FILM DOSIMETRY OF X-RAYS BY MEANS OF RADIOACTIVE SOURCES IN A SHIELDED, TRANSPORTABLE CALIBRATION FACILITY*

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Abstract—*I. Evaluation of the effective energy of X-rays to which a film was exposed.*

Ilford PM3 films are used. The film badge has one portion without a filter and six portions with filters of various thicknesses of copper (0·1 to 0·97 mm), on both sides. The optical density under the portion without a filter $D(O)$ and under Cu filters $D(t)$, can be used in three different manners for the evaluation of effective energies of X-rays, namely:

1. By measurements of the half value photographic density layer in the case of effective energies ranging between 25 and 82 keV.
2. By the ratio $D(O)/D(t)$ as a function of the thickness of copper filters in the case of effective energies, ranging between 25 and 135 keV.
3. By the ratio $D(O)/D(0.1 \text{ mm Cu})$ as a function of effective energies between 25 and 55 keV, or by the ratio $D(O)/D(0.97 \text{ mm Cu})$ as a function of effective energies between 51 and 156 keV.

II. Use of a ^{226}Ra, ^{137}Cs or $^{90}Sr - ^{90}Y/Al$ source, in a shielded, transportable calibration facility, for the establishment of $\log D(O) = f(\log X)$, in the interval 25 keV $\leqslant E_{eff} \leqslant$ 156 keV of X-rays

1. In one set of experiments $\log D(O) = f(\log X)$ calibration curves were obtained by X-rays of E_{eff} between 25 and 156 keV.
2. In another set, $\log D(O) = f(\log X)$ calibration curves were obtained by means of radioactive sources in a shielded, transportable calibration facility.

   Because of the great difference in photographic sensitivity in the two energy intervals (X-rays : 25 keV $\leqslant E_{eff} \leqslant$ 156 keV; gamma rays : 662 keV to 1·25 MeV mean), it is necessary to give the PM3 films, in the calibration facility with radioactive sources, 6- to 10-fold higher exposures than to the films exposed to X-rays.
3. Using the two sets of measurements, calibration factors were determined.

INTRODUCTION

The energy dependence of the sensitivity of photographic film to X- or gamma-rays especially in the range of approximately 0.02 MeV to 0.3 MeV, is a well-known difficulty in film dosimetry. The knowledge of the effective energy, or energies, to which the film was exposed, as well as the corresponding calibration curves are therefore needed.[1, 2]

If the calibration curves for different energies are given for a certain quality of photographic film, only one more calibration curve, with a known X-ray effective energy, is then necessary for each set of exposure measurements.[3-12]

We considered it worthwhile to replace this single calibration with X-rays by a calibration using a radioactive source. This is placed in a calibration facility which is transportable, protected against radiation hazards, easily operated, having a well-defined and reproducible geometry and radiation. Our experiments were made with Ilford PM3 films for personnel monitoring. We report here the results which make possible the evaluation of the effective energy of X-rays to which such a film was exposed; the photographic density versus exposure curves for different effective energies of

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X-rays; the calibration curves obtained with different radioactive sources in our calibration facility, and the corresponding factors enabling the construction of other calibration curves.

exposure was measured with a Victoreen ionization chamber.

The X-ray source was a Coolidge type, tungsten anode, oil cooled, glass X-ray tube. The applied voltage was stabilized and had an insignificant ripple. The tube was operated at voltages from 34 to 183 kV and at a constant current of 5 mA. The X-ray beam was filtered through pure copper of 0.047 mm to 15.5 mm thickness. The corresponding effective energies, determined by the half value layer (HVL) of

