CLM - R 11

United Kingdom Atomic Energy Authority

RESEARCH GROUP

Report

FILM CALIBRATIONS AND ABSORPTION CURVES FOR THE X-RAY BREMSSTRAHLUNG OF LOW ENERGY (5-20 KeV) ELECTRONS

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1961

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September, 1961.

HL.61/4433 (C.18)

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Film calibrations and absorption curves are presented for the X-ray Bremsstrahlung generated by monochromatic electrons with selected energies between 5 and 20 KeV. Results for stainless steel and tungsten targets are given. Absorption curves are shown for aluminium and copper absorbers using both target materials. Two isotope calibrations for higher energies are also included. The results are in a form which is convenient for X-ray studies in the C.T.R. field.

FILM CALIBRATIONS AND ABSORPTION CURVES FOR THE X-RAY BREMSSTRAHLUNG OF LOW ENERGY (5-20 KeV) ELECTRONS

1. Introduction

A significant fraction of the discharge energy in Zeta is carried to the torus walls by non-thermal electrons. On striking the stainless steel liner the electrons generate X-Rays with energies ranging from 1 KeV to several MeV. However only those of the order of 10 KeV are intense enough to represent any appreciable energy loss from the plasma. The study of these X-Rays by photographic techniques affords a convenient method of determining the electron energies and intensities. [1]

Before these techniques can be applied calibration curves for various films and absorption curves for selected absorbers must be determined. Published data is largely for monochromatic or filtered X-Rays and cannot be conveniently applied to the continuous X-Ray spectrum emitted from Zeta. The calibrations are required in terms of the energy deposited by monoenergetic electrons on a known target at a fixed distance from the film. The absorption curves are required for X-Rays generated by monoenergetic electrons striking a known target. Experimental conditions on Zeta make it necessary for the absorbers to be placed in contact with the film. Consequently the same arrangement was used for the absorption calibration. Fluorescent radiation may contribute to the darkening of the film.

Two materials are of particular interest as targets, stainless steel (Cr. 17.5%, Ni 7.5%, Si 0.9%), and tungsten. Stainless steel is the material from which the Zeta liner is constructed, and tungsten, because of its high atomic number and good refractory properties, is often used when an X-Ray target is introduced into a discharge. [2. 3.]

A simple X-Ray set has been used to obtain the required calibration and absorption curves. In this report calibrations are given for three types of film (see section 2), for 5, 8, 10 and 20 KeV electrons incident on targets of stainless steel and tungsten. Calibrations for monochromatic X-Rays from Co^{60} and Cs^{137} isotope sources are included to indicate the form of curves at higher energies. Absorption

curves in aluminium and copper for X-Rays generated from stainless steel and tungsten targets by 5-10 KeV electrons are given.

The apparatus and methods used to obtain the curves are described.

2. Films calibrated

2.1 Recordak Microfile (Kodak)

Though not manufactured for use as an X-Ray film this film provides a useful low speed emulsion.

2.2 Industrial 'F' (Ilford)

A slow double sided industrial X-Ray film of fine grain and high contrast, roughly ten times faster than Recordak.

2.3 Industrial 'G' (Ilford)

This is a very fast high contrast double sided industrial X-Ray film, in turn some ten times faster than Industrial 'F'.

2.4 Intensity Range

Together these three films cover a wide range of sensitivities and can be used for detecting X-Rays with as much as $3X10^4$ variation of intensity. This has proved sufficient for X-Ray measurements on Zeta.

3. Experimental Methods

3.1 The X-Ray Set

The X-Ray Set is shown in Fig. 1. The centre cross-piece was made from aluminium tubing to prevent the formation of surface changes which can defocus the electron beam. Satisfactory focussing was then obtained by surrounding the hairpin tungsten filament with a 1.25cm diameter copper cylinder maintained at -60 volts. The target was held in a 1 inch diameter mild steel bar which served to conduct heat away. The film was 49 cm from the target. The inter-space between the two loading valves was pumped by a separate rotary backing pump, so that the films could be changed without disturbing the main vacuum system. E.H.T. for the X-Ray Set was provided by a 0-30 K.V. Brandenburg generator. An ionization gauge power unit, type 1075D was modified to stabilize the emission current at 100 μ A. and 450 μ A.

3.2 Calibration Using the X-Ray Set

For Calibration exposures the film was held in circular, 1.1/4 inch diameter cassettes, having a light seal of 2×10^{-4} inch, (5×10^{-4} cm) aluminium foil. Each exposure was made with a separate cassette as described below:-
One cassette was loaded into position between the two valves, V_1 and V_2 Fig. 1, and pumped down to a pressure lower than 2×10^{-2} torr. by the rotary pump, before opening V2 to the high vacuum. The pressure in the X-Ray Set was allowed to fall to below 2.5×10^{-5} torr. before each exposure. The diffusion pump was trapped with liquid nitrogen to prevent pump oil diffusing into the X-Ray Set and contaminating the target. The target was cleaned with emergy paper and washed in alcohol before each set of exposures.

Before any calibration exposures were made an X-Ray pinhole photograph was taken to check that the electron beam was focussed on the target. Fig. 2 shows two typical pinhole photographs, Fig. 2(a) is at an applied voltage of 5 K.V. and Fig. 2(b) is at 20 K.V. The target is faintly discernible and the position of the electron beam striking the target is clearly defined. In this region the film is saturated.

Exposures were made at a series of constant voltages for various times of exposure, with currents of 10, 100, and 450 μ A. With each set of exposures one film was left clear to provide a control for density measurements.

3.3 Calibration Using Isotope Sources

For calibration at high energies Industrial 'G' X-Ray film was subjected to gamma radiation from two standard isotope sources, namely:

Cs^{137}	Gamma Energy	662 KeV	Dimensions - 4mm diameter 5mm thick
Co^{60}	Gamma Energy	1.25 MeV	(Transitions of 1.17 MeV and 1.33 MeV). Dimensions - 4mm diameter 4mm thick.

A lead block was drilled in such a way as to accommodate the sources and to collimate the gamma rays. The film to be exposed was then placed under the block with an aluminium spacer maintaining the source 1cm. from the film. The calibration was performed by making a series of exposures of varying duration.

The specific activity (mc/gm) of the standard isotope is known, together with the geometrical factors involved. Thus the number of photons/cm^2 incident on the film for a given exposure can be determined. Scattering and self absorption effects have not been taken into account.

3.4 Absorption Measurements

The films for absorption measurements were exposed in the same way as the calibration films. Aluminium or copper absorbers were placed in front of, and in contact with, the film to be exposured, generally four different absorber thicknesses were used in each cassette. Fig. 3 is a print of a typical film exposed with absorbers.

3.5 Film Processing

The films were developed in 'Ilford P.Q.X.-1. High Contrast X-Ray Developer', diluted one part developer to three parts water. The dilution was accurately carried out using standard measuring flasks, and the temperature was standardised to $20^{\circ}C \pm 1^{\circ}C$. Industrial 'G' and Industrial 'F' films were developed for 6 minutes, Recordak was developed for 4 minutes. The films were agitated for 5 seconds at 30 second intervals. A dark green safe light (ILFORD G.B. No. 908) was used with Recordak, and a light green (ILFORD X. No. 905) for Industrial 'G' and Industrial 'F'. All films were fixed for $2\frac{1}{2}$ minutes in 'Amfix' at the recommended dilution (1 + 3).

3.6 Density Measurements

Film densities were measured on a Joyce Loebl Recording Microdensitometer. This instrument incorporates a double beam system in which the two beams originate from a single light source and terminate in a single photomultiplier. Thus the machine is independent of its own parameters and good reproducibility of records is possible.

The exposed and the control (clear) films are compared with linear grey wedges of known density gradient, the density difference between the two films being recorded directly.

