THE EFFECT OF THICKNESS OF SUPPORTING FILMS FOR THIN TARGETS USED IN X-RAY INTENSITY MEASUREMENTS

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I INTRODUCTION

This thesis concerns the measurement of absolute x-ray intensities of the continuous x-ray spectrum, and a comparison of the experimental values with theory. The best available theory concerning this subject is that due to Sauter (1). It is shown that the intensity of x-ray radiation produced when electrons interact with nuclei is dependent on several factors, namely, the energy of the incident electron, the angle of observation from the direction of the incident electron, the atomic number of the bombarded nucleus and the frequency of the radiation emitted. Due to the mathematical difficulty in treating the more complex cases, the theory is based on the assumption that a single bombarding electron interacts with an isolated nucleus of an atom of the target material to produce an x-ray quantum. It can be seen that the assumption regarding the isolated nucleus will be more closely approximated the fewer the number of atoms present in the x-ray tube target. However, targets of the thinness necessary to approximate the theory are not self-supporting, and consequently a backing material must be used on which the target material is deposited. Since it is desired to find only the effects produced by the target atoms, and not the

backing material, it is necessary that the effect due to the backing material in the path of the incident electrons either be negligibly small, or that it be a known quantity in order that a correction for it may be made.

In previous work on the measurement of absolute x-ray intensity, H. R. Kelly (2) and A. F. Reno (3), used cellophane as the target backing material. Their basis for using this material was that when a target consisting merely of the backing material, and no deposited metal, was placed in the x-ray tube, no measurable quantity of x-rays were produced under the same conditions of tube current and voltage as were used for the experiment with the deposited metal on the target. However, with electron currents of one hundred times normal, x-rays were produced, but the intensity was so small as to result in no detectable change in the value of absolute intensity at the frequency being studied.

In spite of the evidence to the contrary, it can be seen that the target material might produce two possible effects. First, it is conceivable that the backing material, since it is made of finite material, should produce some x-rays, and second, it is possible that it could rediffuse the electrons back through the metallic film, both of which would cause more x-rays to be produced than would be with the ideal conditions.

The basis for this second assumption is that the thickness of the backing material is approximately five hundred times the thickness of the deposited metallic film. It is not known why the backing material, with no deposited metal, did not produce x-rays in larger quantities. It is possible that it might be caused for two reasons: (1) cellophane is composed of elements of small atomic number, and it is known that the intensity of x-rays produced varies roughly as the square of the atomic number for the light elements, and (2) the density of cellophane is small, which implies not only light atoms but loosely packed atoms.

In view of these possibilities and considering the fact that the results of Reno (3) and Kelly (2) are somewhat higher than the theoretical values, it was thought advisable to conduct experiments to find what effect the backing material has, and if possible to find this quantitatively, in order that the more usable, thicker backing material might be used, and these values corrected to values that would be obtained if no backing material were present.

There are two methods of attacking the problem which might be used for this experiment. The first would be to use one thickness of backing material and to deposit various thicknesses of metallic film, to measure the x-ray intensity from these various targets, and then from a graph of intensity versus target thickness, to

extrapolate the curve to zero thickness of metallic film. This consequently results in the effect of having only the backing material. This procedure has three major shortcomings. The first is that as the thickness of the film is increased, the approximation to the theory of the electron striking a single atom is decreased. The second is that the method used here (4) for the measurement of the thickness of the film cannot be used for the small thicknesses necessary for accurate extrapolation of the curve to the zero thickness of metallic film. And the third is that the thinner film would, PRODUCE SO SMALL A QUANTITY OF X-RAYS AS TO greatly decrease the accuracy of any results obtained.

The second method of attacking the problem, and the one used in this work, is to, as nearly as possible, use one thickness of metallic film which can be easily and accurately measured, and which will produce a sufficient quantity of x-rays, and vary the thickness of the backing material. From a curve of x-ray intensity against backing material thickness, extrapolation to zero thickness will give results, due only to the foil thickness itself. The disadvantage in using this method lies in the fact that the thinner backing material is relatively weak and therefore will not stand up well in the tube. But it has the added advantage that it is easy to vary the thickness of the backing material, and targets with

different thicknesses are quickly constructed.

It was decided for this work to use four different thicknesses of backing material, one of them being the commercial cellophane used in the previous (2) (3) experiments, for comparison purposes, and three thicknesses of another material to be described later. A set of four targets, one of each thickness, would be coated by the same evaporation with a thin metallic film. This would give the same thickness of target material and any variation in results from different targets would be due to the backing material alone.

II THEORETICAL EQUATIONS

A. Discussion of Sauter's Theory

For the theoretical work with which the experimental results are compared, an equation developed by Sauter (1) was used. His work was used because to date it represents the most complete result of theory, being a relatively complete relativistic treatment of the problem. This theory is based on the assumption of a single bombarding electron of known total energy striking an isolated atom, which may result in the production of a quantum of continuous x-ray energy at a specific frequency and a certain azimuthal angle.

The equations given by Sauter, which were evaluated for this experiment, are the following:

$$J_\nu d\nu = \frac{2e^6 Z^2}{R^2 c^3}\frac{p}{p_0^3}d\nu\left\{\frac{(3E_0^2 - c^2p_0^2)m^2c^4\sin^2\theta}{\mu^4} - \frac{2E_0^2 - c^2p_0^2}{\mu^2}\right.$$

$$-\frac{Ecp_0\cos\theta}{2\mu^2} - \frac{cp_0^2}{2p\mu}\log\frac{E+cp}{E-cp} + \frac{cp_0^3(h\nu\cos\theta - cp_0)}{2p_0^2\mu^2}$$

$$+\left(\frac{m^2c^4}{2\mu^2} - \frac{h\nu}{\mu} + \frac{(h\nu)^2(h\nu - cp_0\cos\theta)}{2c^2p_0^2\mu}\right)\frac{p_0^2}{pp_0}\log\frac{p_0+p}{p_0-p}$$

$$+\log\frac{E_0E - m^2c^4 + c^2p_0p}{E_0E - m^2c^4 - c^2p_0p}\left[\frac{(3E_0h\nu m^2c^4 - E_0Ec^2p_0^2)m^2c^2\sin^2\theta}{2p_0p\mu^4}\right.$$

$$\left.\left.+\frac{3E_0^2c^2p_0^2 - 4E_0h\nu m^2c^4 + c^4p_0^2p^2}{4c^2p_0p\mu^2} - \frac{(E_0E + c^2p_0^2)h\nu\cos\theta}{4cp\mu^2}\right]\right\}$$

The correction factor which this must be multiplied by to make the formula valid for the whole spectral range is:

$$\frac{\frac{(2\pi\alpha Z)^2}{\beta\beta_0}}{\left(e^{\frac{2\pi\alpha Z}{\beta_0}} - 1\right)\left(1 - e^{-\frac{2\pi\alpha Z}{\beta}}\right)}$$

This results in the final equation:

$$J_\nu d\nu_{(CORR)} = J_\nu d\nu \frac{\frac{(2\pi\alpha Z)^2}{\beta\beta_0}}{\left(e^{\frac{2\pi\alpha Z}{\beta_0}} - 1\right)\left(1 - e^{-\frac{2\pi\alpha Z}{\beta}}\right)}$$

This final equation gives $J_\nu d\nu$ as the energy per unit area, per electron, per second, per atom per unit area of target, where observations are made at an azimuthal angle Θ, with respect to the direction of the incident electrons, at a distance R from the target.

The terms appearing in the formula are defined as:

h = Planck's constant

e = Charge on the electron

m = Rest mass of the electron

C = Velocity of light

R = Distance of the defining aperture from the x-ray target

Z = Atomic number of the target material

E_o = Initial total energy of the bombarding electron

E = Total energy of the electron after collision

p_o = Initial momentum of bombarding electron

p = Momentum of the electron after collision

$q = \frac{h\nu}{C}$ = Momentum of the quantum

Θ = Azimuthal angle of emitted quantum with respect to incident electron direction

$P_o = p_o^2 + q^2 - 2pq\cos\Theta$ by definition

β_o = Ratio of velocity of incident electron to that of light

β = Ratio of velocity of electron after collision to that of light

$u = E_o(1 - \beta_o \cos\Theta)$

$\alpha = \frac{2\pi e^2}{hc}$ = the fine structure constant

$p^2 = \frac{E^2}{c^2} - m^2c^2$

$p_0^2 = \frac{E_0^2}{c^2} - m^2c^2$

These last two are derived in the following manner:

$$E = mc^2 + mc^2\left[\frac{1}{\sqrt{1-\frac{v^2}{c^2}}} - 1\right] = \frac{m^2c^2}{\sqrt{1-\frac{v^2}{c^2}}} \quad (a)$$

$$p = \frac{mv}{\sqrt{1-\frac{v^2}{c^2}}} \quad (b)$$

from (a)

$$v^2 = c^2\left[1 - \frac{m^2c^4}{E^2}\right]$$

which substituted in (b) gives:

$$p = \frac{m^2c^2\left[1 - \frac{m^2c^4}{E^2}\right]}{1 - 1 - \frac{m^2c^4}{E^2}} = \frac{E^2}{c^2} - m^2c^2$$

B. Quantities Used in the Computation

For the evaluation of the equation, the following values of the constants were used:

h = 6.63428 x 10^{-27} erg-sec.

e = 4.80650 x 10^{-10} esu

m = 9.11780 x 10^{-28} gram

c = 2.99776 x 10^{10} cm/sec.

R = 34.0 cm.