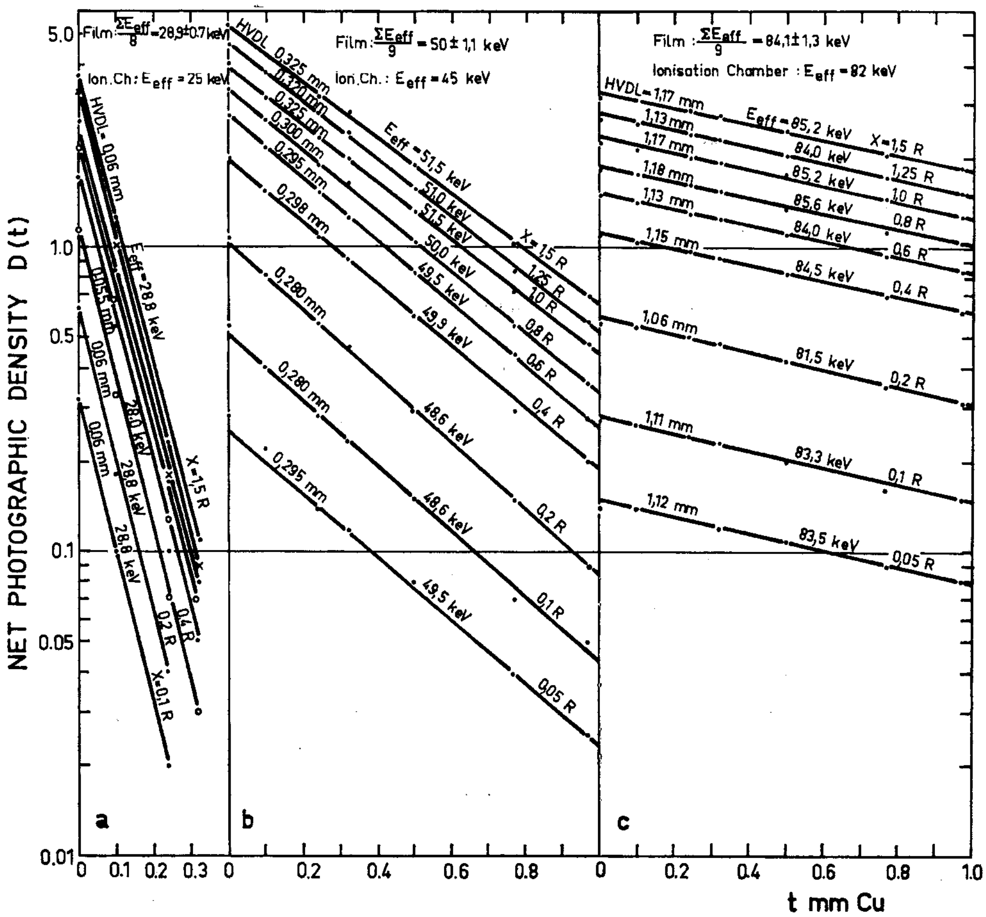

FIG. 1. Determination of effective energies of X-rays by measurements of half value density layers (HVDL) of copper. The results are independent of exposures in the interval from 0·05 to 1·5 R. Three examples for effective energies of (a) 25 keV, (b) 45 keV and (c) 82 keV obtained by measurements of HVL with ion chambers are given.

MATERIAL AND METHODS

A film badge[18] containing an Ilford PM3 film, having an unfiltered portion and six portions filtered back and front by pure copper filters (0.1, 0.24, 0.32, 0.5, 0.77 and 0.97 mm thick, 10 mm long and wide), was exposed to a given narrow energy band of X-rays. The copper, as described by Johns,[14] using a Victoreen ionization chamber, were in the range of 25 to 156 keV.

The exposed films were developed in Ilford Phen-X developer for 5 min at 20 ± 0.2°C. The photographic densities were measured with a Baldwin densitometer.

EVALUATION OF THE EFFECTIVE ENERGY TO WHICH A FILM WAS EXPOSED

The nett photographic density $D(t)$, as function of the thickness t of copper filters, and the exposure X is shown (Fig. 1) for three different energies. Two facts merit attention.

1. For a given exposure, log D is a linear function of t. At first sight this is not to be expected when the intensity is measured by means of photographic films. There is no proportionality between the nett photographic density and the exposure.

2. All the effective energies, determined by the half value photographic density layer (HVDL), are fairly independent of the exposure, but are systematically about 11% higher than determined by HVL measured with an ionization chamber.

There is evidently a difference in the two kinds of measurements. The ionization chamber measures only the radiation leaving the filter, whereas the film detects also the radiation backscattered from the back filter.[15] The absorption coefficient therefore appears to be smaller and the effective energy correspondingly greater than in the former case.

The results of the measurements can be presented in two other useful forms:

1. As a family of curves, representing log $D(\mathrm{O})/D(t)$ as function of the thickness t of copper filters for a given effective energy E_{eff} (Fig. 2).

These curves established once for all, enable one to evaluate the unknown energy to which a film was exposed.

2. As curves, representing $D(\mathrm{O})/D(t)$ for a given thickness of copper filters as functions of the effective energy (Fig. 3.)

