

RECOMMENDATION FOR
DATA ON SHIELDING
FROM IONIZING
RADIATION

Part 2. Shielding from X-radiation

BS 4094 : Part 2 : 1971

Confirmed
February 2011

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BRITISH STANDARDS INSTITUTION

Incorporated by Royal Charter

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The Institution desires to call attention to the fact that this recommendation does not purport to include all the necessary provisions of a contract.

In order to keep abreast of progress in the industries concerned, British Standards are subject to periodical review. Suggestions for improvements will be recorded and in due course brought to the notice of the committees charged with the revision of the standards to which they refer.

A complete list of British Standards, numbering over 5000, fully indexed and with a note of the contents of each, will be found in the British Standards Yearbook. The BS Yearbook may be consulted in many public libraries and similar institutions.

This recommendation makes reference to the following British Standard:

BS 4094. Recommendation for data on shielding from ionizing radiation. Part 1. Shielding from gamma radiation.

British Standards are revised, when necessary, by the issue either of amendment slips or of revised editions. It is important that users of British Standards should ascertain that they are in possession of the latest amendments or editions.

The following BSI references relate to the work on this standard:

Committee references NCE/2, NCE/2/2, NCE/2/2/2 Draft for comment 66/18981

CO-OPERATING ORGANIZATIONS

The Nuclear Energy Industry Standards Committee, under whose supervision this British Standard was prepared, consists of representatives from the following Government departments and scientific and industrial organizations:

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*British Electrical and Allied Manufacturers' Association
British Insurance (Atomic Energy) Committee
British Mechanical Engineering Confederation
*Department of Employment and Productivity
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*Scientific Instrument Manufacturers' Association of Great Britain
*United Kingdom Atomic Energy Authority

The Government departments and scientific and industrial organizations marked with an asterisk in the above list, together with the following, were directly represented on the committee entrusted with the preparation of this British Standard:

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BRITISH STANDARD RECOMMENDATION FOR DATA ON SHIELDING FROM IONIZING RADIATION

Part 2. Shielding from X-radiation

FOREWORD

Part 1 of this recommendation, dealing with shielding from gamma radiation, was published in 1966. Part 2 of the recommendation is to provide data adequate for the calculation of shielding barriers against X-radiation. The data presented have been chosen with the radiation shielding problems of industry in mind. Most of the material has been drawn from existing sources although a certain amount has been measured or calculated specially. It is not possible to provide a compendium to cover all possible contingencies, but data are provided to allow for calculations to be made for a wide range of materials and geometry likely to be encountered, and it is envisaged that additional data will be added from time to time.

Provision of data alone is not sufficient to permit the calculation of the required barriers and the methods of calculation which are necessary are given in the text together with examples.

Section One of this part deals with the calculation of barriers against the primary X-ray beam, and Section Two provides the data which permit the calculation to be carried out. Appendices A and B are concerned, respectively, with the calculation of the secondary barriers which are required against scattered, and against leakage radiation. Appendix C gives methods and data for the calculation of barriers against bremsstrahlung radiation, arising from electron

beams or beta particles from radionuclides. Appendix D gives guidance on the secondary hazards associated with high energy X-ray generators, namely, the production of neutrons, noxious gases and radiation arising from the activation of materials, radiation damage and the fire risk. Appendix E gives guidance on the design of shielded rooms.

Where possible, methods have been simplified to allow calculations to be made by designers who do not have any specialist knowledge of radiation shielding.

This recommendation does not attempt to define maximum permissible dose nor does it make any recommendations as to exposure rates for design purposes. Such matters are outside the scope of this recommendation as they are, in many cases, subject to legislation or various codes of practice.

Exposure rates are quoted in roentgens per hour (R/h), roentgens per mA minute (R/mA min) or milliroentgen per hour (mR/h). Calculations may be required in millirads in air per hour. Although the millirad is a slightly larger unit than the milliroentgen, calculations giving the required answer in milliroentgens rather than millirads will be acceptable for protection purposes. However, it is to be noted that in Appendix D reference is made to secondary sources of radiation, where it is necessary to refer to the appropriate units for exposure rate or dose.

SECTION ONE: INTRODUCTION

GENERAL

1. This section of the recommendation presents the collected data required for the estimation of shielding against a primary X-ray beam. Graphs of the variation of exposure rate for a range of kilovoltage (kV) and filtration are given; such data may be used when accurate measurement of exposure rate is not possible. The transmission data are given for lead and concrete shields since they are the commonest materials encountered, and in addition some limited guidance is given on the equivalent shielding in other materials. The information given in this section may be used with confidence for design purposes, when due allowance is made for any limitation in the data or methods to which references are made in appropriate parts of the text. The methods of calculation are illustrated with a number of examples.

Where guidance on the measurement of X-ray intensity or further information on health precautions is required, advice may be obtained from the Radiological Protection Service ⁽¹⁾ at Sutton or from one of their Regional Centres in Birmingham, Glasgow, Leeds and Manchester, or from the Advisory and Information Unit of the Department of Employment ⁽²⁾.

The problems of scattered radiation, leakage radiation and bremsstrahlung are dealt with in the appendices.

Definitions of terms used in this recommendation are given (Appendix G) and a list of references included (Appendix F) so that the original papers from which the data was compiled may be consulted.

The main difficulty in shielding against X-rays arises from the use of experimental data which does not cover the entire field of X-ray usage, so that designers have sometimes to rely upon interpolation or on their own measurements.

It is usual to describe an X-ray beam in terms of

a. The kilovoltage (kV) on the tube, which may be given as constant potential kV_{cp} or as the peak voltage kV_p . X-rays excited by direct-current potentials usually give a harder spectrum than pulsating (peak) potential sets and for the same potential the direct current set may require more shielding.

b. The tube current (mA).

c. The tube filtration. This is made up of two parts, the inherent filtration of the tube and any added filter, the latter normally being the greater.

d. Target material. For a given tube voltage, if a target of higher atomic number is used the X-ray output is in-

creased and the wavelength of the line spectrum is reduced.

The X-ray data have been considered in two energy bands, those generated below 500 kV and those above 500 kV. The main reason for this split is that the treatment of scattered radiation in these two energy bands is different, as is shown in Appendix A. This also conforms roughly with the change in type of X-ray generator from a conventional X-ray set to the more complex Linacs and Betatrons.

To assess a shielding requirement it is necessary to know the exposure rate; this information may be given by the manufacturer but it is advisable to use measured values provided these have been obtained with a properly calibrated instrument in carefully controlled conditions. If it is not possible to obtain a precise measure of the exposure-rate then Figs. 1 to 6 should be used. In certain circumstances it may be possible to relate the permitted exposure-rate to the type of area outside the shield wall, making different allowances, for example, for a corridor, a store room or a working area. This procedure may lead to a saving in shield thickness.

Knowing the exposure-rate at a given point it can then be determined at any other point from the inverse square law. For instance, an exposure-rate of y R/h at a distance of d cm from the tube target becomes $y(d/d')^2$ at a distance of d' cm. The output is directly proportional to the current (mA) and increases with kV as can be seen in Figs. 1 to 6.

Departures from the inverse square law occur if air absorption becomes significant. The following data ⁽³⁾ may be used as a rough guide to the percentage reduction in beam intensity due to air absorption.

Distance	1.5 MV	0.5 MV	250 kV	100 kV	25 kV
cm	%	%	%	%	%
50	0	0	0	1	1.5
100	0	1	1	2	3
500	2	4	5	8	12

The transmission curves are given for broad beam conditions for filtrations which are considered to be those most likely to be encountered for each range of kV. As the attenuation is dependent on the spectral distribution of the X-rays care must be taken in interpolating for filtrations of kV other than those given.

