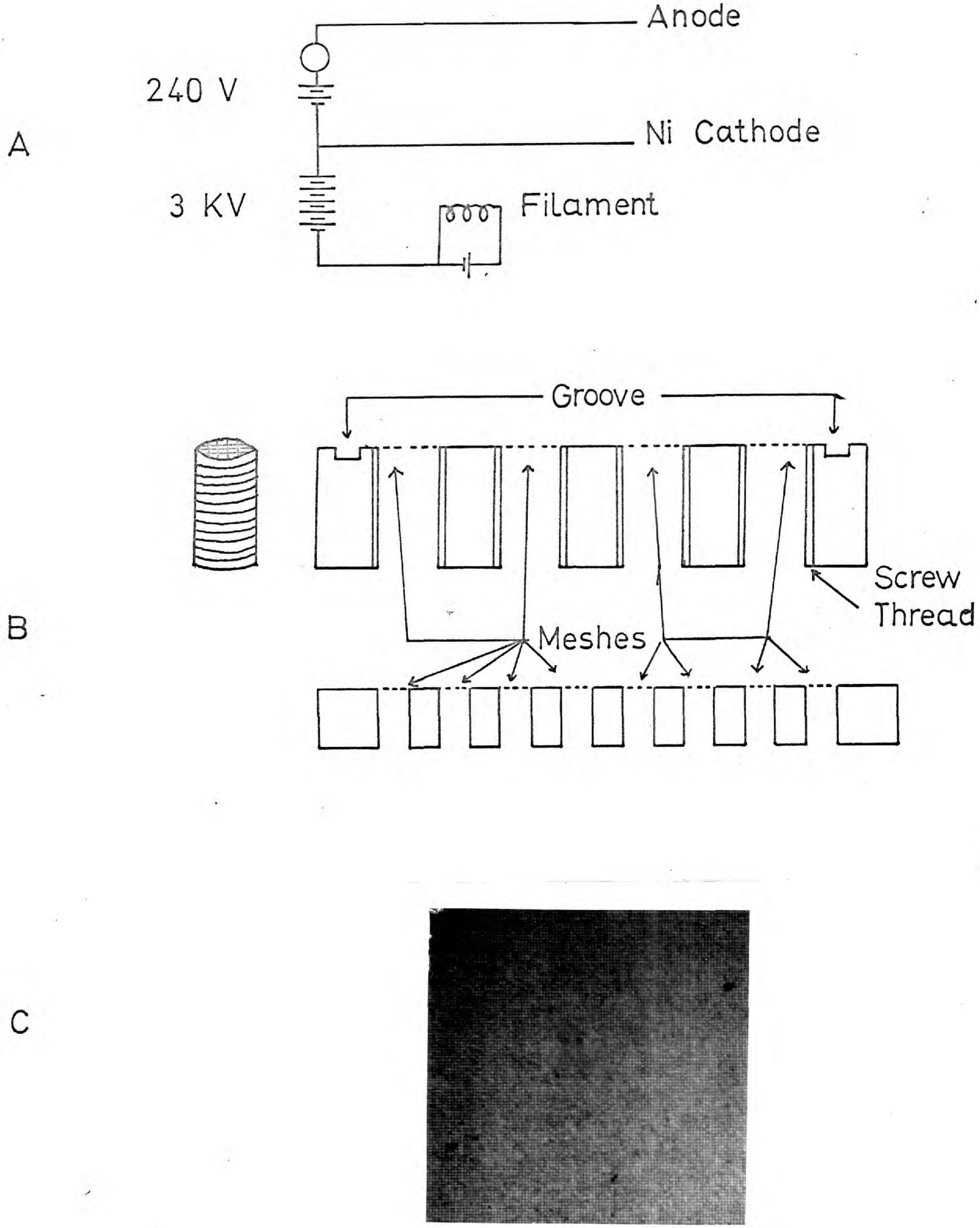


on a phosphor screen the latter is observed through a microscope whether the image of mesh can be resolved or not.

(vi) A copper mesh was sandwiched into two stainless steel rings, the mesh was 600 meshes/1". The mounted mesh was placed on the phosphor so that the distance between the phosphor surface and the mesh was about 1 mm. This composite assembly was put in a cathode ray tube (described in chapter V) and a voltage of 15 kV was applied between the hairpin filament and the phosphor screen. The shadow of the mesh appeared on the phosphor screen and this was viewed through a microscope, if the mesh is just resolved then the resolution of the screen will be the number of meshes/mm. In the above experiment the contrast was not good. The contrast of the mesh shadow was improved by decreasing the distance between the mesh and the phosphor screen. A survey of literature at a later stage showed that a similar technique for resolution measurement was published by Leavitt[135].

A device, shown in Fig. 11B, was constructed which would take a number of meshes of different pitches and which could keep the meshes at a distance of 0.25 mm from the phosphor layer. The device could take 4 meshes of 3000, 2000, 1500, 1000 meshes per inch which corresponded to 120, 80, 60 and 40 meshes per mm. Each mesh was cemented flat on the face of a cylinder with potassium silicate. Each cylinder had a screw thread on its outer surface so that it could be screwed into a plate which had four threaded holes for this purpose. The cylinders were screwed into the holes and the meshes were brought in the plane of the face plate. The plate itself had a circular groove 5 mm wide having an outer diameter of 48 mm and an inner diameter of 38 mm and a depth of 0.25 mm

Fig. IV 11


A
240 V
3 KV
Anode
Ni Cathode
Filament
B
Groove
Screw
Thread
Meshes
C

to take the mounting ring of the phosphor screen and thus bring the phosphor screen very close to the meshes.

On exposure to the atmosphere, the copper meshes formed a green compound in the areas where pot. silicate was applied. This spoiled the adhesion of the silicate and the meshes dropped off. In order to overcome this difficulty a new device was made which consisted of a stainless steel plate having twelve holes in it. Each hole had a push-fit stainless steel plug such that the lower end of each plug was flush with the surface of the plate when inserted in a hole. The meshes were mounted by squeezing the mesh in between the walls of the plug and the corresponding hole.

In the case of the mesh technique it is difficult to correlate the resolution in terms of lp/mm because bars and spaces of the mesh do not have the same width. A number of settled phosphor screens were tested for resolution with mesh technique. A mesh of 1500 meshes/1" (60 meshes/mm) could be just seen on the phosphor screens. In the case of settled screens the resolution was measured to be 50-60 lp/mm, from single stage image tube results so the mesh technique gives a resolution in lp/mm approximately.

This technique is limited in use due to the limited range of very fine meshes available. The finest mesh which is available has 3000 meshes/1" (120 meshes/mm) while our cataphorized phosphor screens of 0.67 mg/cm^2 in thickness can easily resolve the finest mesh. So some other method is needed for measuring the resolution of these phosphor screens.

The mesh technique was modified by putting the mesh in between the electron source and the phosphor screen such that the distance between the phosphor and the mesh was 7.5 cms. The mesh and the phosphor screens were electrically connected. When a voltage of 15 kV was applied between the filament and the phosphor screen, the image of the mesh could be seen but the contrast of the image was poor. By employing a thin magnetic lens in between the mesh and phosphor screen the mesh image could be demagnified, a demagnification of 3 was easily achieved. A variable demagnification could be achieved by adjusting the position of the magnetic lens or by varying the strength of magnetic field. In this modified mesh technique the contrast of the mesh image was poor and on this basis this technique was not fully investigated.

Photographs of 120 lp/mm mesh resolved by a cataphorized screen is shown in Fig. IV-11C.

CHAPTER V Evaluation of the Phosphor Screens.

The important characteristics of phosphor screens such as efficiency, image definition, coverage, surface texture etc. have been studied and the results are discussed in this chapter.

I. Efficiency.

The cathodoluminescence efficiency of phosphors is a subject of a number of papers by Gergley, Garlick and others[136-40]. The cathodoluminescence efficiency of a ZnS:Ag (P-11) phosphor has been theoretically predicted to be 25% while its experimental value is 20-23%. The efficiency of a phosphor screen may be defined as the ratio of the total output light energy to the total input electron energy.

In practice relative efficiencies of phosphor screens are measured under identical conditions to find the effects of different screen formation parameters. A demountable cathode ray tube (shown in Fig. V-1) was used to measure the relative efficiencies. The phosphor screen to be tested is fixed in the cathode ray tube and an electron beam (beam current 0.02 μA) is accelerated on to the phosphor screen. The output light is measured by a photocell with S-9 (Sb-Cs) photocathode having a photosensitivity of 10 μA/Lum for white light. The photocell is pressed against the cathode ray tube face-plate on which the phosphor screen is mounted. The ratio of the photocell current to the primary beam current is a measure of the relative efficiency of the phosphor screens.

The efficiency of the phosphor screens depends upon the energy of the incident electrons, the beam current, screen thickness, aluminium backing, particle size of the phosphor material, method of the preparation of the phosphor, and the coverage of the substrate. All the factors will be

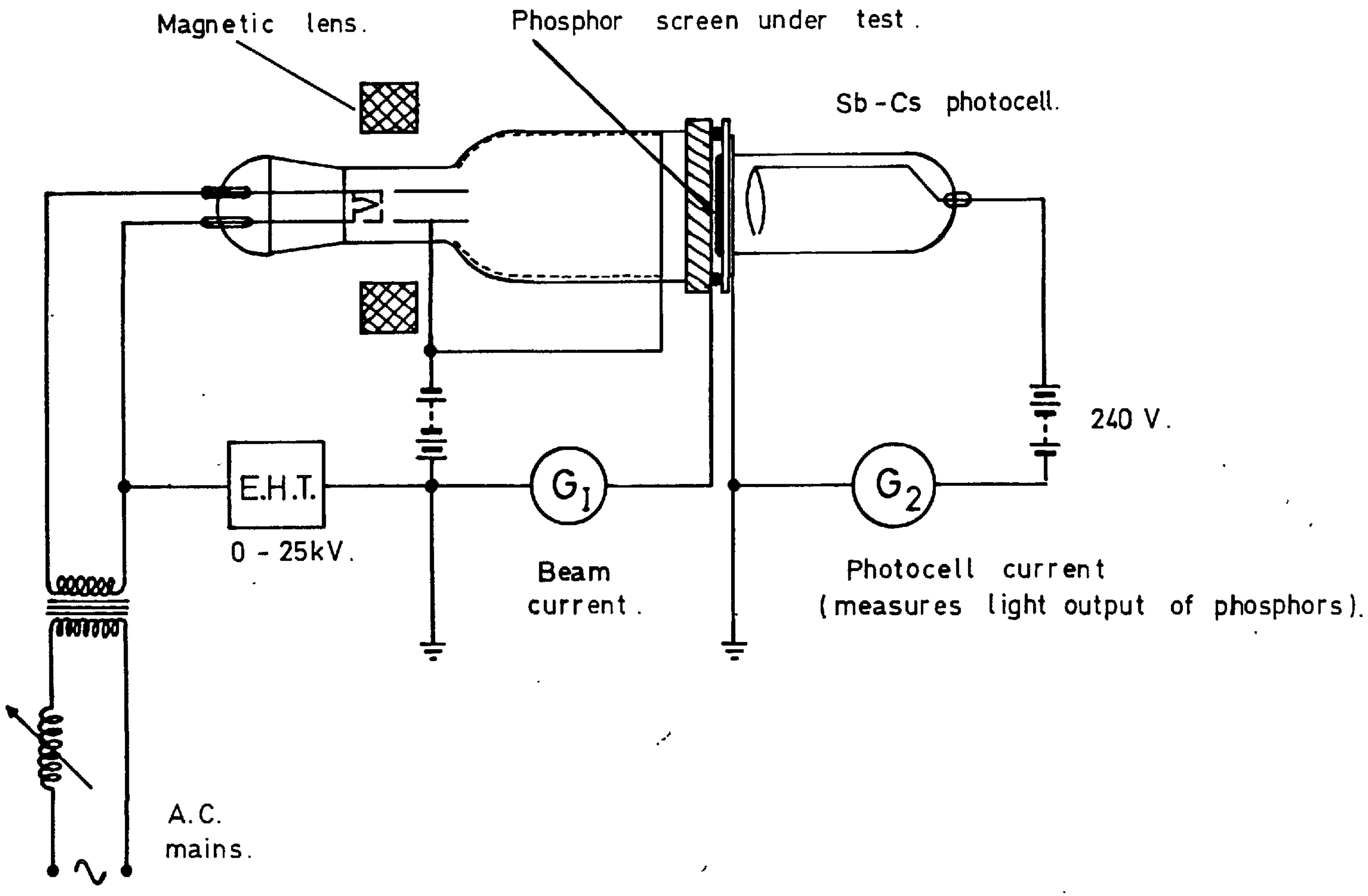


Fig.V-1

Demountable C.R.T. phosphor test apparatus.

considered in detail.

(A) Energy of Electrons.

For a given screen thickness the cathodoluminescence efficiency (output light energy) of a phosphor rises with the energy of the electrons and reaches a maximum after which it slightly falls presumably due to the possibility of increased elastic scattering of the electrons at higher voltages[96]. Gergely[141] reported that the cathodoluminscence efficiency is proportional to the energy of the electrons provided the saturation level is not reached and the energy of the electrons is not less than 5 keV. He further suggests that the non-linear relationship between the efficiency and the energy of the electrons (between 3 - 5 keV) is due to non-radiative loss of energy in the dead surface layer of a phosphor grain.

Fig. V-2 is a typical curve showing the relationship between the efficiency of a phosphor screen and the energy of the incident electrons. The phosphor screen was prepared by sedimentation technique and had a thickness of 1 mg/cm^2, EMI type 214 P -11 phosphor was used for the preparation of the screen.

(B) Beam Current.

For a given screen thickness and a fixed energy of the electrons, the cathodoluminescence efficiency of the screen depends upon the number of electrons incident on the screen, i.e. the beam current. The output light from a screen is proportional to the beam current until current saturation point is reached.

Fig. V-3 represents the behaviour of the efficiency as the beam current is increased. The same phosphor screen was used as in section I(A). High beam currents were not used because of the fear of electron burn of the screen which decreases the efficiency of the screen.

Fig. V 2

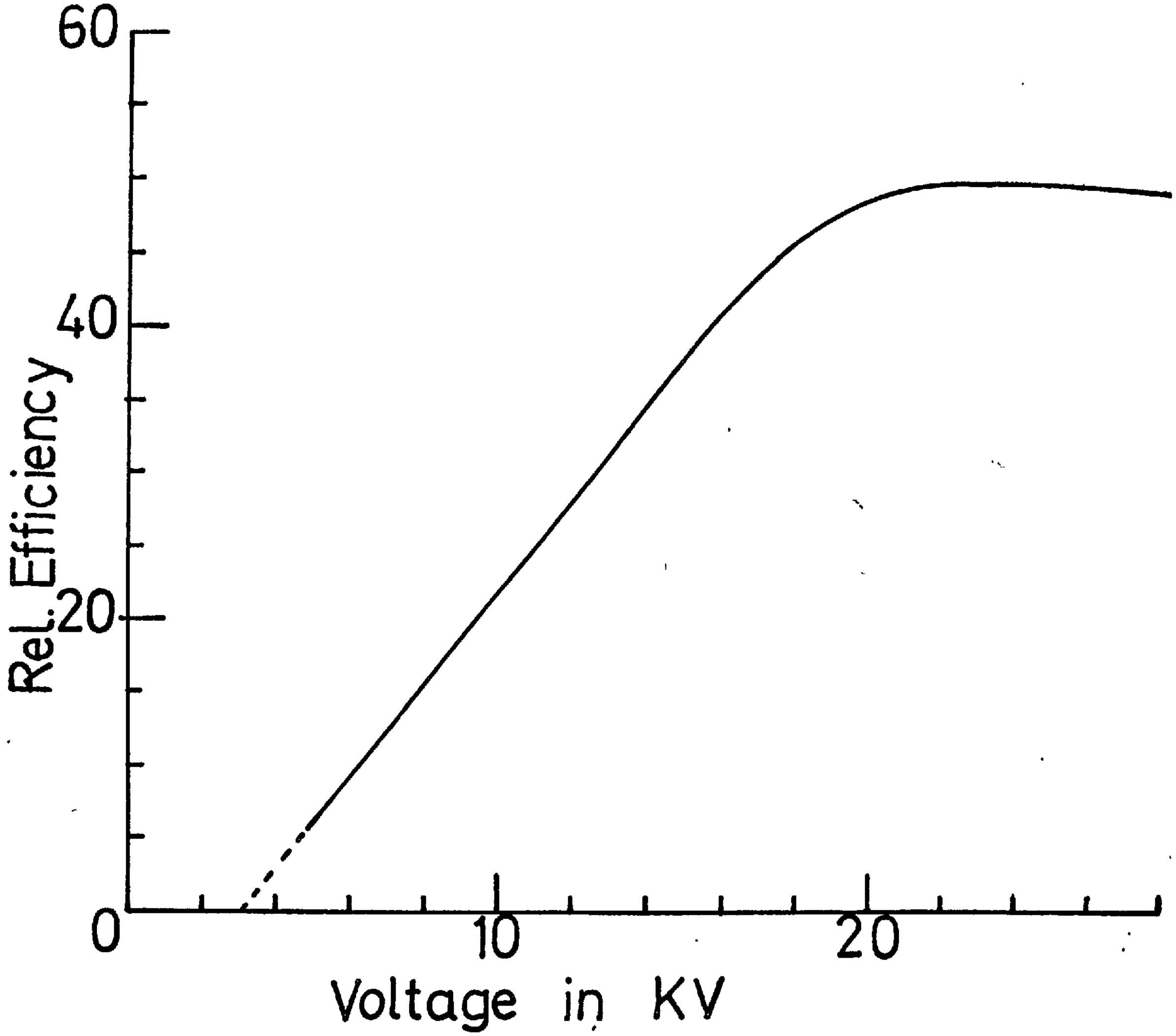
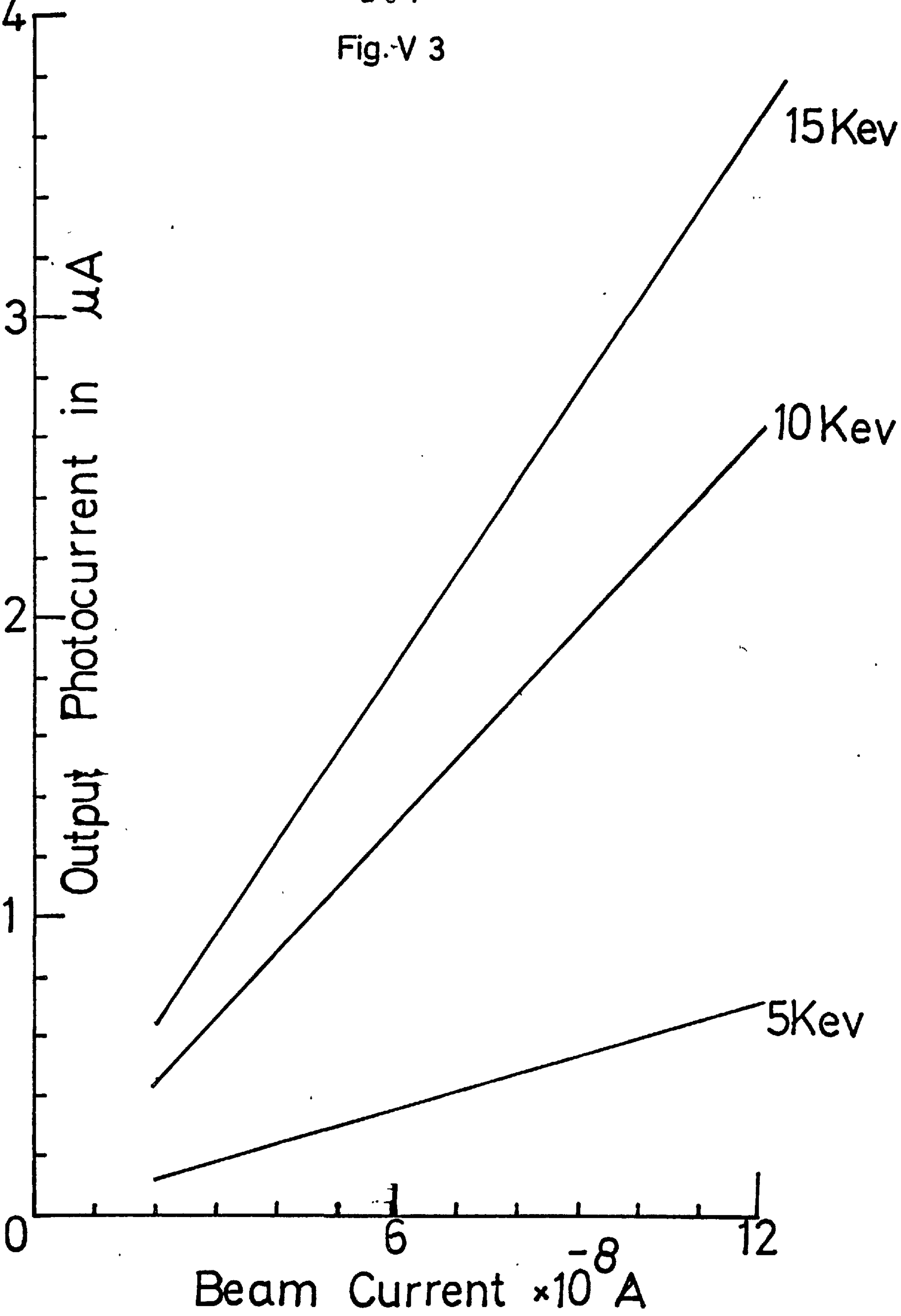


Fig.-V 3


4
3
2
1
0
Output Photocurrent in μA
15 Kev
10 Kev
5Kev
6
12
Beam Current ×10^{-8} A

Stoudenheimer[142] reported a non-linear relationship between the efficiency and beam current at very low excitation currents $\sim 10^{-10}$A.