4. Description of Graphs

4.1 Calibration Curves from the X-Ray Set (Fig. 4 - Fig. 8)

Beatty's Law indicates that the efficiency of X-Ray production is proportional to the atomic number of the target material and to the target voltage. Calibration graphs are plotted showing film density against the logarithm of, the Beatty's Law Parameter (ZV) multiplied by the Electron Energy (VIt), at a series of applied voltages. ZV^2It is expressed in joule-volts; Z is the atomic number of the target material; V is the potential difference, measured in volts, between the target and filament; I is the current, in amps, passing through the X-Ray set; and t is the exposure time in seconds. The logarithmic plot is convenient because it gives a straight line at densities greater than 1.5 density units; at densities below this, however, there is, as is well known, a linear relationship between density and intensity.

The density of each film was measured as described in section 3.6. A separate set of calibration curves was produced for each of the films and for each of the two target materials.

Calibrations have been made during the period September 1959 to July 1961 and are reproducible to better than $\pm 1\%$, although samples of film over this interval are likely to have come from different production batches. On the 10 K.V. Industrial 'G' and Recordak calibration curves, (Figs. 4 & 6) using a stainless steel target, are some results obtained by G. Barsanti in January 1960. The main curves were produced in June 1961.

4.2 Calibration Curves Using Isotope Sources (Fig. 9)

For each isotope source the film density is plotted against the photons/cm^2 incident on the film.

4.3 X-Ray Set Absorption Curves (Fig. 10 - Fig. 12)

The density of the absorber films was measured for each thickness of absorber. A graph was plotted of $\text{Log}_{10} {}^{Io}/_{I}$, I being the transmitted intensity and Io the incident intensity, against absorber thickness at each voltage. I and Io were obtained from the relevant calibration curve.

Aluminium absorption curves were determined for both stainless steel and tungsten targets, but copper absorptions were only made for a stainless steel target.

5. Discussion of Results

The separation of calibration curves for different energies is different for the two target materials. For stainless steel there is an appreciable spread between the calibrations for different applied voltages whereas for tungsten the calibrations for each film type are very close together; this indicates that in the case of stainless steel there are deviations from Beatty's Law. The spacing of the curves gives an indication as to the cause of this, it will be noticed that the 8, 10, 20 KeV curves are disproportionately displaced from the 5 KeV curve. This is probably due to the excitation of iron $K\alpha$ radiation at energies greater than 6.4 KeV.

This radiation is comparable in intensity to the continuum for energies near to, but greater than, the critical energy for excitation[4]. The curves (Fig. 7, 8) show that for a tungsten target, Beatty's Law is closely obeyed.

The aluminium absorption curves (Fig. 10, 11) indicate, that for 10 KeV electrons, the X-Rays from the tungsten target are softer than those from stainless steel. While for 5 KeV electrons the X-Rays from the tungsten target are harder than those for stainless steel. The various components of the X-Ray spectra for iron and tungsten likely to cause these effects are

Iron - Continuum and $K\alpha$ (6.4 KeV)

Tungsten - Continuum, M lines (1.34-2.4 KeV) and $L\alpha$ (8.37 KeV)

An explanation based solely on the shape of the continuum seems unlikely as it would require the intensity of the low energy tail of the tungsten continuum to be relatively more intense than the tail of the iron continuum for 10 KeV electrons, whereas for 5 KeV electrons the opposite would have to be true. The iron $K\alpha$ and the tungsten $L\alpha$ radiation would give the opposite effect to that observed at 10 KeV if they were the dominant factors. However the tungsten M radiation if sufficiently intense can explain the observations. Thus for 10 KeV electrons the M radiation would obviously have a softening effect. Whereas at 5 KeV the mean energy of the

continuum (1.7 KeV) is lower than the energy of most of tungsten M lines (1.39-2.4 KeV).

Aluminium has an absorption edge at 1.56 KeV resulting in a "window" for X-Rays below this energy. This "window" is blocked if the aluminium is preceded by a suitable thickness (5×10^{-3}") of beryllium. The effect of using this beryllium in front of the aluminium absorbers is shown for a number of energies in Fig. 11. In all cases the beryllium causes an apparent hardening, this shows that for 5 KeV electrons the three tungsten M lines that lie within the window are unimportant. If this were not the case the beryllium would have softened the 5 KeV curve (tungsten target) since X-Rays within the window have the same absorption coefficient as 4 KeV X-Rays.

The mass absorption coefficients derived from the limiting gradients of the curves in Fig. 10 are similar to those for the maximum photon energies generated. For example, the mass absorption coefficients obtained from the 10 KeV aluminium absorption curves correspond to those for 7.8 KeV and 3.1 KeV X-Rays respectively[5]. For the 10 KeV case the mean energy of the X-Ray spectrum transmitted through 4×10^{-3} aluminium foil has been calculated and is 7.8 KeV. This suggests that fluorescent radiation from the absorber has little or no effect.

6. Acknowledgements

We are grateful to Dr. A. Gibson, who initiated this work, for helpful discussion and advice. Dr. G. Barsanti* contributed to this work while visiting this Laboratory from December 1959 to May 1960.

* C.A.M.E. Laboratory, Livorno, Italy.

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4. V.E. Cosslett, X-Ray Microscopy and Microanalysis, Elsevier 1960.