In fact two such curves, namely for $D(\mathrm{O})/D(0.1 \text{ mm Cu})$ and $D(\mathrm{O})/D(0.97 \text{ mm Cu})$ cover the entire range of energies taken into consideration. Knowing the convenient ratio $D(\mathrm{O})/D(t)$

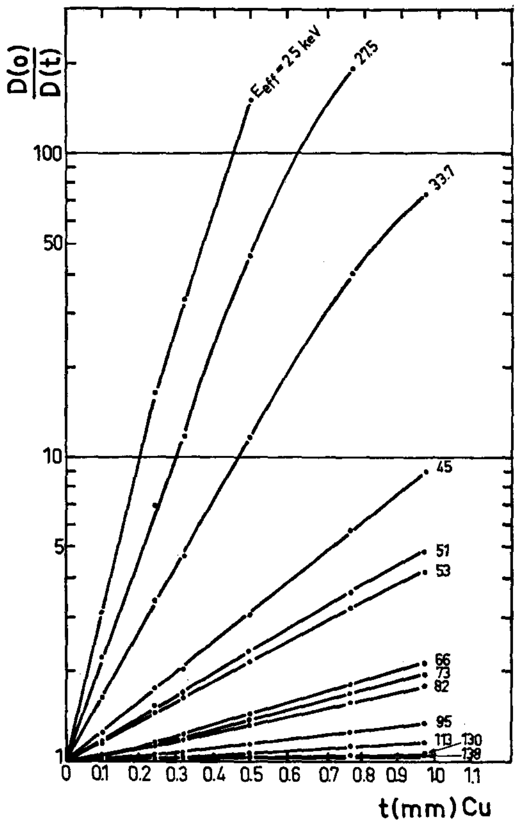

FIG. 2. Ratio of the densities of the unfiltered and filtered portions of the film, $D(\mathrm{O})/D(t)$, as functions of the thickness t of copper filters for various effective X-ray energies. $D(\mathrm{O})$ and $D(t)$ are mean values of densities corresponding to exposures between 0·6 and 1·5 R.

and t, the curves, established once for all, make it possible to find the effective energy to which the film was exposed.

DENSITY-EXPOSURE CURVES FOR X-RAYS OF VARIOUS EFFECTIVE ENERGIES

The experimental data, partially represented in Fig. 1, include the corresponding set of values $D(\mathrm{O})$, X and E_{eff}. This makes it possible to find the relation between $D(\mathrm{O})$ and X for a given E_{eff}.

Ehrlich,[16] Brodsky[17] and Kathreen and Brodsky[18] have shown, for different types of duPont and Kodak Films, exposed to betatron

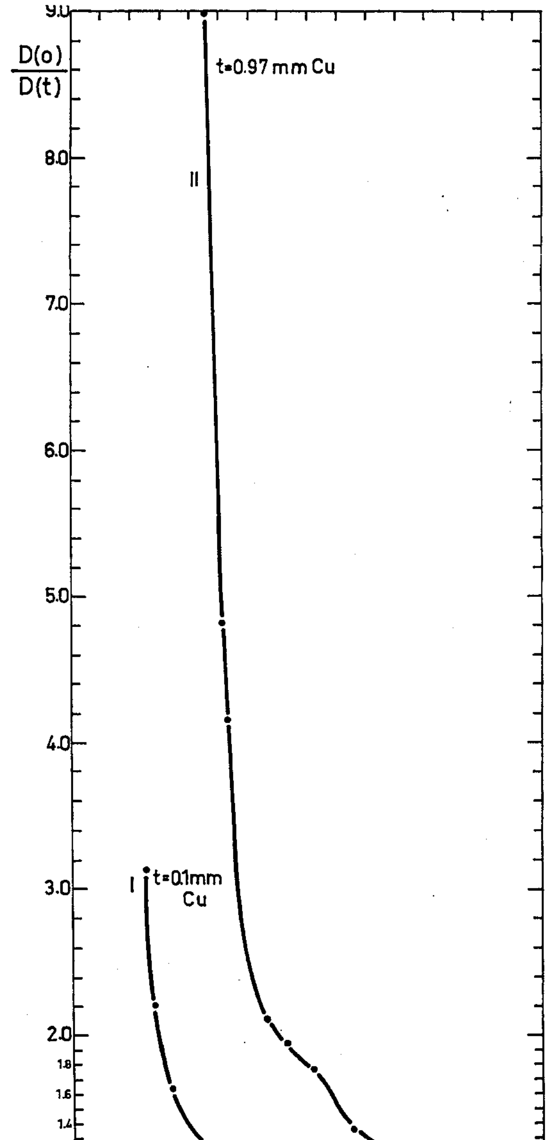

FIG. 3. Curve I: Ratio of densities of unfiltered portions and portions filtered by 0·1 mm Cu $D(O)/D(0\cdot 1$ mm Cu) as a function of effective X-ray energies between 25 and 55 keV.