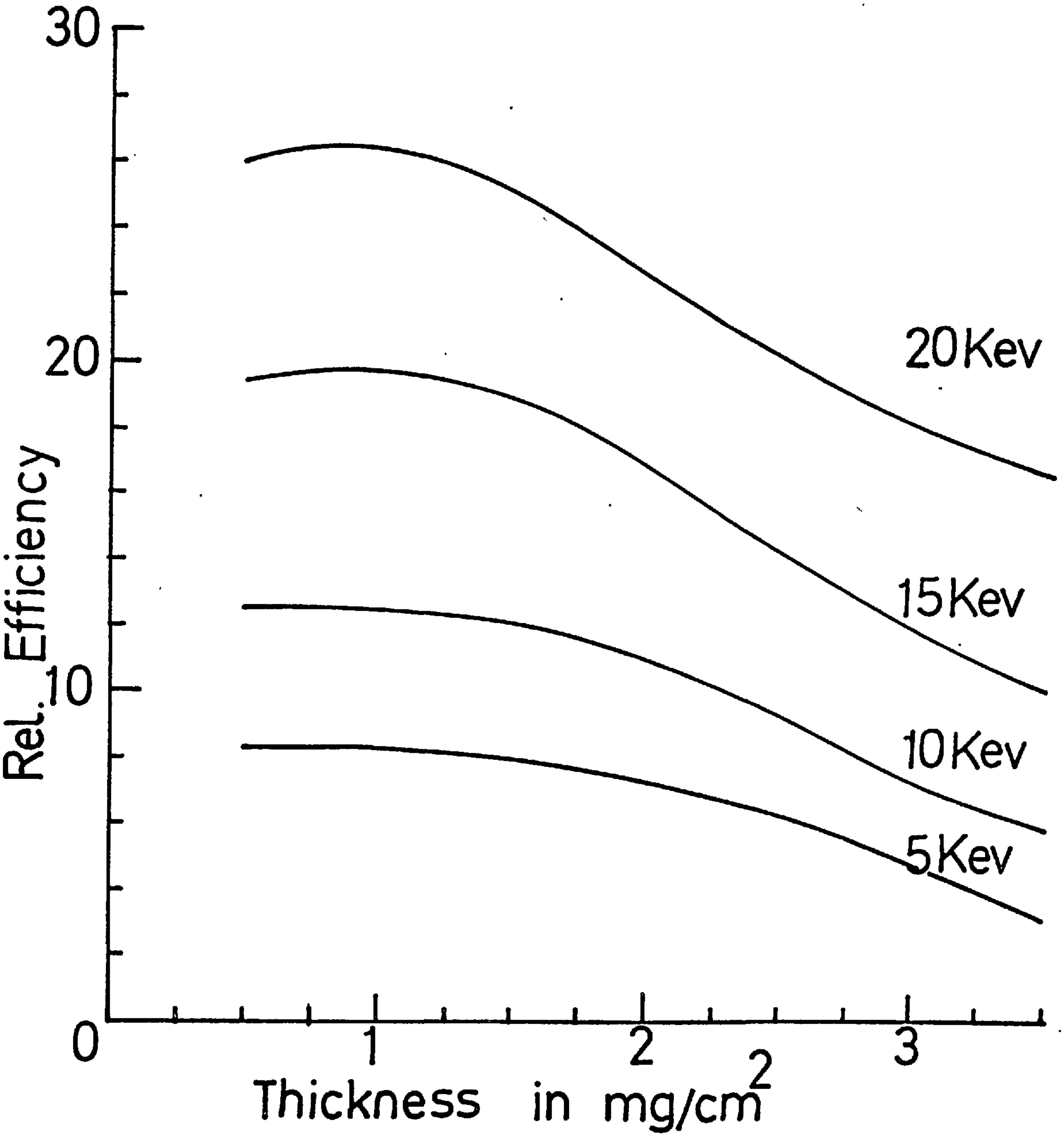
(C) Screen thickness.

For a given electron energy and beam current the cathodoluminescence efficiency depends upon the thickness of the phosphor layer, the phosphor screens may have been prepared by any process. The efficiency increases with screen thickness, passes through a broad maximum and then falls off. The initial rise is due to incomplete electron energy conversion which increases until a point is reached when the electrons have just enough energy to penetrate the phosphor layer. Then the efficiency attains a maximum value which is not significantly affected by further increase in screen thickness until the screens are too thick. Then the efficiency begins to fall due to increased scattering and absorption of light in the phosphor layer between the luminescent point and the detector.

In order to study the behaviour of efficiency with the increase in phosphor thickness, a number of phosphor screens were prepared by the sedimentation process using EMI type 214 phosphor. Fig. V-4 shows the variation of the relative efficiency with increase in screen thickness for unbacked phosphors, while Fig. V-5 shows the same for aluminium backed screens. "Floated" aluminium backings were used.

The experiment was repeated for the phosphor screens prepared by the electrophoretic method using EMI type 214 phosphor. The screens were aluminized by "floated" aluminium backings. Figures V-6 and V-7 show the behaviour of efficiency at four different voltages (5, 10, 15 and (screen ? 20 keV) for a set of phosphor screens.

Fig. V 4



30
20
10
0
Rel. Efficiency
1
2
3
Thickness in mg/cm^2
20 Kev
15 Kev
10 Kev
5 Kev

Fig. V 5

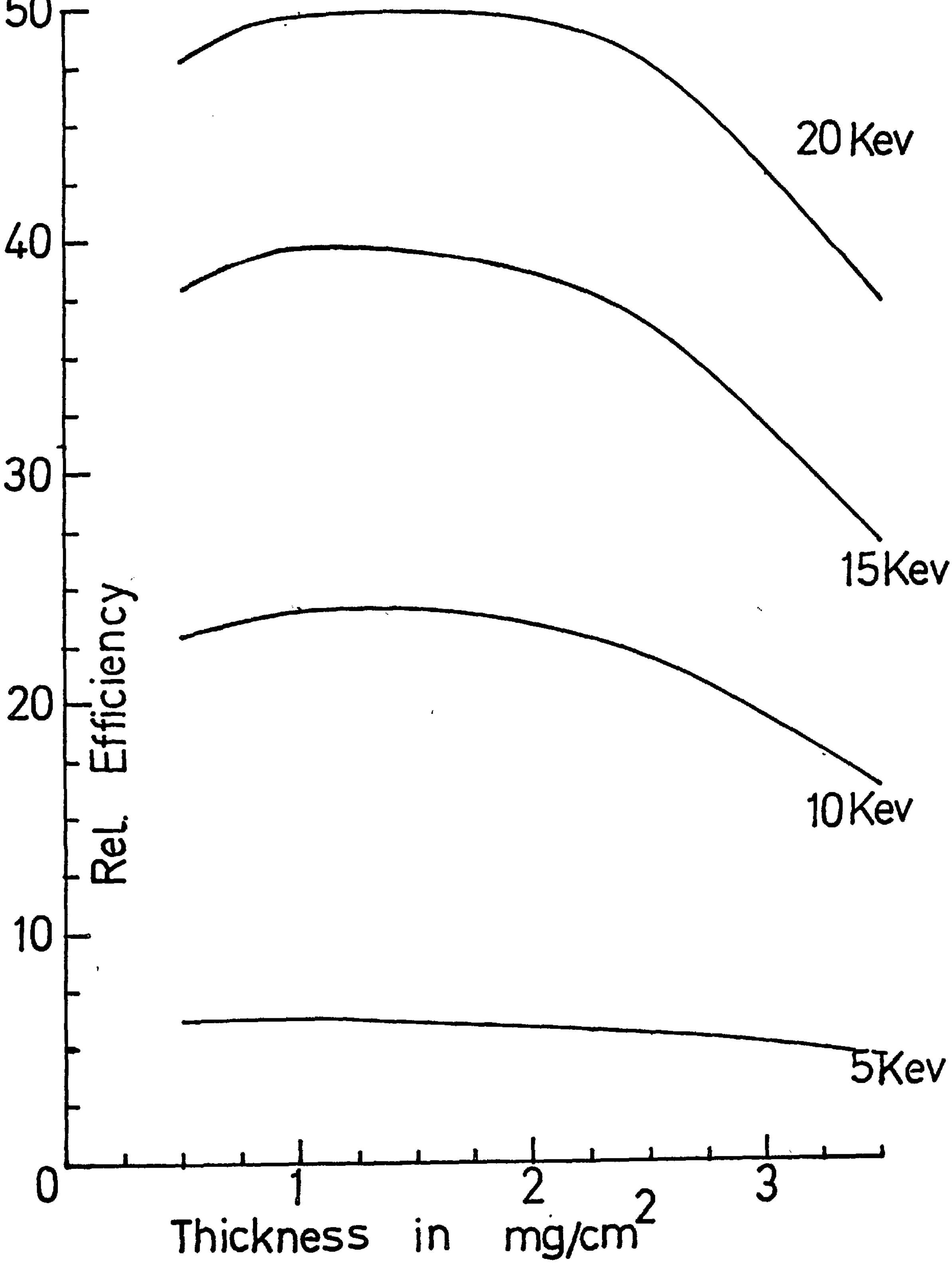

50
40
30
20
10
0
1
2
3
Rel. Efficiency
Thickness in mg/cm^2
20 Kev
15 Kev
10 Kev
5 Kev

Fig. V 6

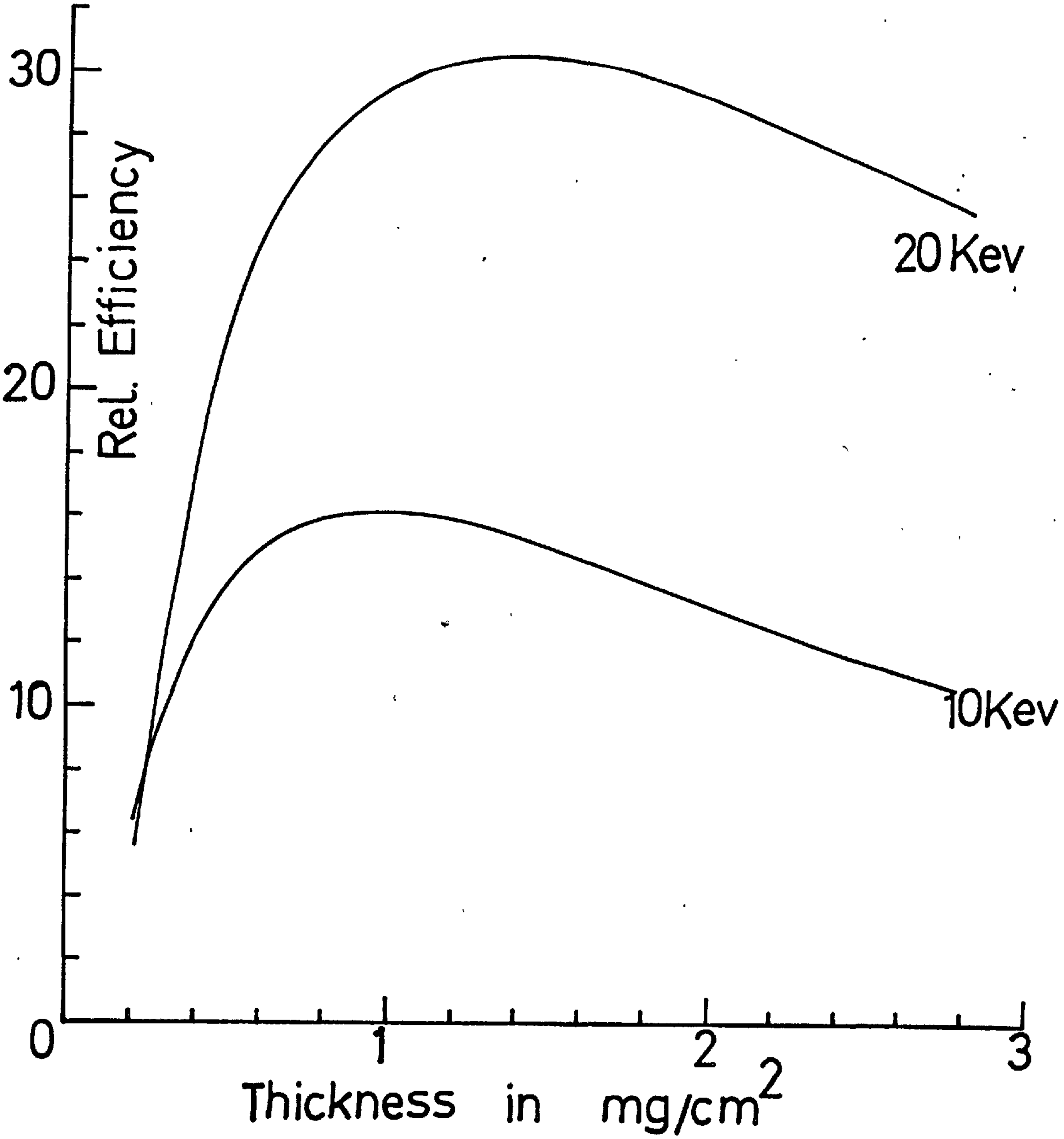
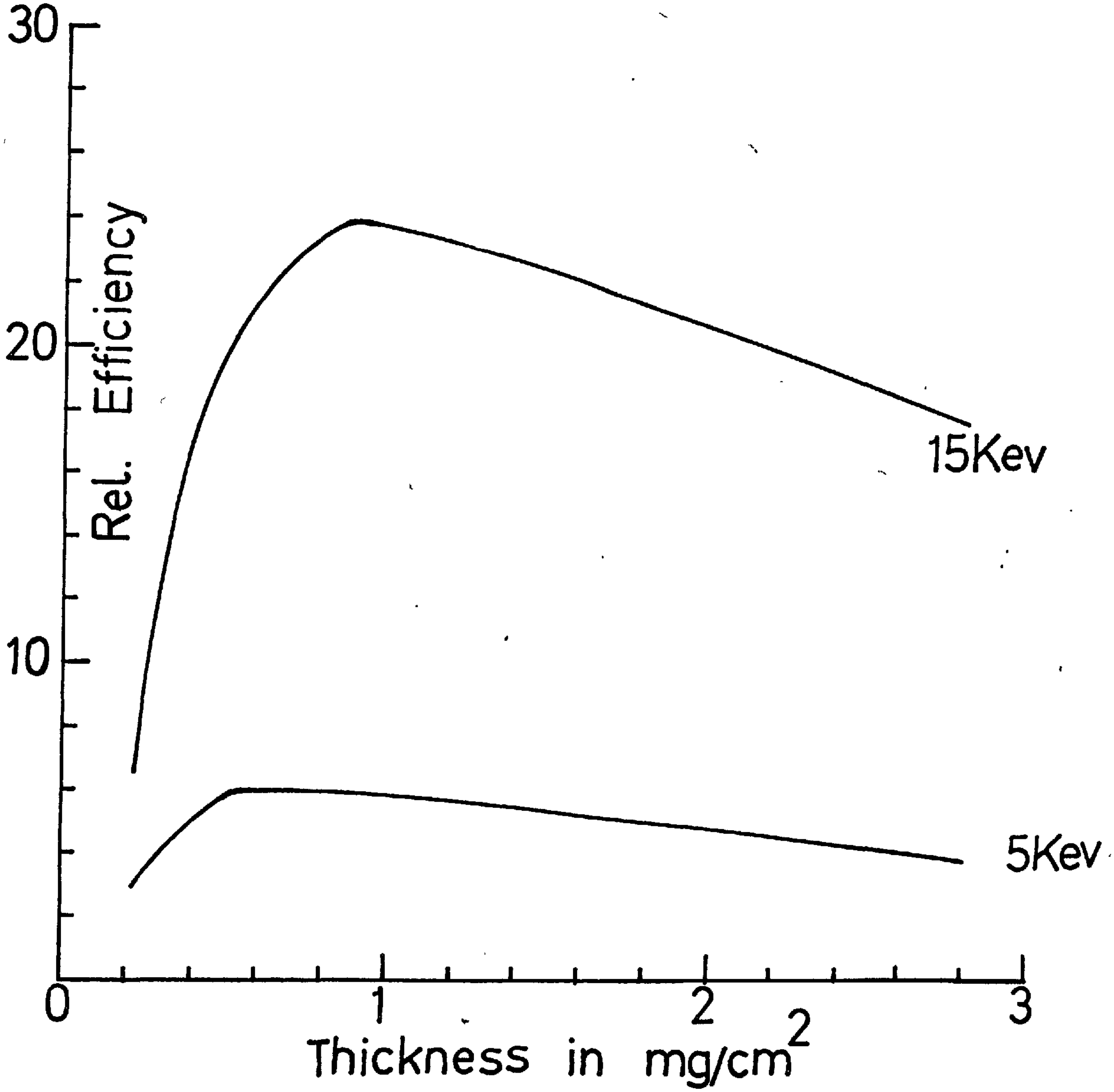


Fig. V 7



The optimum screen thickness may be defined as the minimum phosphor thickness for maximum light output and a nearly complete coverage of the substrate, so the optimum screen thickness depends upon the energy of the electrons and the particle size of the phosphor used. From energy considerations alone the penetration depth (p) of an electron in a ZnS phosphor screen is given by Bethe's formula[143]

$$p = 2.83 \times 10^{-12} V^2 \text{ cm.}$$

For 15 kV electrons the penetration depth works out to be 6.3 μm. Bril and Klasens and others[55,96,125] reported that the range of 15 keV electrons in a phosphor is $\sim$1.5 μm while Koller and Alden[127] claim that 90% of the electron energy is dissipated in the first half of the range of an electron. Hence the effective range of a 15 keV electrons should be $\sim$1 μm. The difference between the value of the range predicted by Bethe's formula and the measured values suggests the inapplicability of Bethe's formula in the case of the crystal phosphors.

In order to obtain nearly complete coverage the granular screens are several times thicker than the single-grain layers of the phosphor of the same particle size. According to Leverenz[78] the optimum screen thickness of a phosphor screen will be $\sim$4 times the thickness (diameter) of a single phosphor grain provided the penetration depth of an electron of a given energy is equal to the diameter of the grain size.

EMI type 214 phosphor has an average grain size of 1 μm so one would expect the optimum thickness of the phosphor screen to be $\sim$4 μm. The phosphor screens were prepared by electrophoresis technique and their thicknesses were measured (to be described in section III of this chapter) and it was found that a screen of 0.67 mg/cm^2 in thickness had an average layer thickness of 4 μm which is in very good agreement with Leverenz's results.

The packing density of a phosphor screen may be defined as mass per unit volume of the deposit and its measure will give the degree of packing by a given screen manufacturing method. If a phosphor screen has a diameter d cms. and average thickness of the phosphor layer is t microns then the total vol. of the deposit = $\pi \frac{d^2}{4} x t x 10^{-4}$ c.c. If the mass per unit area is m mg/cm^2 then the total deposited mass = m mg/cm^2 x $\pi \frac{d^2}{4}$ or $m x 10^{-3} x \pi \frac{d^2}{4}$ gms.

$$\text{Packing density} = \frac{10m}{t} \text{ gm/c.c.}$$

Table I gives the packing densities of different screens.

Trace Cavity [illegible] 2.5 μm

TABLE I

Phosphor	Deposition Process	Thickness in mg/cm^2	Average layer thickness in μm	Packing density g/cc
EMI	Settling	1	8	1.25
EMI	Electrophoresis	0.67	4	1.7

Thus the screens prepared by electrophoresis process are more tightly packed than the screens prepared by sedimentation process.

The optimum thickness of the screens was determined experimentally. Table 2 gives the optimum thickness of the phosphor screens:-

TABLE 2.

Phosphor	Deposition Process	Optimum thickness of the screens.
G.E.	Settling	2mg/cm^2
EMI type 214	"	1mg/cm^2
"	Electrophoresis	0.8 mg/cm^2
Derby Lum.	"	0.45 "

The above optimum thicknesses are for 15 keV energy electrons.

Fig. V-8 is for electrophorized phosphor screens prepared from Derby Luminescents A/259 phosphor, giving optimum screen thickness of 0.45 mg/cm^2. The thickness of the phosphor layer in microns can be calculated by using the calculated value of packing density of phosphor (1.7). The optimum thickness can be calculated to be $\sim$2.7 microns which is approximately four times the particle size of the Derby Luminescents type A/259 phosphor as the particle size of the phosphor is less than one micron. Our experiments support Leverenz's conclusions that the optimum screen thickness is approximately four times the particle size of the phosphor used in the case of granular phosphors.

(D) Aluminium backings.

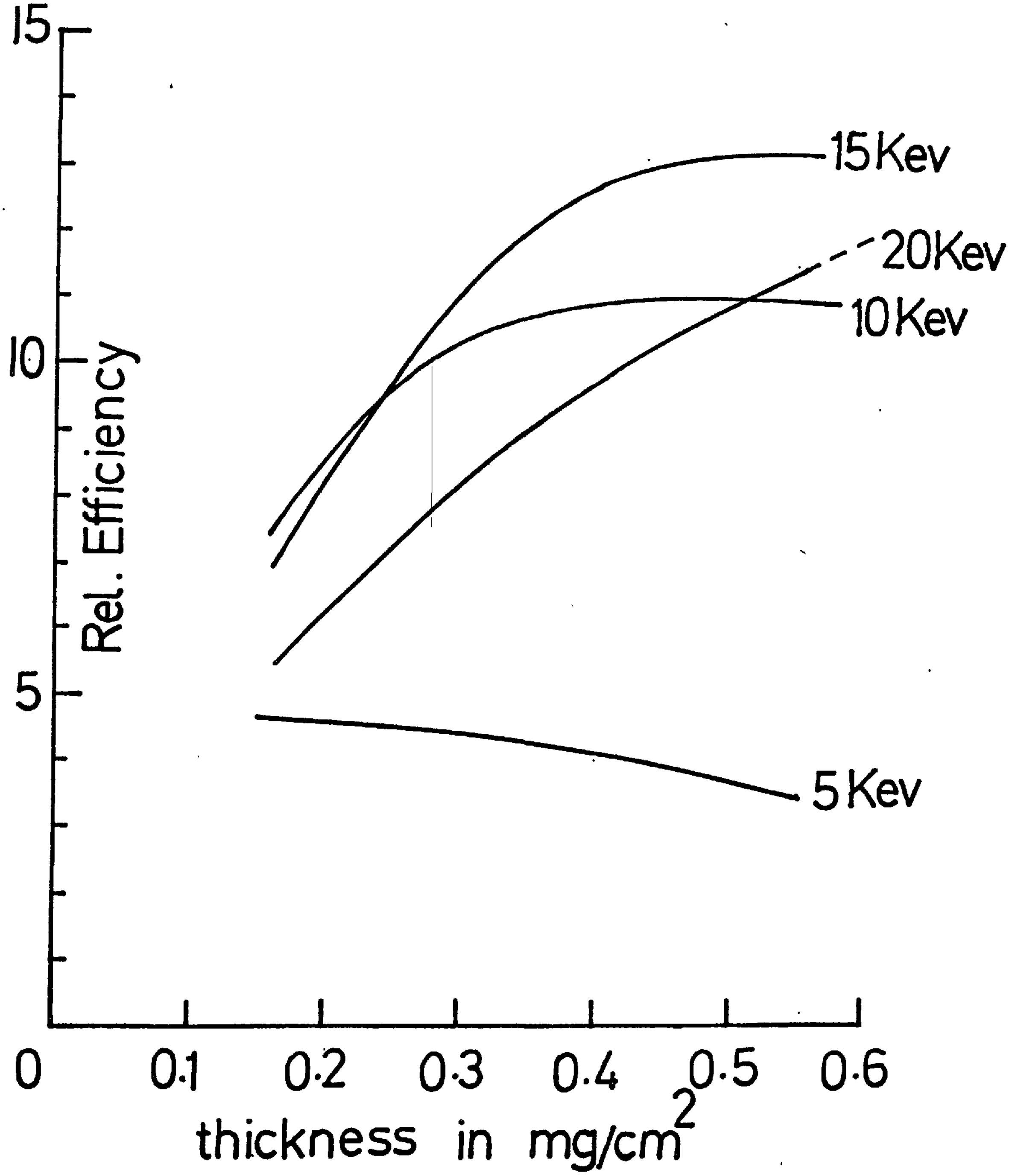
The effect of aluminium backings on the output light of a phosphor screen and on the image definition will be described in the next section.