X-RAYS 10 kV to 500 kV

2. This section details the use of the data sheets and transmission graphs contained in Section Two.

X-ray output data are provided in Figs. 1 to 6 of Section Two and broad beam transmission data is given in Figs. 7 to 16 for various shield materials. For energies of less than 500 kV, shields are usually made of either lead-plywood, steel, brick, concrete, or barium concrete blocks. To obtain transmission data for materials other than lead or concrete reference should be made to Table 1. This table gives the lead equivalence of various materials and although the data refer to narrow beam conditions they can be assumed to apply to broad beam conditions with sufficient accuracy.

For low energy X-rays in the range 10 kV to 50 kV transmission data are given for a wide range of materials; this is intended to cover the shielding problems peculiar to the construction of television receivers, X-ray crystallography sets and ancillary equipment.

Wherever possible, transmission data have been given

for both pulsating and constant potential generators. Where data are not available, it is normally safe to assume that a constant potential unit requires approximately 10 % greater thickness of shield than a pulsating unit, if all other conditions are the same.

Although changes in filtration do change the spectrum of the beam and the set output, it is usually found that the transmission factors required are so large that the shield thickness is very large compared with the small differences in filtration, and these differences in filter thickness have little effect on the total shield thickness required. Where transmission data for a particular filtration are not provided the following procedure is recommended. Suppose the output (in R/mA min) of an X-ray unit is known for a filtration x , but the only transmission data available for the same potential are for a different filtration, y . The thickness of shielding required to reduce the exposure rate to the required value is read off the transmission curve; let this thickness be z . The shielding required for the beam of filtration x is then $z + (y-x)$, where x and y are both expressed as equivalent thickness of the shield material. The equivalent thickness may be obtainable from Table 1; failing this it is recommended that the data at the same kV for either an unfiltered beam, or for one with filtration less than that which is required, be used. In general z alone may be used.

The following examples will serve to familiarize the user with the data sheets and methods of calculation.

Examples. The general procedure is as follows:

a. Exposure-rate. If this is not known then use Figs. 1 to 6 in Section Two for the appropriate kV, interpolating as necessary. Suppose it is S R/mA min at 1 m. Use the inverse square law to obtain exposure-rate at distance y metres: $S \times \left(\frac{1}{y}\right)^2$ R/mA min. Allow for proposed tube current I mA;

$$S I \left(\frac{1}{y}\right)^2 \text{ R/min}$$

b. Usage and occupancy factors. The derivation and use of these and similar factors is not within the scope of this document, since the use of such techniques is subject to differing interpretation by interested parties. Some guidance is given in the I.C.R.P. Committee III Report⁽⁴⁾.

c. Transmission. If the required exposure rate at distance y is D mR/h the transmission factor is,

$$T = \frac{D \times y^2}{S \times I \times 60 \times 10^3} = \frac{1}{6} \times \frac{D}{S} \times \frac{y^2}{I} \times 10^{-4}$$

From Figs. 7 to 16 and Table 1 values of T for various materials can be inferred.

Examples.

(i) An X-ray set operates at 250 kV_{cp} with a beam current of 15 mA. What lead shielding should be added to a 23 cm (9 in) brick wall to reduce the exposure-rate to 2 mR/h at a distance of 3 metres? The beam is filtered by 1.5 mm Cu. Fig. 4 gives the exposure-rate for a 250 kV_{cp} set for two filtrations. The exposure-rate for a 1.5 mm Cu filter may be taken roughly as mid-way between the two curves. This is not a critical decision since very large transmission factors are usually required and the difference in transmission between curves A and B is only equivalent to the effect of about 0.1 mm Pb. We then have an exposure rate of about 1.3 R/mA min at 1 metre. For 15 mA and

3 metres this becomes $\frac{1.3 \times 15 \times 60}{(3)^2}$ R/h = 130 R/h. The required transmission factor is then,

$$\frac{2}{130 \times 10^3} = 1.54 \times 10^{-5}$$

From Fig. 12 we see that for 250 kV_{cp} a thickness of 9.5 mm Pb is required. From Table 1 a 23 cm (9 in) brick wall is equivalent to 2.8 mm Pb. An additional 6.7 mm of Pb is therefore required; it is usual to round up the thickness required to give an added factor of safety, e.g. 7 mm would be used in practice

NOTE. When two materials, e.g. brick and lead, are to be used together as a shield, the position of the lead may alter the transmission. If the lead precedes the brick, the lead filters the source beam and the transmission depends upon the degradation of the peak energy transmitted through the brick. If the brick precedes the lead, the source beam is degraded in the brick and the absorption in the lead is enhanced, so the overall transmission is less. The preferred arrangement is, therefore, to have a structural shield (containing, for example, brick or concrete) followed by the thinner shield of high mass number, for example, lead. In most cases, however, this is not an important issue and it is common practice to place, say, lead-ply on the inside both for economy of shield material and to reduce the risk of damage.

(ii) It is necessary to design a mechanical interlock system for an X-ray crystallography set where space is very limited. The beam in one particular direction can only be shielded by a 1 mm thickness of material. What metal should be used if the exposure-rate at 1 m must not exceed 7.5 mR/h? The operating conditions are given as 30 kV, 15 mA; various filtrations may be used.

Take the maximum output shown in Fig. 1 of 5.8×10^5 mR/mA min at 10 cm. The unshielded exposure-rate at 1 m is then:

$$E = 5.8 \times 10^5 \times 15 \times 60 \times \frac{(10)^2}{(100)^2} \text{ mR/h,}$$

$$= 5.2 \times 10^6 \text{ mR/h.}$$

The required transmission factor is then,

$$T = \frac{7.5}{5.2 \times 10^6} = 1.44 \times 10^{-6}$$

From Figs. 7a, 7b and 7g, this corresponds to considerably more than 18 mm Al, 0.95 mm Fe and approximately 0.12 mm Pb.

As only 1 mm space is available aluminium could not be used; the choice of iron or lead would then rest on constructional requirements.

X-RAYS 500 kV to 35 MV

3. For high energy X-rays concrete is the more commonly used shielding material, transmission curves for which are given in Figs. 14 and 16. Transmission in lead up to 2.0 MV is also given in Fig. 15. X-ray outputs are given in Figs. 4 to 6 for a range of filtrations. The methods used for the calculation of primary beam shielding do not differ from those at lower energies.

After adequate shielding has been attained, consideration must be given to the problem of photonuclear reactions, notably the production of neutrons. These reactions begin at about 7 MV to 10 MV, there being a threshold value for each element. However, the effect is not very significant below about 10 MV and the question of shielding against photonuclear products is discussed in Appendix D.

Example. An X-ray beam of 3 MV has an output of about 270 R/mA min at 1 m target distance. The direct beam is to be attenuated to 6 mR/mA h through a concrete wall placed 3 m from the target. What thickness of concrete is necessary?

Exposure rate at 3 m from the target

$$\frac{(1)^2}{(3)^2} \times 2.7 \times 10^2 \text{ R/mA min} = 30 \text{ R/mA min,}$$

i.e. at the inner surface of the concrete barrier.

Required exposure rate at the outer surface = 6 mR/mA h or 10^{-1} mR/mA min.

Transmission required

$$= \frac{10^{-1}}{30 \times 10^3} = \frac{10^{-5}}{3} = 3.3 \times 10^{-6}.$$

Referring to Fig. 14, it will be seen that 136 cm of concrete are necessary.