Curve II: Ratio $D(O)/D(0\cdot 97$ mm Cu) as a function of effective X-ray energies between 51 and 156 keV. $D(O)$, $D(0\cdot 1$ mm Cu) and $D(0\cdot 97$ mm Cu) are mean values of densities corresponding to exposures between 0·6 and 1·5 R

X-rays, ^{60}Co- or ^{226}Ra-gamma rays, that density–exposure curves can be fitted to a straight line on a log–log plot.

Our results for $D(O)$ and X in this representation fitted to a least square line are given in Figs. 4 and 5. Most of the $\log D(O) = f(\log X)$ relations can be represented by a straight line (Fig. 4), whose corresponding equations are given on the figure.

For some energies a reasonable fit is obtained only if the experimental results are represented by two straight lines, one from 50 mR to about 200 mR, the other from about 200 mR to 1500 mR (Fig. 5).

From Figs. 4 and 5 it is seen that, irrespective of exposure, the maximum sensitivity of the film is about $E_{eff} = 45$ keV.

DENSITY EXPOSURE CURVES OBTAINED BY MEANS OF RADIOACTIVE SOURCES IN THE SHIELDED, TRANSPORTABLE CALIBRATION FACILITY

1. The calibration facility constructed for ^{226}Ra (4.52 mg, 0.5 mm Pt) and ^{137}Cs (15 mCi, 0.5 mm Pt) (Fig. 6), a modification of a previous device,[9, 10] consists essentially of two units:

(a) A lead block LB, containing a radioactive source RS in a source holder SH, as well as a cylindrical lead shutter and collimator SC, which can slide in the hole H of the lead block LB. By axial translation of SC, the source can be shielded or permitted to radiate through the collimator and the window W.

(b) A film holder FH, with its base BH, made of aluminium alloy, makes it easy to place the films in exactly known positions relatively to the source.

The assembled facility is shown in Fig. 7. Taken to pieces it can be packed into a small volume; it weighs 12.7 kg.

2. For the ^{90}Sr–^{90}Y/Al bremsstrahlung source (620 mCi) a much simpler lead source holder SH was used, as shown in Fig. 8.

The assembled facility is shown in Fig. 9; it weighs 10.2 kg.

If for a set of measurements on personnel monitoring films, the density–exposure curves (Figs. 4 and 5) have to be corrected by comparison with a corresponding curve, obtained by means of a radioactive source, it is necessary that the nett photographic densities of these curves be in the interval O $\angle$ D(O) $\angle$ 5.4 approximately.

Because of the relatively high energies of the radiation spectra of the radioactive sources we have used, and the diminished sensitivity of the PM3 films for these radiations, it is necessary give linear relations; the corresponding equations are indicated in Fig. 10.

END POINTS FACTORS

Table 1 gives numerical factors by means of which the log D(O) $= f(\log X)$ curves, in the