Z = 13 for aluminum

θ = 60°

From Compton and Allison (5) the K absorption limits for the Ag and Cd used in the Ross balanced foils are:

$$\lambda_{Cd}\ (\text{K limit}) = 463.13\ \text{XU}$$

$$\lambda_{Ag}\ (\text{K limit}) = 484.43\ \text{XU}$$

Which gives:

$$\nu_{Cd}\ (\text{K limit}) = 6.4728 \times 10^{18}\ \text{sec}^{-1}$$

$$\nu_{Ag}\ (\text{K limit}) = 6.1876 \times 10^{18}\ \text{sec}^{-1}$$

These give a mean frequency between the K absorption limits of:

$$\nu = \frac{\nu_{Cd} - \nu_{Ag}}{2} = 6.3302 \times 10^{18}\ \text{sec}^{-1}$$

$$d\nu = \nu_{Cd} - \nu_{Ag} = 2.85244 \times 10^{17}\ \text{sec}^{-1}$$

$$h\nu = 4.19963 \times 10^{-8}\ \text{ergs}$$

$$1\,ev = 1.60336 \times 10^{-12}\ \text{ergs}$$

$$q = \frac{h\nu}{c} = 1.40092 \times 10^{-18}\ \text{gm-cm/sec.}$$

For electron energies of 36.7 and 41.74 K.V. the values of $J_\nu\, d\nu$ are taken from calculations by A. F. Reno (3):

K.V.	$J_\nu\, d\nu$
36.70	1.25×10^{-36}
41.74	1.15×10^{-36}

C. NECESSARY CONDITIONS TO BE MET EXPERIMENTALLY

For this experimental work, the electron energy was measured by careful control of the voltage of the x-ray

tube, the number of bombarding electrons was noted by closely controlling the x-ray tube current, and the assumption of an isolated atom was approximated by using a very thin target, thereby keeping the atoms per unit area small. The frequency range of the quanta produced was controlled by the use of Ross balanced foils, the azimuthal angle was accurately known, and a standard ionization chamber in connection with a Compton electrometer was used to measure the number of quanta produced per unit time. The balanced foils in this case gives $J_\nu \, d\nu$ for a particular frequency ν in a range $d\nu$.

III PRODUCTION OF BACKING FILMS

A. Apparatus and Procedure

Since it is desired to use a target backing material thinner than commercial cellophane, and to use several different thicknesses, and since nothing of this nature was readily available, it was necessary to choose a material and develop a technique for making films of various thicknesses. It is necessary that the backing target material be as strong as possible, not only because the films used are very thin, but also because the positively charged target is in close proximity to the negatively charged x-ray tube case, and consequently

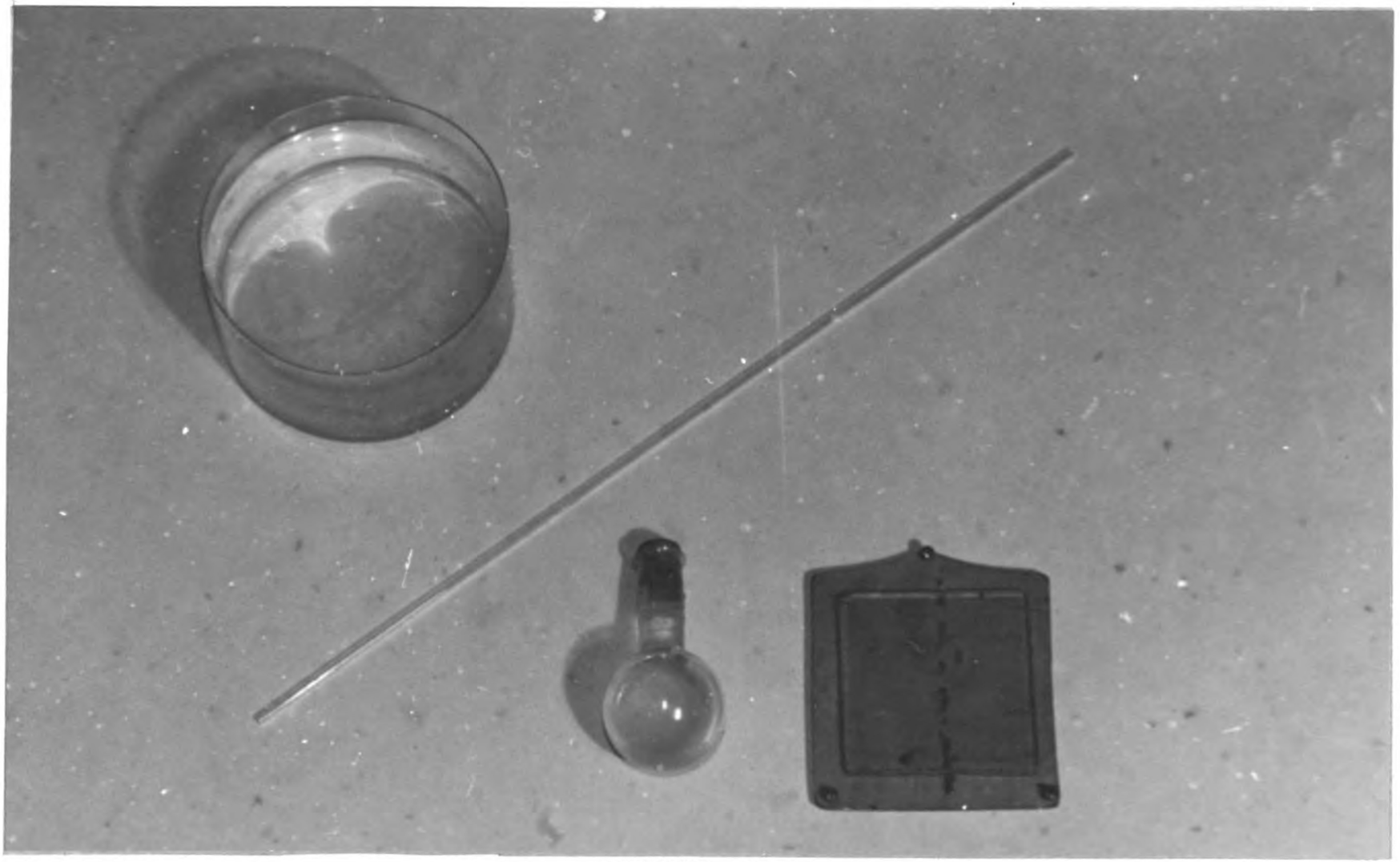

FIGURE 1

dry. Drying took about ten minutes. The dried film adhered to the glass, but it was found that by dipping the glass plate with the film on it in a jar of water, the edges became loosened, and the film could be lifted off. It was found that for very thin films, the best method was to float them off onto the water surface, and to remove them with a wire loop.

For the three thicknesses of film used, the quantities of ethyl cellulose solution were 2.0 cc, 1.5 cc and 1 cc, which in all cases were spread over the same area of approximately six square inches.

B. Thickness Obtained

To quantitatively determine the effect of the thickness of the backing material on the production of x-rays, it is necessary to know the backing film thickness. It was found that a micrometer could not be used with any degree of accuracy on such thin film, although it would give an approximate value. For this purpose, an optical lever was made with a blunt foot which rested on a piece of plate glass. As set up for these measurements, the lever arm of the optical lever was 4.1 cm long, and the distance from the mirror to the cross-hairs of the telescope and to the scale was 500 cm. A typical set of data for these measurements is given in table I.

Table I

Data for the measurement of backing film thickness.

scale readings (cm)	thickness	scale readings (cm)	thickness
4.70	4.90	4.75	5.00
	5.00		5.00
	5.00		5.10
	5.05		5.10
	5.00		5.00
4.70	5.05		5.00
	4.95		5.10
	5.00	4.75	5.10
	5.00		5.10
	4.90		5.15
4.70	5.05		5.00
	5.00		5.15
	5.10		5.20
	5.00	4.75	5.10
	5.10		5.20
	5.10		5.20
4.75	5.10		5.10
	5.10		5.05
	5.00		5.20
4.75	5.10	4.75	5.20

Average difference = .335 cm

$$t = \frac{.335 \times 4.10}{2 \times 500} = .00137 \text{ cm}$$

These measurements gave an average value of thickness for the thickest film of .00137 cm, for the middle one, .00103 cm, and for the thinnest, .00069 cm. The cellophane was .00205 cm thick.

C. Target Construction

These films were then cemented with Duco Household Cement to the wire frames which act as target supports in the experimental x-ray tube. It was found that the cement dissolved the films, but by using a minimum quantity on the frames, and by careful handling until it had dried, it hardened into a very firm support for the films.

In this manner several sets of targets were made, each set containing one target of each thickness of ethyl cellulose material, and one target made of the commercial cellophane used in the previous (2) (3) experiments. Four targets could be constructed from each piece of cellulose acetate made, and therefore four sets of targets could be made at once, which would make the sets comparable to each other as far as thickness of backing material was concerned.

IV EVAPORATION OF ALUMINUM ON BACKING

The evaporation of aluminum onto the target was carried out in a cylindrical glass tank with steel top

and bottom plates, the inside size of which was twelve inches in diameter and twelve inches high. The vacuum was obtained with a Cenco Megavac pump in connection with an oil diffusion pump. This was sufficient to produce no noticeable discharge when tested with the high voltage from an automobile spark coil.

The aluminum was evaporated from tungsten filaments placed near the bottom plate of the tank. A holder was constructed which would hold an interferometer plate and four targets above the filament within the distance of the mean free path of the aluminum molecules, which in this case was approximately seven inches. As can be seen from the illustration of figure(2), the interferometer plate was held in the middle, surrounded as closely as possible by the four targets. At the distance from the filaments used, this should give a uniform coating to the four targets and the interferometer plate. It should be noted that this type of holder completely coated the backing material, providing an electrical connection between the evaporated aluminum film and the supporting frame.