SECTION TWO: DATA SHEETS AND BROAD BEAM TRANSMISSION GRAPHS

X-Ray Output and Transmission Data

Output. The outputs of X-ray apparatus at a given potential, when measured in R/mA min at a fixed distance from the targets, are reasonably constant provided:

- (1) The generators are of the same type.
- (2) The target materials are the same.
- (3) The targets are either transmission or reflection types.
- (4) The total beam filtrations are the same.

Therefore, the information given in data sheets for Figs. 1 to 6 inclusive may be used as a guide to output values if consideration is given to the foregoing conditions. Ideally the output of the apparatus in question should be measured.

Transmission. Broad beam transmission data in concrete, lead and other materials are given in the data sheets for Figs. 7 to 16 inclusive. The following factors influence the shape of the transmission curves for a given peak accelerating voltage:

a. Generator type: Parallel data for pulsating and constant potential generators are provided where available.

b. Total beam filtration: The transmission curves herein are mainly for typical beam filtrations and may be used for most cases. However, beam filtration can significantly affect the transmission pattern and may need to be taken into consideration in special cases. The ideal procedure is to use a transmission curve with beam filtration matching that of the machine in question.

c. Concrete density: The curves are for normal concrete of density 2.35 g/cm³ (147 lb/ft³).

For small differences in density it is sufficiently accurate to assume that the thickness required is inversely proportional to density, e.g. that 10 cm of concrete of density 2.35 g/cm³ gives the same transmission as $10 \times \frac{2.35}{2.40}$ cm of concrete having a density of 2.40 g/cm³.

Small differences in brick density may be dealt with in a similar way.

DATA SHEET FOR FIG. 1
X-RAY OUTPUT 4 kV to 50 kV
PULSATING POTENTIAL

Based on:

W. A. JENNINGS, ' Physical aspects of the roentgen radiation from a beryllium window tube operated over the range 2–50 kV_p for clinical purposes '.

Acta Radiologica, 33, 1950, pp 435–484.

Half-wave generator. Tungsten reflection target.

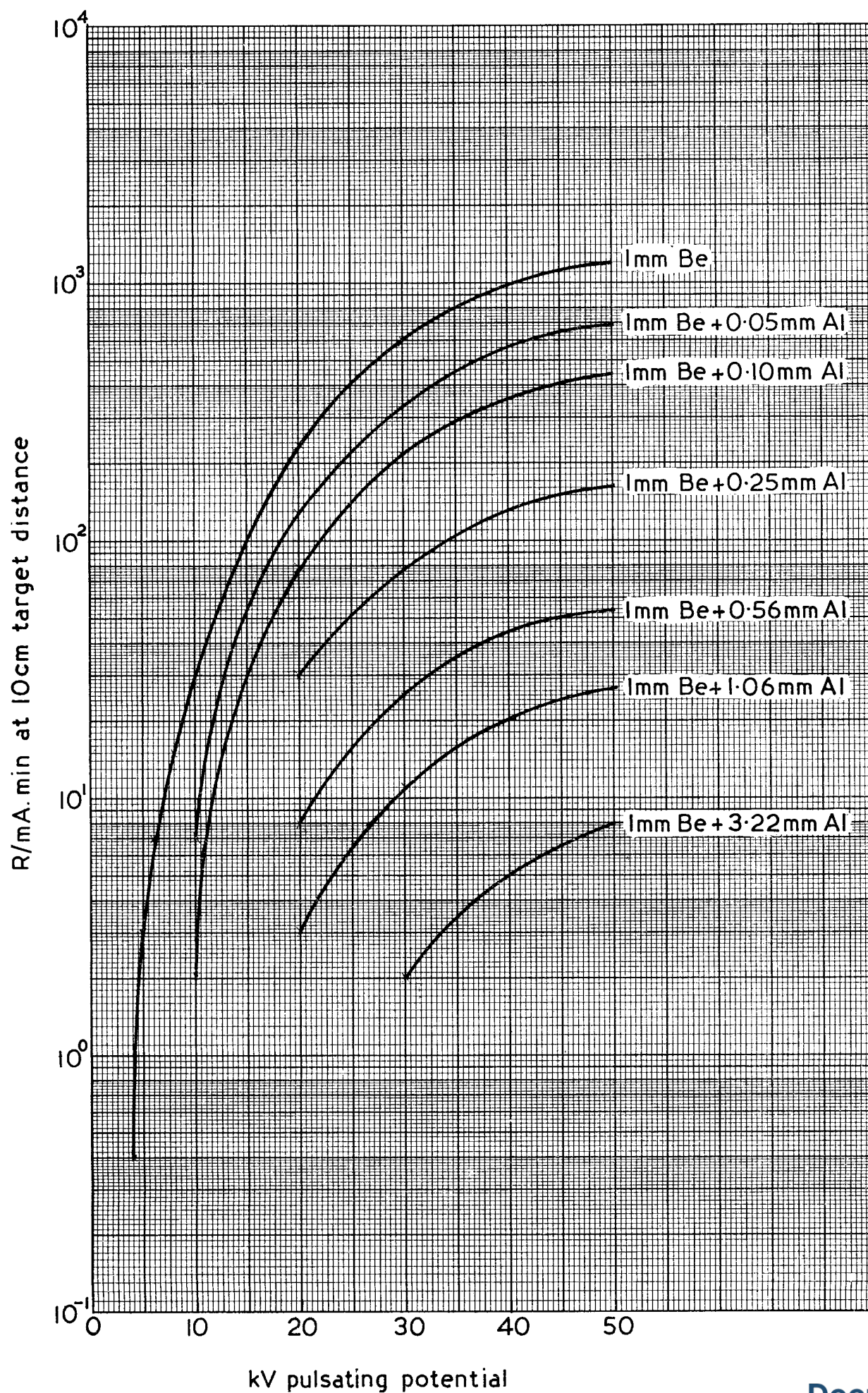


Fig. 1. X-ray output 4 kV to 50 kV pulsating potential

DATA SHEET FOR FIG. 2
X-RAY OUTPUT 5 kV TO 50 kV
CONSTANT POTENTIAL

M. C. O'RIORDAN and B. CATT, 'X-ray output: 5 to 50 kV
constant potential'.

Radiological Protection Service Report R.P.S./I/32, 1968
Tungsten reflection target.