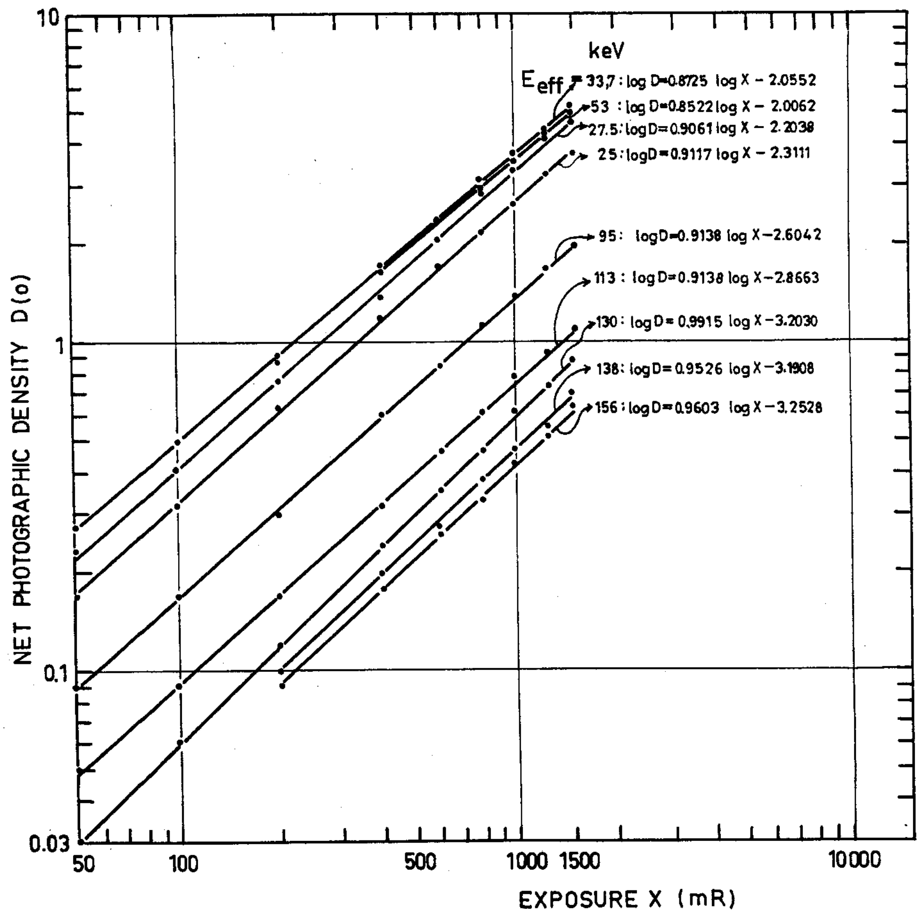

Fig. 4. Density–exposure calibration curves for X-rays of E_{eff}: 33.7; 53; 27.5; 25; 95; 113; 130; 138 and 156 keV. Ilford PM3 films were exposed in the range from 50 to 1500 mR. The densities are those of the unfiltered portions.

to give the films much greater exposures than when irradiated with X-rays in the energy interval we investigated.

We found that the log D(O) $= f(\log X)$ curves fall in the interesting region if we plot log D(O) vs. log $(X/6)$ for the bremsstrahlung source and vs. log $(X/10)$ for the ^{226}Ra or ^{137}Cs sources. The results fitted to a least square line interval 25 keV $\leq E_{eff} \leq$ 156 keV of X-rays can be obtained. If the above relation is a single straight line for a given energy, only two factors F_1 and F'_1 are given. If two straight lines are necessary, four factors are indicated. In comparison with the corresponding curves of Fig. 5 it is easy to see which part of each line should be used.

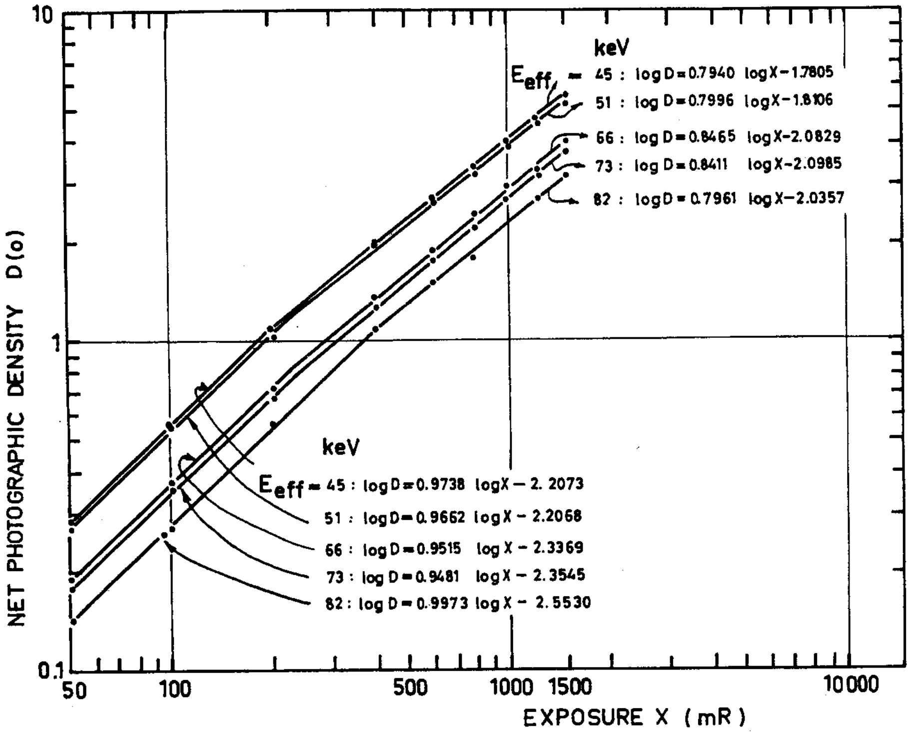

FIG. 5. Density–exposure calibration curves for X-rays of E_{eff}: 45; 51; 66; 73 and 82 keV. Ilford PM3 films were exposed in the range from 50 to 1500 mR. The densities are those of the unfiltered portions.