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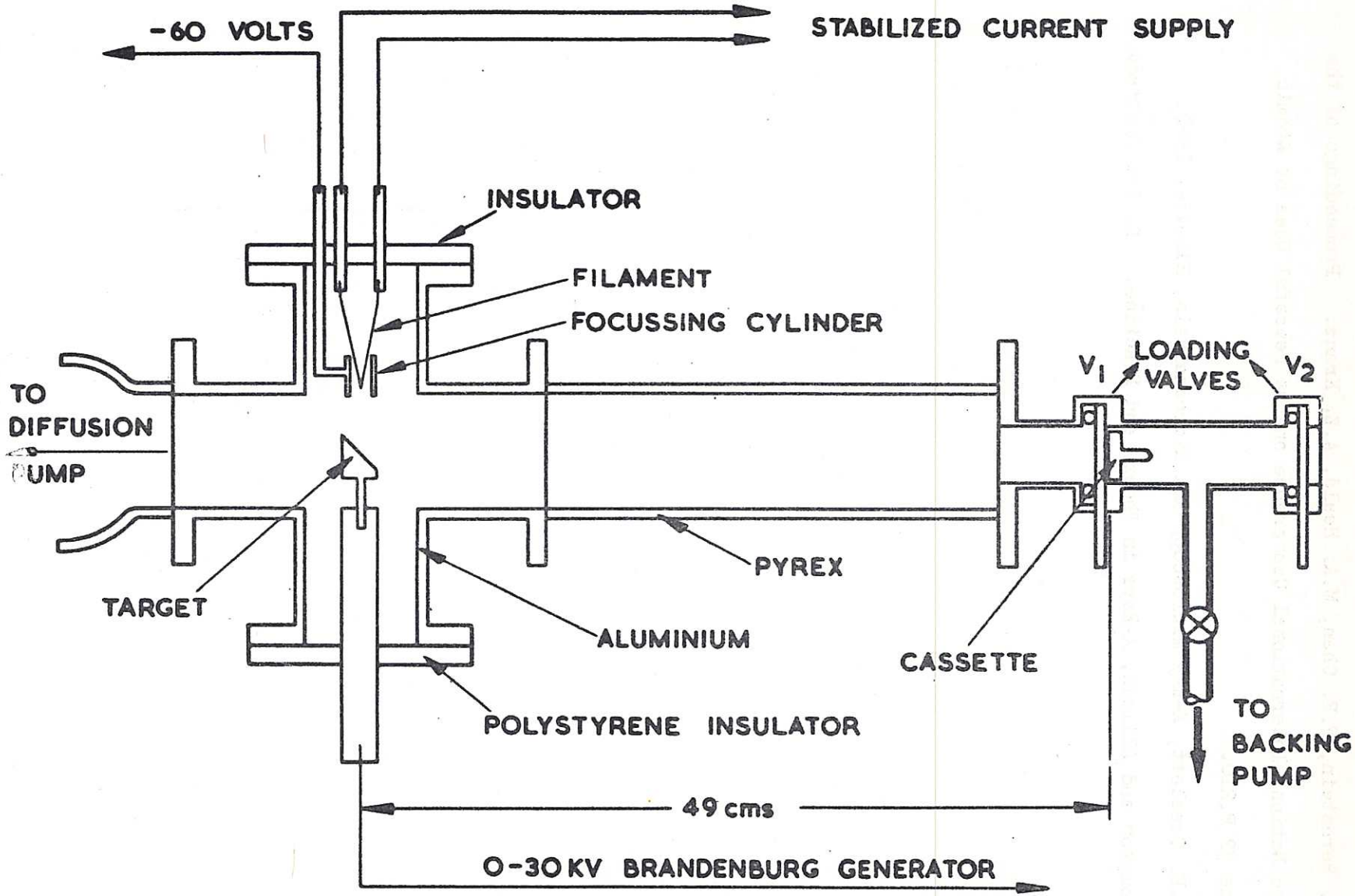
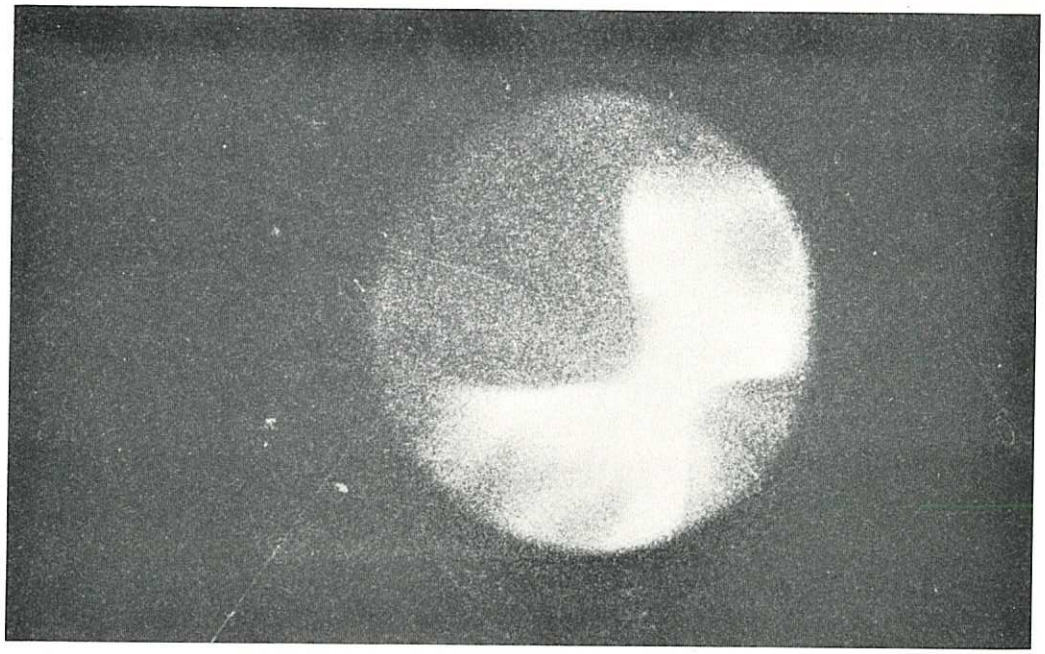
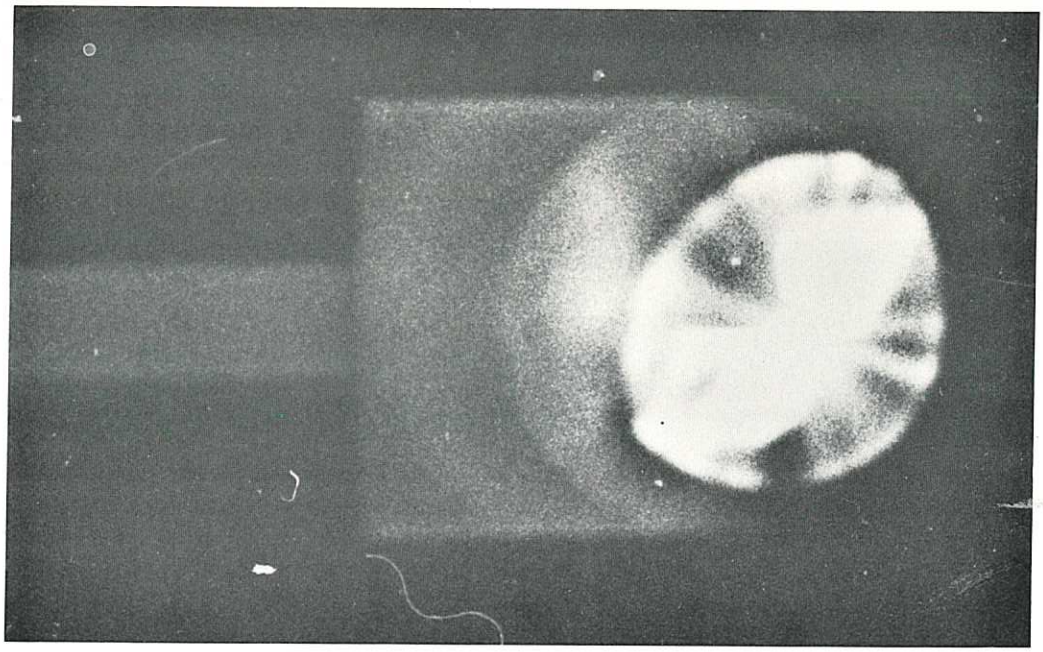


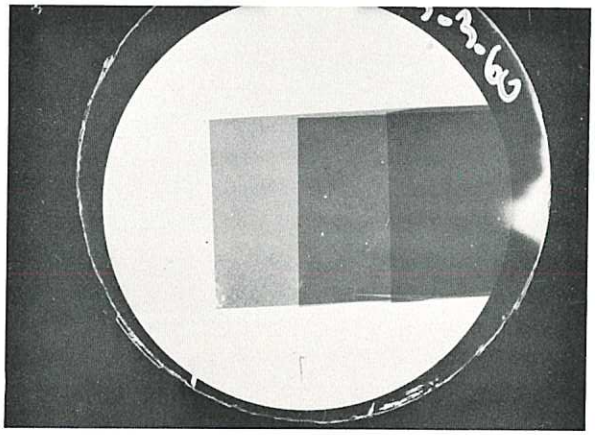
CLM - R 11 FIG. I. SOFT X-RAY SET



CLM - R 11 Fig. 2a
Pinhole photograph at 5 K.V.



CLM - R 11 Fig. 2b
Pinhole photograph at 20 K.V.