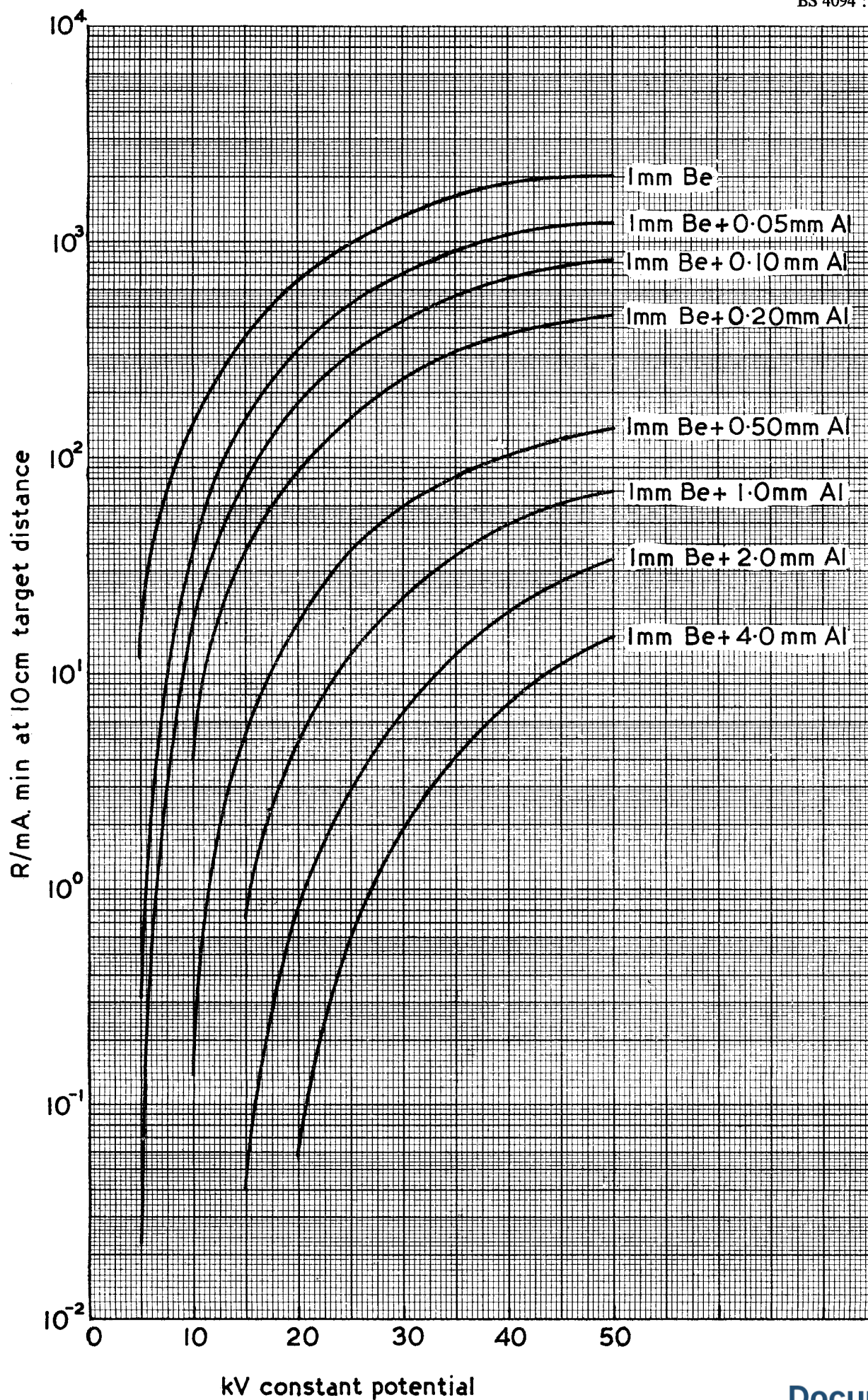


Fig. 2. X-ray output 5 kV to 50 kV constant potential

DATA SHEET FOR FIG. 3
X-RAY OUTPUT 50 kV TO 200 kV
CONSTANT POTENTIAL

National Bureau of Standards, U.S.A.

Quoted in: O. GLASSER, E. H. QUIMBY, L. S. TAYLOR and
J. L. WEATHERWAX, 'Physical foundations of radiology',
Paul B. Hoeber, New York, 1954.

Tungsten reflection target.

For half-wave generators, outputs are approximately one-third
to one half constant potential values.

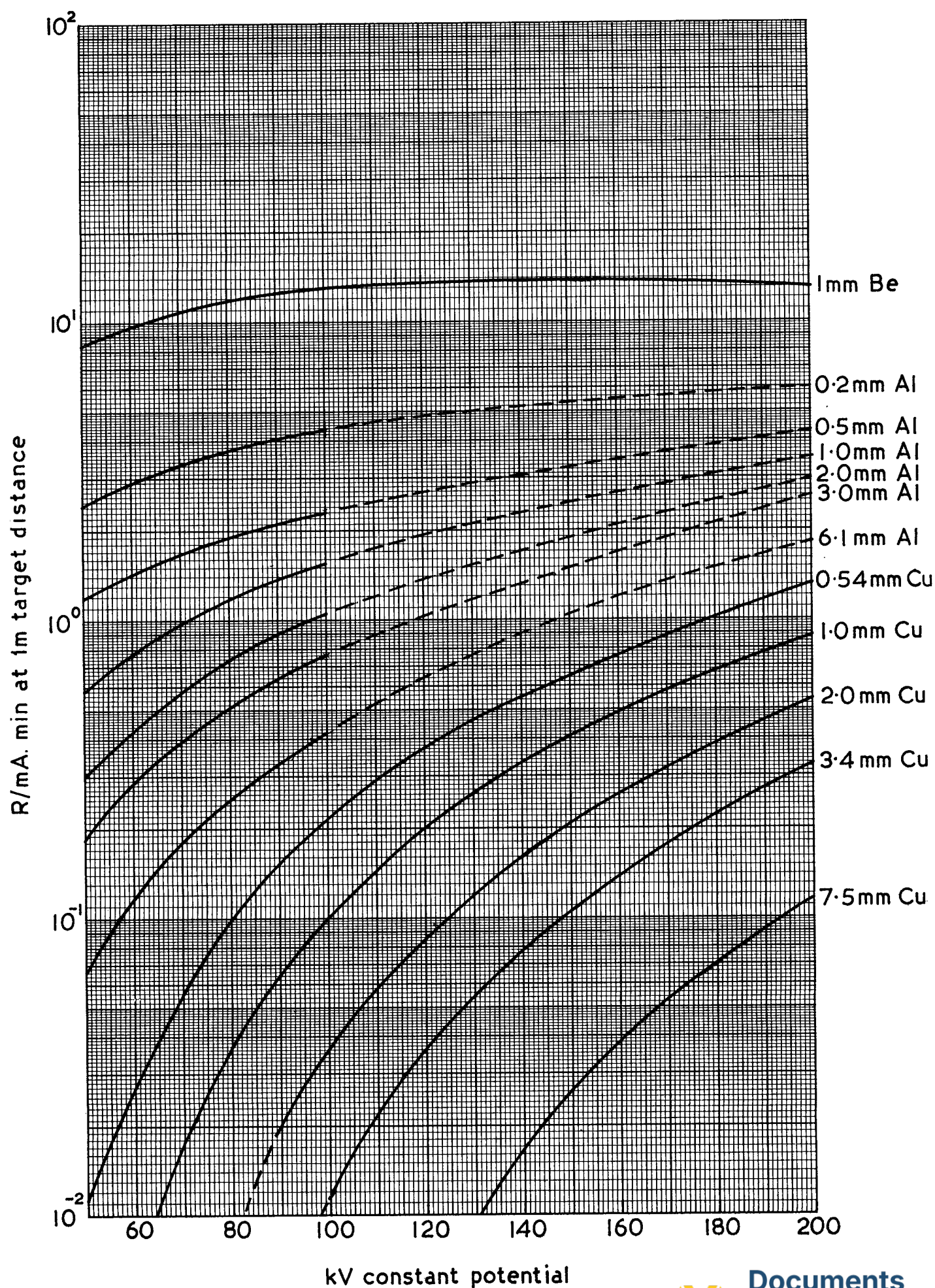


Fig. 3. X-ray output 50 kV to 200 kV constant potential

DATA SHEET FOR FIG. 4
X-RAY OUTPUT 200 kV TO 500 kV
CONSTANT POTENTIAL

a. Based on:

W. MILLER and R. J. KENNEDY, 'X-ray attenuation in lead, aluminium and concrete in the range 275 to 525 kilovolts'.

Radiology **65**, 1955, pp 920–925.

Tungsten reflection target. 3 mm Cu total filtration.

b. G. W. C. KAYE and W. BINKS, 'The emission and transmission of X- and gamma radiation'.

British Journal of Radiology **13**, 1940, pp 193–212.

Tungsten reflection target 0.5 mm Cu total filtration.

For pulsating potential generators, outputs are approximately two-thirds constant potential values.