In order to determine the thickness of the evaporated metallic film, the following procedure was used. An interferometer plate was placed in the evaporation chamber alone and given an opaque surface of aluminum. It was then removed, and a cellophane or mica strip

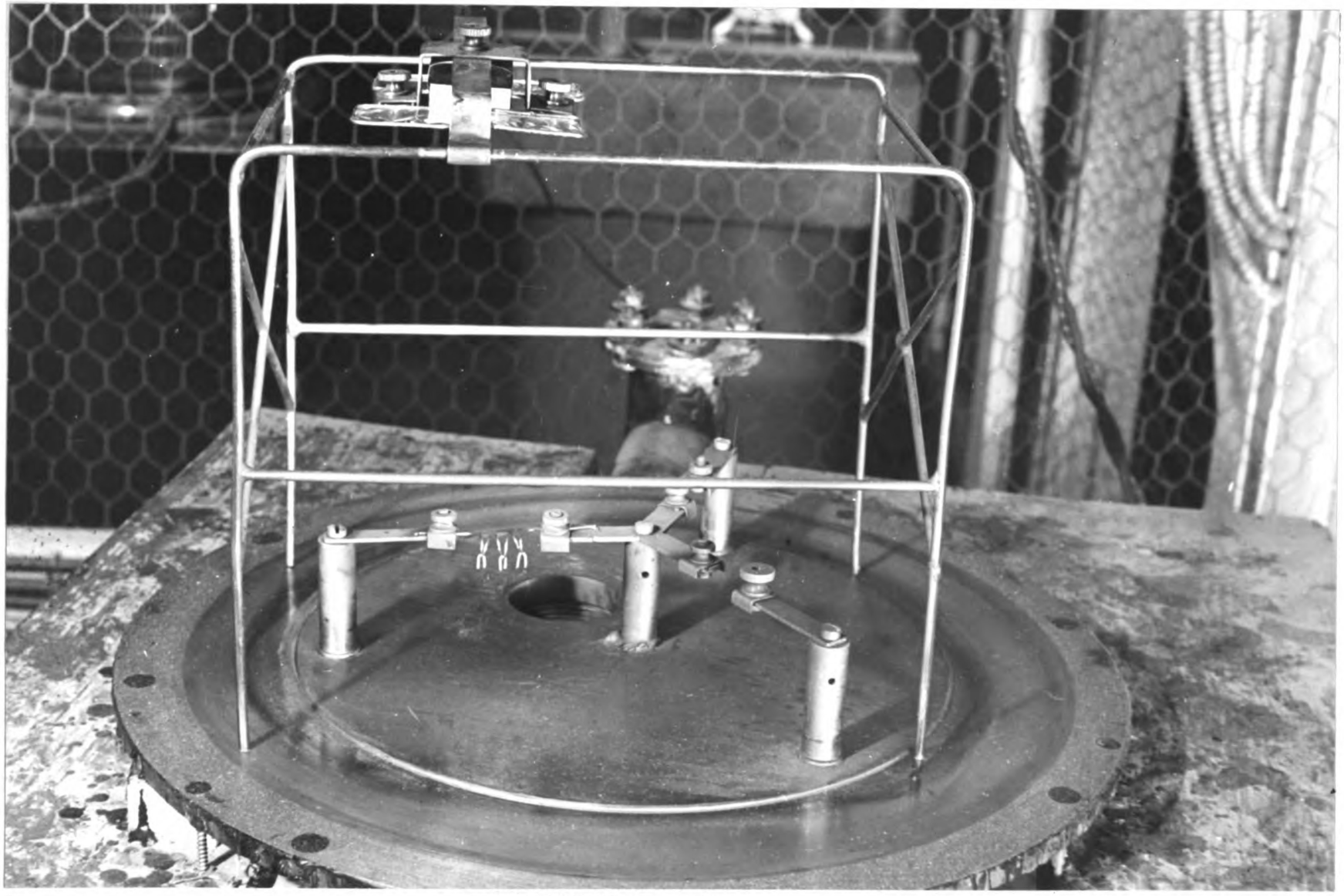

FIGURE 2

about one-third its width was cemented over the aluminized surface in the center region of the plate. It is important that care be taken that the edges of this strip be as smooth as possible. It was then cemented only at the edges of the plate, so none of the aluminum would be pulled off when the mica was removed. This was again placed in the evaporation chamber along with the four targets to be coated. For the sets used in this experiment, one and one quarter inches of number eighteen aluminum wire was cut into three equal lengths, hung from three loops in the filament, and evaporated by heating the filament with an electric current. As will be shown later, this method produced very uniform results as regards the thickness of films obtained from different evaporations.

V. Measurement of Thickness of Aluminum Films

A. Method

From the preceding, it can be seen that the outer two-thirds of the interferometer plate received an additional coating of aluminum equal to the target thickness while the center section, protected by the mica strip did not. Upon removal of the mica strip, it can be seen there results an interferometer plate with two reflecting surfaces, at a distance of the thickness of

the target film from each other.

The plate was put in a Michelson interferometer which was then adjusted so the straight fringes ran perpendicular to the section shielded by the mica strip. This produces a step-like pattern of the fringe system due to the different distances the light travels to the shielded and unshielded portions of the interferometer plate. In all cases the interferometer was adjusted to obtain the white light fringes, to confirm the fringe shift as being limited to the same order - that is, the fringe shift was a fraction of a fringe, not one or more and the fraction. Using a suitable monochromatic light as a source, this fringe pattern was then photographed, and measurements made from the photograph gave the thickness of the aluminum film evaporated on the targets.

B. Wavelength of light used to make the photographs

If the fringe pattern produced by the unshielded portion of the interferometer plate is shifted one fringe from that produced by the shielded portion, it can be seen that this corresponds to a thickness of film deposited by the second evaporation, of thickness of $\lambda/2$, where λ is the wavelength of the light source used to produce the interference pattern. Correspondingly, any fraction of a fringe shift will be due to the same fraction of $\lambda/2$ for the deposited film thickness. It can be seen, therefore, that the shorter the wavelength of light used,

the correspondingly greater will be the fringe shift for any given thickness of deposited film because of its greater fraction of $\lambda/2$. For example, using the mercury green line, isolated by suitable filters for the monochromatic source, a thickness of deposited film of 300Å will produce a fringe shift of :

$$300/5460/2 \simeq 1/9 \text{ of a fringe.}$$

On the other hand, using a wavelength of 3654Å, the fringe shift will be:

$$300/3654/2 \simeq 1/6 \text{ of a fringe.}$$

This greater fringe shift will facilitate the measurement of film thicknesses, and will also make possible the measurement of thinner films.

In the low pressure mercury arc spectrum there is a triplet composed of λ = 3650, 3655 and 3663Å of relative intensities of 10, 7 and 6 respectively, the mean weighted wavelength of which is λ = 3654Å. Corning filters Nos. 584 or 586 have a maximum transmission at λ = 3600Å, and will reduce the only other line near the λ = 3654Å group (λ = 3341Å) to about 1/12 the intensity of the λ = 3654Å group.

The mercury arc used for the source was the Cooper-Hewitt laboratory arc Type K21Q230, quartz bulb unit which operates (with built-in controller) from 105-125 volts A.C. or D.C. using 2.2 amperes. As compared to the capillary tube high pressure lamp, and the common low pressure discharge tubes, it is about a medium pressure lamp.

To show that the desired wavelengths were transmitted by the various parts of the interferometer optical system, and all others were either cut out, or reduced to an insignificant intensity with respect to the desired wavelength, a spectrogram was made. Using a Gaertner quartz optical system, Littrow mounting, spectrograph, with a plate not sensitive to the red and yellow, a spectrogram was made of the source, and the source with various parts of the optical system used also in the light path. Fig. (3) shows this spectrogram, the explanation of which is:

(1) The spectrum of the arc using an ordinary glass lens to focus the light on the spectrograph slit. This lens was the one used to collimate the source for use with the interferometer. Exposure 2-1/2 minutes.

(2) Same as (1) with Corning No. 584 filter in the light path. Exposure 5 minutes.

(3) Same as (2). Exposure 10 minutes.

(4) Same as (3) with interferometer compensating plate in the light path. Exposure 10 minutes.

(5) Same as (4) except the glass lens used in (1) was removed and camera lens (later used for photographing interference fringes) was put in its place to focus the light on the spectrograph slit. Exposure 10 minutes.

This spectrogram shows not only that the λ = 3654Å group gets through the entire optical system, but also that the other wavelengths are reduced to insignificant intensities compared to this group. The λ = 3341Å line

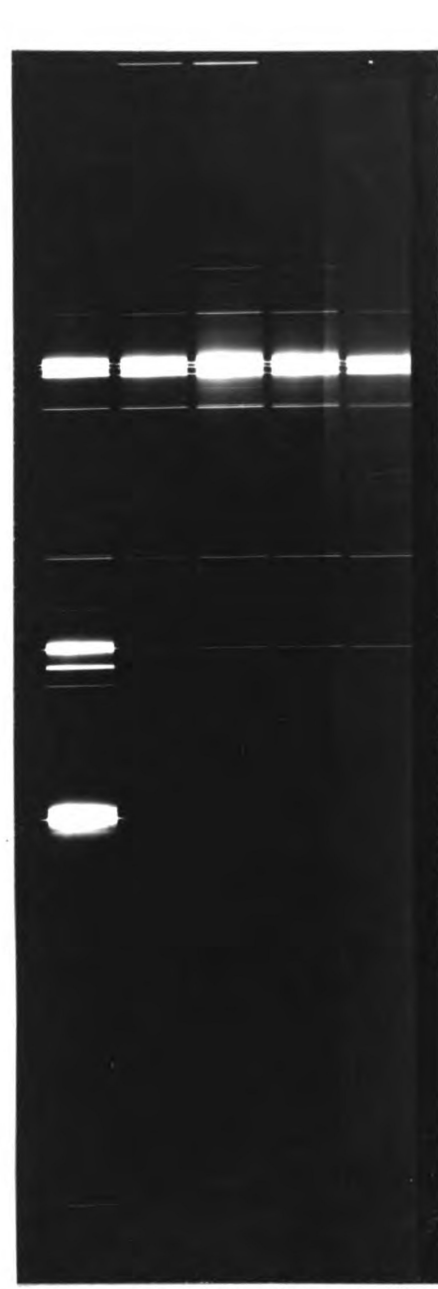

FIGURE 3

is further reduced in intensity due to absorption by the glass in the system.