CLM - R 11 Fig. 3
A photograph of an absorption exposure

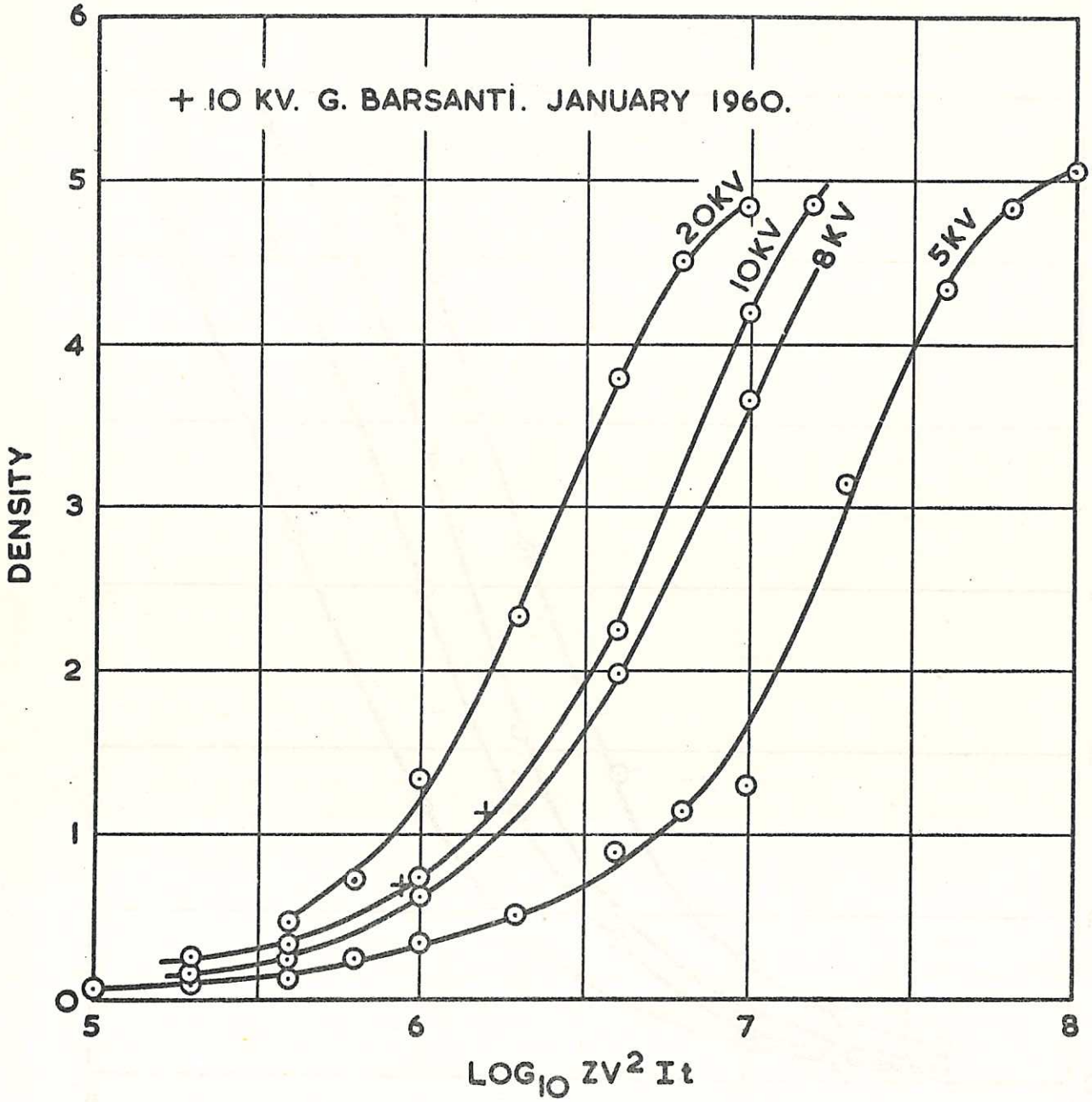


FIG. 4. INDUSTRIAL 'G' CALIBRATION. STAINLESS STEEL TARGET.

CLM - R 11

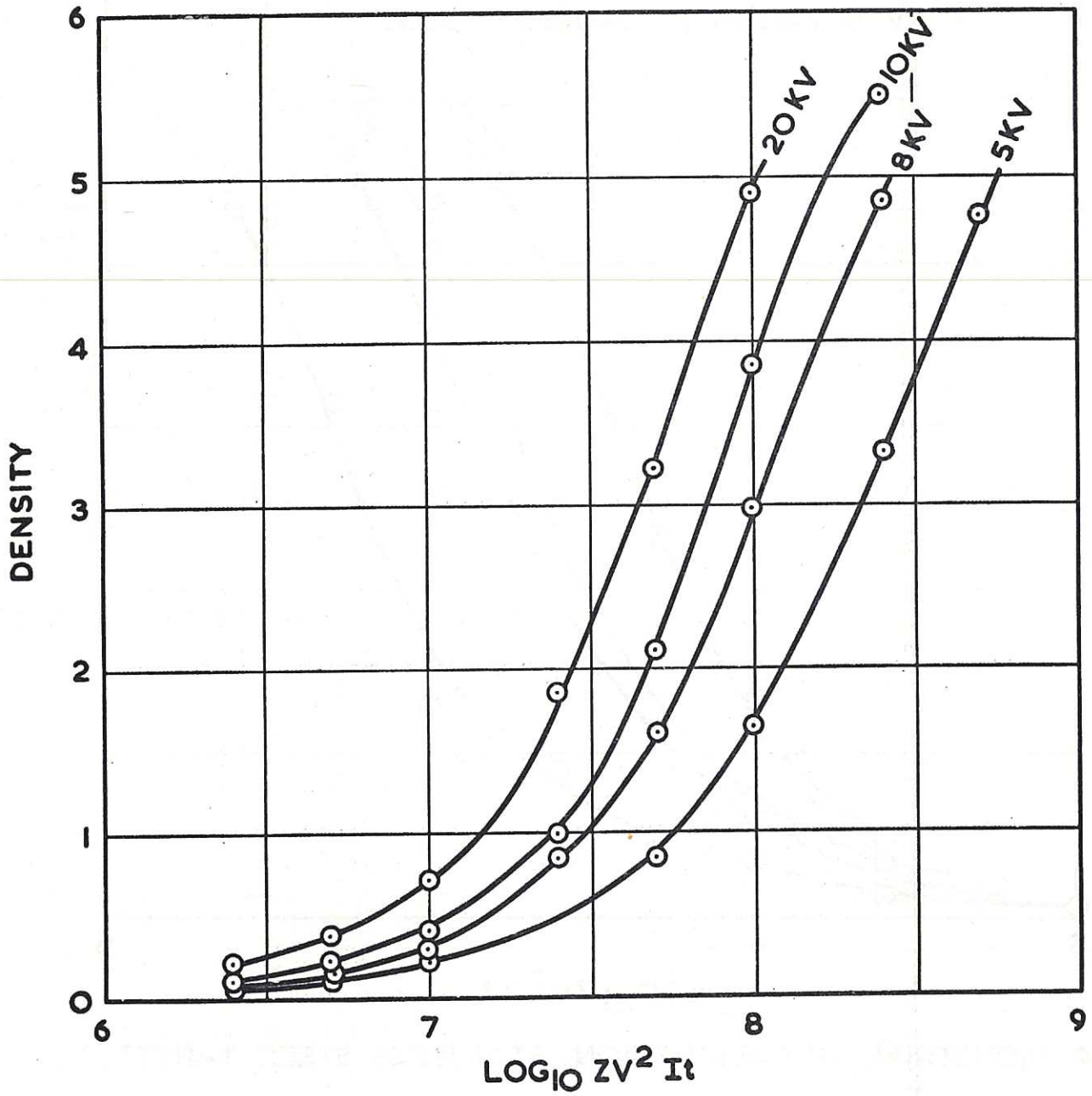


FIG. 5. INDUSTRIAL 'F' CALIBRATION. STAINLESS STEEL TARGET.