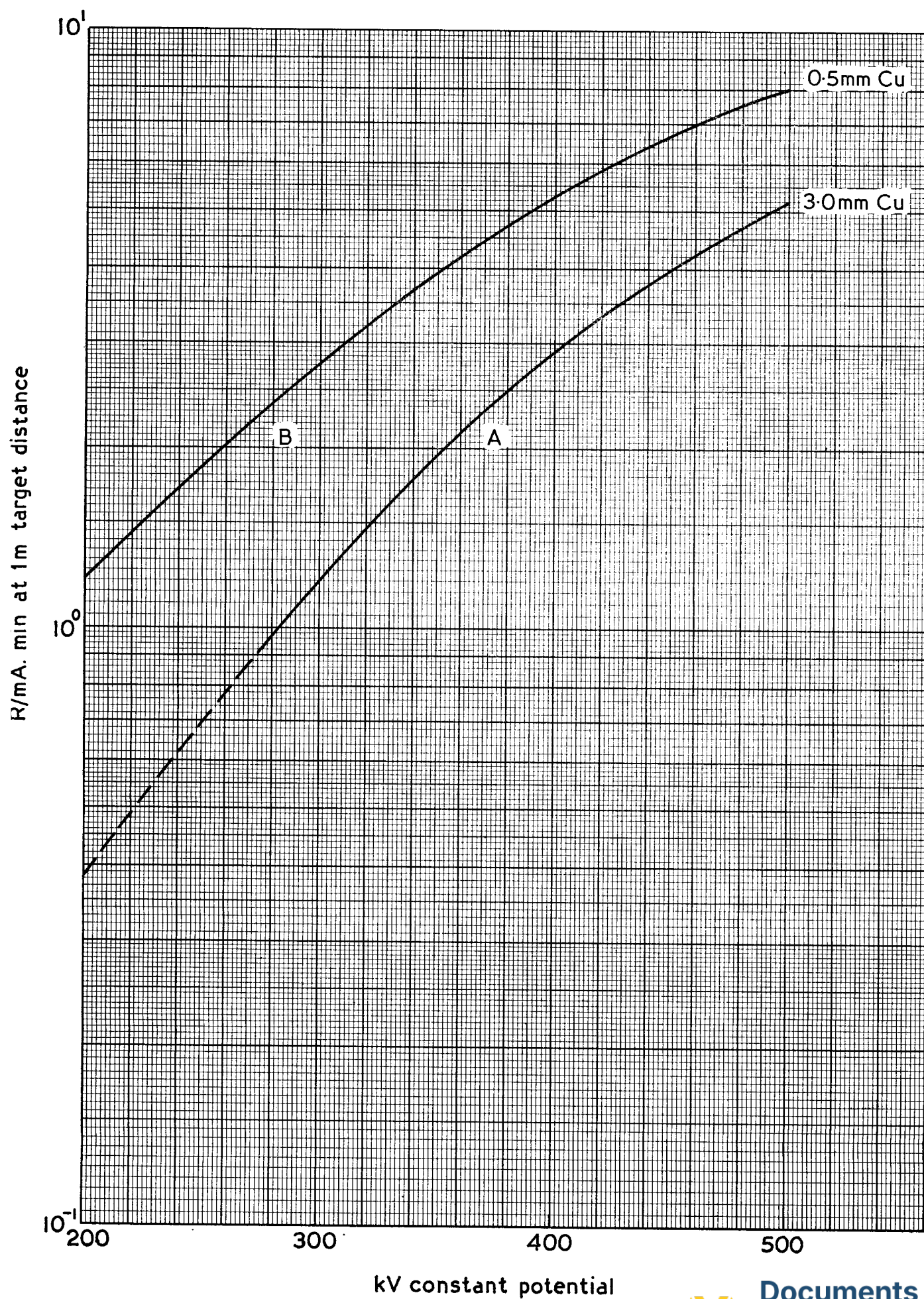


Fig. 4. X-ray output 200 kV to 500 kV constant potential

DATA SHEET FOR FIG. 5
X-RAY OUTPUT 0.2 MV TO 3 MV
CONSTANT POTENTIAL

a. A. A. PETRAUSKAS, L. C. VAN ATTA and F. E. MYERS,
‘Measurements on X-ray production and absorption in the
range 0.7 to 2.5 MV’.

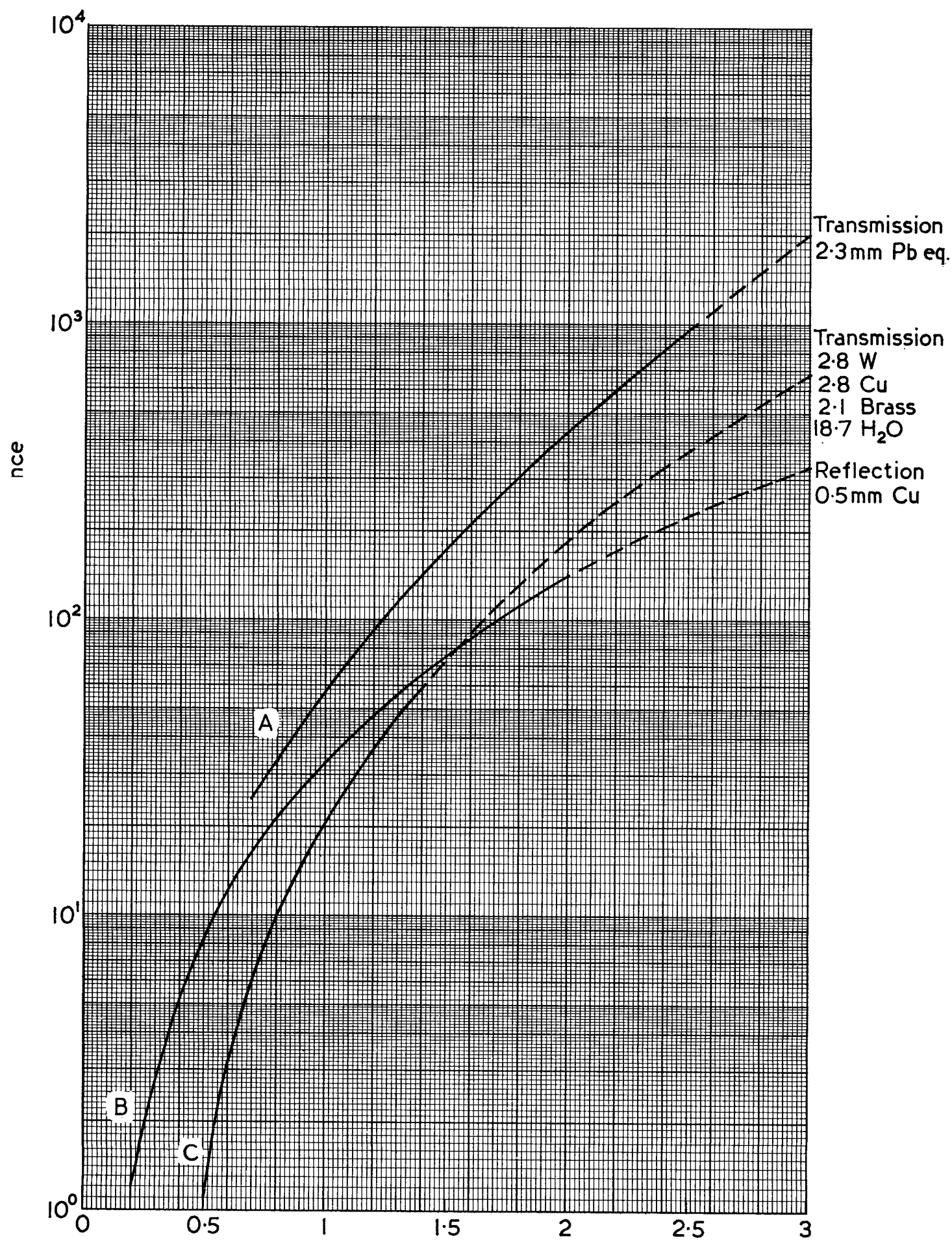
Physical Review **63**, 1943, pp 389–399.
Gold transmission target. 2.3 mm lead equivalent total
filtration.