(E) Phosphor Material.

The efficiency of a phosphor screen depends upon the type of phosphor, type of impurity (activator), grain size, method of manufacture and the batch of its preparation, provided other variables are kept constant.

Levshin and Ryzhikov[92] have claimed that the phosphor efficiency decreases as the particle size of the phosphor is decreased due to the reduction in yield (supposed to be due to reduction in particle size) of the luminescent light and increased scattering of light due to finer particle size of the phosphor. It seems that their claim is not strictly true as finer phosphors have been prepared without appreciable loss of efficiency by employing refined techniques for the preparation of the phosphors; for example EMI type 214 P-11 is a fine grain phosphor with a particle size $\sim$ 1 micron and experiments show that optimum screen

Fig. V 8


15
10
5
0
0.1
0.2
0.3
0.4
0.5
0.6
Rel. Efficiency
thickness in mg/cm^2
15 Kev
20 Kev
10 Kev
5 Kev

thickness for this phosphor in the case of phosphor screens prepared by sedimentation method is 1 mg/cm^2. G.E. type 118-2-11 (P-11) phosphor has a particle size of 3-5 microns and EMI (coarse grain) P-11 phosphor has a particle size of 3-5 microns. The optimum screen thicknesses for the later two phosphors are 2 mg/cm^2 in the case of settled screens. The screens of optimum thickness were prepared from all these phosphors and these were tested for efficiency. The efficiency of all the screens was of the same order, though EMI type 214 P-11 screen had slightly less efficiency presumably due to increased scattering of luminescent light due to finer particle size of the phosphor.

(F) Process of Screen Formation.

Some screen formation processes leave a non-luminescent layer on the phosphor grains embedded into the phosphor layers, for example, in the case of sedimentation process a non-luminescent layer of silicate and barium compound ($BaO:SiO_2$) has been observed by radioactive tracer technique[88], while in the electrophoretic process thorium seemed to be embedded into the phosphor layers. The effect of this non-luminescent layer is more significant at lower electron energies (5 - 9 KeV) while at 15 keV the effect is almost negligible. However, the decrease in phosphor efficiency is not negligible even at 15 keV if too much silicate is used for settling process. Double layer phosphor screens (in which the amount of silicate was twice the amount of silicate required for a single layer phosphor) showed less relative efficiency (output light) than single layer phosphor screens of the same thickness (mg/cm^2).

(G) Screen Texture.

The variations in the grain sizes or clumps of grains give rise to variation in the light output but the integrated output light energy is not affected. If the screen is free from pin-holes then none of the incident electrons is lost, so electron energy is more efficiently converted into light energy.

(H) The output light also depends upon the amount of back-scattered electrons from the aluminium backing, phosphor crystals and the binder layers. The scattering of the electrons decreases the output light. Some of the electron energy is dissipated as heat energy in heating the host crystals and in this way a loss in output light results.

II <u>Resolution</u>

The resolution or the image definition of the phosphor screens depends upon the energy of electrons, screen thickness, aluminium backings, particle size of the phosphor, method of the preparation of the screens, surface texture of the screens and on thickness of the substrate in the case of cascade screens which was discussed in Chapter IV. The other factors will be discussed in detail now.

(A) <u>Energy of Electrons</u>.

? why?

The electron-optical resolution depends upon the energy with which the electrons impinge on the phosphor screen (see chapter IV), keeping the other variables constant. The resolution can be improved by increasing the energy of incident electrons. For efficient energy conversion the phosphor layer must be thick enough to absorb all the incident energy, which would tend to decrease the resolution due to increase in the layer thickness. These are contradictory requirements, so generally a compromise is made. In practice a value of electron energy of 15 keV has been used for calculations, etc., because the potential applied in a cascade tube of 15 kV per stage.

(B) Particle Size of the Phosphor.

Keeping the other variables constant, the image definition of the phosphor screens will depend upon the particle size of the phosphor used. The image resolution increases as the particle size of the phosphor decreases, so fine grain phosphors should be used for the preparation of high resolution phosphor screens. EMI type 214, P-11 phosphor (grain size ~ 1 micron) and Derby Luminescents P-11 phosphor type A/259 (grain size ~ 1 micron) were used for the preparation of most of the phosphor screens.

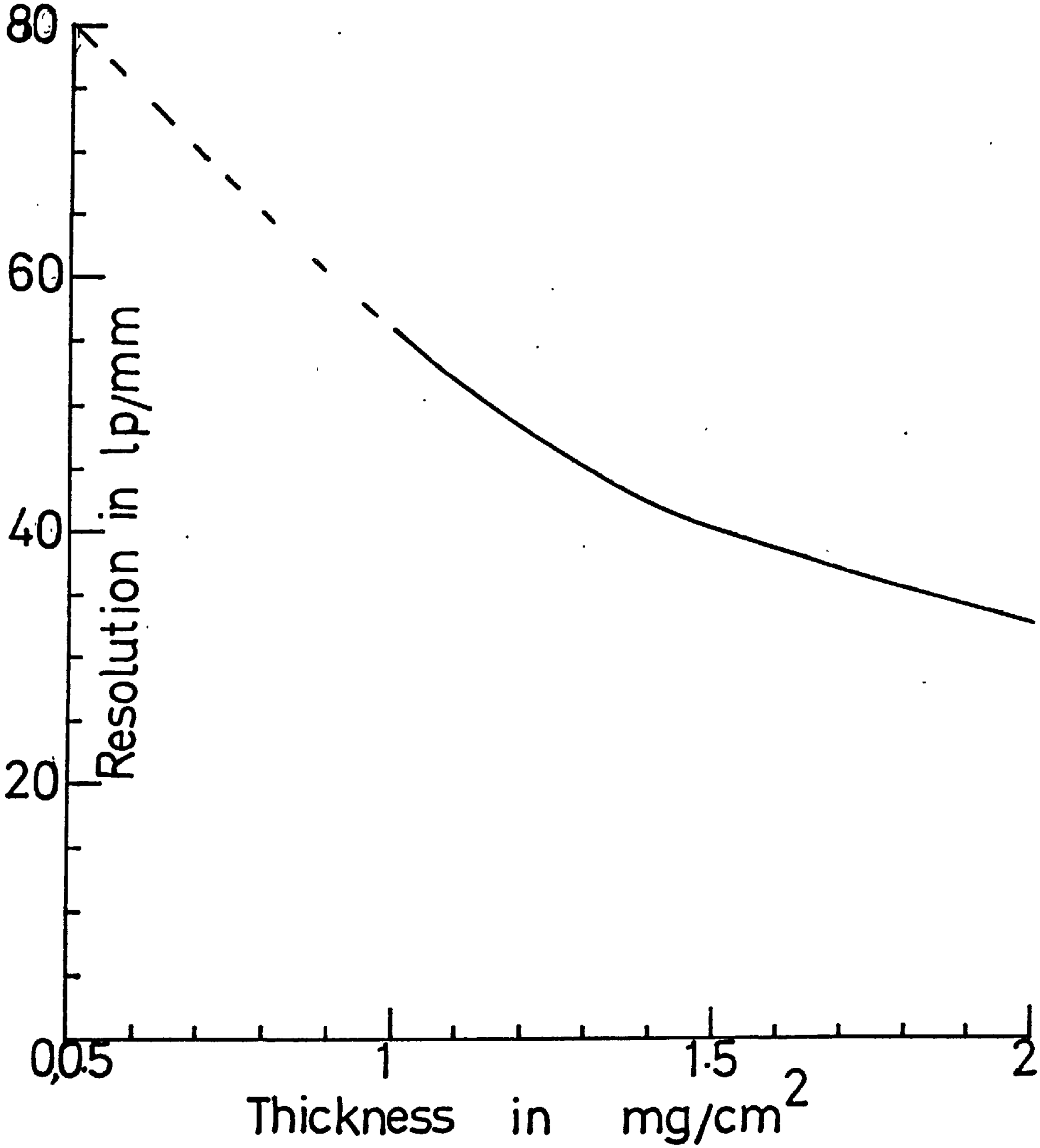
Settled phosphor screens made from G.E P-11 phosphor and EMI type 214 phosphor were tested for image definition for the same thickness (2 mg/cm^2). The image resolution of G.E phosphor screen was 30 lp/mm while for the EMI type 214 phosphor screen the resolution was 40 lp/mm with additional advantages of complete coverage of the substrate and smoother surface texture in the latter case, because of finer particle size of the EMI type 214 phosphor.

(C) Thickness of the phosphor screen.

If the phosphor screen is a single grain layer then the resolution is limited by the particle size of the phosphor. In practice, the screens are usually thicker than a single grain layer. It has been found that the image definition of a phosphor screen increases as its layer thickness decreases, the theoretical and experimental values of the image definition have been discussed in chapter IV.

In order to determine a screen thickness which would give high resolution, good efficiency and good coverage of the substrate phosphor screens were prepared by sedimentation process from EMI type 214 phosphor. The resolution of the screens was tested in image tubes and the results are shown in Fig. V-9, indicating that a settled screen of 1 mg/cm^2 has a good resolution ~ 60 lp/mm. The efficiency has

Fig. V 9



already been discussed. When the phosphor screens were prepared by electrophoretic process the thickness was reduced to 0.7 mg/cm^2 without any loss of efficiency, good improvement in resolution and 99.8% coverage. With a later batch of EMI type 214 phosphor the thickness of the phosphor layer was further reduced to 0.5 mg/cm^2 without any loss in coverage, a small drop in efficiency and improved resolution. Experimental measurements suggest a resolution $>$ 120 lp/mm when the measurements were made by the mesh-shadow technique.

The thickness of a phosphor screen prepared from Derby Luminescents P-11 type A/259 phosphor . by the electrophoresis process can be reduced to 0.4 mg/cm^2 without any appreciable loss of efficiency and coverage as compared with a phosphor screen of 1 mg/cm^2 thickness of the same phosphor. The image resolution of such a screen should be very high and definitely it is more than 120 lp/mm. However its efficiency is low.

(D) Method of the Preparation of the Screens.

The method of screen preparation can also influence the image definition of the screen. If a particular method gives more tightly packed phosphor screens (electrophoresis compared with sedimentation process) then the layer thickness can be further reduced and hence image definition can be increased as described in Section II (C) of the present chapter.

The sedimentation method of phosphor screen preparation leaves binder layers in between the phosphor grains, the incident electrons can be scattered from such binder layers and hence a loss of image definition is likely to occur but contribution due to this factor is comparatively small as compared with the other factors influencing the resolution.

(E) Surface Texture

A small variation in the image definition may occur due to change in the surface texture (variations in thickness) of the phosphor screens. Sedimented phosphor screens of 1 mg/cm^2 thickness prepared from EMI type 214 phosphor were tested for image definition. The image resolution observed ranged from 50-60 lp/mm for aluminium backed screens. It suggests that the variations observed are due to the difference in the texture of the screens.

(F) Aluminium Backings.

The aluminium backings contribute towards the loss of resolution by scattering the incident electrons and by reflecting the light from the luminous grains which is scattered by the phosphor layer. The effect on image resolution has been considered in chapter IV section II-3.

III Effect of Backings on the efficiency and Resolution of the Phosphor Screens.

The methods of the application of the backings have been discussed in chapter III.

The relative efficiency of a phosphor screen is measured by the output light for the same input electron energy. Since the different backings change the amount of light in the forward direction, the relative efficiency of the phosphor screens is dependent on the reflectivity of the backings and hence on the technique of aluminization or application of the other backings.

An investigation was made to study the effect of backings on the efficiency and the resolution of the phosphor screens. The results of the experiments are discussed and typical examples are given. All the phosphor screen samples prepared were numbered, the first letter indicates the substrate (G for glass and M for mica) and the following number is the serial number of the phosphor screen.

The phosphor samples G-80 and G-85 were prepared under identical conditions in the same settling batch having a thickness of 1 mg/cm^2. The two samples were tested for relative efficiency. Then a conventional backing was applied to G-80 while a "floated" aluminium backing was applied to G-85. The two screens were baked at 350°C for one hour, and were then tested for relative efficiency.

Phosphor	Relative Efficiency		
Sample No.	unbacked	Conventional Backing	Floated backing
G-80	15	20	-
G-85	15	-	29.5

Similar results were obtained for the relative efficiency measurements of a number of phosphor screens with conventional and floated aluminium backings. It has been found that relative efficiency of a screen with floated aluminium backing is always higher than a screen with a conventional backing, keeping the other variables constant. The results of the experiments show 20-50% higher relative efficiency for the screens with floated aluminium backings than the screens with conventional aluminium backings.

The image definition (resolution) of the screens was measured by making single stage image tubes with the phosphor samples as the output phosphor. The results of the sample G-35, which consisted of four segments, will be considered. Two segments were single layer phosphor screens of 1 mg/cm^2 in thickness and the remaining two were double layer phosphor screens with the same thickness as the single layer ones. EMI type 214 phosphor was used and the screens were prepared by the sedimentation process. The screens were aluminized by conventional and floated backing techniques and the results are:-

Characteristic	Single layer		Double layer	
	Floated aluminium backing.	Conventional aluminium backing.	Floated aluminium backing.	Conventional aluminium backing.
Relative Efficiency	26.9	5.8	20.7	5.4
Resolution	46 lp/mm	60 lp/mm	40 lp/mm	55 lp/mm

The relative efficiency of the conventionally backed screens is so very low in this particular case that it must be considered as being due to the imperfect application of the conventional backings. The results are quoted only because they indicate two other results: (1) a higher resolution in the case of conventionally backed screens than for the floated aluminium backing ones and (2) a loss in the relative efficiency and the image resolution in the case of double layer screens as compared with the single layer screens. So from here onwards only single layer screens were prepared and tested for relative efficiency and image definition.

In order to find out something more about the effect of aluminium backings on the relative efficiency and image resolution of the screens an image tube was made with G-45 as the output phosphor. G-45 had six segments onto which a phosphor layer was sedimented at the same time, having a thickness of 1 mg/cm^2 and prepared from EMI type 214 phosphor. All the screen samples were aluminized differently but the thickness of the aluminium backings was kept to be approximately the same ($\sim$1000 A^o). Table 3 shows the results.

Table 3

	Backing	Rel. Eff.	Resolution
1.	Unbacked	12.8	100 lp/mm
2.	Conventional aluminium backing.	5.9	80
3.	Floated aluminium backing.	29.5	50

Table 3 (continued)

Backing	Rel. Eff.	Resolution
4. Aluminium oxide film (365 A^o) applied to the phosphor screen followed by the evaporation of the aluminium layer.	23.1	45
5. 1% transparent floated backing followed by the evaporation of aluminium.	28.2	60
6. Direct evaporation of aluminium onto a screen followed by a floated aluminium backing.	5	100

The results are quite informative and will be discussed in detail. The most probable explanation of the first three results is that in the case of an unbacked phosphor screen only half of the luminescent light passes through the phosphor layer and thus gives rise to a minimum spread of light (radius of the disc of confusion) as explained in chapter IV. Thus the resolution is the highest. In the case of the aluminized screens the other half of the luminescent light is reflected back from the aluminium backing and forced to pass through the phosphor layer. This increases the spread of light and hence the resolution of aluminized screens should be less than an unbacked screen.

In the case of a conventionally backed screen the aluminium layer closely follows the contours of the phosphor surfaces while a floated aluminium layer sits on the "hill-tops" in the surface of the phosphor layer. The light spread on the output side of the phosphor screen will be greater in the case of a screen with a floated backing than a screen with a conventional backing. As the light spread in the phosphor screen determines the diameter of the disc of confusion therefore it will be greater for a screen with a floated, than for one with a conventional backing. Hence the resolution of conventionally backed screen will be higher than the one with floated aluminium backing.

The above explanation is further supported by the results of the sample 5 in which a comparatively thinner aluminium film (1% transmission) was floated onto the phosphor screen. This might be expected to follow the contours of the phosphor screens more closely and so increase image resolution. This was found to be so. The relative efficiency is not much reduced as compared with that of a screen with an opaque floated aluminium backing. This technique offers a possibility of making phosphor screens with good relative efficiency and good image definition, however, the limits of this technique are investigated in a later experiment.

The application of an aluminium oxide film to a phosphor screen followed by an evaporation of aluminium film would be an alternative to a conventional backing if the image definition is not degraded. The results of sample 4 show that the relative efficiency in such a case was better than conventionally backed screen but not as good as a floated backing but the resolution was very much down (45 lp/mm). So this method of aluminization can not be very beneficial.

It seems that all self-supporting backings sit on the "hill-tops" in the surface of the phosphor screen and hence cause a loss of image resolution. An aluminium oxide film of 365 A^o thickness is a self-supporting film so the resolution is less with such a backing as compared with others.

In the case of sample 6 the resolution is as good as in the case of unbacked phosphor but such a technique of aluminisation can not be used for usable phosphor screens because the relative efficiency is very low.

The results of the above experiment suggest three ways of improving screen characteristics.

(i) To make the phosphor surface as smooth as possible, which was eventually done when the phosphor screens were prepared by electrophoretic process.

(ii) To apply semi-transparent floated backings on to the phosphor screen followed by aluminium evaporation to make the aluminium films opaque, this is the subject of the next experiment.

(iii) To improve the technique of applying a conventional backing to increase the relative efficiency, which at present is always 20% - 50% less than that of floated backings on the screens.

Phosphor screen G-104 was tested in an image tube for image definition. G-104 consisted of six segments on to which phosphor was deposited by sedimention. process in the same settling batch, the thickness of the phosphor was 1 mg/cm^2 and EMI type 214 phosphor was used for screen preparation. Aluminium films of different thickness were prepared and floated on to the phosphor samples. The thickness of the aluminium films was monitored by the proportion of light transmitted through the aluminium film and picked up by a selenium cell.

The results are shown in Table 4.

TABLE 4.

Sample No.	% transmission of aluminium film.	Thickness of the aluminium film.	Relative Efficiency	Resolution lp/mm.
1	37.5	80 A^0	14	70
2	24.0	100 A^0	19	67
3	16.5	110 A^0	22	64

TABLE 4 (continued)

Sample No	% transmission of aluminium film.	Thickness of the aluminium film.	Relative Efficiency	Resolution lp/mm.
4	9.4	140 A°	25.2	64
5	7.3	160 A°	26	61
6	3.1	225 A°	29	57

The results are shown in the graphs of figures V-10 and V-11. The two curves in graph of fig. V-11 correspond to two sets of phosphor screens out of which the above values pertain to one set while the other set consisted of phosphor samples G-70 to G-75 which were prepared under identical conditions by sedimentation process. Aluminium backins of various thickness were floated on to them.

It is clear from the above results that a slight improvement in resolution can be achieved by using partially transparent aluminium backings floated on to the phosphor screens but at the cost of relative efficiency.

For some applications of image tubes the use of anti-reflection backings was advocated in chapter III. The techniques of the applications of such backings have already been described in the same chapter.

The samples G-51 to G-53 were prepared under identical conditions by the sedimentation process, having a thickness of 1 mg/cm^2 and using EMI type 214 phosphor.
The results obtained were:-

Phosphor Screen	Rel. Efficiency	Type of backing
G-51	6.9	lamp black
G-52	7.4	unbacked
G-53	1.2	an "alcohol dag" layer

Thus the relative efficiency of the two is less than the efficiency of the unbacked phosphor screen and also the lamp black does not adhere very well to the phosphor screen.