C. Production of photograph

Fig. (4) shows the experimental arrangement used to photograph the fringe system. The white light fringes were obtained and the mercury arc was then filtered to give only the λ = 5460Å wavelength for the purpose of focussing the camera. It was found that the focus was not changed appreciably from the λ = 5460Å wavelength to the 3654Å wavelength. The 5460Å filter was then replaced by the 3654Å filter, and a photograph made of the fringe system. An enlargement of such a photograph is given in Fig. (5).

The camera was a Century with a double extension bellows, which was used at full extension, and an f7.5 Graf anastigmat lens, which was used at the widest aperture. This gave a picture of the fringe pattern of about 3 cm x 3 cm in size, on which the fringes were adjusted to about a millimeter apart. A three second exposure on Eastman Super Ortho Press film was given, and the film was then developed four minutes in slightly dilute D-11 developer. This film was used to preclude any possibility of red light which might pass through the filter, effecting the film, since this film is not sensitive to the red.

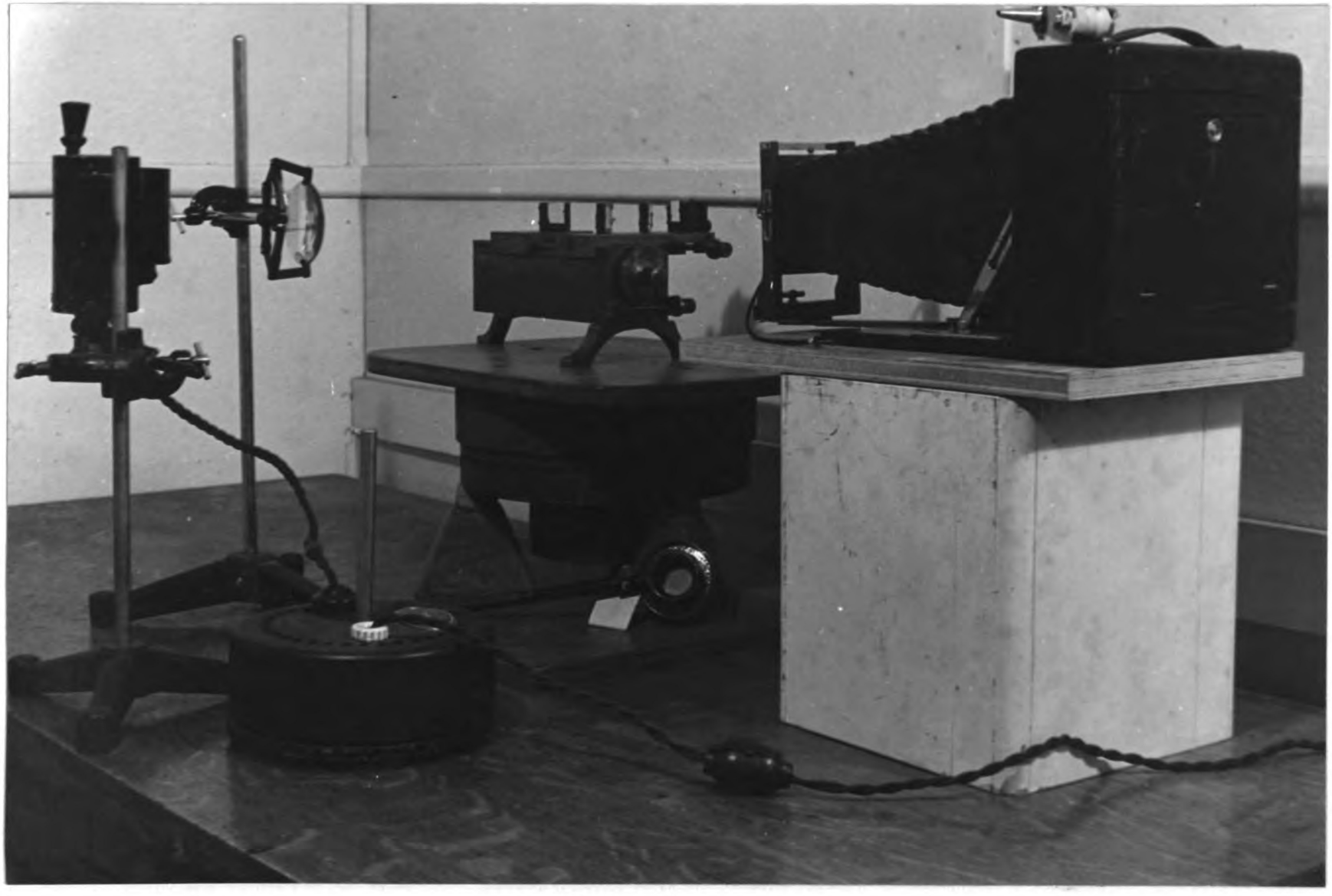

FIGURE 4

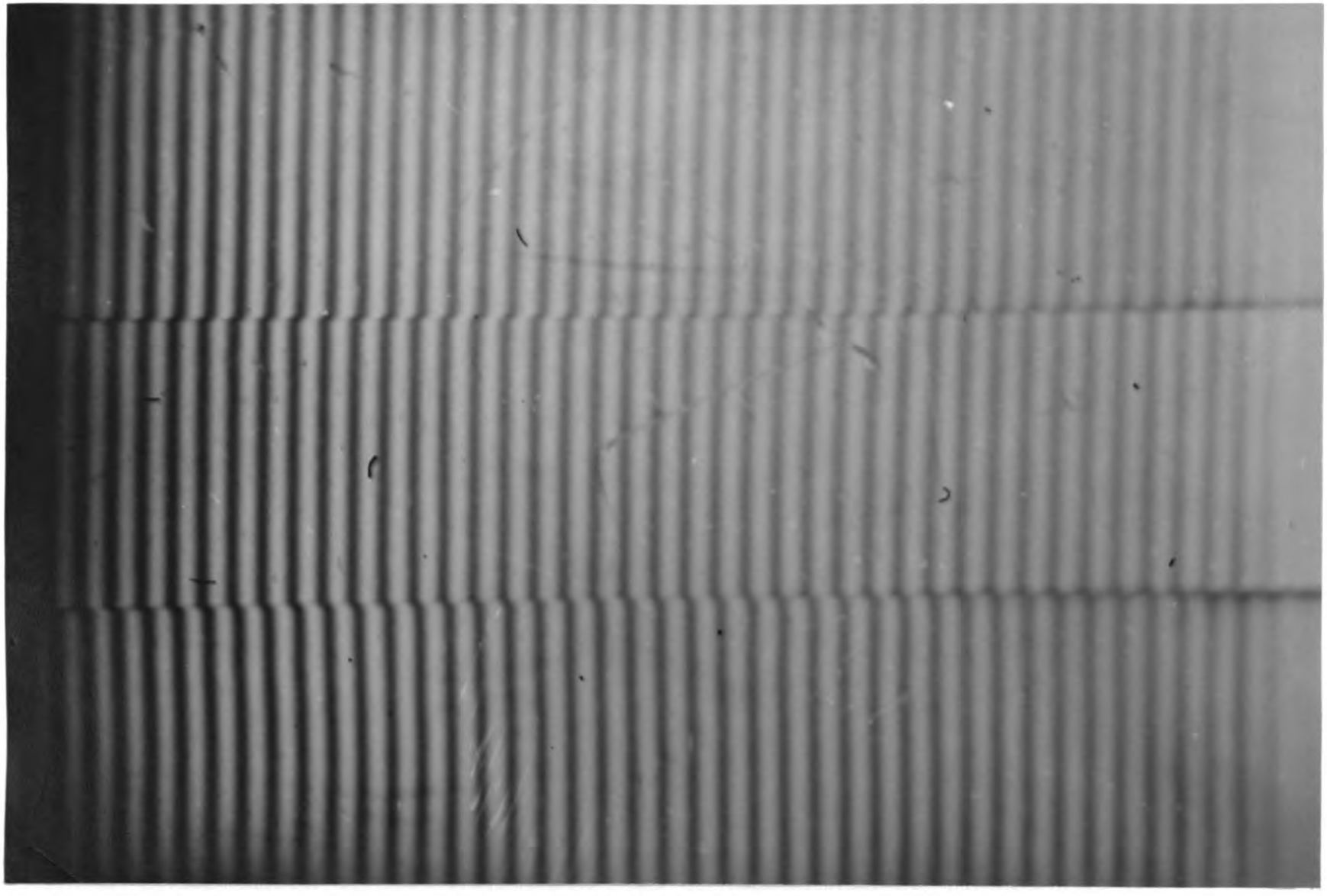

FIGURE 5

Three photographs were made of the fringe pattern produced by each interferometer plate, for the purpose of checking more accurately the actual thickness of the deposited film. Comparison of these results also gives a measure of the accuracy in the determination of the thickness.