b. G. W. C. KAYE and W. BINKS, ‘The emission and trans-
mission of X- and gamma radiation’.
British Journal of Radiology **13**, 1940, pp 193–212.
Tungsten reflection target. 0.5 mm copper total filtration.

c. H. O. WYCKOFF, R. J. KENNEDY and W. R. BRADFORD,
‘Broad and narrow beam attenuation of 500 to 1400 kV
X-rays in lead and concrete’.
Radiology **51**, 1948, pp 849–859.
Tungsten transmission target. 2.8 mm tungsten + 2.8 mm
copper + 2.1 mm brass + 18.7 mm water filtration.
The lead equivalents of this filtration are as follows:

MV	0.5	0.6	0.8	1.0	1.4	2	3
mm Pb	5.0	5.6	6.2	7.0	7.8	9.2	10.0

For pulsating potential generators, outputs are approximately
one half to two-thirds constant potential values.



MV constant potential

Fig. 5. X-ray output 0.2 MV to 3 MV constant potential

DATA SHEET FOR FIG. 6
X-RAY OUTPUT 2 MV TO 35 MV

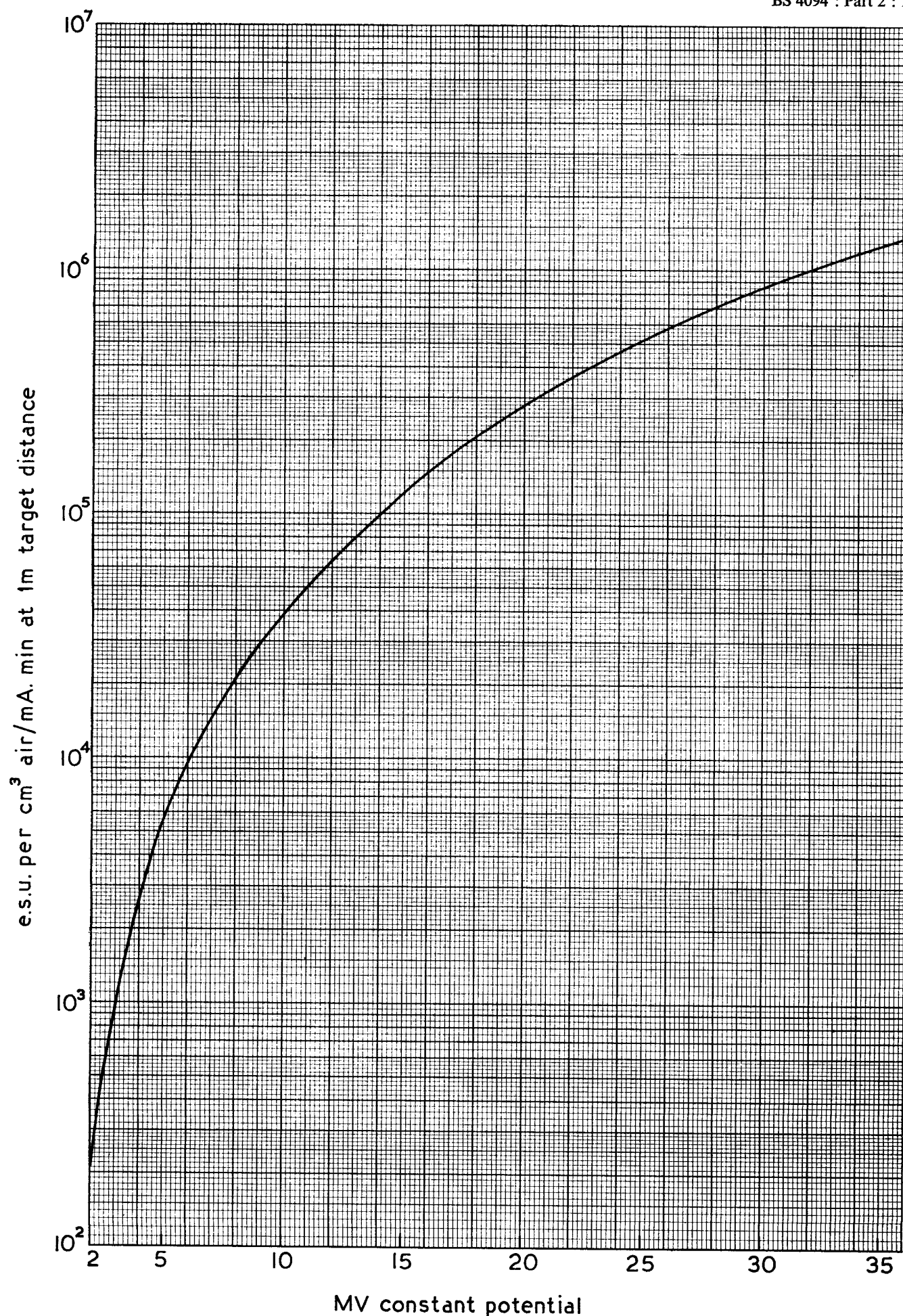
M. H. MACGREGOR, 'X-ray production with linear accelerators'.

Nucleonics **17**, No. 2, 1959, pp 104–105.

K. M. MURRAY, 'Shielding moderate energy electron accelerators'.

Nucleonics **22**, No. 2, 1964, pp 61–67.

Optimum thickness high atomic number target, e.g. 1.6 mm lead approximately.



NOTE. At voltages above a few MV it is difficult to measure output in roentgens. However, an ionization yield of 1 e.s.u. of charge per cm³ of air approximates to 1 R under certain measurement conditions and permits smooth extension of the output data to higher energies.

Fig. 6. X-ray output 2 MV to 35 MV constant potential

DATA SHEET FOR FIG. 7
TRANSMISSION OF 10 kV TO 50 kV
CONSTANT POTENTIAL X-RAYS
THROUGH ALUMINIUM, MILD
STEEL, SHEET GLASS, PERSPEX,
WOOD, BRASS AND LEAD

7(a)–(e). M. C. O’RIORDAN and B. R. CATT, ‘Low-energy X-ray shielding with common materials’.

Health Physics **17**, 1969, pp 516–518.

- (i) Generator: constant potential
- (ii) Total filtration: 1.0 mm beryllium
- (iii) Tungsten reflection target.

NOTE. When using Fig. 7e, the thickness of wood is obtained from the relationship

$$\text{Thickness (cm)} = \frac{\text{g/cm}^2}{\text{density (g/cm}^3\text{)}}$$

7(f)–(g). I. BIRCHALL—unpublished data

- (i) and (ii) as above, (iii) copper target.