CLM - R 11

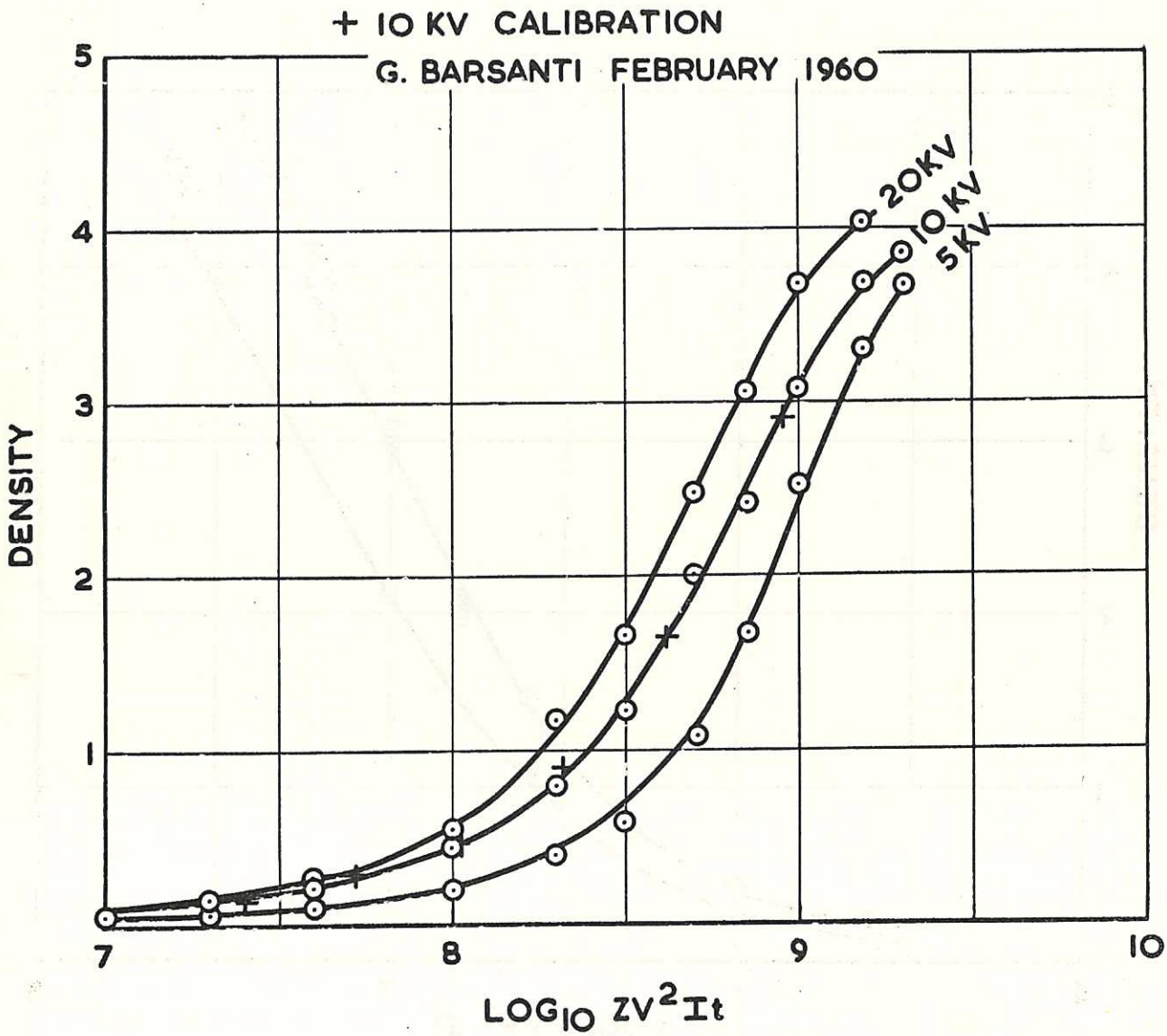
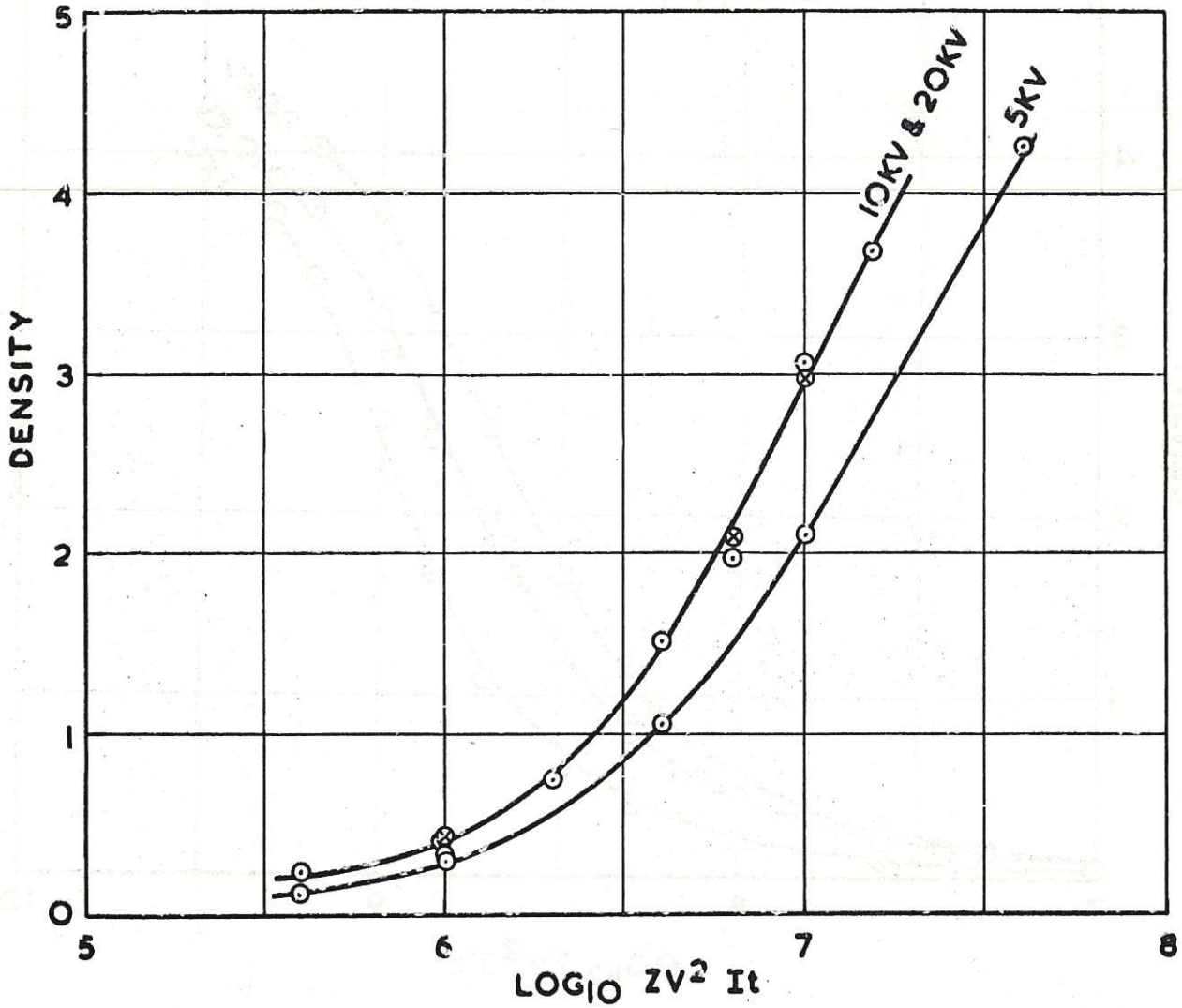
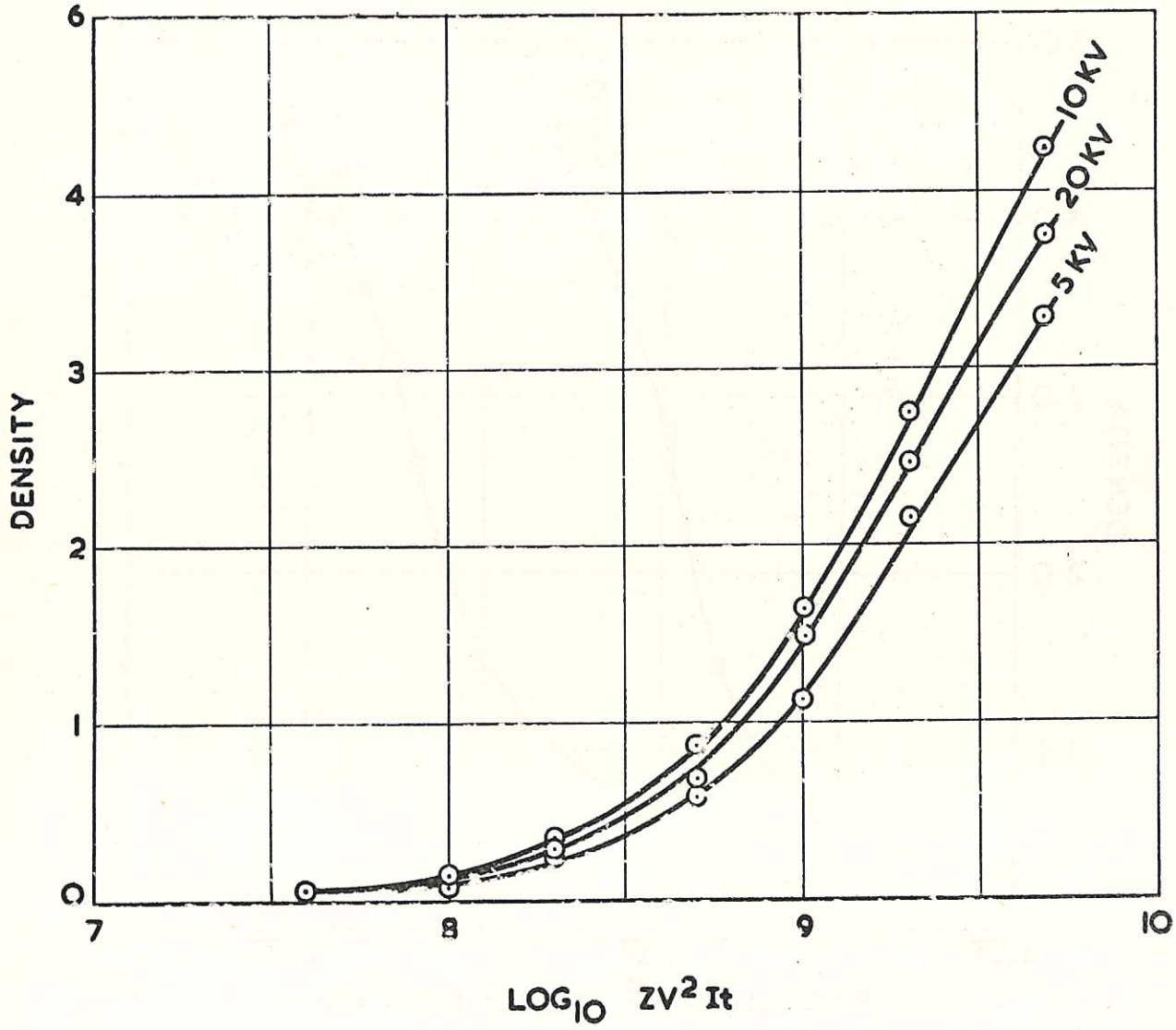