D. Measurement of photographs

In order to measure these photographs to obtain the thickness of deposited aluminum on the targets, the film was first cut to a size of 2" x 2" so as to fit in the standard Eastman Kodaslide projector. The image of the fringe system was formed on a large sheet of paper fastened to a vertical support, so the projected image was approximately 50 cm x 50 cm. As can be seen later, and as is shown in Fig. (6) it is best that this paper be cross-ruled. The projected image was adjusted so the fringes ran parallel to the horizontal rulings and the "step" in the fringe pattern ran parallel to the vertical rulings.

On each side of the "step" in the projected fringe pattern, a small mark was placed in the center of each light fringe. The light fringes were chosen because of the greater ease in estimating the center of the fringe. This was done for both lines where the fringes were displaced and altogether gave a measurement on about 30 fringe shifts.

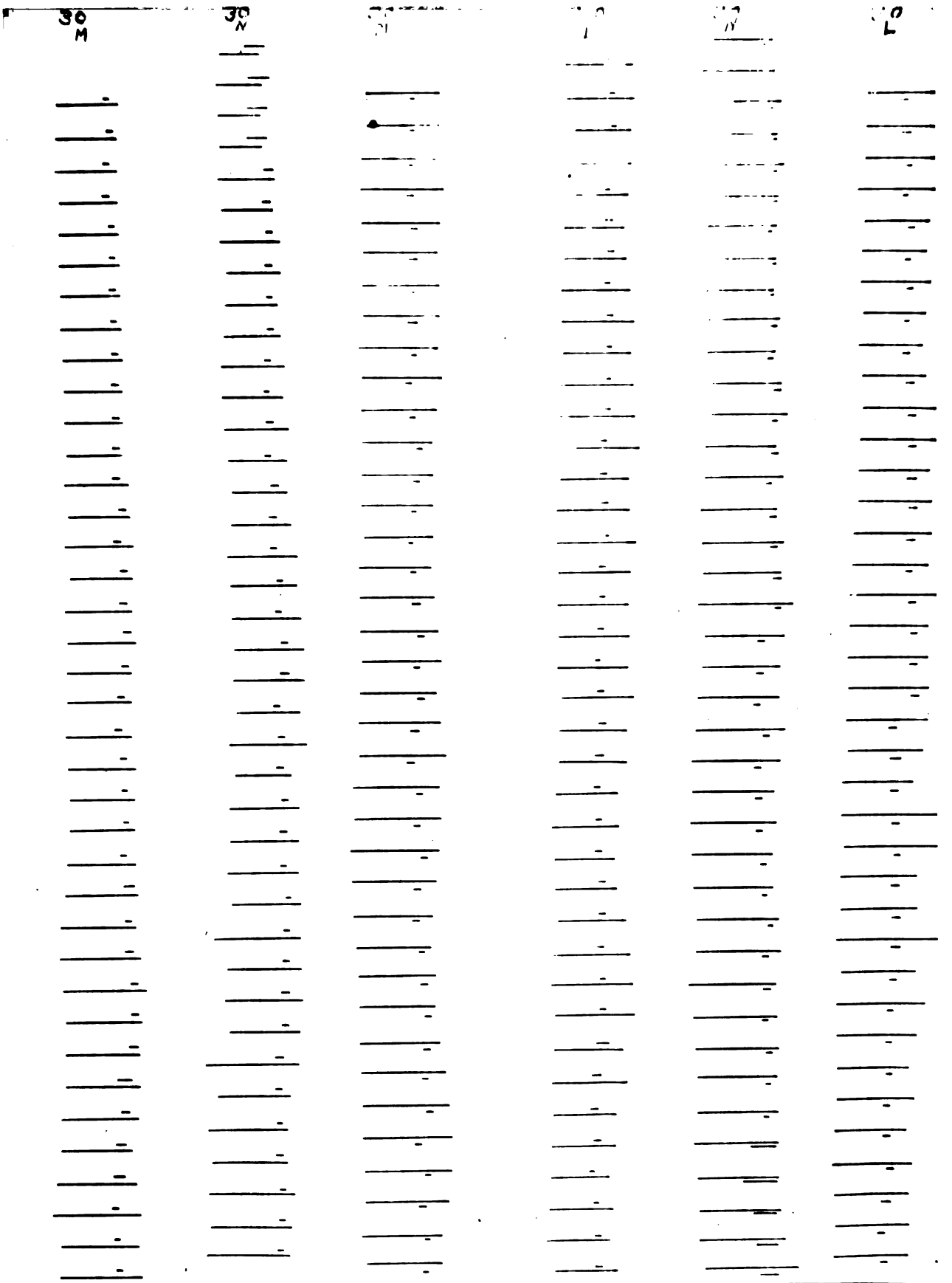

FIGURE 6

The paper was then removed from the support, and as can again be seen by referring to Fig. (6), lines were drawn through the marks on one side of the "step", parallel to the horizontal rulings, and consequently parallel to the fringes, over through the system of marks on the other side of the "step". By direct measurement, therefore, the distance of one fringe line from the corresponding one on the other side of the "step" will represent a number proportional to the fringe shift, while the distance between two consecutive lines on the same side of the "step" will represent the corresponding fringe separation. From these two measurements, the fractional shift may be determined.

To measure all the shifts and separations on one plate, a steel scale was placed so that readings could be made on the lines from one side of the "step", and on the points marked on the other side. The scale was set in one position and successive readings taken down the length of pattern (Table II). This was then repeated for the fringe shift on the other side of the plate, and the averages of all the fringe shifts and separations made. The fractional shift then calculated, multiplied by 3654/2 Å gave the thickness of the metallic film in Angstrom Units. That this method gives accurate values of the thickness can be seen from the tabulated data

Table II

Sample data sheet for computation of thickness of thin metallic films. Interferometer plate 30, photograph M.

scale (mmx10) lines	scale (mmx10) points	fringe width	fringe shift	scale (mmx10) lines	scale (mmx10) points	fringe width	fringe shift
0	27		27	0	13		13
111	136	111	25	126	144	126	18
240	269	129	28	254	282	123	28
364	393	124	31	380	403	126	23
491	518	127	25	514	535	134	21
615	644	124	29	629	655	115	26
750	784	135	34	761	784	132	23
865	905	115	40	881	907	120	26
1004	1033	139	29	1006	1034	125	28
1132	1165	128	33	1126	1145	120	19
1262	1294	130	32	1255	1283	129	28
1387	1417	125	30	1384	1407	129	23
1515	1545	128	30	1512	1538	123	26
1639	1666	124	27	1632	1656	120	24
1767	1806	128	39	1760	1780	128	20
1891	1925	124	34	1882	1899	122	17
2026	2058	135	32	2000	2024	118	24
2147	2185	121	38	2135	2152	135	17
2270	2312	123	42	2255	2278	120	23
2398	2425	123	27	2380	2404	125	24
2535	2558	137	23	2500	2532	120	32
2651	2680	116	29	2632	2658	132	26
2770	2812	119	42	2756	2783	124	27
2895	2938	125	43	2882	2910	126	28
3025	3055	130	30	3010	3038	128	28
3153	3173	128	20	3130	3163	120	33
3270	3300	117	30	3270	3287	140	17
3397	3424	127	27	3394	3414	124	20
3513	3543	116	30	3509	3542	115	33
3643	3663	130	20	3630	3668	121	38
3768	3795	125	27	3774	3801	144	27
3890	3916	122	26	3882	3916	118	24
4013	4045	123	32	4021	4046	129	25
4145	4170	132	25	4148	4175	127	27
4266	4296	121	30	4281	4297	133	16
4389	4422	123	33	4405	4426	124	21
4515	4542	126	27	4541	4555	136	14
4638	4670	123	32	4653	4687	112	34
4766	4798	128	32	4783	4808	130	25
4903	4927	137	24	4901	4932	118	31

Mean shift 27.5 Fraction .218 .218 x 3654/2

Mean width 126 = 398A

Table III

Results of the measurement of thickness of thin metallic films.

Plate		30	31	33
PHOTO	L	406A	424A	400A
	M	390A	400A	415A
	N	390A	406A	398A
Average		395A	410A	404A

(Table III) on the results for the thicknesses, as computed from the three photographs of each of three separate evaporations. As can be seen, the maximum uncertainty is about ± 10Å in 400Å, while the probable uncertainty is less than that. These results also show the uniformity of film obtained from separate evaporations, using similar conditions and equal quantities of aluminum. The maximum deviation from the mean of these three is ± 6Å which is within the experimental uncertainty of the measurement of one thickness.

VI Measurement of Absolute X-ray Intensities

A. Production of x-rays

1. X-ray Tube

As was stated previously, the theory with which we are making comparisons is based on the assumption of a single bombarding electron of known total energy striking an isolated atom, which may result in the production of a quantum of continuous x-ray energy at a specific frequency and a certain azimuthal angle. The following will show how these are satisfied.