Fig. V 10

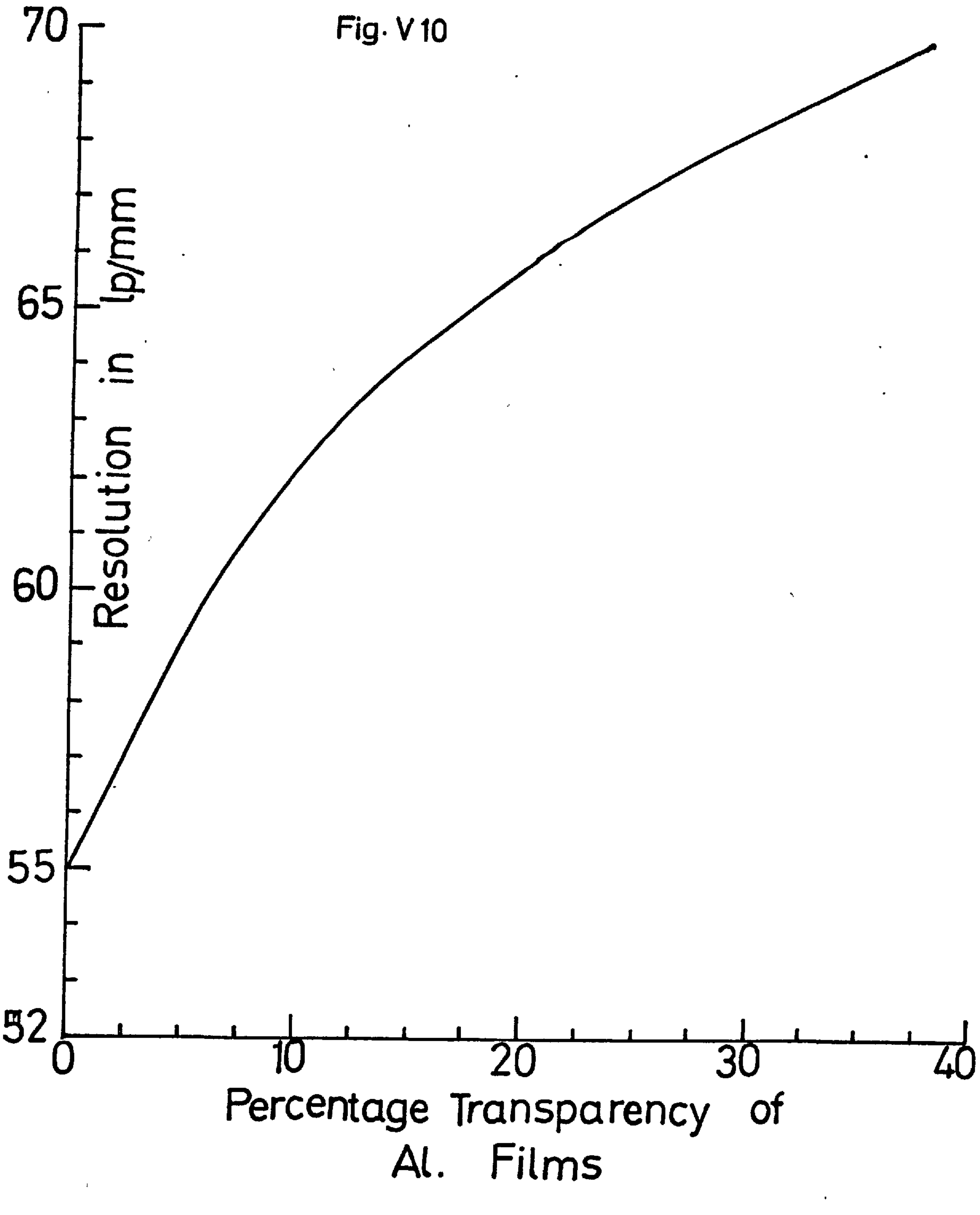
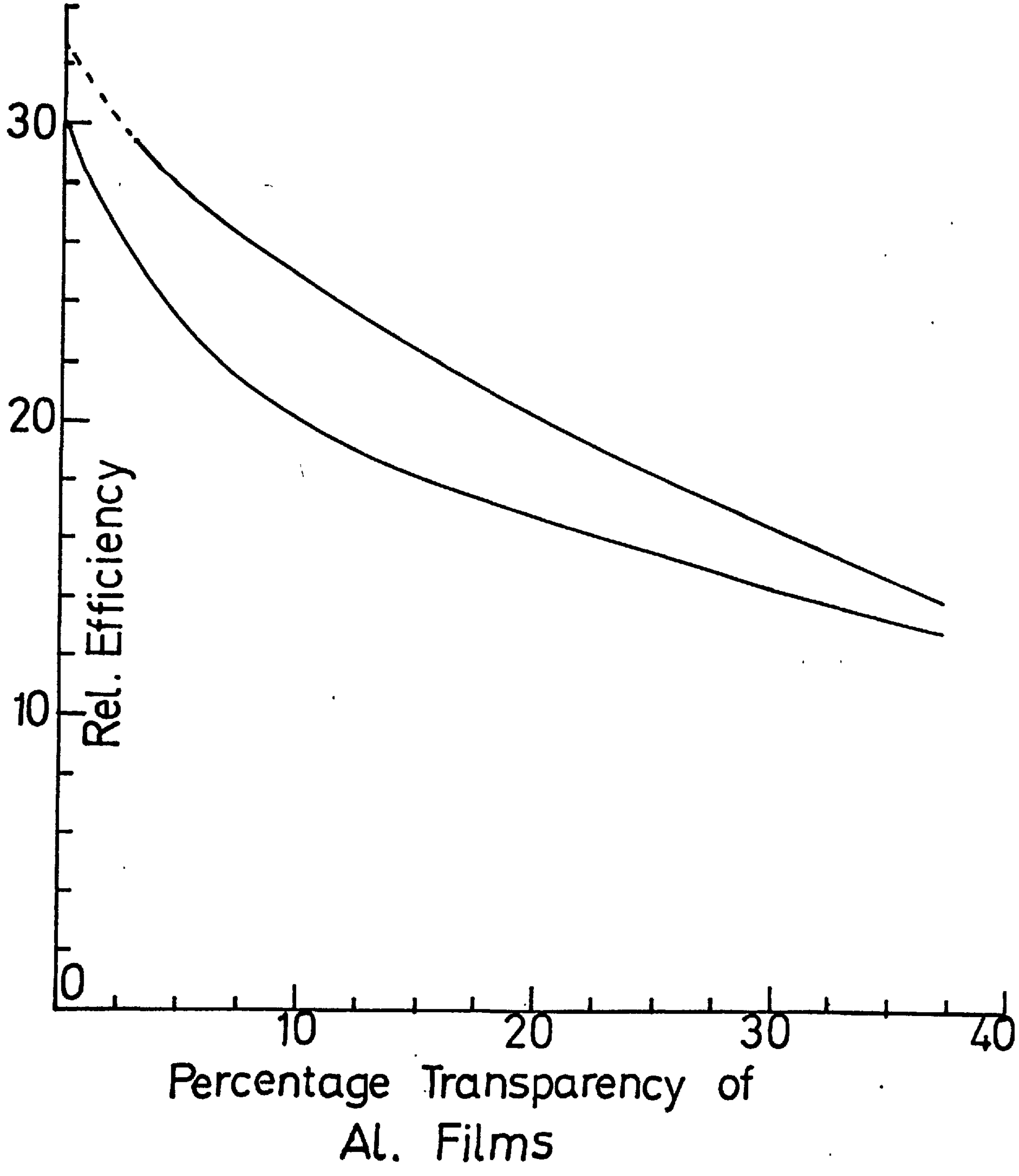

70
65
60
55
52
0
10
20
30
40
Resolution in lp/mm
Percentage Transparency of Al. Films

Fig. V 11


30
20
10
0
Rel. Efficiency
10
20
30
40
Percentage Transparency of
Al. Films

Some more phosphor screens were prepared by the sedimentation process and different backings were applied to them, the results are:-

Phosphor Screen No.	Rel. Efficiency	Type of Backing
G-61	13	An organic film was applied to a phosphor screen followed by evaporation of carbon and on to it an aluminium film was floated. The sample was baked at 350°C for ½ hour.
G-61	6.6	Aluminium black and floated aluminium backing.
	7.1	Aluminium black
	12.4	unbacked.

Experiments on Derby Luminescent type A/259 phosphor were also performed. The thickness of the screens was 1 mg/cm^2 and these were prepared by the electrophoretic process on to nesa coated glass plates. The results obtained were:-

Sample No.	Rel. Efficiency	Backing.
G-61	6	Unbacked
	2.1	Evaporated carbon backing.
G-62	5.0	Unbacked
	3.2	An organic film was applied to the phosphor screen followed by evaporation of aluminium black.
G-63	6	Unbacked
	5.9	Floated carbon film backing.

From the above results it is clear that the relative efficiency of a screen with floated or conventional carbon backing is about the same as that of the unbacked phosphor, while with the aluminium black backing the relative efficiency is lower than the unbacked screen.

The experiments were repeated with different backings. Some of the backing materials (aluminium, carbon, aluminium black) were evaporated on to cooled phosphor surfaces at a temperature ~ - 100°C in a vacuum chamber. The results are:-

Screen No.	Rel. Efficiency.	Backing
G-66	3.5	unbacked
	0.5	50% transparent directly evaporated carbon layer on to a cooled phosphor surface.
G-67	3.5	unbacked
	0.4	50% transparent carbon layer evaporated directly on to the phosphor surface at room temperature.
G-68	14	unbacked
	6.9	Directly evaporated aluminium backing on to phosphor surface at ~ -120°C
G-69	16	unbacked
	4	An organic film was applied to a phosphor screen. The screen was cooled to -120°C and aluminium black was evaporated on to it.
G-80	15	unbacked.
	20	Conventional aluminium backing. The backing was applied at room temperature.

	10	Conventional backing. Screen at low temperature at the time of the evaporation of aluminium.
G-81	15	unbacked
	9	Conventional aluminium black backing at room temperature.
	9.5	Conventional aluminium black backing when the screen was at -120°C
G-82	15	unbacked.
	9	Conventional carbon backing at room temperature.
	8.5	Conventional carbon evaporation at low temperature.
G-83	15	unbacked.
	2	Direct evaporation of aluminium black on to the screen at low temperature.
	4.5	Direct evaporation of aluminium black on to a screen at room temperature.
G-84	15	unbacked
	2	Direct evaporation of carbon. Screen at room temperature.
	1.5	Direct evaporation of carbon Screen at low temperature.
G-85	15	unbacked
	30	Floated aluminium backing.
G-79	12.5	unbacked.
	4.1	Direct evaporation of aluminium onto screen at low temperature.
	3.1	Direct evaporation of aluminium on to the screen at room temp.

It is quite conclusive that the relative efficiencies of the screens with anti-reflection backings applied directly to the phosphor are always less than the relative efficiency of an unbacked screen.

In the case of the phosphor screens with anti-reflection backings one would expect the resolution higher because there is no reflected light from the backing. Hence there will be no scattering of the reflected light and hence the resolution of such a screen should be equal to the resolution of an unbacked screen (chapter IV). To test this hypothesis a phosphor screen G-61, which consisted of four sedimented samples of 1 mg/cm^2 thickness and two electrophorized samples of the same thickness, was prepared. Different backings were applied to the specimens and the image resolution was tested in an image tube. The results are:-

Type of backing	Rel. Efficiency	Resolution (1p/mm)
A. EMI type 214 phosphor		
1. Conventional carbon backing followed by floated aluminium film for stabilizing the phosphor potential, and preserving the carbon layer during the screen bake at 350°C for $\frac{1}{2}$ hour.	13	40
2. Aluminium black followed by floated aluminium film for stabilizing phosphor potential.	6.6	86
3. Aluminium black.	7.1	100
4. Unbacked	12.4	100
B. Derby Luminescents A/259 phosphor.		
5. Evaporated carbon.	2.1	100
6. Unbacked.	6.0	100

Later on electrophorized phosphor screens were tested for the resolution by casting an electron shadow of a fine mesh as described in chapter IV. The resolution of electrophorized screens of a thickness of $\sim$ 0.7 mg/cm^2 of EMI type 214 or D.L. A/259 phosphor is $>$ 120 lp/mm irrespective of the type of aluminium backing.

IV The Screen Thickness.

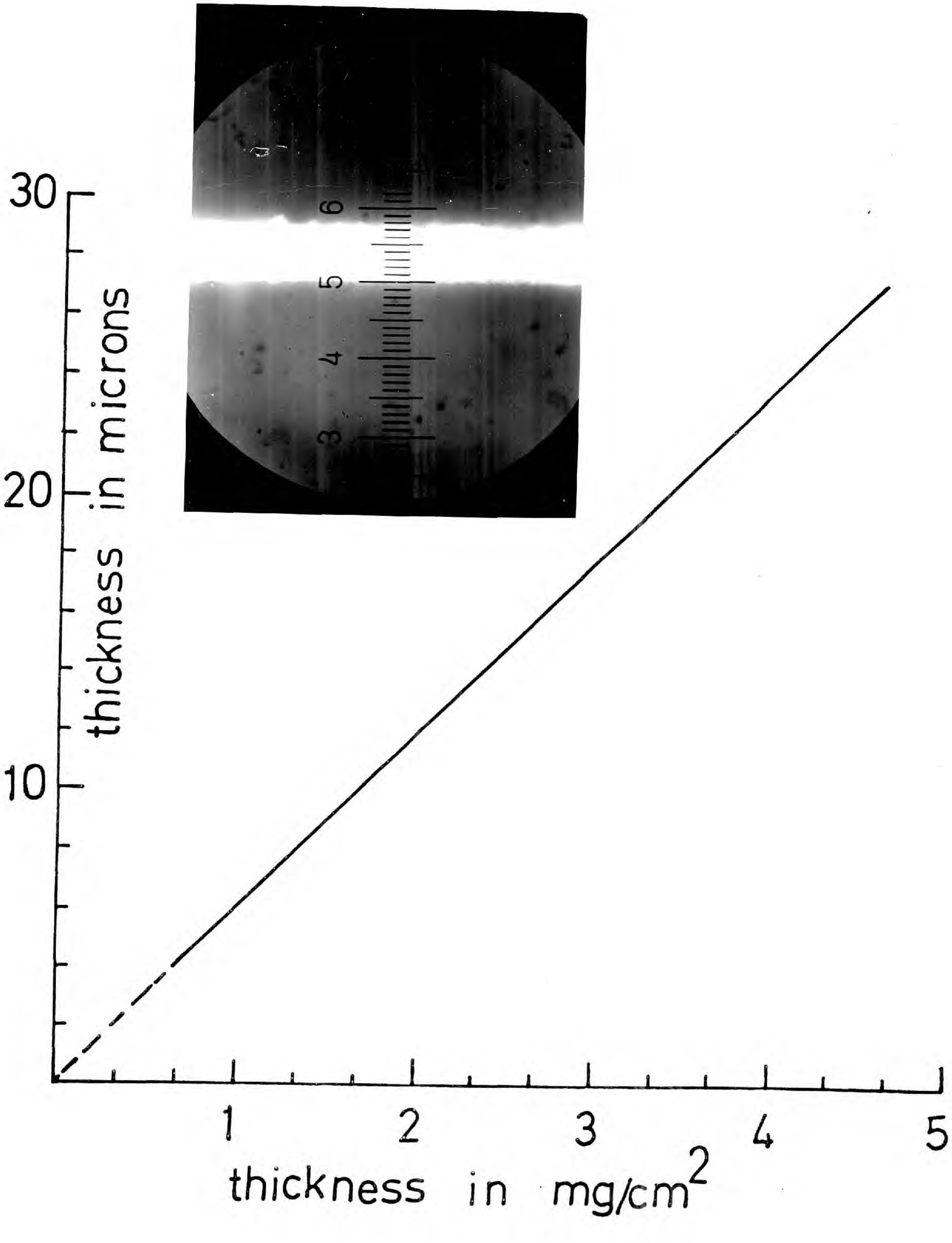
The screen thickness is generally measured in terms of mg/cm^2 but it would be quite interesting if the thickness in mg/cm^2 could be correlated with the average thickness of the phosphor layer in microns. To do this the following experiment was performed.

A number of glass plates were cleaned and then scratched across the middle with a sharp glass knife. The glass plates were cleaned again. EMI type 214 phosphor was electrophorized, as described in chapter II, on to the glass plates which were then broken into two parts by balancing the scratched line on a sharp wedge and gently pressing.

The broken edge of the glass plates was seen through a microscope of high magnification (600). The eyepiece had a calibrated scale on which the thickness of the phosphor layer was measured. At least 10 observations were taken for each specimen and the average thickness was calculated for each specimen. Fig. V-12A shows a graph relating the thickness of phosphor screen in mg/cm^2 and the average thickness of the phosphor layer in microns. Fig. V-12B shows a microphotograph of a phosphor layer as seen through a microscope.

Airey[144] measured the average thickness of the settled phosphor screens by embedding them in a resin and polished the resin after setting so that the phosphor layer was visible. Then viewing through a microscope as above he determined the thickness of the phosphor layers.

Fig. V 12



Phosphor	Thickness in mg/cm^2	Average thickness in microns
G. E	2	12
EMI type 214	1	8

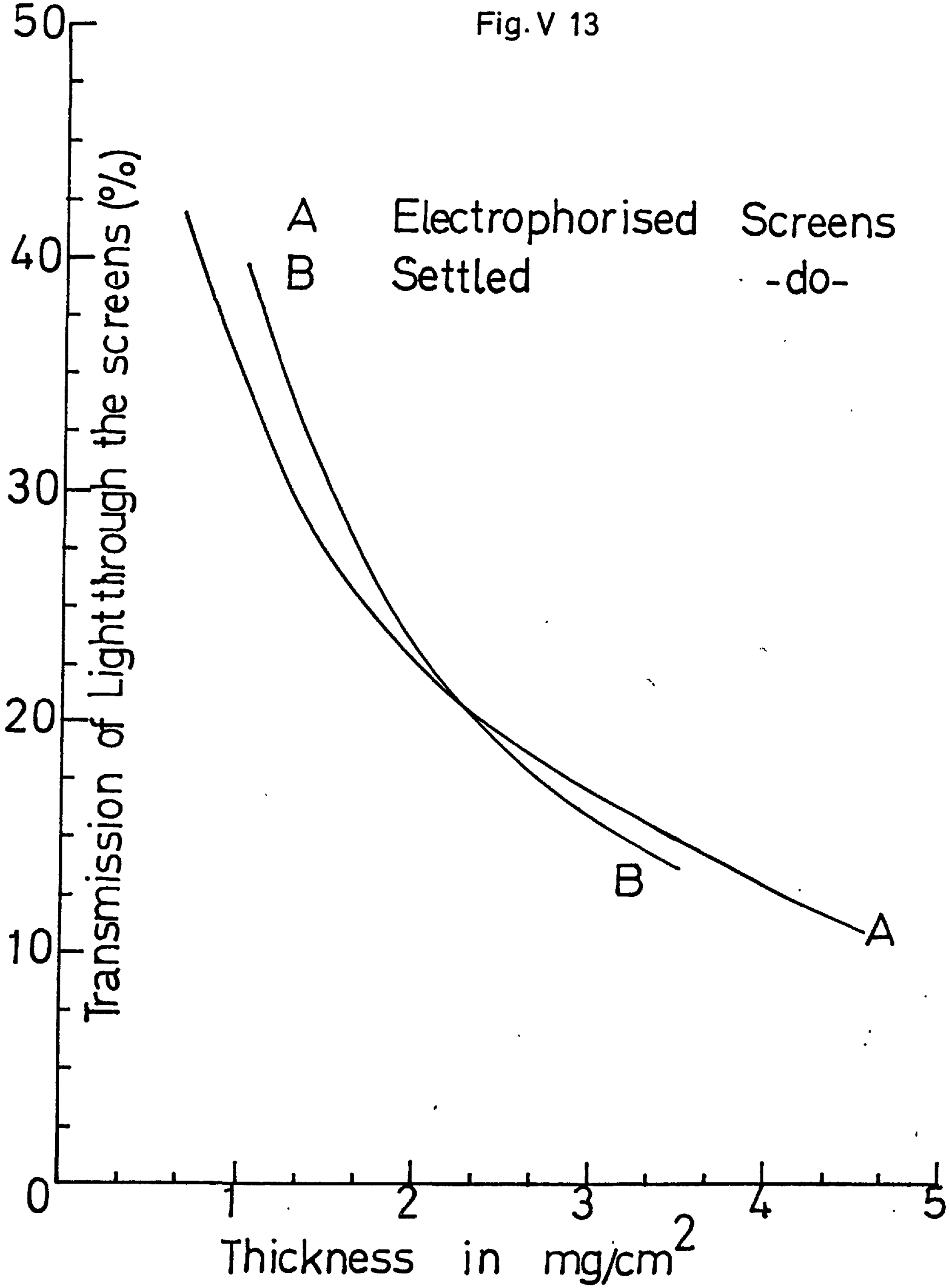
The thickness of the phosphor screens could also be measured in terms of the percentage of light transmitted through the phosphor screen from a standard light source. This calibration of the thickness will depend upon the method of the preparation of the phosphor screens and the phosphor used. Keeping these two variables constant a graph can be plotted between the thickness of the phosphor layer in mg/cm^2 and percentage transmission of light.

A standard white light source was used and the transmitted light through the phosphor layer was measured by a selenium cell and the results are shown for settled and electrophorized screens in Fig. V-13. This method could be used for estimating the thickness of a screen with a reasonable accuracy.

V. Coverage.

When a phosphor is deposited on to a substrate then in general the coverage of the surface is not complete due to the granular structure of the phosphor. The total uncovered area of a substrate will depend upon the grain size of the phosphor, thickness of the phosphor layer and the method of deposition of the phosphor layer. The percentage covered area of a substrate increases with a decrease in particle size for a given thickness (mg/cm^2) and for a fixed particle size and increases with the increase in mg/cm^2 of the phosphor layer. The covered area is also influenced by the deposition technique. For a given screen thickness in mg/cm^2 and a given particle size of a phosphor the coverage of the substrate is better for electrophorized

Fig. V 13


A Electrophorised Screens
B Settled -do-
Transmission of Light through the screens (%)
Thickness in mg/cm^2
0
10
20
30
40
50
1
2
3
4
5
A
B

than for settled screens.

In order to get quantitative information the total uncovered areas of the substrates were measured by the following method. A number of phosphor samples were prepared by sedimentation and electrophoretic processes from different phosphors. The sample under test was illuminated by transmitted light and was viewed through a miscroscope of a suitable magnification (150 or 600). When the microscope was focused on to phosphor surface then the uncovered areas appeared as pin-holes.

The eyepiece of the microscope contains a graticule which has a large rectangle marked in it. The large rectangle is subdivided into 9 rectangles of equal area. The area of any rectangle can be found by calibrating the length and breadth of the rectangle against a standard scale. For example, the areas of the large rectangle are:-

Magnification of the microscope.	Area of the large rectangle
150	0.1215 mm^2
600	0.006 mm^2

The graticule has also four circular dots of diameters 5, 2.5, 1 and 0.5 microns marked near the boundary of the large rectangle.

The number of pin-holes in a specimen was counted in a rectangle and the sizes of the holes were approximated to the sizes of circles on the graticule. At least three observations were taken in each case and in this way the total uncovered area of the substrate in the specimens was calculated.