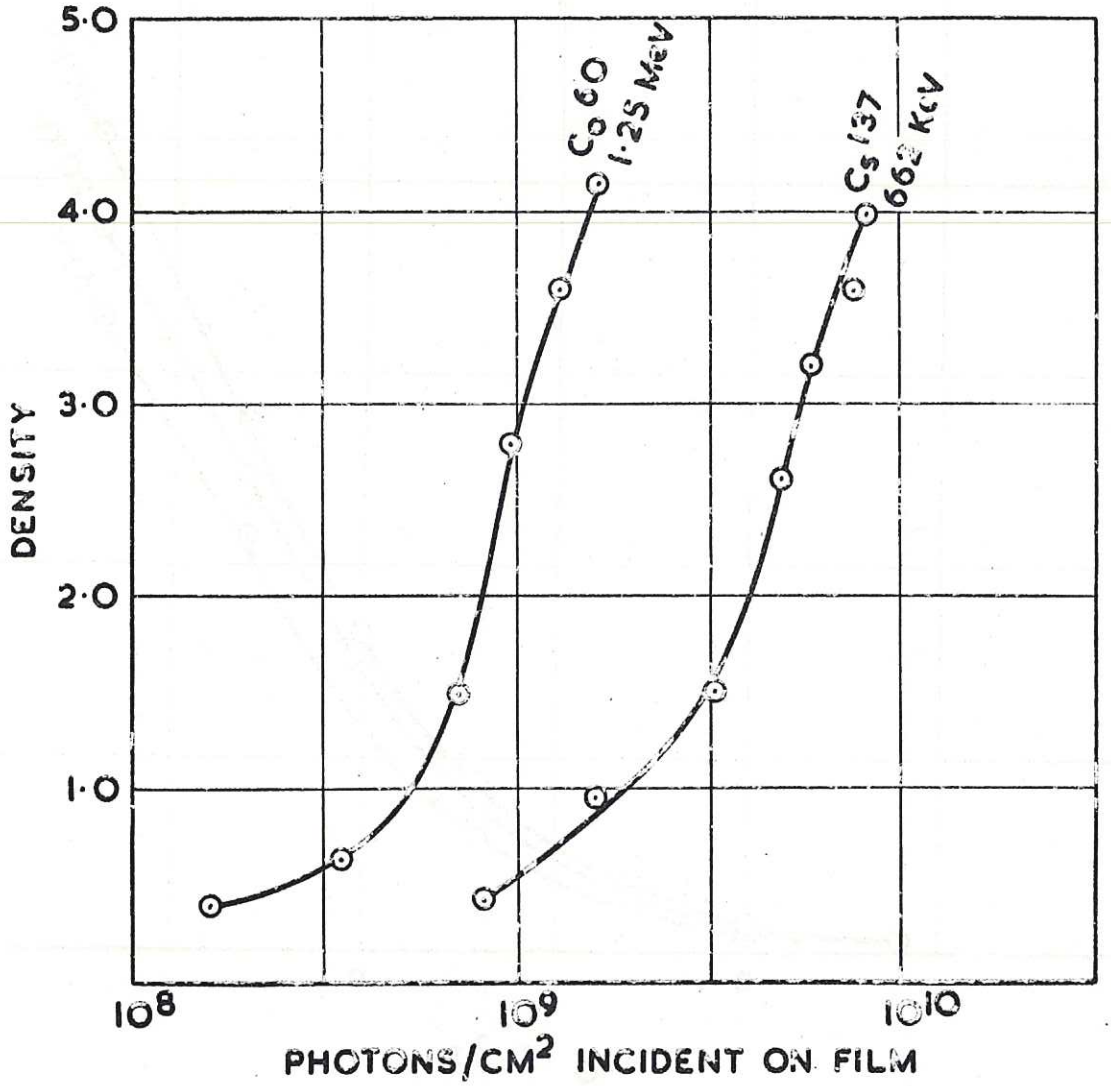
FIG. 6. RECORDAK CALIBRATION. STAINLESS STEEL TARGET.