The experimental tube which is shown in Fig. (7) is made of a steel cylinder of 3" diameter and 2" depth with a solid bottom and removable top. From the center of the bottom runs a 2" pyrex tube to the oil diffusion pump for evacuation. Another pyrex tube of 1-3/4" diameter is

A ANODE

T TARGET

K CATHODE

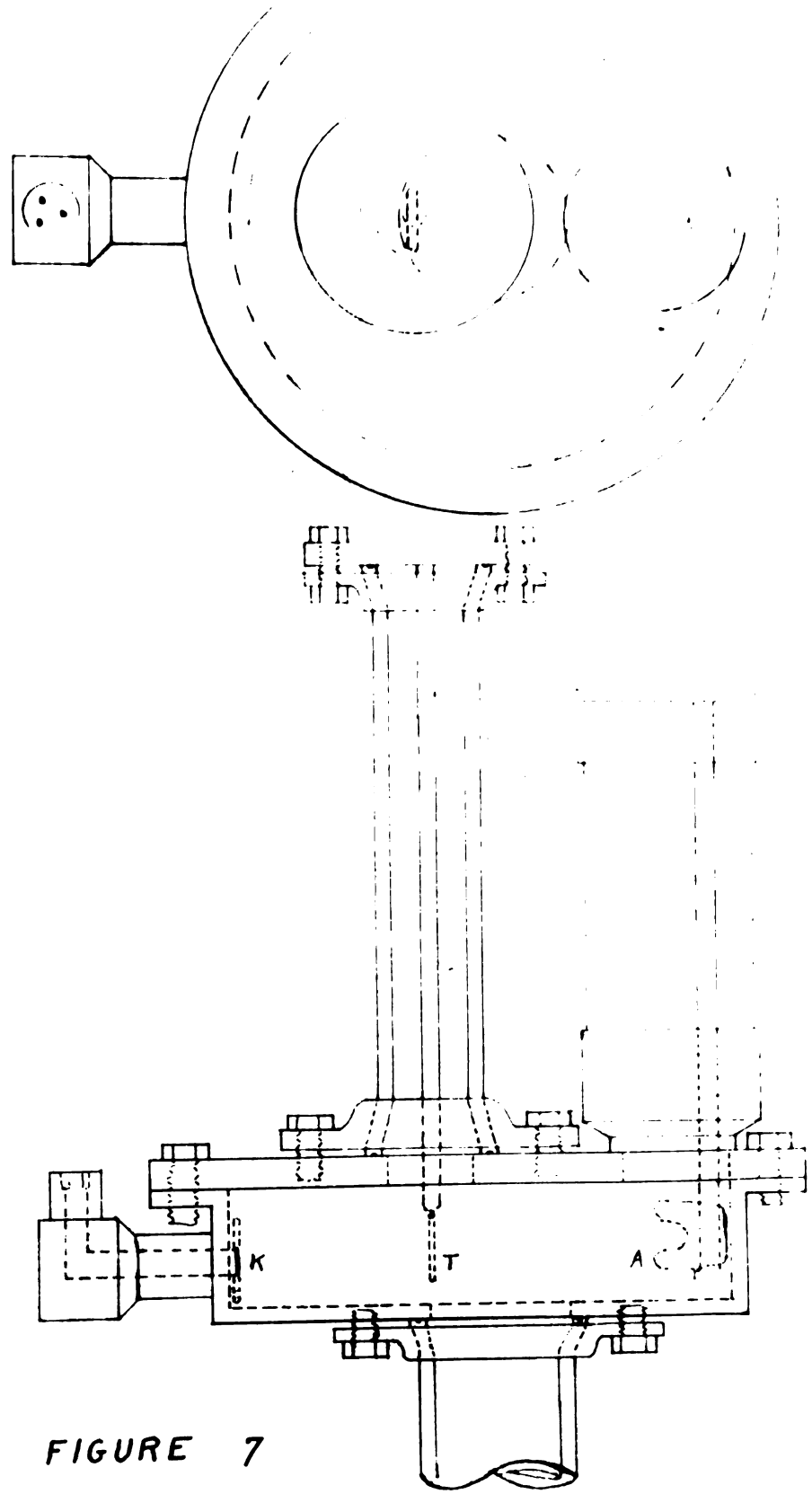

FIGURE 7

mounted in the removable top of the tube one inch off center in the direction toward the cathode. The thin target anode is mounted on the end of a brass rod which extends to and is fastened to a removable brass plate at the top of this tube. This allows the changing of the thin targets. The aluminum anode cup is mounted on the same diameter of the tube as the thin target and is fastened to the tube in a similar manner except the top plate is not removable, and the pyrex tube diameter is 2-3/4". The cathode is mounted on the wall of the tube on the same diameter as the anode and thin target. It is a spiral tungsten filament surrounded by an iron ring for focussing purposes. The x-rays are permitted to leave the tube through a 3/4" slot in the side of the tube which is covered with an aluminum window of .0193 cm thickness. This thickness does not seriously diminish the x-ray beam due to its low absorption coefficient at the wavelength used, but it must nevertheless be taken into account later for the absolute intensity measurements.

From the foregoing it is seen that the anodes are well insulated from the tube itself, and since the whole tube is at the negative potential, all the space current will be collected on the anode. The tube must be insulated from the ground for one-half the potential on the tube, which is accomplished by mounting it on four porcelain insulators.

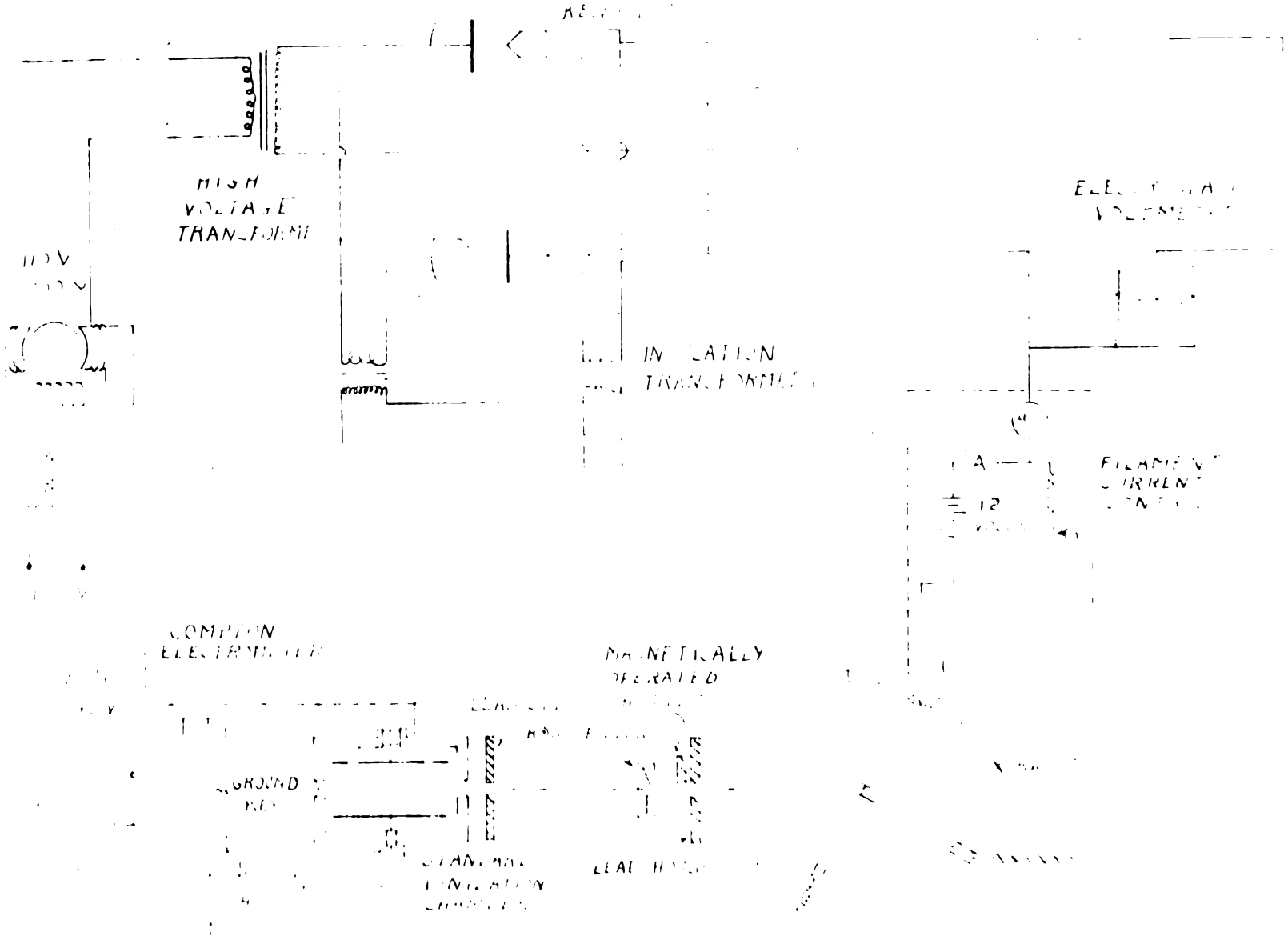
HIGH
VOLTAGE
TRANSFORMER
IGNITION
TRANSFORMER
FILAMENT
CURRENT
12
COMPTON
ELECTROMETER
MAGNETICALLY
OPERATED
GROUND

FIGURE 8

2. Voltage Source and Control

The High voltage circuit used (Fig. 8) is a voltage doubler circuit using two rectifier tubes, and supplied by a 500 cycle generator. The electrostatic type voltmeter used was calibrated from short wavelength limit measurements using a Bragg spectrometer. The voltage is controlled by controlling the current in the field coils of the generator. Thus it can be seen we have satisfied one of the theoretical conditions - that the energy of the bombarding electron be accurately known.

3. Current Source and Control

The current is supplied by two storage batteries and since the quantity used is so small, it is necessary that the whole circuit be shielded at the cathode potential in order that corona currents do not interfere with the measurements. The ammeter is connected between the shield and the current source, and will therefore give the space current of the x-ray tube. The galvanometer used is a General Electric cat 32c 236 G1 and was calibrated in the position used. The sensitivity was determined to be $.93 \times 10^{-8}$ amperes per division. This high sensitivity allowed the use of very small currents on the order of 9.3×10^{-3} amperes, which small current more nearly approximates the theory, and also aids in prolonging the life of the target, which breaks very easily with high currents.