The results confirm the above postulates about the coverage of the substrates by phosphors. The results of the screens used in image tubes are:-

Phosphor	Grain Size	Thickness of phosphor screen	Method of deposition	Uncovered area %
G.E	3-5 microns	2 mg/cm^2	Settling	2.3
"	"	2	Electrophoresis on. nesa coated plates.	1.2
EMI type 214	<2 microns	1	Settled	0.3
"	"	1	Electrophorized on a temporary metal coated glass plate.	0.1
"		0.7 mg/cm^2	"	0.3
Derby Luminescents type A/259	1 micron	0.4 mg/cm^2	"	0.3

Double layer phosphor screens were prepared, by sedimentation process, having a thickness of 1 mg/cm^2. EMI type 214 phosphor was used. Complete coverage of the substrate was achieved although such screens have lower relative efficiency and lower image resolution.

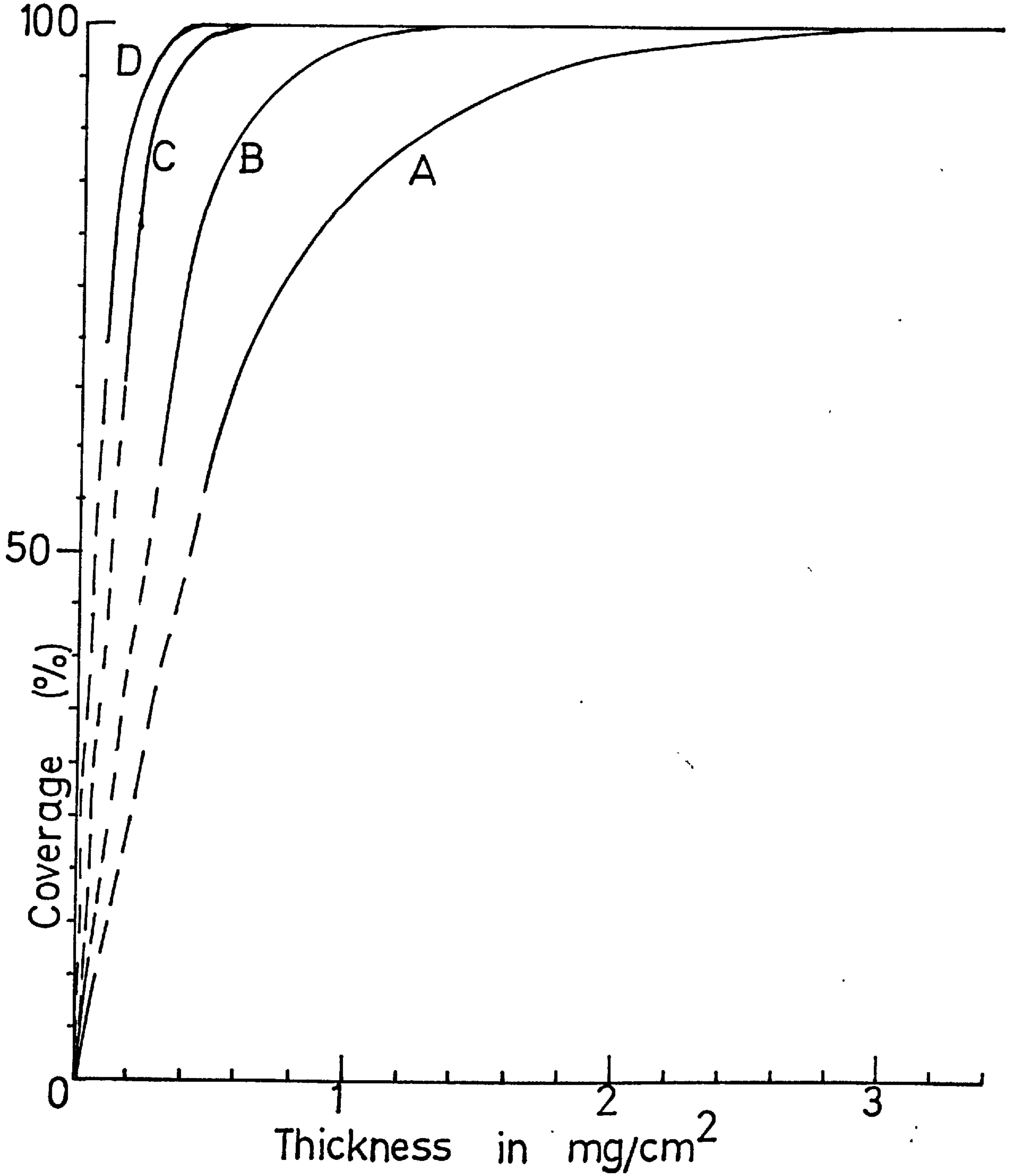
The % covered area is shown in Fig. V-14 for a number of phosphors and screens prepared from them.

VI Surface Texture.

When a phosphor screen is viewed through a microscope of high magnifying power, randomly scattered hills and dales can be seen. The hills correspond to lumps of phosphor grains which could not be separated during the preparation of the phosphor suspension or some of them may have been formed during the screen deposition process.

The surface texture of a phosphor screen depends upon the particle size of the phosphor and the method of deposition of the phosphor. The surface texture becomes better (more uniform) with the decrease in the particle size of the phosphor.

Fig. V 14



A more uniform surface texture was obtained by ball-milling the phosphor in a small amount of pot.silicate. It was found that ball-milling on a rotor machine for 15 minutes in about 20-30 c.c. of dilute potassium silicate solution was desirable. The ball-milling, in fact, helps in breaking the aggregates of phosphor particles. Ultrasonic agitation of the phosphor suspension also improves the surface texture of the phosphor screen. These two processes were used for settled screens.

The phosphor suspensions prepared for electrophoretic process are given ultrasonic agitation. The surface texture of the electrophorized screens is better than that of the settled screens. Four photomicrographs are shown in Fig.V-15. The details are:-

(a) G.E. phosphor	2 mg/cm^2	Sedimentation Process
(b) EMI type 214	1 mg/cm^2	"
(c) "	"	Electrophoretic process
(d) Derby Luminescents A/259 phosphor.	0.4 mg/cm^2	"

The surface texture of electrophorized screens is better than the settled ones showing its dependence on the method of the deposition of the phosphor. The uniformity of the surface texture improves as the particle size of the phosphor decreases as in the case of Fig. 15(d).

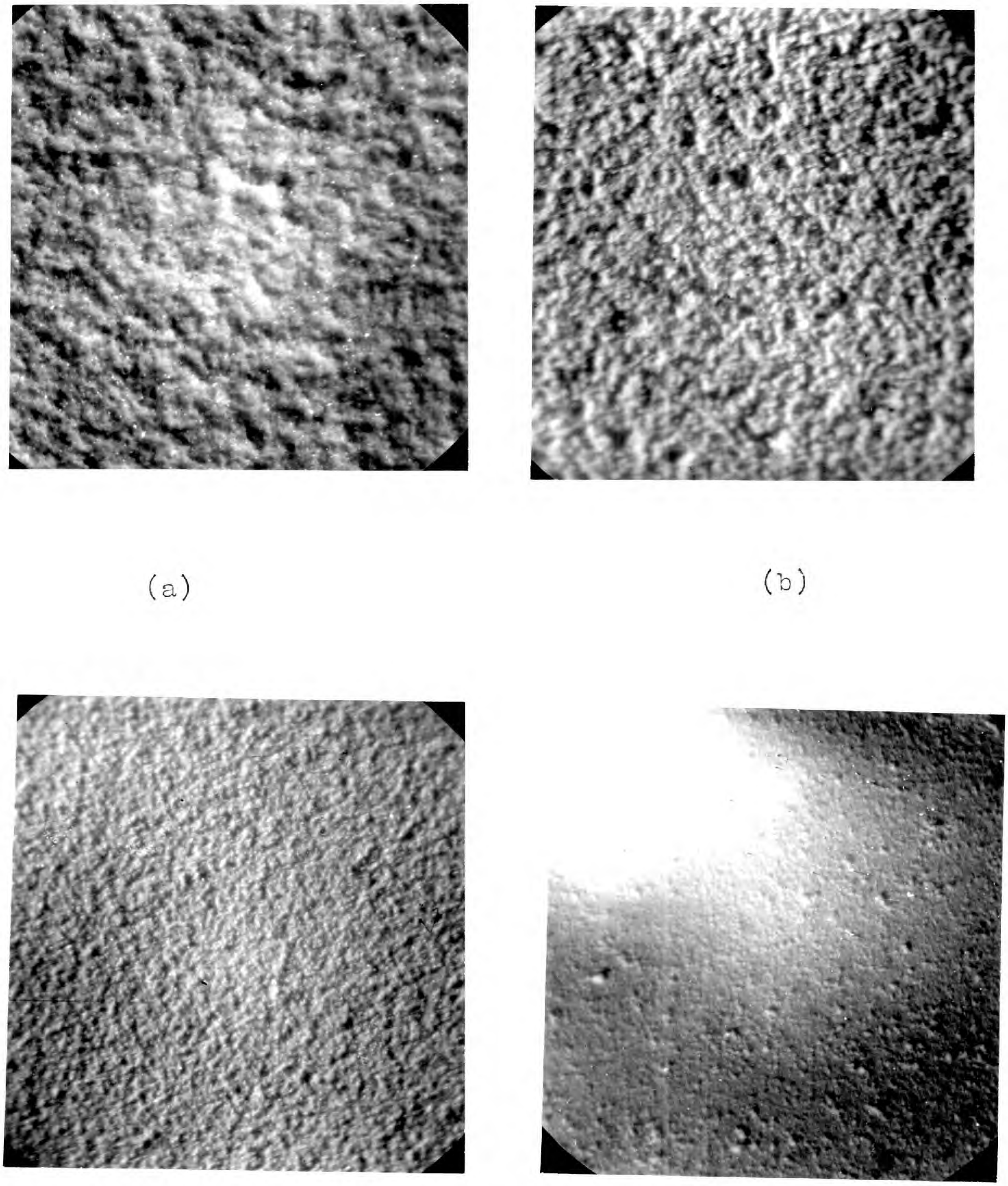
VII Other Characteristics

Noise.

One form of "noise" in the output image results from the non-uniformity of the surface or the "graininess" of the phosphor screen. Evidently with a more uniform surface texture the noise in the output light signal should decrease.

The noise due to "graininess" of the phosphor was not measured on a quantitative basis but when electrophorized

Fig. V-15



(a)

(b)

(c)

(d)

phosphor screens were used in an image tube, the quality of the image on the output screen was much superior to the image of the tube with settled screens, indicating the lower noise level in electrophorized screens or more uniformity of the phosphor surface.

VIII Effect of baking.

The aluminium backed phosphor screens are baked at 350°C in the image tube prior to the activation of the photocathodes in the image tube. It was desirable to find out whether the relative efficiency of a phosphor screen depends on baking temperature or not. It was invariably found that the relative efficiency is not affected by baking the ZnS phosphor screen up to 400°C in air.

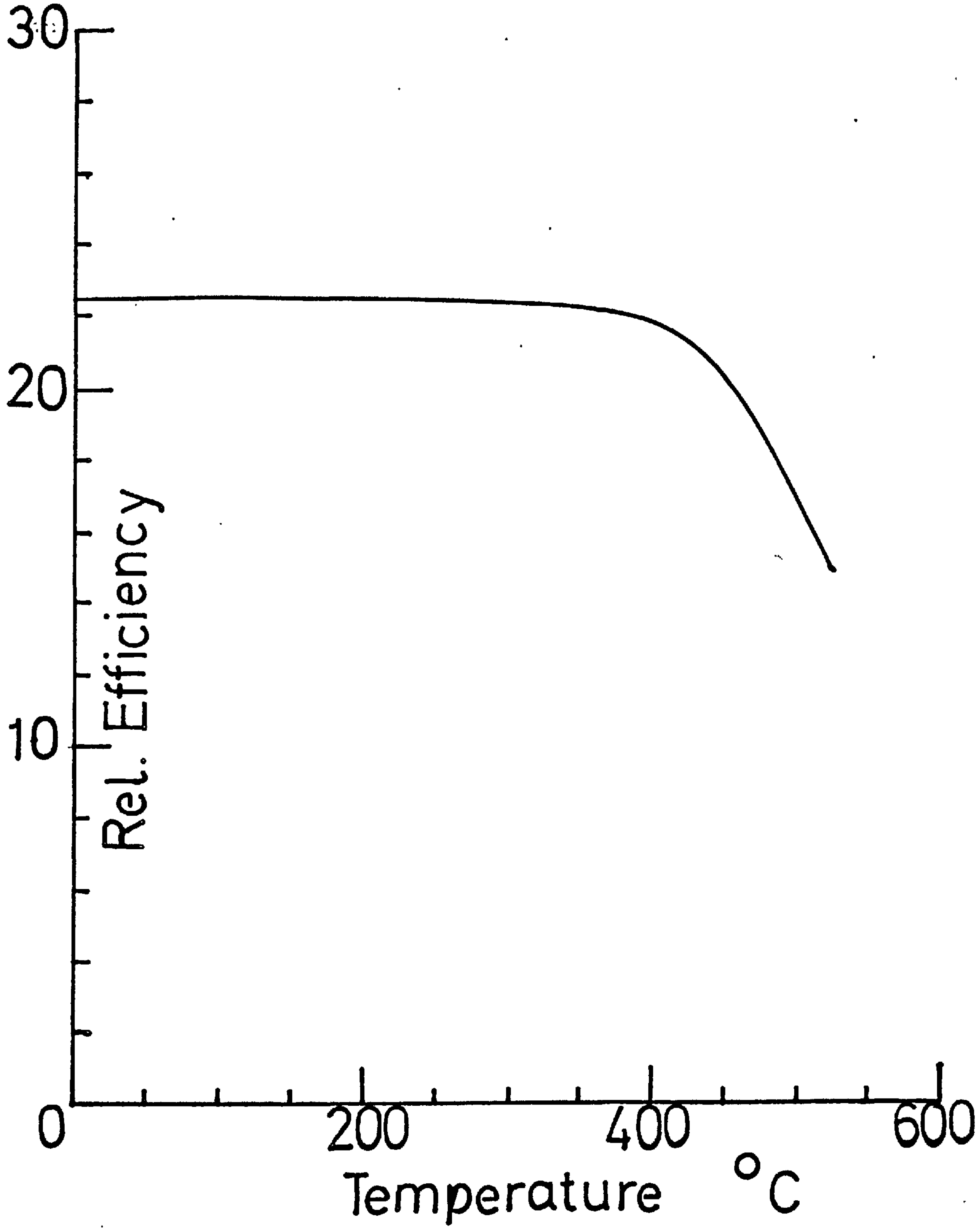
In an experiment a settled screen with an aluminium backing was baked at temperatures of 100, 200, 300, 350 and 400°C for one hour successively. The phosphor screen did not show any drop in relative efficiency. Then the screen was baked at 450°C for one hour, after which its relative efficiency was found to have dropped and the characteristic blue luminescence of ZnS:Ag had changed to bluish green colour. The screen was again baked at 520°C for one hour after which the fall in relative efficiency was much greater. The results are shown in Fig. V-16.

The change in the luminescence colour may be attributed to the redistribution of the impurity (activator) in the phosphor as reported by Korovkina[145].

IX Ageing of Phosphor Screens.

Experiments were performed to investigate the effect of ageing on phosphor screen efficiency. Some phosphor samples were prepared and aluminized. These were tested for relative efficiency and stored in a desiccator placed in the dark. The phosphor screens did not show any drop in relative

Fig. V 16



efficiency after 7 to 10 weeks. Hence it was concluded that if the phosphor screens are stored in a dry dark environment then the efficiency does not drop with age.

CHAPTER VI Manufacture of Image Tubes.

Two-stage, and three-stage cascade image intensifiers and single-stage image tubes have been made. Most of the constructional and processing details are common to all of them so a general treatment of the subject will be given.

I The glass Envelope.

A glass envelope with two flat end-windows, a couple of side arms and platinum tapes sealed into the glass wall to provide electrical connections from the inside to the outside[146] is prepared by the glass blowers. Initially such an envelope was pumped, baked, sealed off under vacuum and kept on the shelf for 4 weeks after which it was tested with Tesla coil and if no discharge was detected then the envelope was assumed to be free from leaks. Later on, in the work, a helium mass spectrometer was employed for leak detection. The envelope, if free from leaks, is cut open at the point where the final silver chloride seal is to be made after assembly and the cut ends are ground and polished flat.

In the completed tube each metal part is held in position by three metal springs which fit into slots ground in the wall of the tube. These slots extend about half way through the tube wall and are cut with a thin rotary diamond cutting wheel, after approximately marking the outside of the tube. The tube is mounted on to a lathe and the rotary diamond wheel is rigidly held on a support so that it can be moved sideways, backwards and forwards at will. A continuous flow of water is arranged to cool the glass and to wash off the ground glass from the slot.

The tube is now cleaned to prepare for metallizing rings. The envelope is scrubbed with a dilute Teepol solution, rinsed in water for 30 minutes to remove all traces of the detergent. Then it is given two or three rinses in double-distilled water and vapour degreased in isopropyl alcohol bath.

The next process in the preparation of the tube is the painting of the metal accelerating rings, these are painted on the inside wall of the tube using platinum metallizing paste type number T-177 made by Johnson-Mathey & co. The paste brush is firmly held on a support and the lathe is driven by an electric motor and in this way accelerating rings of uniform width can be painted, these rings cover the platinum tapes sealed into the walls of the tube. On the outer surface of the tube, in corresponding position, are painted rings of silver metallizing preparation type No. X-351. Liquid bright platinum is applied on the outside surface where the platinum tapes are sealed into the glass walls, and on the ground and polished ends of the tube where silver chloride is to be applied later, and platinum paint makes it run round the joint. The envelope is now heated to 600°C in an oven to fire platinum and silver paste into the glass surface. The tube is cooled and silver metallizing paste type Number X-353 is applied on the outside conducting rings in order to solder connections to the rings. The silver paste is dried and tube is again heated to 600°C, while it is cooling down then at about 460°C silver chloride is applied at the points where the platinum tapes emerge from the tube wall. This is a precautionary measure against leaks through the tape seals, which have been known to appear during firing and baking of the tubes.

The metal parts (as will be discussed in the next section) are all provided with four metal springs of which three hold the metal parts in position and the fourth makes contact with the platinum paste rings. If this particular tag is not properly positioned, it can cause field emission from the pointed end, so in some of the tubes slots were painted with platinum paste and the contact springs were removed from the metal parts.

The platinum paste rings inside the tube are buffed to remove any loose material and the electrical continuity to the outside is checked. The tube is rewashed and dried as described earlier. Aqua-dag is now painted on the silver chloride on the tape seals to protect it from deterioration due to the action of light. The glass envelope is then stored in dust free conditions until required for the assembly of the metal parts.

II Metal Parts.

The metal parts for cascade image tubes were made from stainless-steel base rings which are prepared and shaped (according to requirements) in the departmental workshop. These rings are rinsed in trichloroethelyne and vacuum stoved at 1000°C. After taking them out of the vacuum stove spring clips, stops, guides are spot-welded on to them. Completed metal parts are shown in Fig. I. The construction of the different metal parts will be discussed in detail.

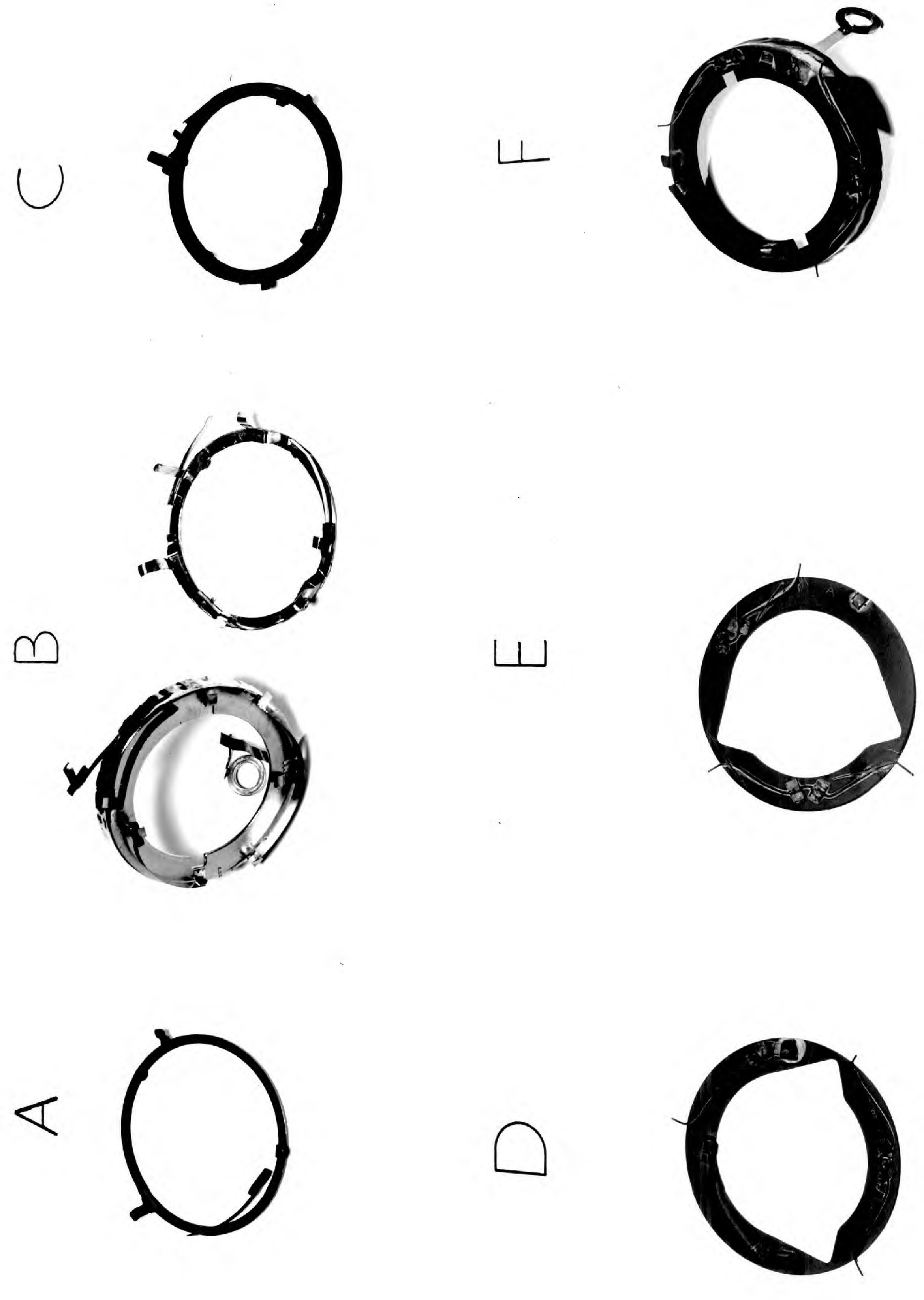
(A) Photocathode-plate holder (Fig. I-A)

The photocathode plate holder is made from an annular ring of 0.040" stainless-steel, which is held in place in the tube by three spring clips made from inconal strip. The photocathode plate is clipped into the operating position by the fixed holding clip and the moving clip which can be operated by a magnet from the outside. The photocathode plate is 47 mm in diameter and 1 mm in thickness made from lime-soda glass which is painted at the edges with bright platinum and fired. Pyrex glass plates of the same dimensions are now being used.