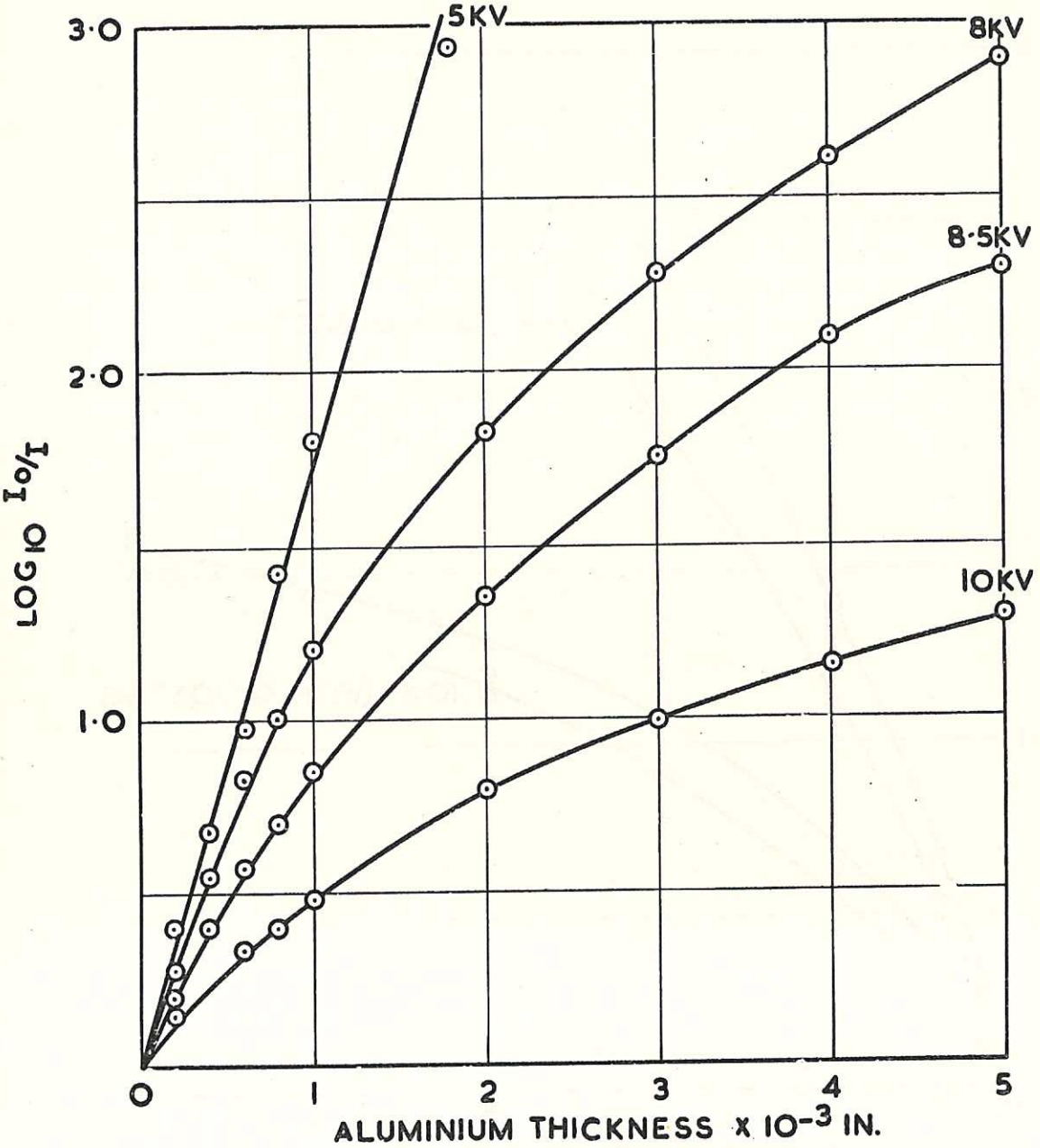
CLM - R 11 FIG. 7. INDUSTRIAL 'G' CALIBRATION.
TUNGSTEN TARGET.



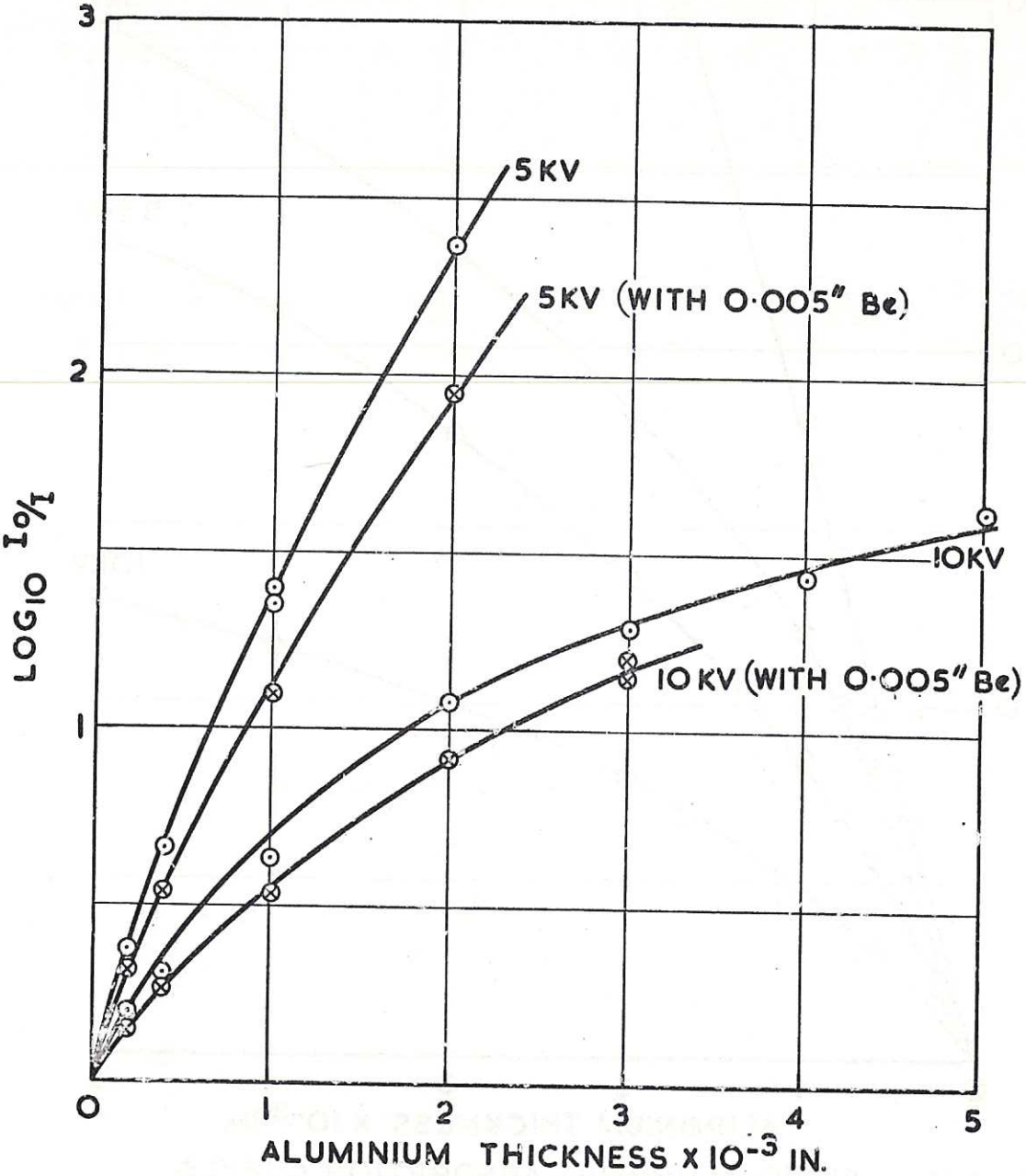
CLM - R 11 FIG. 8. RECORDAK CALIBRATION TUNGSTEN TARGET.