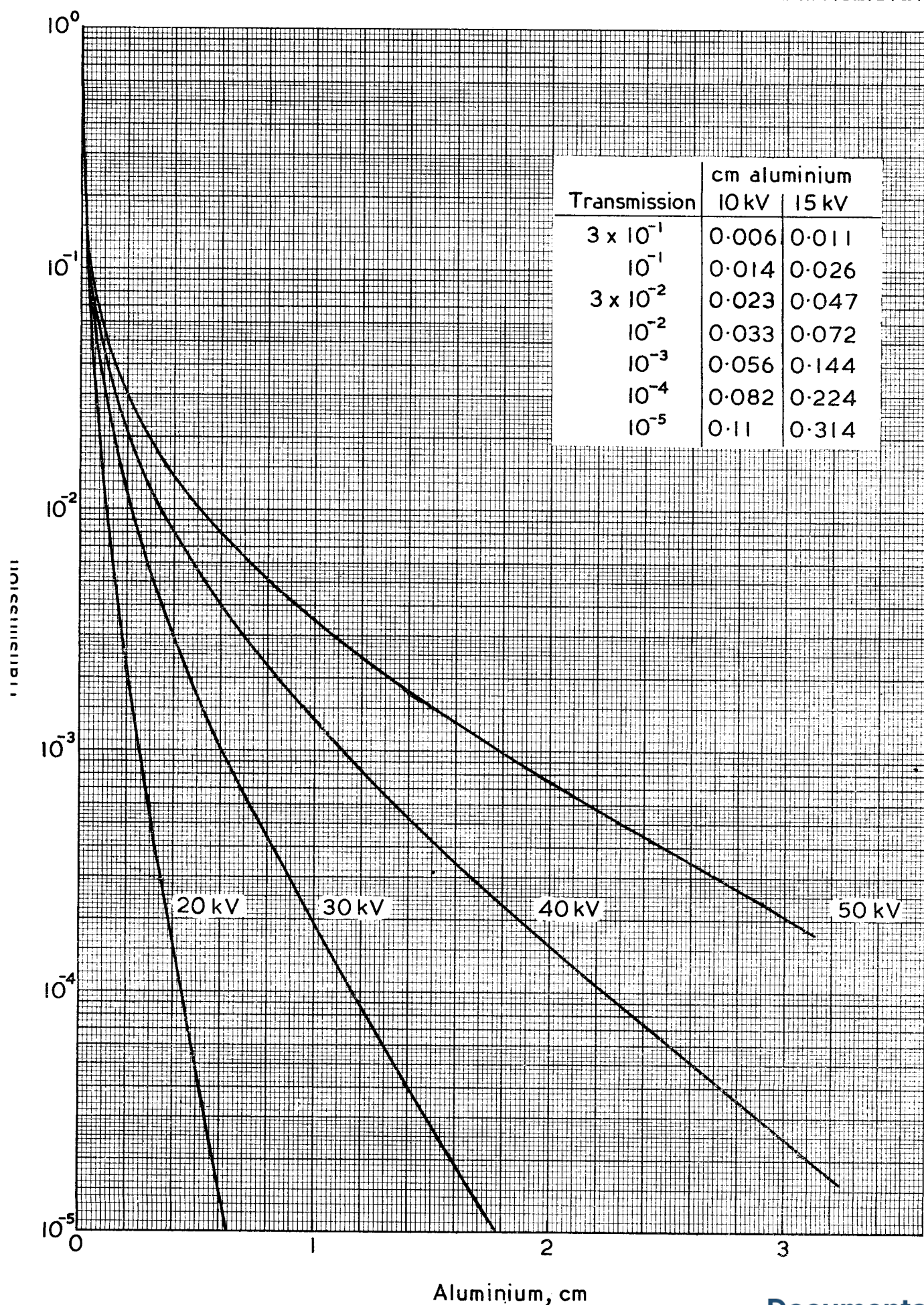


Fig. 7a. Transmission of 10 kV to 50 kV constant potential X-rays through aluminium.

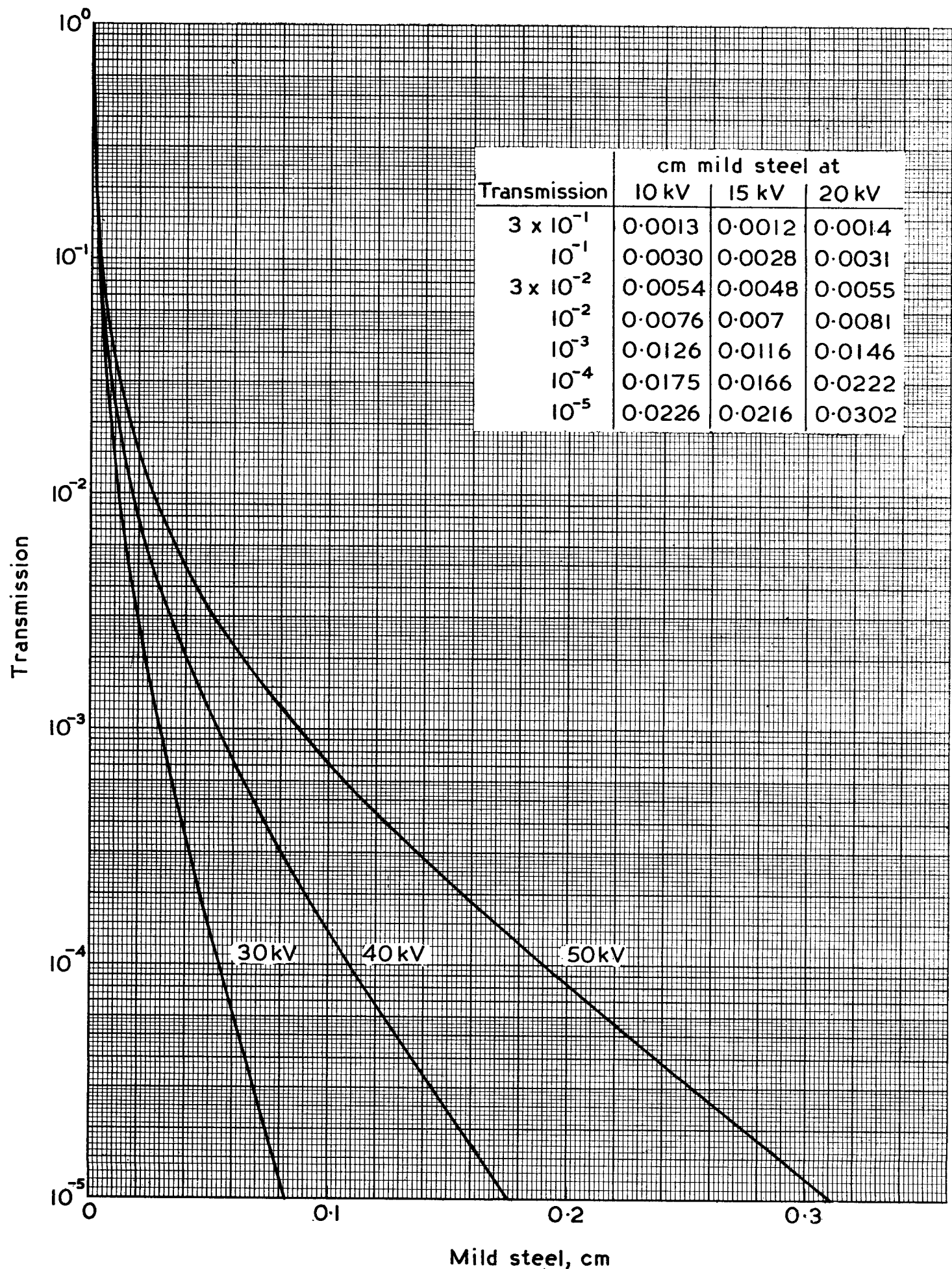


Fig. 7b. Transmission of 10 kV to 50 kV constant potential X-rays through mild steel