(B) Output Phosphor Holder.

This holder mechanism is the most complex part in the

Fig. VI-1



whole of the cascade tube. It is provided with three inconel springs to hold it in position and two movable clips each with a magnetic operating slug. One of these clips holds the end-phosphor in position and the second holds one cascade screen on top of the end-phosphor in the processing position. For a three stage cascade tube an extra fixed clip is mounted on to this metal part to help to hold the other cascade screen in the side flat. The end phosphor holder for a three stage tube has been shown in Fig. VI-IB and for a two stage tube in Fig. VI - IC.

(C) Processing Shelf.

The photocathode-shelf is an annular ring of 0.040" stainless steel of I.D.48 mm and O.D = 56.5 mm and it is held in position by three springs. A thin stainless steel skirt is spot-welded to the edge of the ring and it fits into a part of the tube which is collapsed on to a mandrel to form a short length of the tube which is accurately circular and of uniform internal diameter. The photocathode shelf has two diametrically opposite slots of 3 x 4 mm so that the effective diameter at this position is 46 mm which allows a cascade screen to pass through after processing. The photocathode plate is held in position by two fixed clips and one movable clip with a magnetic slug. Processing shelf is shown in Fig. VI-I B & F for three stage and two stage tubes respectively. The movable clip is arranged to prop up the photocathode plate during the pumping and baking of the tube, forming a passage so that the tube can be pumped with one pumping stem only. Just before admitting caesium to the processing chamber the movable clip is pulled back to allow the cathode plate to drop flat on to the shelf and in this way it forms a caesium-tight seal. For a three stage tube a spring strip is spot-welded to the reverse side of this shelf to hold the cascade screen in the side flat during processing. An aluminium-zirconium getter is also spot-welded on the reverse side of the photocathode shelf.

(D) Annuli (Fig. VI - I-E)

Annular stainless steel discs mounted perpendicular to the tube axis are held at suitable potentials to establish a uniform axial field and this type of electrode is also effective in suppressing background. These discs are, 0.020" thick, having an I.D 40 mm and O.D 56.5 mm. The annuli are shaped in such a way that at one point the I.D extends to 48 mm which allows the passage of the photocathode plate and mica cascade screens after processing. The annuli are held in position by two fixed lugs of inconel strip and one sprung lug, engaging in the slots in the tube wall. The annuli cannot be dislodged by a reasonable vibration or tapping of the tube which is necessary when the cascade screens and photocathode plates are being transferred from the processing section to their operating places in the tube.

(E) Cascade Screen Holder. (Fig. VI -I D)

The movable cascade screens are mounted in operation on holders which are similar to an annulus (Fig.ID) in shape and are provided with two fixed lugs and one movable spring lug to hold them in position in the tube. Each is provided with three fixed stops and one movable clip on its inner circumference with which to lock the cascade screen in its operating position.

All the metal parts are immersed in trichloroethylene after spot-welding the clips, etc., on to them to remove any traces of finger grease, although care is taken not to handle them during the process of fixing of clips. The metal parts can now be vacuum stoved at 600°C and fitted into their respective places in the tube such that the sides having clips etc. are facing the photocathode end of the tube. This enables the side facing the anode end of the tube to be free from sharp points from which, being the negative electrode, field emission is likely to occur.

In later tubes the metal parts were further cleaned by electropolishing after spot-welding all the clips etc. This electropolishing process also removes any sharp points or edges. The electropolishing bath consists of a mixture of 45% glycerol, 45% orthophosphoric acid and 10% analar water by volume[147]. The metal part to be cleaned is made the anode in the bath and a current of 5 A is passed through the solution for 10 minutes. After polishing the metal parts are rinsed in running hot water for 30 minutes and then placed in a 20% solution of hydrochloric acid for a few minutes to remove all traces of the polishing bath. The acid bath is followed by a rinse in cold running water for ten minutes, then two rinses in double-distilled water and they are dried in an I.P.A bath. The metal parts are then vacuum-stoved at 600°C (the highest temperature at which the springs do not lose their temper) prior to the assembly of the tube.

The inconel lugs and tags on the metal parts when in position in the tube are strong enough to stand a reasonable tapping of the tube but it was considered desirable for more rigid mounting system to be evolved. So tungsten wire springs were fixed on to the metal parts by means of spot-welding inconel strips on to metal parts to hold the springs, which in turn held the metal part in position in the tube. Such springs have been shown in Fig. VI-I. When such metal parts were blackened by black chromium plating process and vacuum stoved at 600°C, the tungsten springs became brittle, so the use of tungsten wire was discontinued and Nimonic 90 wire springs were used instead which do not become brittle after blackening and vacuum stoving at 600°C.

On all the metal parts contact springs are attached to make contact with the metallized ring on the tube wall. If the end of such a contact spring is very sharp then it may be a source of field emission. The contact spring was eliminated by printing the slots with platinum paste as described earlier and in this way the Nimonic springs which hold the metal part in position in the tube also provide electrical contact between the metal part and metal electrode painted on the wall of the tube.

(B) Blackening of the metal parts.

Some part of the incident light is transmitted through the semitransparent photocathodes of an image tube. The transmitted light can be reflected from the electropolished metal parts and the aluminium backing of the next cascade screen and may reach the photocathode thus producing signal induced background. The reflection of transmitted light can be minimized by blackening the metal parts and by blackening the aluminized screen.

As the metal parts are to be blackened after spot welding clips, springs, etc on to them so the blackening process should be such that the metal parts are not to be heated above 600°C, clearly this condition eliminates the possibility of blackening stainless steel by heating to 900°C in an atmosphere of oxygen[148,149]. A number of experiments were performed for blackening the electrodes and following results were obtained.

1. Carbon was evaporated on to stainless steel parts and on vacuum stoving at 600°C it was found that the carbon film became shiny and patchy, so this method did not seem to be very promising.

2. Aquadag mixed with pot. silicate was painted on to some metal parts and heated to 600°C in an oven, after cooling it was found that the aquadag could be scrapped off very easily. Vacuum stoving after drying the painted part yielded similar results.

3. A layer of aluminium black[150] was evaporated on to a stainless steel metal part and the metal part was vacuum-stoved at 600°C. It was found that aluminium black soot turned into a white powder which could easily be rubbed off the surface but it gave a blue colouration to the stainless steel part.

A survey of literature offered a number of possibilities which were tried in succession:-

4. Electropolished stainless steel parts could be blackened by soaking them into molten potassium dichromate for 15-20 minutes[151]. The blackened part is washed in hot water for 10-15 minutes and dried and any loose matter is rubbed off. This process makes the electropolished metal part dark brown in colour and the white-light reflectivity falls to 25% as compared with an electropolished part. The metal parts blackened by this process were used in the cascade tubes, but still nearly completely non-reflective metal parts were desirable.

5. Black chromium plating was also considered[152]. The metal parts were first electropolished. The black chromium plating process is a two step process: a thin dull chromium layer is plated in a normal chromium[153,154] bath and rinsed well in distilled water. This plating is followed by plating in a black chrome bath[154,155] where a finely dispersed dark brown or black coating of pure chromium may be obtained. The metal parts are washed and dried. This type of coating is found to adhere to the metal parts. The process described in ref.152 was carried out but no black deposit was obtained,

so this process had to be abandoned.

A slight modification of the black chromium plating bath gave excellent results, and it was also found that the initial layer of bright chromium was not necessary. The standard procedure is to electropolish metal parts to remove all sharp points and then apply black chromium by making the metal part the cathode in an electrolytic cell containing:-

Chromic acid (Cr_2O_3)	330 gms	per litre of water.
Acetic acid	5 c.c.	
Barium carbonate	4 gms.	

The anode is lead containing antimony. A current of 1 A/cm^2 is required for a good black coating. Better results are obtained if the temperature of the bath does not go above 25°C. The metal parts are washed and dried after blackening.

Such metal parts were vacuum stoved at 600°C after black chromium plating, it was found that the tungsten springs on the metal parts became brittle and the black chromium deposit was not mat-black but rather shiny. So further investigation was made for an effective blackening process.

6. In the next process tried the metal parts are etched in a solution[156] consisting of

Sulphuric acid	42.5%
Distilled water	57.5%

The metal part to be etched is made the anode and a lead cathode is immersed in the etching solution and current of 50 A/ft^2 is passed for 2 or 3 minutes.

After etching the metal parts they are washed in running water for 15 minutes and then rinsed in 20% hydrochloric acid followed by a thorough rinse in water.

The stainless steel metal parts are now nickel plated in a solution[157] of

Nickel chloride	240 gms.
Hydrochloric acid (Conc)	132 c.c.

Water is added to make one litre of the solution. The metal part to be plated is made the cathode and with a nickel anode a current of 150-200 A/ft^2 at 6 volts is passed through the solution for 2-3 minutes. The metal parts are now washed in running water and they are not allowed to dry before black-plating. The black-plating solution consists of[158] :-

Chromic acid (Cr_2O_3)	200 gms/l
Ammonium meta-vanadate	20 "
Acetic acid	6.5 ml/l.

The metal part to be coated is made the cathode and the anode is lead or graphite. A current of 1 . A /cm^2 at 12-15 volts is passed through the solution for about 5 minutes followed by a thorough rinse in water. The temperature of the blackening bath should be from 35-50°C.

This process gives mat-black adherent layers on the metal parts, which are at present being used in the cascade image intensifiers.

III Phosphor Screens.

Phosphor screens were prepared as described in chapter II and III. Fig. VI-2E and F show a cascade and output screen respectively.

IV Antimony Evaporator and Caesium Ampoules.

Sources of antimony and caesium are needed for the formation of photocathodes.

(A) Antimony Evaporator.

The antimony metal source takes the form of a bead that can be evaporated to deposit uniform layers of antimony on the photocathode substrates. The evaporator strip is of tantalum metal sheet 1 mm. wide and 0.002/3" thick with 1 mm. diameter circle of nickel sheet spot-welded to it, this is necessary because antimony wets nickel but not the tantalum, so a bead of antimony on the circular nickel disc forms approximately a point source. The tantalum strip is surrounded by a nickel shield, to restrict the direction of evaporation of antimony, and can be heated by current picked up in a coil by high frequency induction heater.

The wide angle of evaporation imposed by the geometry of the tube would give a non-uniform antimony layer on the surfaces on which cathodes are to be formed if evaporated from a point source, as the evaporated layer covers a surface 4 cms. in diameter only 2.5 cms from the evaporating source. The tantalum strip is located 2.5 mm inside the nickel shield, which has a 4 mm diameter aperture. A 2.5 mm diameter disc of a fine nickel mesh, with a shadow ratio of about 50% is fixed in the centre of this aperture by sandwiching it between two layers of a coarse tungsten mesh of low shadow ratio. The nickel mesh obstructs the evaporation at angles near the perpendicular, thus reducing the variation in the thickness of evaporated antimony layer. This nickel mesh is mounted on a flap so that it can easily be moved aside to allow the evaporator to be loaded. This is done, after thoroughly degasing the evaporator, by putting a suitable piece of antimony on tantalum strip and heating it in argon so that the antimony wets on to the nickel.

A tungsten wire filament is incorporated in the electrical circuit of the evaporator. The thickness of this filament is arranged so that it glows during evaporation to provide an indication of the amount of current passing through the tantalum strip.

While evaporating the antimony layer on to the photocathode substrate the thickness of antimony layer is monitored by noting the absorption of transmitted light through the layer in the case of the primary photocathode (glass substrate) and by noting the increase in the amount of reflected light from the mica substrate in the processing chamber of a cascade image tube. This method of evaporating antimony could yield antimony layers of unequal thicknesses on the substrates and would also need separate adjustments for monitoring the thickness of antimony layer on to the different substrates. The author suggested a possible way in which the same amount of antimony could be evaporated on to all the substrates at the same time. If the nickel shield in the evaporator described above is provided with two or three apertures of 4 mm size facing the substrates in the tube and the antimony bead is fused on to a platinum coated molybdenum wire and the position of the evaporator is arranged so that the antimony bead is equidistant from all the substrates, then at least in theory, equal amounts of antimony should go to all the substrates. For close distance evaporation nickel mesh fixtures could be used as in the case of the previous evaporator. Such a type of evaporator could also be used for building up the photocathodes in layers of antimony - Cs - Sb - Cs which has been found necessary for processing multialkali photocathodes.

In order to test the above idea an antimony bead was wetted on to an 0.008" platinum coated molybdenum wire and the shield was made out of stainless steel having two holes of diameter 4 mm. accurately lined with each other. The antimony evaporator was designed to slide on a railing for the final adjustment of its position and to provide electrical contact for evaporation of antimony as electric current was used to heat the filament. In the first experiment one of the nickel meshes was blocked so no conclusions could be drawn, however, the experiment is being repeated.

(B) Caesium Ampoule

The caesium metal is contained in a glass ampoule with a thin glass tail which can be broken off by a magnetically operated hammer. As caesium metal reacts with air, the metal must be generated from one of its salts, under vacuum. The ampoules are prepared by sealing a caesium generator and a suitable number of the empty ampoules on to a vacuum system. The caesium generator is a nickel capsule containing caesium chromate, aluminium powder and tungsten powder in the proportions 1:1:8 by weight or caesium chromate and silicon (1:2), about one gram of the mixture is allowed for each ampoule. After evacuation, the caesium is generated by eddy current heating the nickel capsule. The caesium salt reacts with aluminium or silicon to liberate caesium and the tungsten powder acts as a moderator. The caesium is distilled into the ampoules, which are then sealed off and stored until they are ready for use.

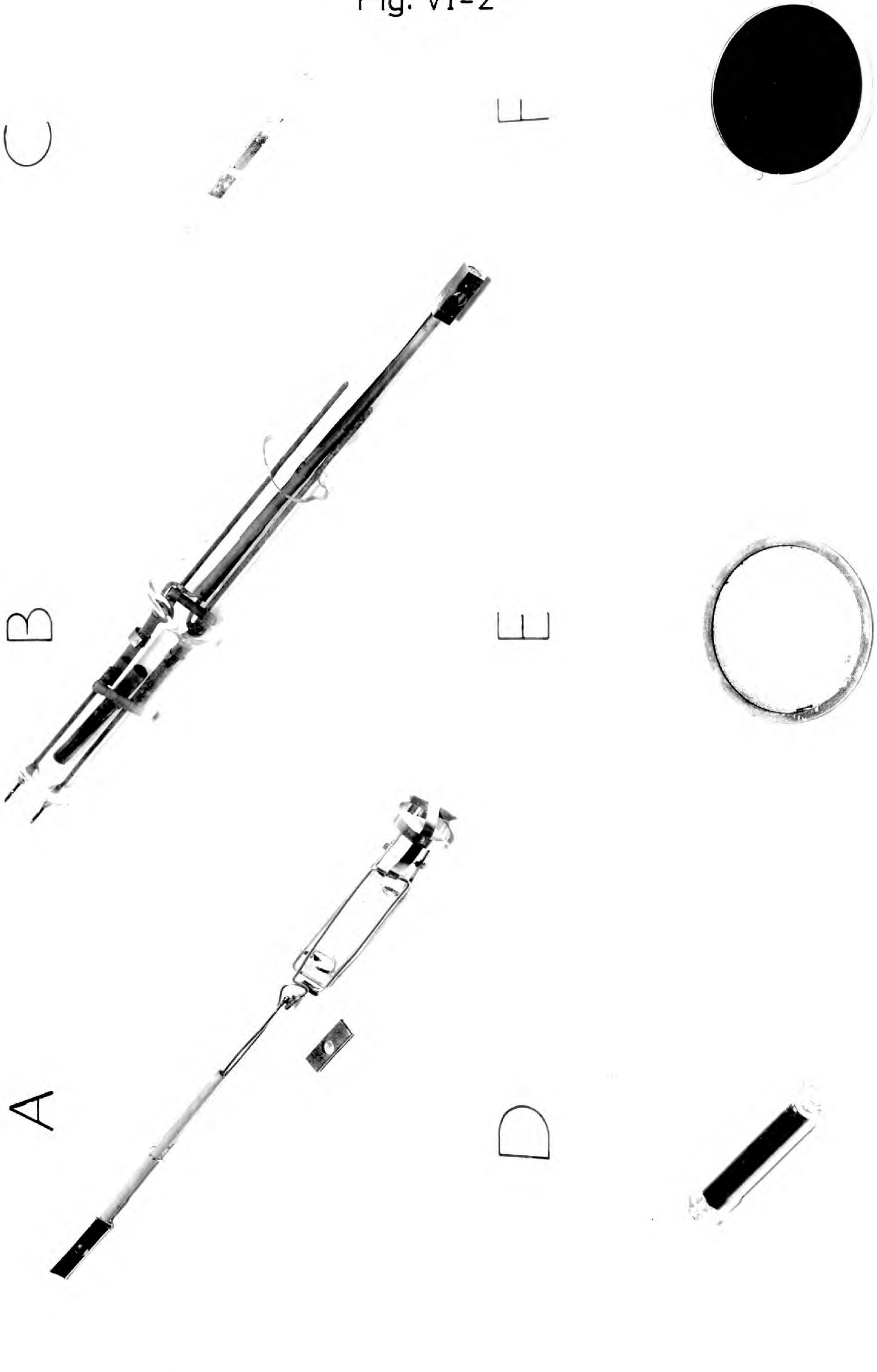
Fig. VI-2 shows:-

A. Antimony Evaporator.
B. " " (under experiment)
C. Caesium Ampoule.
D. Hammer.
E. Cascade screen.
F. Output phosphor screen.

V Assembling the Tube.

The two parts of an envelope (as described in Section I) are taken and the metal parts are fixed into their appropriate positions. In the processing chamber the end-phosphor holder is fixed in position against the end-plate of the tube, it holds the output phosphor facing downwards

Fig. VI-2



and a cascade screen on top of the output phosphor in the processing position. In a three stage image tube the second cascade screen is fixed in the flat in the wall of the tube such that the phosphor side is facing the glass wall. The photocathode plate is fixed into its position on the photocathode shelf leaving a small gap through which the whole tube is pumped by one stem. Electrical continuity between the inside and outside rings is checked and the catch mechanisms are tested with dummy parts.

Now the two parts of the envelope are sealed together with a silver-chloride seal at the point where the parts have flat polished ends.

VI Evacuation and Processing.

The image tube envelope is sealed on to the pump and the side arms are sealed on to it. The Cs side arm contains a caesium ampoule and a hammer. The tube envelope is pumped very slowly through a fine leak at the beginning so that the aluminium backing is not pulled away from the phosphor due to the quick pumping of trapped air in between the phosphor and the aluminium backing. After about 15 minutes the full pumping speed is achieved by opening the main channel (stop-cock) to the backing pump. The glass envelope is tested for leaks with a Tesla coil, and if no leak is detected then carbon tetrachloride is sprayed on the tube and if there is any leak then the Tesla discharge will assume greenish colour, if there are no leaks then the colour of the Tesla discharge will not change.

If no leaks are detected in the system then the tube is given a short bake at 150^{0} - $200^{0}C$ for one hour to drive off the water vapour in the system. The tube is cooled and tested for leaks again. If there are no leaks then the tube is baked. It is desirable to bake the tube under vacuum at as high a temperature as possible, as the outgassing rate increases with temperature. The limit is set by the temperature at which silver-chloride begins to soften and to allow a safety margin the tube is baked at 380°C. The side arms can not be baked to this temperature, however, as the caesium would react with the glass of the ampoule and the antimony would tend to evaporate off the evaporator, Hence, for the vacuum bake the intensifier is wrapped in electrical heating tape. The tube and side arms are surrounded by an oven. The oven is heated to 250°C and the body of the tube at about 370° - 380°C by the increased local heating of the heater tape. The temperature of the tube body is maintained constant during baking by a thermostat, and the oven temperature is regulated by feeding the heating elements through a variable transformer. The temperature is raised slowly so that the pressure does not rise above 5×10^{-5} mm.Hg because it has been found to give better results. The tube is generally baked overnight ($\sim$16 hours).

The tube is cooled next day and generally the pressure is good indication whether the tube is leak-tight or not. When hot the pressure ranges from 10^{-6} to $(4-9) \times 10^{-7}$mm Hg after the first night bake and when cold the pressure falls to $1-2 \times 10^{-7}$ mm.Hg. When the tube is cold then aquadag is applied to the silverchloride layers covering the platinum tape seals and also to the silver chloride seal made to join the two parts of the envelope. This is to exclude light which can destroy the AgCl and hence the efficiency of the seal. The getter attached to the photocathode shelf is degassed by means of an eddy-current heater keeping the getter at dull red heat until the pressure does not rise above 10^{-6} mm.Hg.

The tube is "spot-knocked" now by earthing one ring on the tube and applying Tesla coil to the next one, this process knocks off any sharp loose material from the rings and thus minimizes any potential source of field emission. The getter is again degassed and the tube is again baked at 380°C tape temperature and 250°C oven temperature overnight (~ 16 hours).