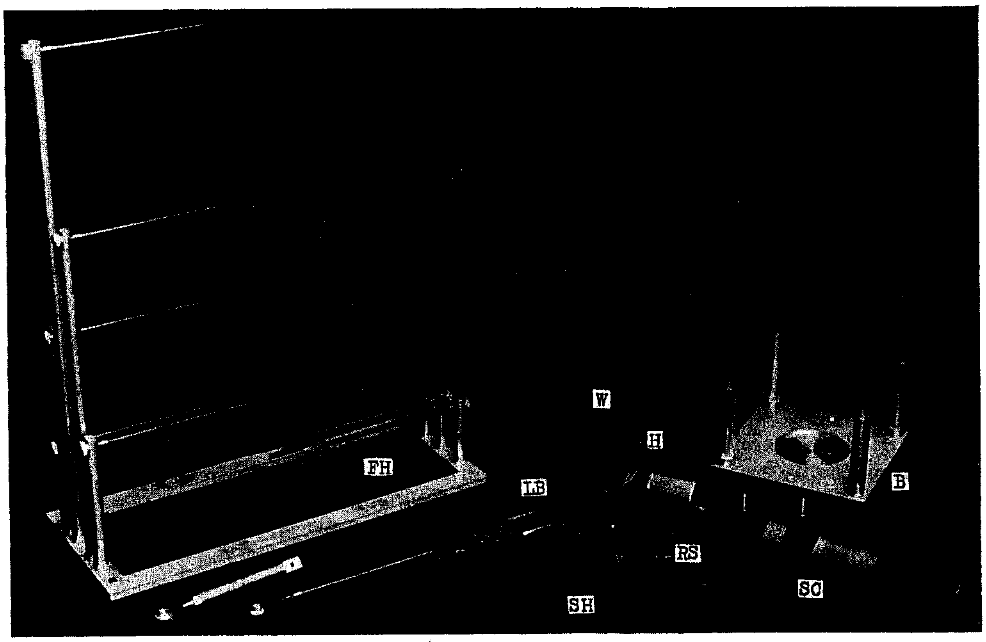

FIG. 6. The shielded, transportable calibration facility constructed for ^{226}Ra (4.52 mg, 0.5 mm Pt) and ^{137}Cs (15 mCi, 0.5 mm Pt). Shutter and collimator, SC. Source holder, SH. Hole, H. Lead Block, LB. Window, W. Radioactive source, RS. Film holder, FH. Base, B.

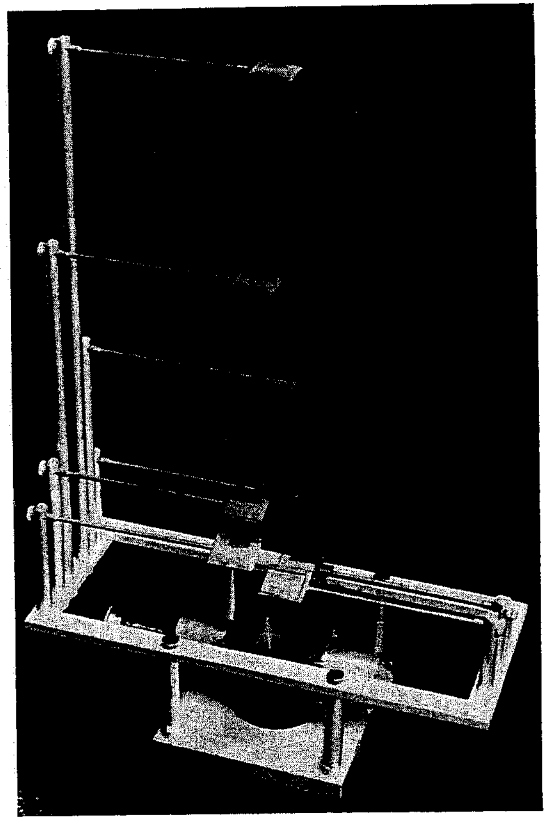

FIG. 7. The assembled facility for ^{226}Ra and ^{137}Cs.