B. Ross' balanced foils

For isolating a certain frequency of radiation, a method devised by Ross (6) and discussed by Kirkpatrick (7) was used. Two filters of adjacent elements in the periodic table are made such that their absorption is the same for all wavelengths except for that region between the two K absorption limits. If first one and then the other filter is imposed in the beam of radiation, the difference in the electrometer deflections will be a measure of the effect of that band of wavelengths between the two K absorption limits. The more narrow this band is, the more nearly monochromatic will be the effective radiation, but on the other hand, it must be large enough to give a measurable difference in electrometer deflections.

H. R. Kelly (2) determined the preferred filter thickness as given by Kirkpatrick(7) for Ag and Cd which were used in this experiment. These elements give a wavelength band of 21.35 XU wide at a mean wavelength of 473.30 XU.

C. Measurement of quantity of x-rays

The quantity of x-rays produced was measured by allowing them to pass into a standard ionization chamber, and measuring the charge produced by means of a Compton electrometer.

The ionization chamber used was cylindrical, made of brass with thin mica windows at either end, aluminum collector plates, and guard rings to insure a uniform electric field on the collector plate. It was filled with CH_3Br gas at 68 mm of Hg pressure at 27°C.

The sensitivity of the electrometer was calibrated regularly during the experiment by applying a known voltage and noting its deflection. The voltage was applied using a Leeds and Northrup Co. student type potentiometer, and was applied uniformly over the time interval used for the exposure time in the experimental work. This was done for a number of voltages and graphs were made of the deflection plotted against the applied voltage. In all cases, the relationship between applied voltage and electrometer deflection was linear, and the slope of the curve gave a sensitivity of 7120 mm per volt.

In order to find the relationship between the charge collected in the ionization chamber, and the effective voltage this charge puts on the electrometer, it is necessary to know the capacity of the electrometer circuit. This has been determined for the circuit used, by R. E. Esling (8), by noting the deflections produced both by directly applying a voltage, and by applying a voltage to the circuit with a standard capacitance in series. From a plot of the electrometer deflections against applied voltage, and knowing the standard capacitance used, the

capacitance of the electrometer circuit was determined. It was found to be 94 x 10^{-12} farads.

VII Working Equation

Due to the absorption of various materials in the path of the x-rays, all the energy produced at the target in the direction of the ionization chamber will not reach the ionization chamber. Considering the various materials in the path, their thicknesses and absorption coefficients, it has been calculated by Reno (3) for the system used in this experiment, that the ratio of the energy collected by the ionization chamber to that produced at the target is 0.146.

The experimental procedure used was, for each target, to take a large number of readings for each Ross filter in the path. This was done to give a more accurate value of the difference between the two electrometer deflections. Where possible, measurements were taken at two x-ray tube voltages. A sample of this data is included in table IV.

The formula used to reduce the data to $J_\nu d\nu$ comparable to theory can be shown to be:

$$J_\nu d\nu = \frac{CA\epsilon(\Delta V)1.60 \times 10^{-12}}{Sa N\rho \chi_o i t^2}$$

$$= \frac{CA\epsilon\ 1.6 \times 10^{-12}}{Sa N\rho i t^2} \cdot \frac{\Delta V}{\chi_o}$$

$$= K \frac{\Delta V}{\chi_o}$$

Table IV

Table of electrometer deflections

azimuthal angle of observation = 70°
electron current = 9.3 x 10^{-3} amperes
electrometer deflection with Ag filter in path = δ_{AG}
" " " Cd " " " = δ_{CD}
kilovolts = 35.7
exposure time = 30 seconds

Ross foil	δ_{AG} (MM)	δ_{CD} (MM)	Mean δ (MM)
Ag	70.4		
Cd		88.0	
Ag	70.0		
Cd		86.2	
Ag	70.2		
Cd		85.0	
Ag	70.4		
Cd		88.0	
Ag	80.0		
Cd		86.3	Ag
Ag	70.4		72.9
Cd		80.2	
Ag	72.5		
Cd		91.0	
Ag	80.0		
Cd		87.5	
Ag	70.0		Cd
Cd		84.3	87.2
Ag	70.0		
Cd		85.5	
Ag	80.2		
Cd		86.0	
Ag	80.9		
Cd		85.5	
Ag	81.2		
Cd		90.0	
Ag	70.7		
Cd		87.0	
Ag	80.0		
Cd		81.0	

Δ = 7.3 mm

Table IV (continued)

azimuthal angle of observation = 60°
electron current = 9.3 x 10^{-3} amperes
electrometer deflection with Ag filter in path = δ_{AC}
" " " Cd " " " = δ_{CD}
kilovolts = 41.74
exposure time = 30 seconds

Ross foil	δ_{AC} (MM)	δ_{CD} (MM)	Mean δ (MM)
Ag	110.0		
Ag	110.0		
Cd		120.2	
Ag	111.0		
Cd		119.3	
Ag	111.2		
Cd		119.2	
Ag	109.7		
Cd		120.0	
Ag	110.0		Ag
Cd		119.7	119.4
Ag	110.2		
Cd		120.5	
Ag	110.8		
Cd		120.7	Cd
Ag	112.4		119.5
Cd		120.3	
Ag	109.2		
Cd		119.8	
Cd		119.2	

Δ = 9.1 MM

The units associated with these terms may be stated as:

C = capacity of electrometer system in farads

A = atomic weight of target material in grams per gram atom

ϵ = energy per ion pair in electron volts

1.6×10^{-12} = ratio of ergs to electron volts

ΔV = potential difference corresponding to electrometer deflections $\delta_{CD} - \delta_{AB}$ in volts

S = ratio of energy measured by ionization chamber to that produced at the target

a = area of defining aperture in square centimeters

N = Avogadro's number in atoms per gram atom

ρ = density of the target material in grams per c.c.

i = x-ray tube current in amperes

t = exposure time in seconds

χ_0 = target thickness in centimeters

As can be seen, if everything but ΔV in the equation is kept constant, and different thicknesses of backing material are used for the targets, then any change in ΔV is due to the effect of the backing material alone. It is possible to do this in this case, provided χ_0 can be kept constant. For any one set of 4 targets, χ_0 is constant since they were made with the same evaporation, but if it is desired to compare data from set to set, χ_0 will not be constant due to the inability to evaporate exactly the same thickness for any two evaporations.

If it is interested only to find the effect due to the backing material, and to find the value of the correction factor, without determining the absolute value of $J_\nu \, d\nu$, we may write:

$$J_\nu \, d\nu = K \frac{\Delta V}{\chi_o}$$

In this manner, the change in $\frac{\Delta V}{\chi_o}$ due to the difference in backing material thickness will give the correction that has to be applied to give correct results for $J_\nu \, d\nu$.

For this work therefore, the results of $\frac{\Delta V}{\chi_o}$ are plotted against backing material thickness and the correction factor determined graphically. These curves, the data for plotting them, as well as a table of the electrometer deflections for the various targets are included in figures 9 and 10, and tables VI and V.

Table V

Electrometer deflections for various targets

Target Set	K Volts	Foil	A δ(mm)	B δ(mm)	C δ(mm)	D δ(mm)
30	36.7	Ag	90.4	79.4	80.1	73.2
398A		Cd	99.8	86.7	90.3	
	41.74	Ag	126.0	111.5		
		Cd	137.3	127.0	127.5	
31	36.7	Ag	97.6	81.9	79.9	
410A		Cd	101.9	87.7	87.2	
	41.74	Ag	133.0	113.2	110.4	
		Cd	143.9	121.8	119.5	
32	36.7	Ag	94.8	85.7		83.9
*402A		Cd	102.2	92.7		88.7
	41.74	Ag	130.9			77.5
		Cd	142.0			84.5
33	36.7	Ag	94.7	79.9	81.4	75.2
404A		Cd	104.5	88.3	88.3	80.9
	41.74	Ag	137.3	114.1	111.6	94.2
		Cd	147.5	124.3	122.6	103.3
34	36.7	Ag	95.0	85.7	81.8	71.8
*403A		Cd	102.7	93.1	89.2	77.7
	41.74	Ag	135.2		110.5	
		Cd	145.2			

*Estimated thicknesses from δ's

Table VI

$$\frac{\Delta V}{\chi_o} = \frac{\Delta\ (\text{SCALE READING})}{7120\ \chi_o}$$

Target		K. Volts	Δ (mm)	x_o (cm)	$x_o \times 7120$	$\Delta / x_o\ 7120$
30	A	36.7	9.4	393 x 10^{-8}	.0283376	331.71
	B		7.3			257.61
	C		10.2			359.95*
	A	41.74	11.3			398.76
	B		15.5			547.98*
31	A	36.7	8.3	410x10^{-8}	.029192	284.32
	B		6.7			229.51
	C		7.3			250.07
	A	41.74	10.9			373.39
	B		8.6			294.60
	C		9.1			311.73
32	A	36.7	7.4	402x10^{-8}	.0286224	258.54
	B		7.0			244.56
	D		4.3			167.70
	A	41.74	11.9			415.76
	D		7.0			244.56
33	A	36.7	9.3	404x10^{-8}	.0287648	340.69
	B		8.4			292.02
	C		6.9			239.88
	D		5.7			198.16
	A	41.74	10.2			354.60
	B		10.2			354.60
	C		11.0			382.41
	D		9.1			316.36
34	A	36.7	7.7	403x10^{-8}	.0286936	268.35
	B		7.4			257.90
	C		7.4			257.90
	D		5.9			205.62
	A	41.74	11.0			383.36

	A	296.72		A	385.17
Average	B	256.32	Average	B	324.60
36.7 KV	C	249.23	41.74 KV	C	347.07
	D	190.49		D	280.46

* Doubtful

VIII Results and Conclusions

The results of these experiments are shown graphically in figures (9) and (10) for the two electron energies used. Five sets of targets, including four different thicknesses of the backing film for each set, are represented on each of the two curves, except cases where the target was punctured or became torn by the electric field before data could be collected. The final curve drawn represents what is considered to be the best average of the data, and the dotted portions of the curve shows the extrapolation to zero thickness of backing film. Since the thicker commercial cellophane is the material most suitable for use in work of this kind at present, comparison between zero thickness and that for the commercial cellophane is made. For the 36.7 kilovolt case the 400Å thick aluminum evaporated upon commercial cellophane, gives values of x-ray intensities at λ = .474A, and leads to a correction value of .58. And for the 41.7 kilovolt case the correction value is .73. Since the correction value is to be multiplied by the experimental value obtained with cellophane, this data shows the correction to be smaller for higher electron energies and this is what would be expected if the increase in x-ray intensity is due to the rediffusion of electrons within the backing film.