After this bake the pressure generally falls to (2-4) x 10^{-7} mm.Hg when the tube is hot and as it is cooled the pressure falls to 6-8 x 10^{-8} mm.Hg. After cooling the tube Gevac[159] (a vacuum sealing liquid) is applied to the platinum tape seals and to the silver chloride seal as a precautionary measure against a very minute leak. Gevac is cured by baking the tube at 200°C for one hour, a shorter bake at 250°C would also cure it. The tube is cooled down and the getter is degassed.

The photocathode plate is dropped by operating the magnetic catch to seal off effectively the two compartments from each other and thus form a caesium tight seal between the processing chamber and the main body of the tube. Now the caesium ampoule is broken with the hammer and caesium is driven along the side arm by gentle heating. The part of the side arm containing broken ampoule and the hammer is sealed off.

Some of the caesium is driven into the processing chamber and the chamber is heated to 160 - 175°C for ½ an hour so that the caesium is pumped away. This process the so called "precaesiation" has been found to give better photocathodes and presumably caesium reacts with any contaminants on the photocathode surfaces and thus renders them less harmful to the photocathode surfaces eventually made on to them. The processing compartment is cooled down to room temperature and left for about 15 minutes to allow the inside of the tube to assume room temperature.

The antimony evaporator is tested in the side arm and then magnetically pulled into position for evaporation on to the photocathode surfaces. The layer of antimony on the photocathode plate is monitored by transmitted light and is such as to absorb 20% of the light passing through it measured by tungsten light and a photovaltaic cell. The antimony layers on the cascade screen are monitored by reflected light. The antimony is evaporated until an increase of 20% in the amount of reflected light is obtained, the light being incident on the surface of the layer at an angle of 45°. Catchpole[43] claims that this layer corresponds to a layer absorbing 20% of transmitted light. The antimony thickness and photosensitivity was monitored by a monitor assembled by G.E. Busby and the monitor is described in Appendix I.

An electrical contact is made to the processing shelf, and then the processing compartment of the tube is wrapped with heating tape to form an oven for processing the photocathode. The caesium side arm is fitted with a nichrome wire heating coil, and well lagged. The antimony evaporator is used as a processing anode, connection to it being made via a platinum tape sealed through the wall of the side arm. Later on in the work a glass oven designed by R.W. Airey was used for processing the tubes. The photosensitivity of only the primary photocathode was monitored during processing but the sensitivity of the remaining photocathodes should be similar to the primary photocathode.

To start the activation of the photocathodes, the temperature of the processing chamber is raised to 165-170°C and maintained constant by a thermostat; after 15 minutes at this temperature, the caesium side arm is slowly heated and caesium vapour begins to diffuse into the tube. The temperature of the side arm is increased until maximum photosensitivity is achieved and the caesium vapour is stopped when photosensitivity begins to fall. The processing chamber is cooled down to 150°C and the above process is repeated, the same process is again repeated at 130°C and now the processing chamber is cooled to room temperature. The addition of caesium at three different temperatures ensures that the antimony layers are thoroughly saturated with caesium.

Now the caesium side arm is sealed off, the antimony evaporator is pulled back and antimony side arm is collapsed to make a constriction near the tube body. The getter is heated to dull-red for a few seconds and tube is pumped for another 10 minutes before final seal off at the constriction made in the antimony side arm. The photocathode plate and cascade screens are transferred in turn to their working positions. The photosensitivity is checked and the tube is mounted in a Perspex cradle for testing. Fig. VI-3 shows a three-stage and two-stage tubes ready for mounting.

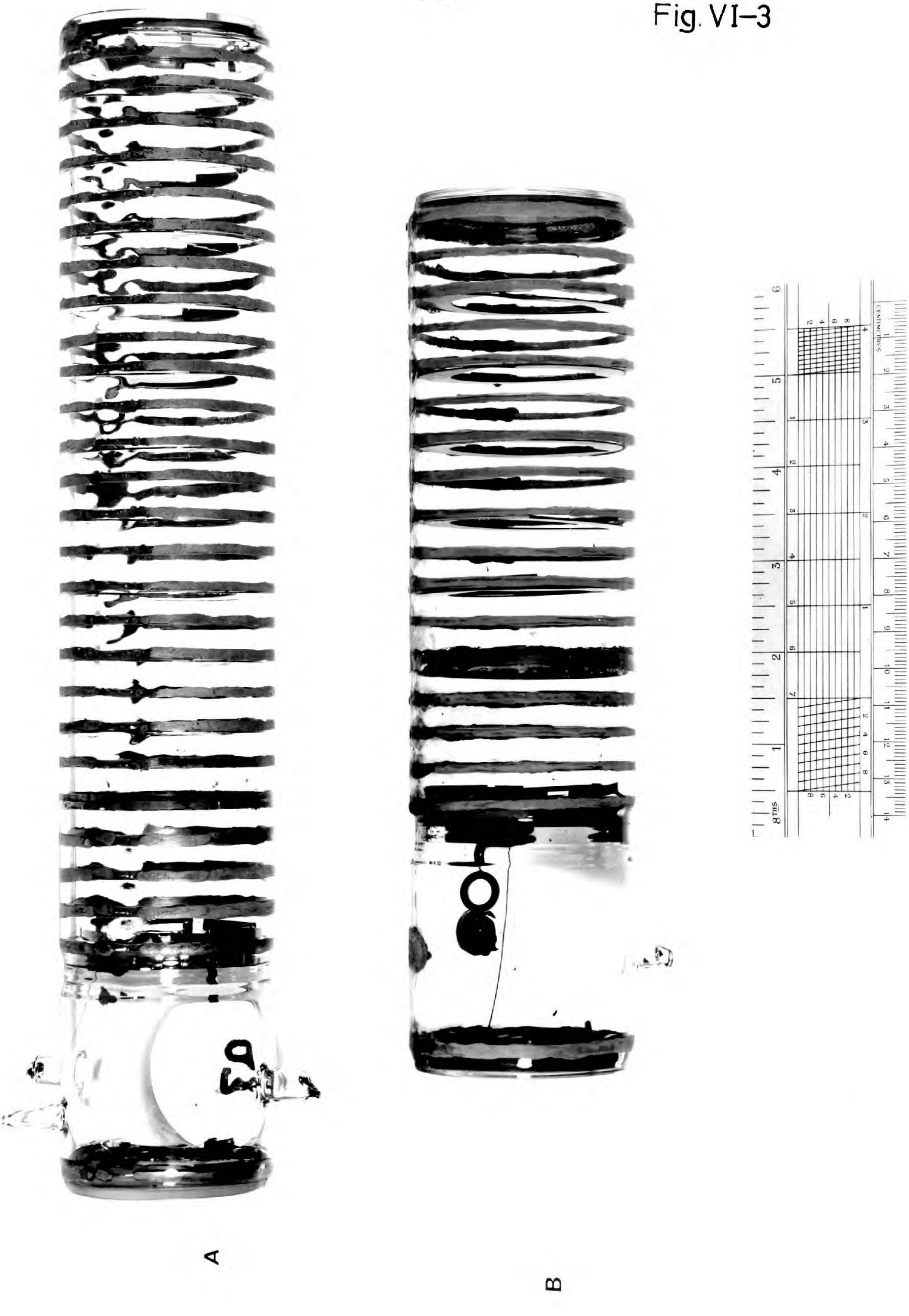


Fig. VI-3

CHAPTER VII The Performance of Cascade Image Intensifiers.

I Mounting of the tube.

The completed tube is mounted in a Perspex cradle which is designed to support the tube axially in the magnetic focusing solenoid. The electrical connections to the metallized rings were made by thin stainless steel bands, clipped into position round the tube by rubber bands. Nickel tags were spot-welded to the stainless steel bands to enable resistors to be soldered in position. It was found that the silver chloride on the tapes and the silver chloride seal reacted chemically with stainless steel in the laboratory atmosphere. Thus damaging the silver chloride seal, in at least one tube. The stainless steel bands were replaced by copper bands, which worked successfully except occasionally the rubber bands would break under tension and hence the copper band no longer made contact to the metallized ring.

In order to remedy this defect contacts were soldered on to Johnson Mathey silver paste type x-353 which had been previously applied on every metallized ring during the preparation of the tube envelope. All the resistors are mounted on a Perspex rectangular sheet and connected to the metallized rings by soldered copper wire. These hold the potentials of intermediate accelerating rings at the correct values relative to the multiplying screens. Well insulated leads are connected to these multiplying screens and to the output phosphor screen . The leads are taken to an external potential divider which is adjustable to enable the potential on each stage to be adjusted to give optimum focusing conditions.

The tube is now placed in a solenoid and the accelerating potential is gradually applied. If the tube is found to be working satisfactorily then it is painted with black paint to minimize optical feed-back and encapsulated in cold setting silicone rubber to reduce corona discharges. The tube is then ready for more accurate tests.

II Measurement of Resolution.

The resolution of the intensifiers is observed visually by projecting an optical test pattern on the primary photocathode with the help of a Baum projector[128]. The interstage potentials on the tube and the focusing magnetic field are adjusted in turn to yield maximum resolution on the output phosphor screen, this being observed by a suitable microscope. The resolution figures quoted here are those which were visually discernable.

The visibility of fringes has been defined by Michelson[160] as:-

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Applying Rayleigh's criterion of resolution two lines would be discernable if the minimum is 80% of the intensity at the maximum, therefore,

$$I_{max} = 100 \;, \quad I_{min} = 80$$

$$V = \frac{100-80}{100+80} \quad \sim 11\%$$

So two lines should be discernable if they have a contrast difference of 11%. However, the human eye can detect contrast differences of 3% after dark adaptation. This minimum detectable contrast difference will increase if the tube has some spurious background luminosity so the resolution figures quoted here are at about 10% contrast difference.

The resolution of two or three stage tubes can be calculated if the contributions to the width of confusion arising from different factors are known. Let

d_1 be the width of confusion due to the spread in the initial energies and velocities of the photo-electrons.

d_2 be the width of confusion due to the spread of image in the mica disc.

d_3 be the width of confusion due to the phosphor.

Then the total width of confusion d will be

$$d^2 = d_1^2 + d_2^2 + d_3^2$$

The contributions to the width of confusion were discussed in chapter IV and the following values were agreed upon.

$d_1 = 5$ microns

$d_2 = 3.33$ microns for a 4 microns thick mica.

The value of d_3 was calculated from the results of single stage image tubes, which gives a resolution of 55 lp/mm using a settled EMI type 214 phosphor screen having a thickness of 1 mg/cm^2 and a floated aluminium backing. In a single stage tube

$$d^2 = d_1^2 + d_3^2$$

Substituting the values of d_1 and $d = \frac{1000}{55} \simeq 18$ microns

$$(18)^2 = 25 + d_3^2$$

$$d_3^2 \simeq 300$$

In a two-stage tube, there are two photocathodes, one cascade screen on mica and two phosphor screens, so the total width of confusion will be

$$d^2 = 2d_1^2 + d_2^2 + 2d_3^2$$

$$d \simeq 25.6$$

Resolution $\simeq$ 39 lp/mm.

A resolution of about 40 lp/mm was visually observed in a two stage tube employing settled phosphor screens of 1 mg/cm^2 in thickness, having floated aluminium backing.

If similar calculations are made for a three-stage cascade tube employing similar screens then the resolution should be $\sim$ 31 lp/mm. Experimentally a resolution of 25 lp/mm has been observed in a three-stage cascade tube employing similar screens, which is in fair agreement with the calculated values.

The resolution in three-stage cascade tubes using 2 mg cm^{-2} thick settled screens of G.E. phosphor on 7-10 microns thick mica substrates was 12-15 lp/mm. Some increase in resolution was noticed by decreasing the thickness of the mica substrates to 5 microns and the resolution figure was 18 lp/mm. This suggested that a greater improvement could be achieved by using fine grain phosphors, so EMI type 214 phosphor was used to prepare phosphor screens. The image resolution of three-stage tubes using 1 mg cm^{-2} thick settled screens on 4 microns thick mica was 20-25 lp/mm. Later on, electrophorized phosphor screens were used having a thickness of 0.7 mg/cm^2 on 4 microns thick mica substrates and an image resolution of 35 lp/mm was achieved. Considerable improvement in image resolution can be achieved by using Derby Luminescents A/259 phosphor having a thickness of 0.4 mg/cm^2 on 4 microns mica and there is a possibility of achieving an image resolution of 50 lp/mm in a three-stage device.

Two-stage cascade tubes were made to determine the limiting resolution in a two-stage device by varying different parameters. The results are summarized here: A two-stage tube with EMI type 214 settled screens (1 mg/cm^2) on 4 microns thick mica, having floated aluminium backins gave a visually limiting resolution of 40 lp/mm.

From our previous experiments we knew that a phosphor screen with a conventional aluminium backing has a higher resolution than a similar screen with a floated backing (80 lp/mm and 60 lp/mm respectively see chapter V). A phosphor screen on 4 microns thick mica and a phosphor screen on glass were prepared by sedimentation process using EMI type 214 phosphor. The thickness of the screens was 1 mg/cm^2 and these were aluminized by conventional aluminium backing technique. A two-stage cascade tube was made by using the above screens. No substantial increase in resolution could be observed and the image resolution was $\sim$ 43 lp/mm which is a little better than the previous case.

Electrophorized phosphor screens with floated aluminium backings were also used in two-stage tubes. The thickness of the screens was 0.7 mg cm^{-2} on 4 microns thick mica substrate, a resolution of 50 lp/mm was achieved. Another two-stage tube was made having a cascade screen on 4 microns thick mica and having a thickness of 0.67 mg cm^{-2} from EMI type 214 phosphor and the output screen was prepared from Derby Luminescents phosphor having a thickness of 0.4 mg/cm^2 and the resolution of the tube was 55 lp/mm. One two-stage tube was made employing Derby Luminescents A/259 phosphor. The thickness of the screens was 0.4 mg/cm^2 and the thickness of mica was 3.5 microns. The image resolution obtained in this tube was 65 lp/mm. This resolution seems to be a limiting resolution with present techniques. The resolution can further be improved by decreasing the thickness of mica supports and by using evaporated phosphor screens. It may be mentioned that the resolution above 50 lp/mm has been achieved at the expense of the light gain of the tube.

The resolution figures quoted above have been observed in the middle of the output phosphor screen and the resolution falls as the distance from the centre increases.

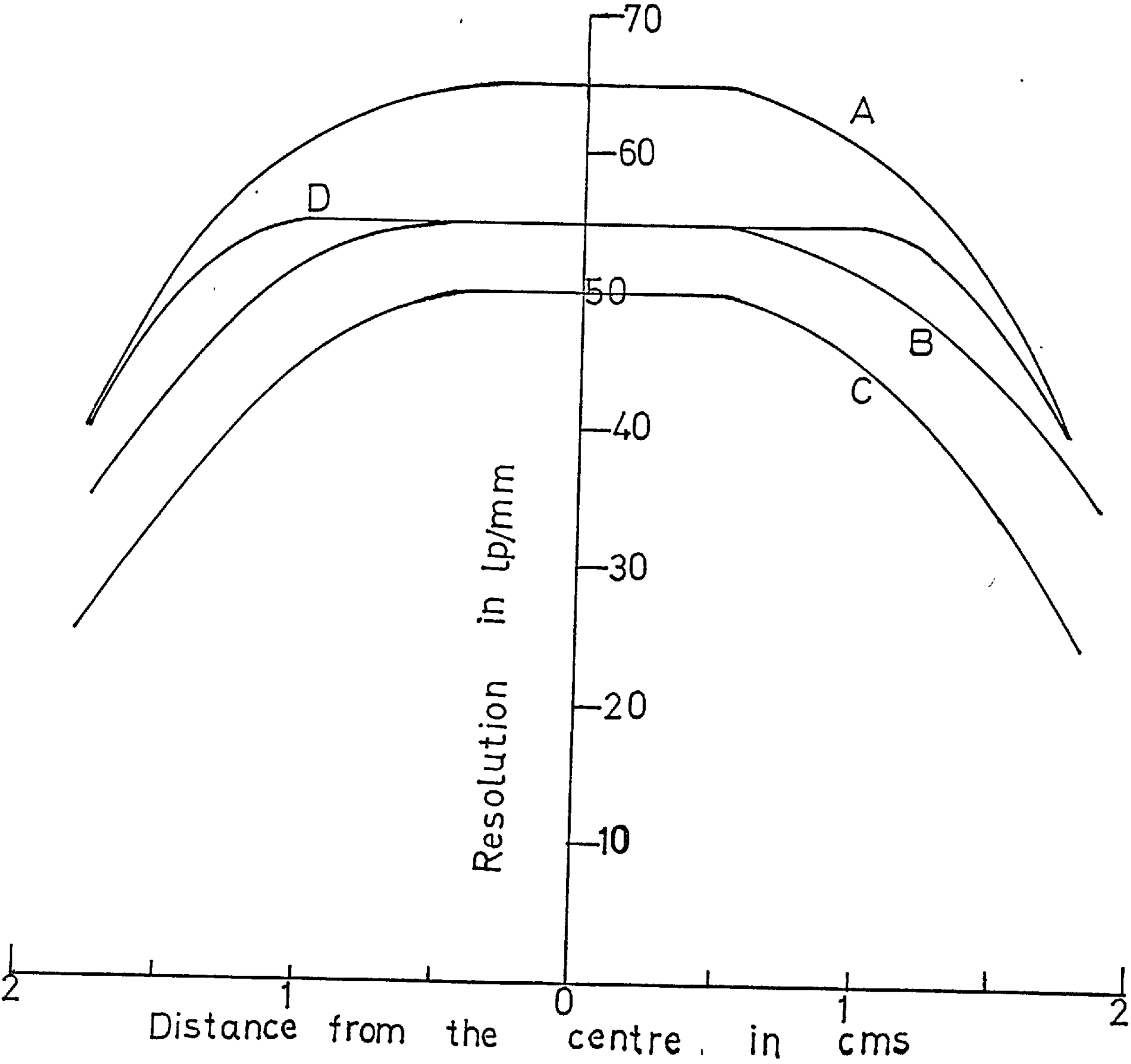
Fig. VII-1 shows a graph between distance from the centre and resolution. The curves "A" and "B" and "C" show the change in resolution with the distance from the centre of the screen for three two-stage cascade tubes keeping the magnetic field constant to give maximum resolution in the centre of the output phosphor screen. Curve "D" represents the change of resolution with the distance from the centre of the phosphor screen by adjusting the magnetic field at all the places of observation. This suggests that with a more uniform magnetic field the change in resolution over the whole area of the screen can be minimized.

III Blue light Gain.

The gain of the tube for blue light is measured by arranging a projector to give a small patch of light on the primary photocathode of the tube. The light from the projector passes through a Wratten 47B filter, the transmitted light has nearly the same spectral distribution as that of the emission from P-11 phosphor. The intensity of the incident light is adjusted to give a current of 0.04 μA when incident on a photo-voltaic cell. The same photovoltaic cell is placed against the output end window of the tube, and the accelerating potential on the intensifier is slowly increased until a current of 0.2 μA is obtained from the photovoltaic cell. The input light intensity is reduced until the photovoltaic cell current is again 0.04 μA and potential on the tube is increased to return it to 0.2 μA. The gain of the tube is thus increased in steps of five as often as necessary, the gain of the tube and the applied potential being noted at each step.

For gain measurements the output phosphor is run at earth potential, negative potential being applied to the cathode. For normal operation the input photocathode is earthed and positive E. H. T. is applied to the output

Fig VII-1


70
60
50
40
30
20
10
Resolution in lp/mm
A
B
C
D
2
1
0
1
2
Distance from the centre in cms

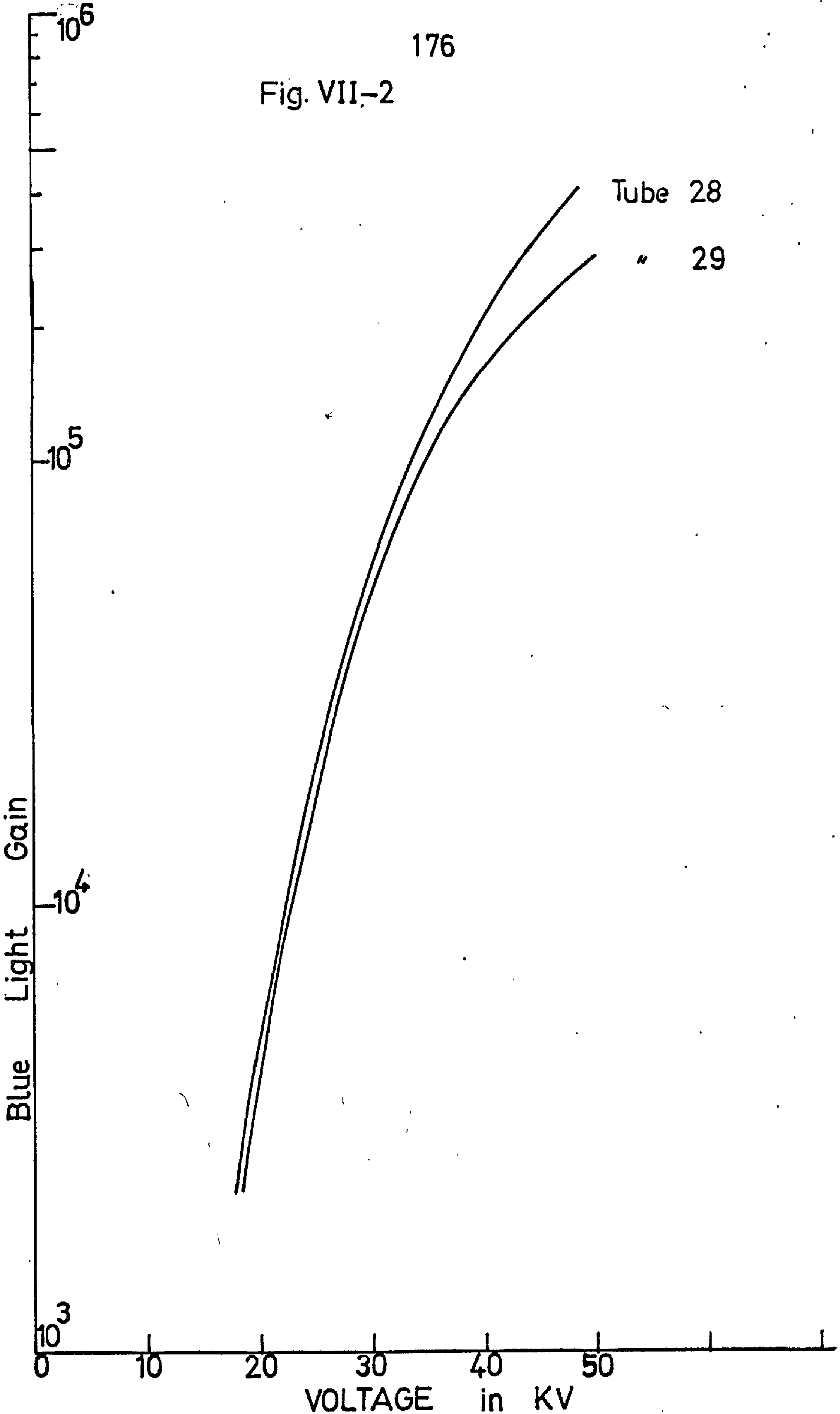
phosphor screen. Fig. VII-2 shows the blue light gain of three-stage cascade tubes 28-29. These curves are corrected to allow for the limited fraction of the total light output from the phosphor screen which is collected by the photovoltaic cell. A correction factor of 1.7 was determined by running a tube and plotting the photovoltaic cell output as a function of the distance from the cell surface to the phosphor surface. Extrapolating to zero distance gave an increase of output of 1.7 times than that obtained in the normal position.