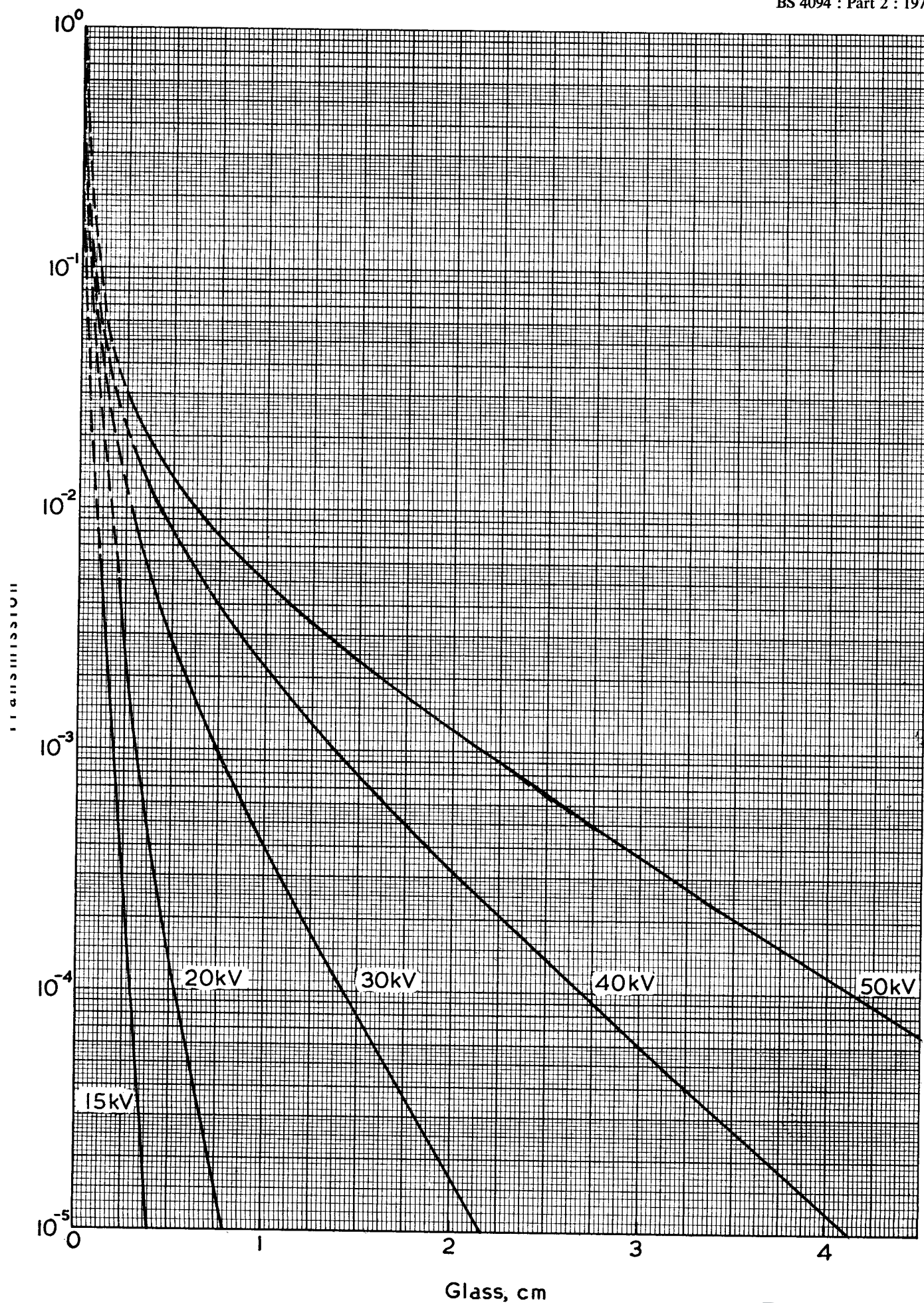


Fig. 7c. Transmission of 10 kV to 50 kV constant potential X-rays through sheet glass

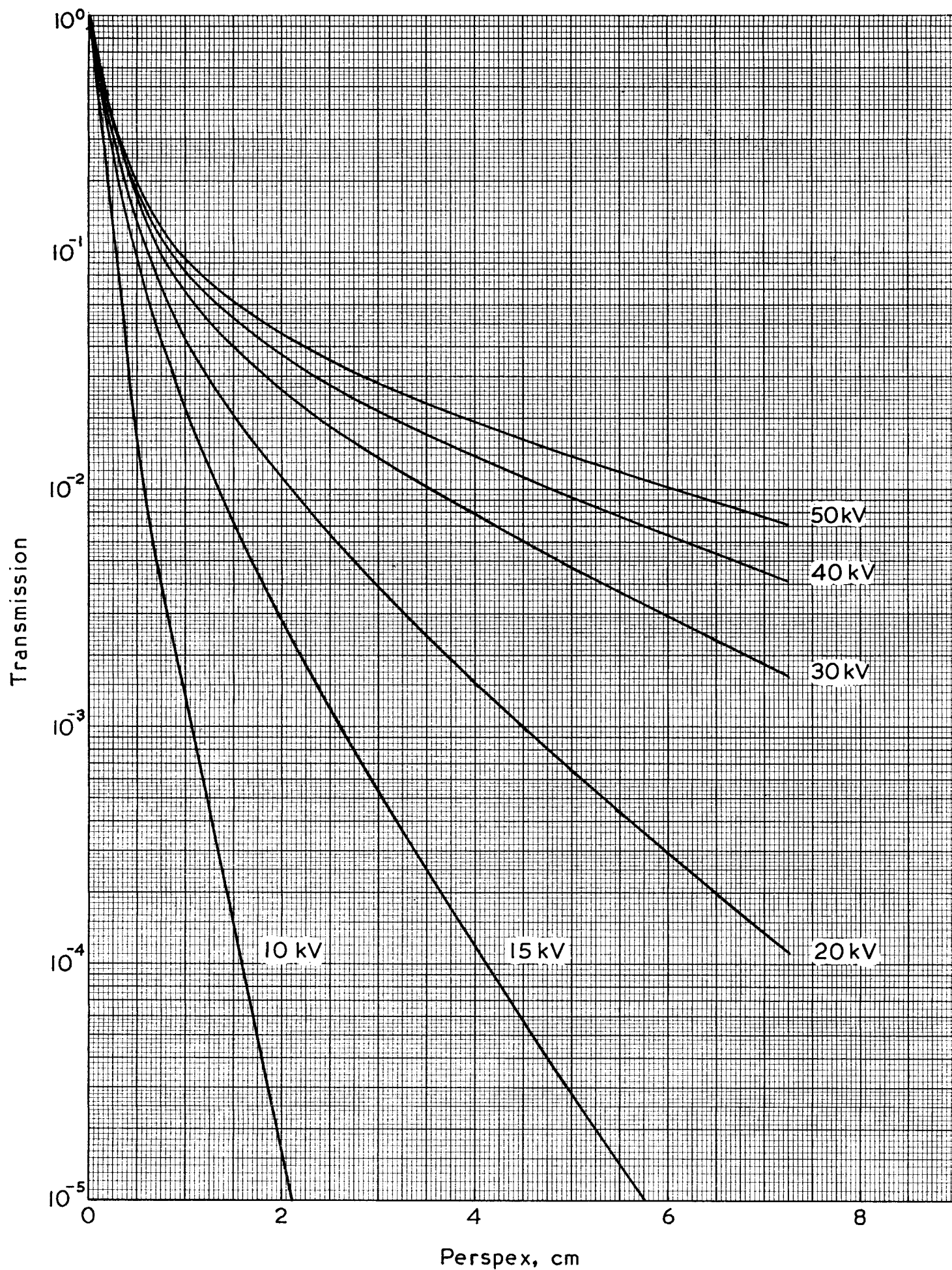


Fig. 7d. Transmission of 10 kV to 50 kV constant potential X-rays through Perspex