When these correction values for experimentally

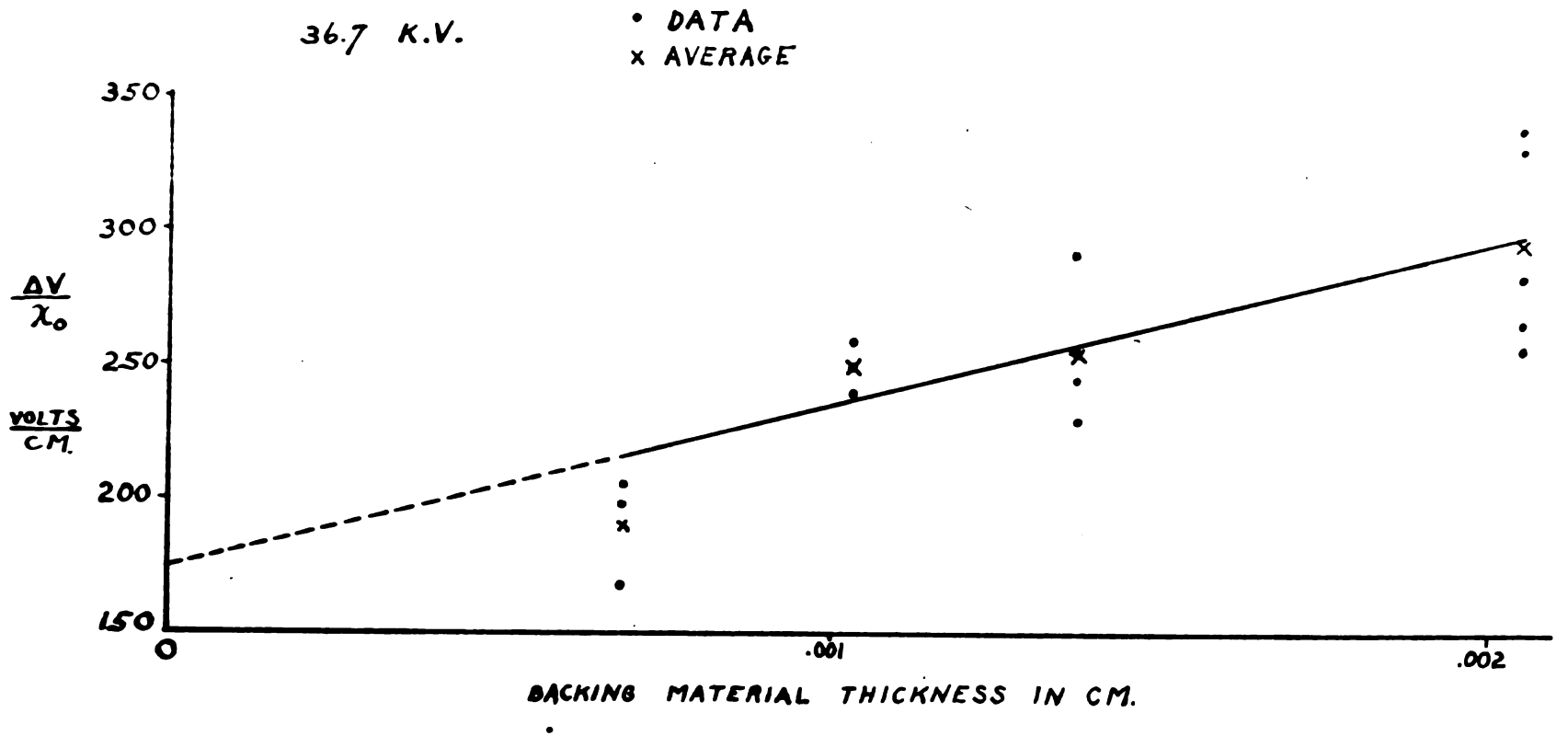
36.7 K.V.
• DATA
x AVERAGE
350
300
250
200
150
0
.001
.002
ΔV / χ₀
VOLTS / CM.
BACKING MATERIAL THICKNESS IN CM.

FIGURE 9

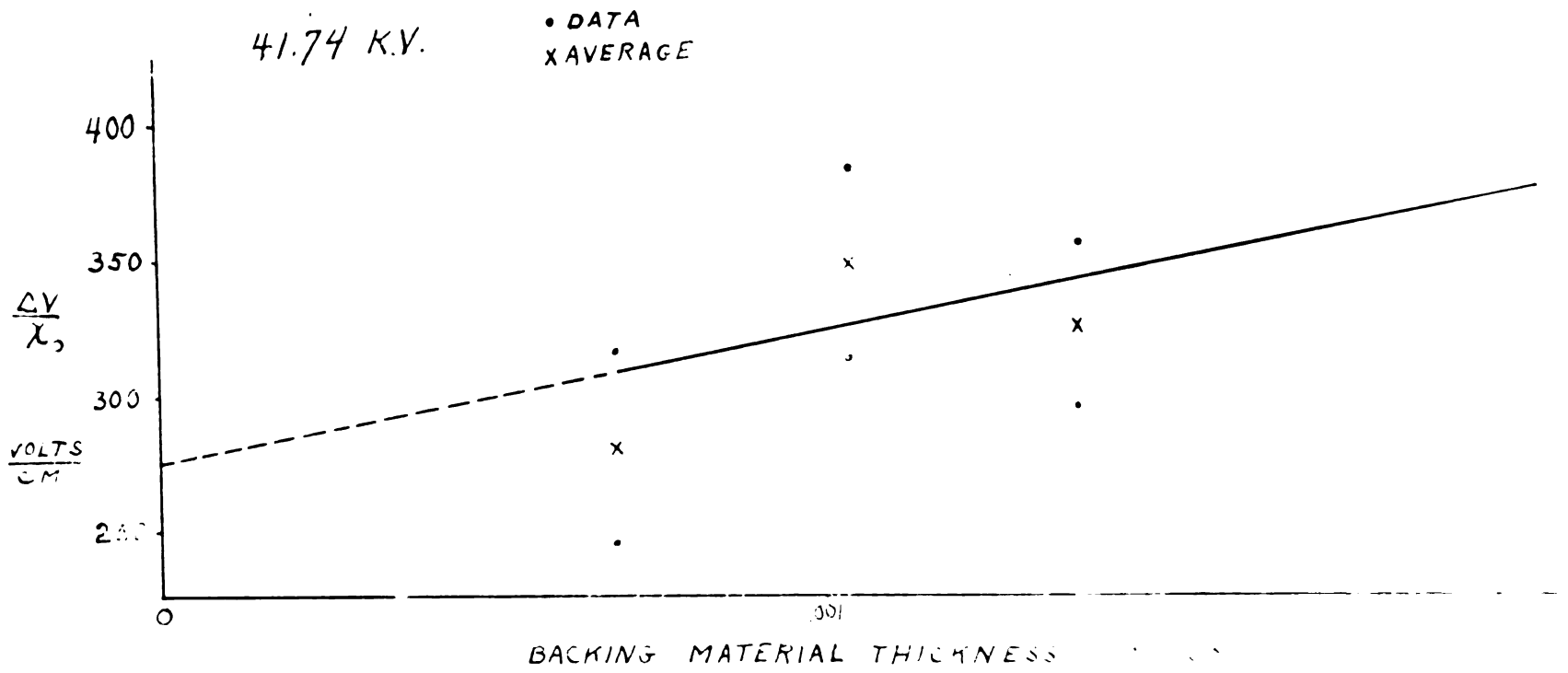
41.74 K.V.
• DATA
X AVERAGE
400
350
300
ΔV/λ
VOLTS/CM
0
.001
BACKING MATERIAL THICKNESS

FIGURE 10

determined intensity are applied to Reno's (3) experimentally determined values of absolute intensity, one obtains:

	$J_\lambda d\lambda$ (EXPERIMENTAL)	$J_\lambda d\lambda$ (THEORETICAL)
36.7 KV	$.88 \times 10^{-36}$	1.25×10^{-36}
41.7 KV	1.71×10^{-36}	1.15×10^{-36}

The data for $J_\lambda d\lambda$ thus corrected are still in appreciable error with Sauter's corrected theory. The technique for properly handling these very thin targets and then measuring the weak x-ray intensities is as yet imperfected, and one can only conclude that the results obtained compare favorably only as regards order of magnitude.

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