The blue light gain of a two-stage or three-stage cascade image tubes can be calculated. Assuming a quantum efficiency of the Sb:Cs photocathode as 10% and the cathodoluminescence efficiency of the ZnS:Ag (P-11) phosphor to be $\sim$ 20%, then the blue light gain in a single stage operating at 15 kev should be $\sim$ 115. This is the maximum attainable gain under the above conditions. In practice only a stage gain of 65 was obtained. There is indirect evidence that the cathodoluminescence efficiency of the phosphor screens $\sim$ 20% (Ref. chapter V) so the smaller stage gain is due to poor photocathodes which, in fact, was the case.

IV <u>Background</u>

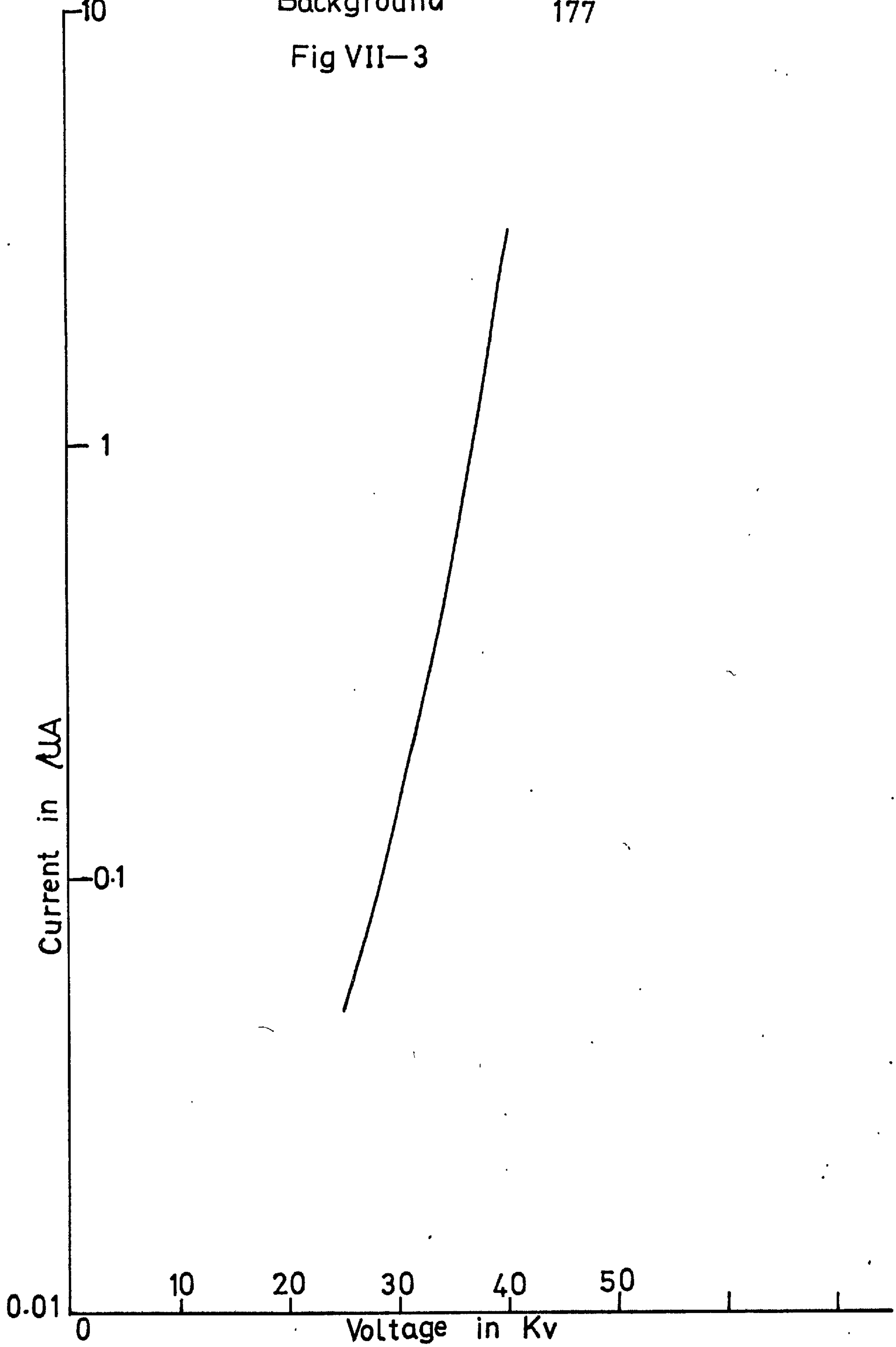
The background of an image tube, or the brightness of the output phosphor screen with no input light, is measured with a photomultiplier. A Perspex light-pipe separates the output screen from the photomultiplier by a fixed distance. The output current of the photomultiplier is noted as the accelerating potential on the image tube is increased. A typical background measurement of a three-stage tube is shown in Fig. VII-3. In a two-stage tube having a blue light gain of 1500 at 30 kV, the background current was 0.05 μA/cm as measured with a photomultiplier. A current

Fig. VII-2


10^6
10^5
10^4
10^3
Blue Light Gain
Tube 28
" 29
0
10
20
30
40
50
VOLTAGE in KV

Background

Fig VII—3



of 1μA corresponds approximately to an output screen brightness of 10^{-4} foot-lamberts.

On visual observation the background of a three-stage cascade tube seems to consist of:

(i) True electron scintillations which arise from the fact that some thermal electrons are emitted from the primary photocathode, and the light due to them on the first cascade screen is amplified by the remaining two stages of the tube to make them visible as single dots on the output screen. Some of these electrons may also be genuine photo-electrons emitted by the primary photocathode due to light leakage or internal or external corona discharge light.

(ii) Bright scintillations which are much brighter than the electron scintillations mentioned in (i)

The origin of the bright scintillations is due to the emission of groups of electrons from points on the photocathode. The electrons in each of these groups are probably liberated by the impact of positive ions on the photocathode. These liberated electrons are focused, by the existing fields in the tube, on the first cascade screen and the output is amplified to give a very bright scintillation at the output screen. It is very difficult to specify the source of these positive ions, however, the following are the possible sources.

(a) Ionisation of the residual gas.

An electron, may collide with and ionize an atom or a molecule of the residual gas, during its journey to the phosphor screen. This ion would then travel towards the photocathode and produce a bunch of electrons which are focused on a point on the phosphor screen, amplified by the later two stages, give rise to a bright scintillation. The chance of the occurrence of the above process is extremely small: firstly the vacuum in the image tube is very good $\sim 10^{-7}$ mmHg and the free path of an electron at such a pressure is $>$ 50 km while the length of the cascade tube is only 30 cm., secondly caesium on the photocathode can act as a getter for the residual gasses and thirdly an aluminium-zirconium getter is used in the tube to absorb the residual gases. So it can be concluded that the residual gas is not a serious source of the positive ions.

(b) Caesium Ions.

The presence of free caesium atoms may be a source of positive ions. The excess caesium on the Sb:Cs photocathode may detach itself and may get adsorbed on the glass walls or the metal parts, from where it could be detached due to field desorption.

Most probably some of the caesium gets into the working part of the tube during processing of the photocathodes because the barrier between the processing chamber and the main part of the tube is not really fully effective. If some system is evolved so that the caesium can be completely excluded from the main part then it will probably minimize the bright scintillations.

(iii) A steady glow of the output phosphor screen which seems to be the luminescence due to electron impact on phosphor screens. These electrons are unable to show themselves as electron scintillations on the output phosphor screen because of insufficient amplification of light due to them. These electrons can be thermal electrons from the first and second cascade photocathodes and the field-emitted electrons from sharp points on the metal parts or metallized rings, and in order to minimize this effect the metallized rings on the inside of the tube wall have been eliminated altogether with the exception of a small platinum paste patch which provides an electrical contact to the outside ring through a platinum tape sealed in the glass wall.

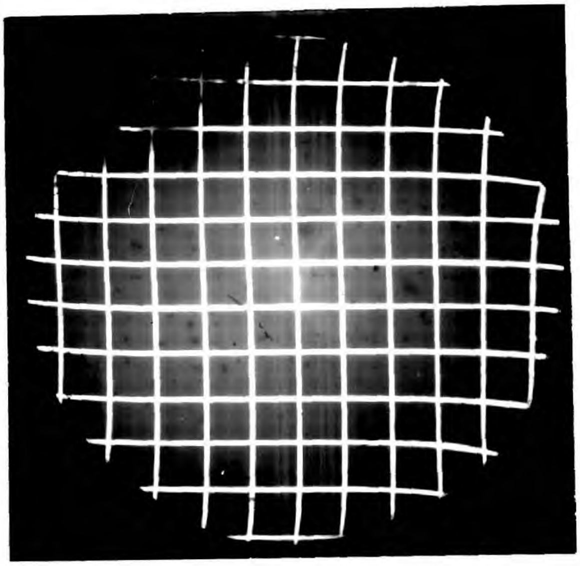
(IV) Some darker patches or points on the output screen which may be due to the contamination of the phosphor screen.

V General Aspects of Performance.

The geometry of the reproduced image is shown in Fig. VII-4 a and b showing the images of a straight line and circular distortion test patterns. There is some S-distortion which becomes more noticeable near the edges.

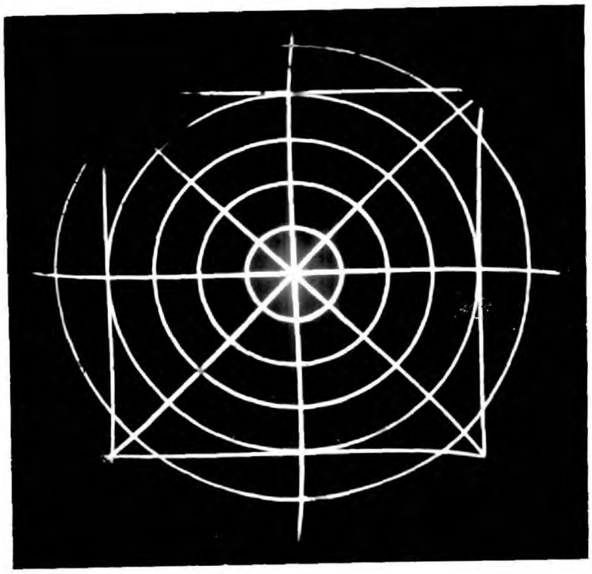
Fig. VII-4c shows a photomicrograph of the limiting resolution of a two-stage cascade tube, it can be seen from the photograph that the resolution is $\sim$ 55 lp/mm.

Fig. VII-4



(a)

(c)



(b)

CHAPTER VIII Conclusions.

Very thin phosphor screens have been prepared by the sedimentation and electrophoretic processes for the use in cascade image intensifiers. The cathodoluminescence energy conversion efficiency of such screens is of the order of 20% and an image resolution better than 120 lp/mm.

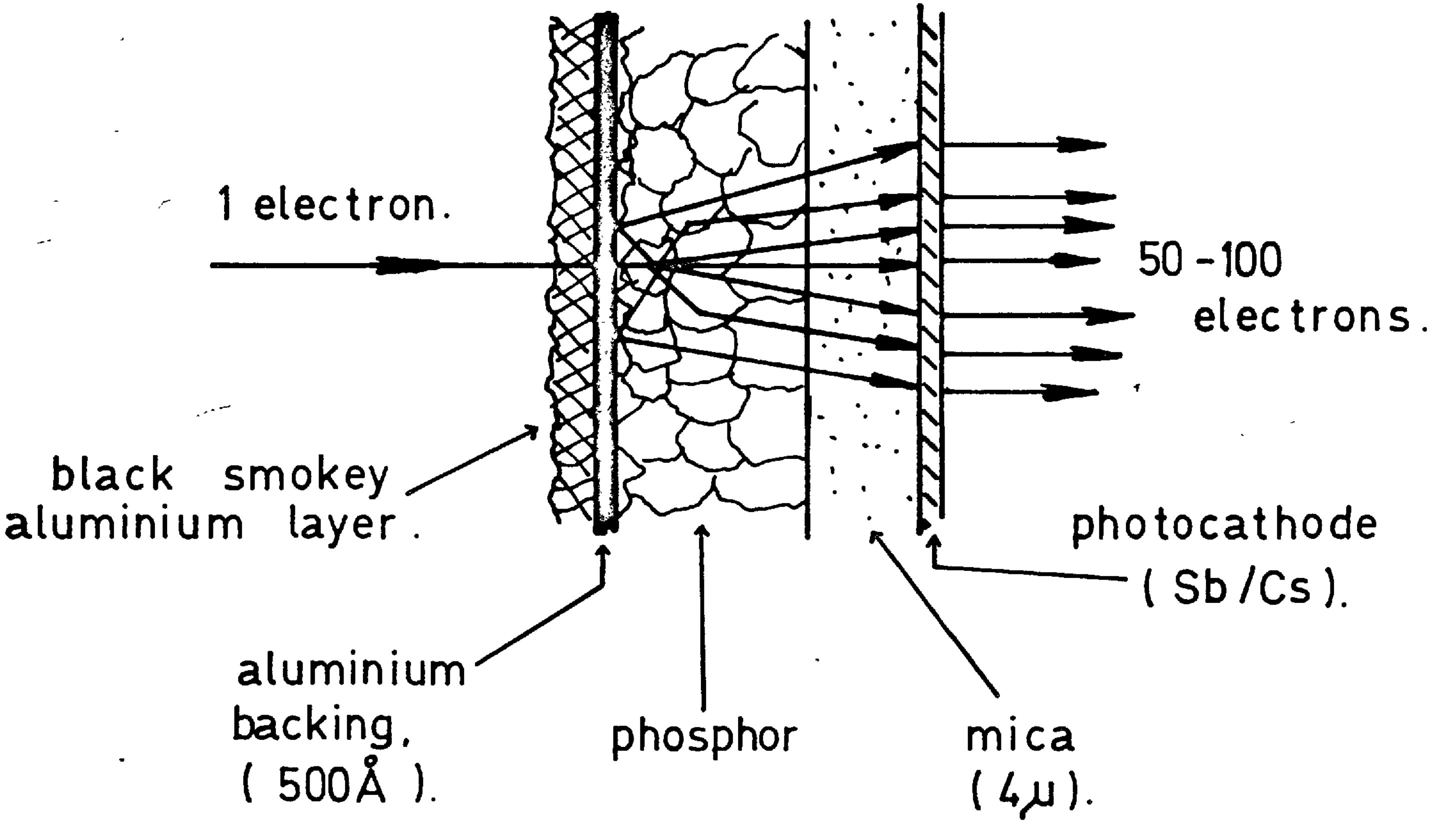
An optical technique of measuring image resolution of the unbacked screens has been developed and the results are in fair agreement with the theory proposed.

The technique of the application of "floated backings" has been developed, and all the screens used in the cascade image intensifiers were aluminized by this process. An electron-optical technique for the measurement of the resolution of backed phosphor screens has been developed to give the image resolution of the screens in lp/mm.

Cascade screens have been prepared on very thin mica substrates (3-4 microns thick) and used in image intensifiers. The thickness of the mica substrates can not be further reduced due to the non-availability of thinner mica discs, but with the present techniques it should be possible to prepare cascade screens on mica discs of a thickness of 1 or 2 microns, which should result in considerable enhancement of the image resolution. A cascade screen is shown in the figure VIII-1.

Two-stage and three-stage cascade image intensifiers have been prepared and the data on some tubes is presented in table I. The applications of the cascade tubes have been outlined by Davis[39] and Catchpole[43]. The cascade image intensifiers, with their present performance, can be used for astronomical research and in the field of "field ion microscopy".

Fig VIII-1



Section through multiplying screen.

TABLE 1

Sensitivity of Photocathodes			Phosphor (P-11) Type and Particle Size (microns)	Thickness of the Screens mg/cm^2	Process of Screen Formation	Thickness of mica Substrates (microns)		Blue light Gain of the Tube.	Resolution lp/mm	Remarks.
1	2	3								
					3- STAGE CASCADE IMAGE TUBES.					
44	-	-	G.E (3-5)	2	Settling	7	8	40,000	16	Background was rather high.
20	-	-	-do-	2	"	5	5	100,000	15	A good tube.
24	-	-	EMI type 214 (~1)	1	"	4.5	5	370,000	20	-do-
28			-do-	1	"	4	4	230,000	22	-do-
44	48	50	-do-	0.7	Electrophoresis	4	4	1,500,000	25	-do-
30	35	40	-do-	0.75	"	4	4	300,000	33	-do-
25	..	..	D.L. type A/259 (~1)	0.4	"	3.5	3.5	----	50	The gain could not be measured due to the instability of the tube.
					TWO-STAGE CASCADE IMAGE TUBES.					
15	...	x	EMI type 214 (~1)	1	Settling	4		1,500	40	
30	-	x	-do-	0.7	Electrophoresis	4		4,000	50	
25	28	x	-do-	0.5	-do-	3.5		2,000	55	
20	22	x	D.L. type A/259 (~1)	0.4	-do-	3.5		1,000	65	

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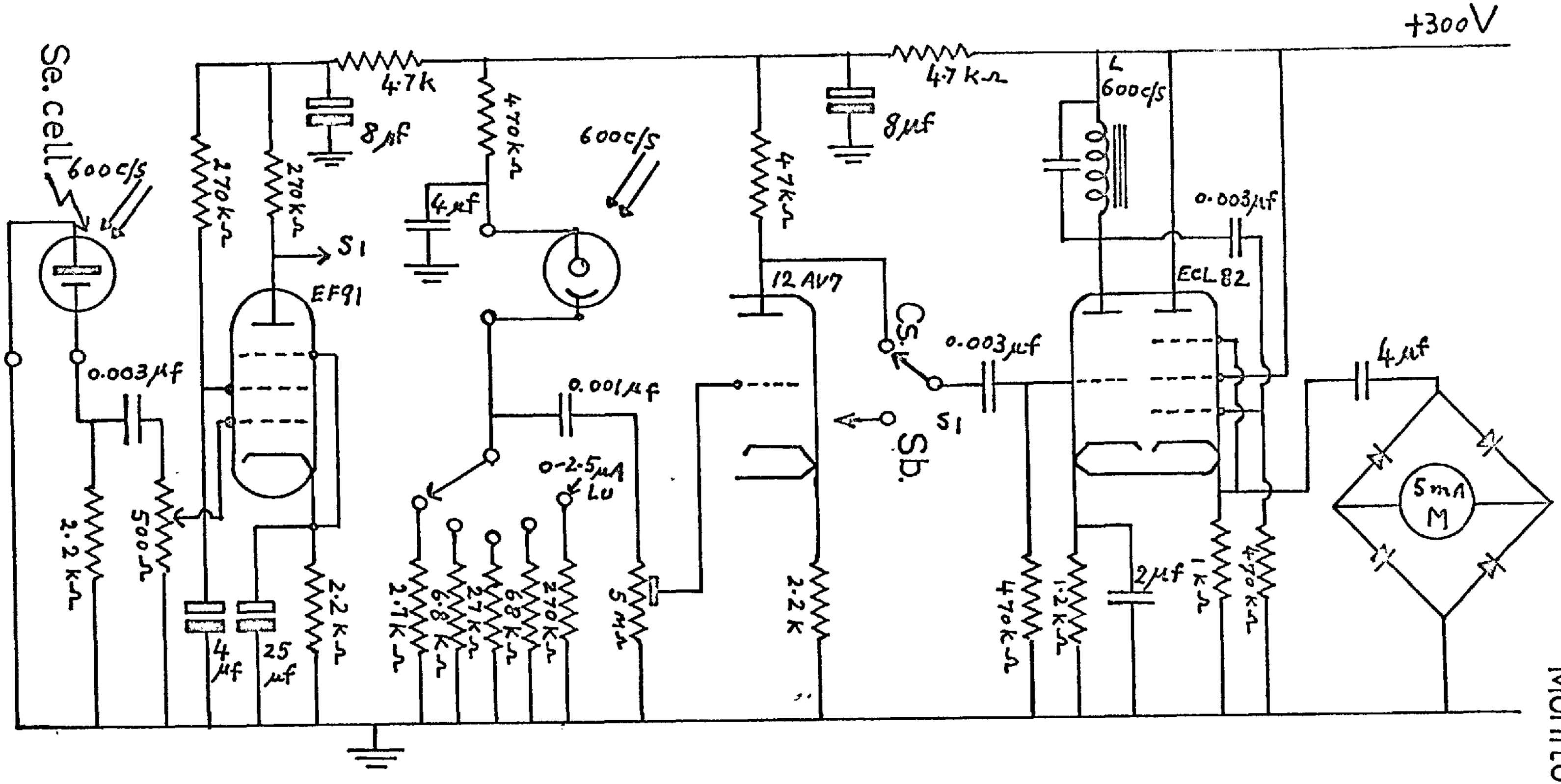
Appendix. 1

Photosensitivity and Antimony layer thickness Monitor



A selenium cell coupled with chopper-amplifier