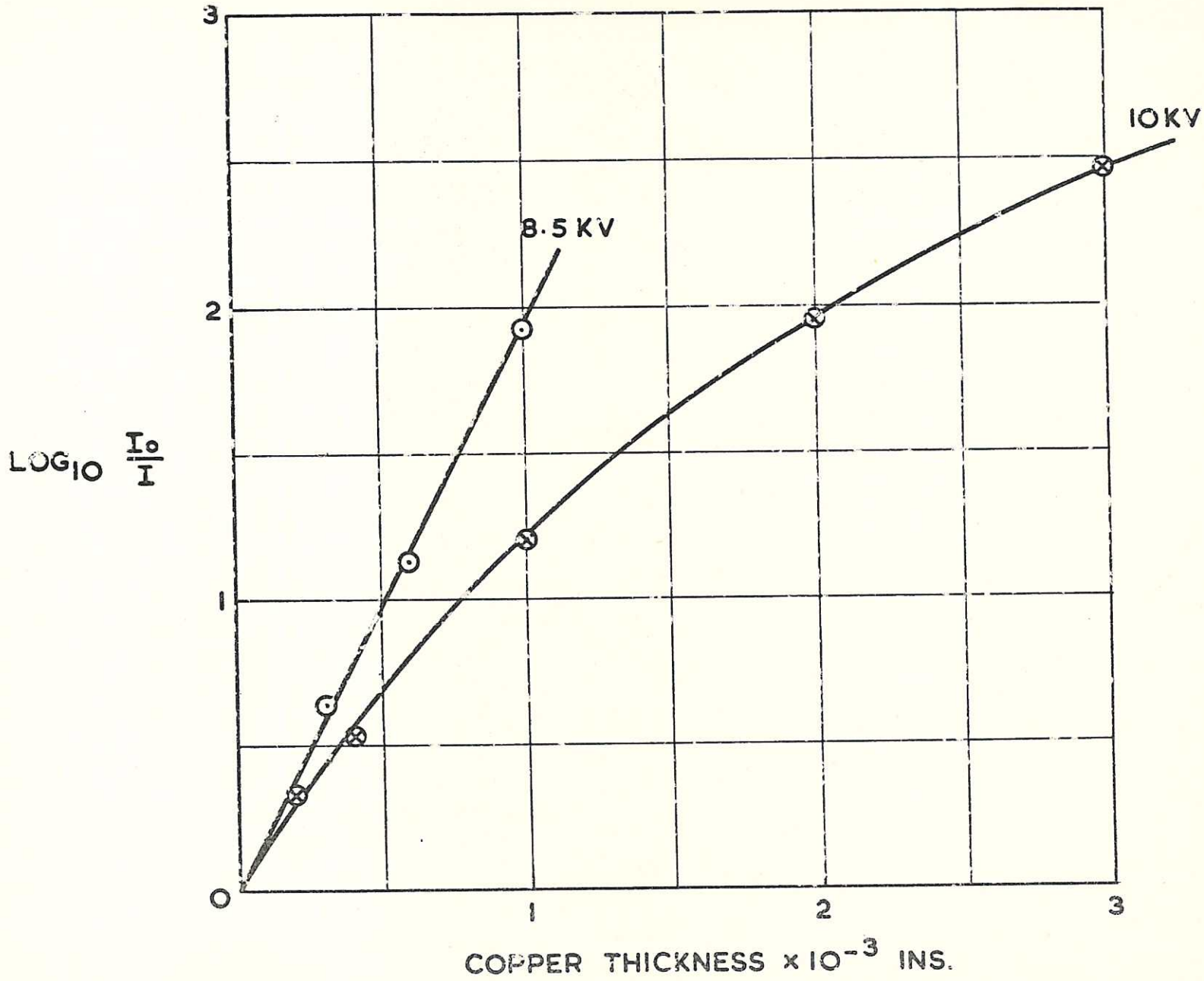
CLM - R 11 FIG. 9. INDUSTRIAL 'G' CALIBRATION.



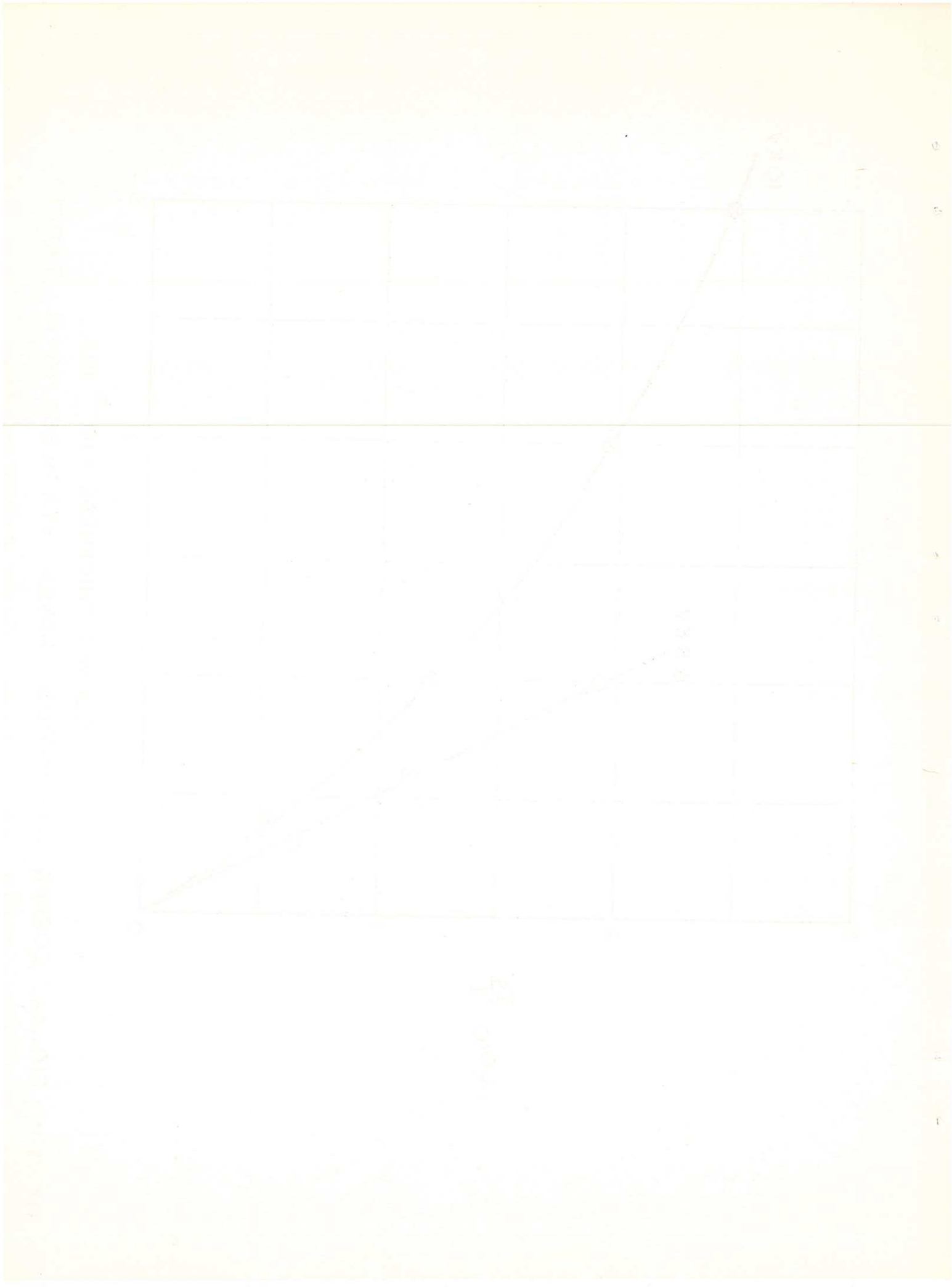
CLM - R 11 FIG. 10. ALUMINIUM ABSORPTION CURVES. STAINLESS STEEL TARGET.



CLM - R 11 FIG. II. ALUMINIUM ABSORPTION CURVES TUNGSTEN TARGET.



CLM - R 11 FIG..12. COPPER ABSORPTION CURVES. STAINLESS STEEL TARGET.



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