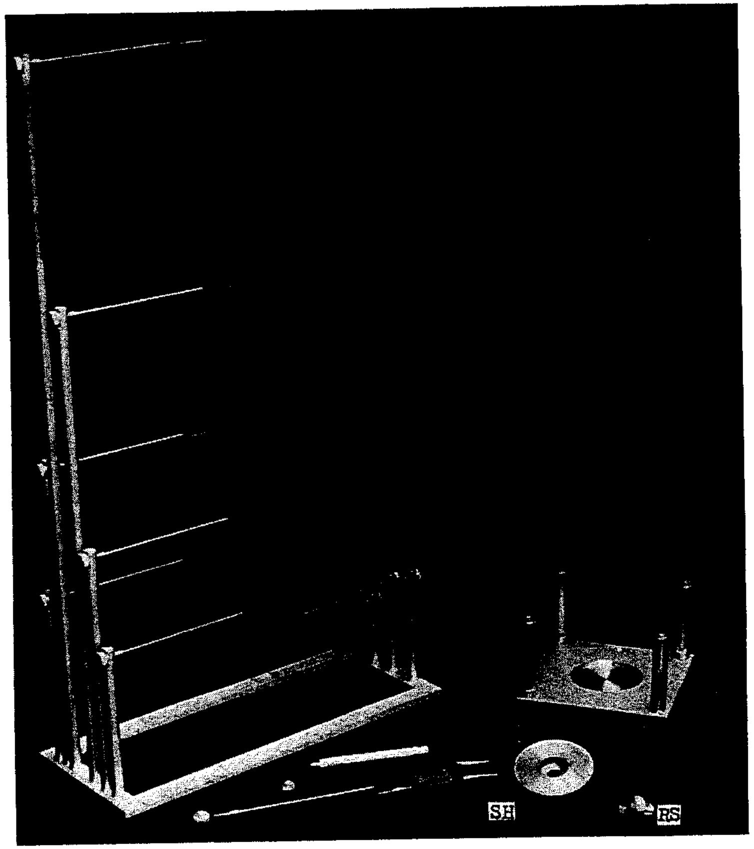

FIG. 8. The shielded, transportable calibration facility for the ^{90}Sr–^{90}Y/Al bremsstrahlung source (620 mCi).

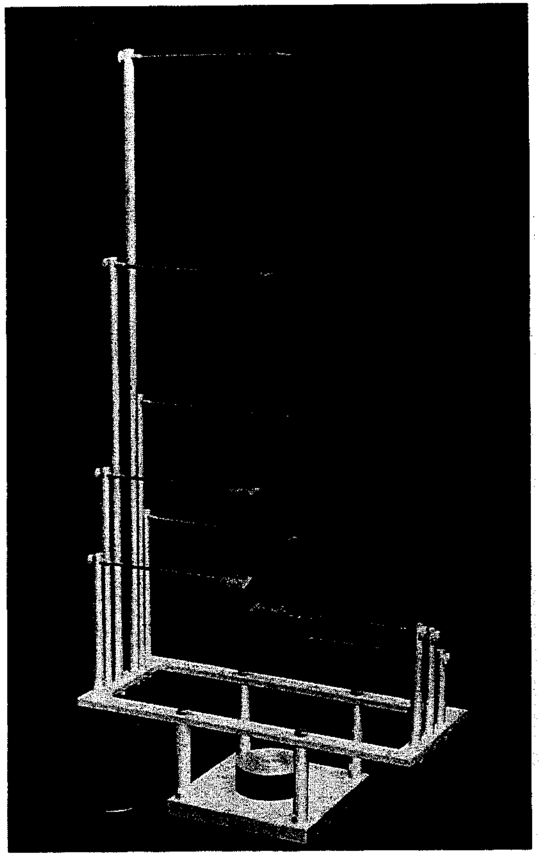

FIG. 9. The assembled facility for the bremsstrahlung source.

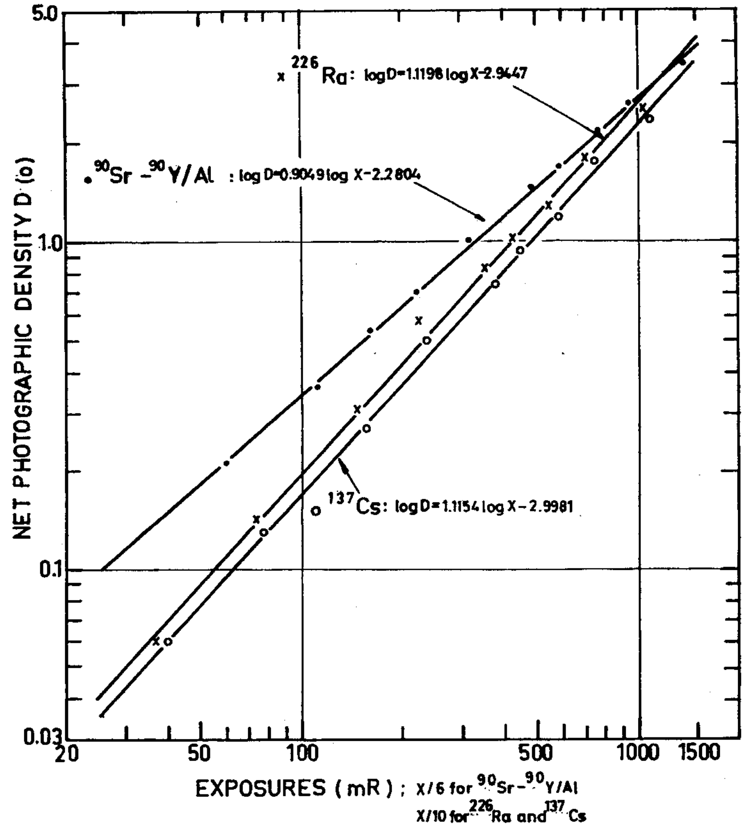

FIG. 10. Density–exposure curves obtained by means of radioactive sources in the shielded, transportable calibration facility.
Three sources were used: 620 mCi ^{90}Sr–^{90}Y/Al bremsstrahlung source, 4.52 mg ^{226}Ra, screened by 0.5 mm Pt, 15 mCi ^{137}Cs, screened by 0.5 mm Pt. The exposures X (mR) indicated correspond to X/6 for the bremsstrahlung source and to X/10 for the ^{226}Ra or ^{137}Cs sources. The densities are those of the unfiltered portions.

Table 1. *Factors for the Determination of End Points of log* $D = f$ (*log* X) *Relations.*

E_{eff} keV	F_1	F_1'	F_2	F_2'	F_3	F_3'
25	0.96	0.98	1.91	0.94	2.19	1.10
27.5	1.20	1.20	2.39	1.15	2.75	1.35
33.7	1.48	1.33	2.94	1.27	3.39	1.48
45	1.55	1.96	3.08	1.88	3.55	2.19
	2.05	1.40	4.08	1.35	4.69	1.57
51	1.51	1.85	3.00	1.78	3.45	2.08
	1.96	1.37	3.88	1.31	4.48	1.53
53	1.53	1.28	3.05	1.23	3.50	1.43
66	1.05	1.23	2.10	1.18	2.41	1.38
	1.25	1.03	2.50	0.99	2.87	1.15
73	1.00	1.16	1.99	1.11	2.29	1.29
	1.18	0.95	2.36	0.91	2.71	1.07
82	0.77	1.05	1.53	1.01	1.76	1.17
	1.15	0.79	2.28	0.76	2.63	0.89
95	0.49	0.51	0.98	0.49	1.13	0.57
113	0.27	0.28	0.54	0.27	0.62	0.31
130	0.17	0.23	0.33	0.22	0.38	0.25
138	0.16	0.17	0.32	0.17	0.37	0.19
156	0.13	0.16	0.26	0.15	0.30	0.18

$$F_1 = \left(\frac{D_{x\text{-rays}}}{D_{Sr\text{-}90, Y\text{-}90/Al}} \right)_{50\ mR}$$

$$F_1' = \left(\frac{D_{x\text{-rays}}}{D_{Sr\text{-}90, Y\text{-}90/Al}} \right)_{1500\ mR}$$

$$F_2 = \left(\frac{D_{x\text{-rays}}}{D_{Ra\text{-}226}} \right)_{50\ mR}$$

$$F_2' = \left(\frac{D_{x\text{-rays}}}{D_{Ra\text{-}226}} \right)_{1500\ mR}$$

$$F_3 = \left(\frac{D_{x\text{-rays}}}{D_{Cs\text{-}137}} \right)_{50\ mR}$$

$$F_3' = \left(\frac{D_{x\text{-rays}}}{D_{Cs\text{-}137}} \right)_{1500\ mR}$$

CONCLUSIONS

1. Using the Ilford PM3 film in a badge provided with six copper filters (0.1 to 0.97 mm thick), it is possible to find the effective energy of X-rays in the interval of 25 to 156 keV.

2. The determination of only one log $D(O) = f(\log X)$ line, by means of the described shielded, transportable calibration facility and a ^{226}Ra, ^{137}Cs or ^{90}Sr–^{90}Y/Al source, enables one to trace other calibration lines, using the given factors for the calculation of the end-points of these lines. Thus the determination of unknown exposures of X-rays, in the above mentioned energy range, is possible.

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