INTERNATIONAL STANDARD

ISO 4037-1

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X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy —

Part 1:
Radiation characteristics and production methods

Rayonnements X et gamma de référence pour l'étalonnage des dosimètres et des débitmètres, et pour la détermination de leur réponse en fonction de l'énergie des photons —

Partie 1: Caractéristiques des rayonnements et méthodes de production

Reference number
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Contents

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 4037-1 was prepared by Technical Committee ISO/TC 85, *Nuclear energy*, Subcommittee SC 2, *Radiation protection*.

This first edition of ISO 4037-1, along with ISO-4037-2, cancels and replaces the first edition of ISO 4037:1979, which has been technically revised.

ISO 4037 consists of the following parts, under the general title *X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy.*

— *Part 1: Radiation characteristics and production methods*

— *Part 2: Dosimetry of X and gamma reference radiation for radiation protection over the energy ranges 8 keV to 1,3 MeV and 4 MeV to 9 MeV*

Annex A of this part of ISO 4037 is for information only.

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X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy —

Part 1:
Radiation characteristics and production methods

1 Scope

This part of ISO 4037 specifies the characteristics and production methods of X and gamma reference radiation for calibrating protection-level dosemeters and rate dosemeters at air kerma rates from 10 $\mu Gy \cdot h^{-1}$ to 10 $Gy \cdot h^{-1}$ and for determining their response as a function of photon energy. The methods for producing a group of reference radiations for a particular photon-energy range are described in four sections which define the characteristics of these radiations. The four groups of reference radiation are:

a) in the energy range from about 7 keV to 250 keV, continuous filtered X radiation and the gamma radiation of americium-241;

b) in the energy range 8 keV to 100 keV, fluorescence X radiation;

c) in the energy range 600 keV to 1,3 MeV, gamma radiation emitted by radionuclides;

d) in the energy range 4 MeV to 9 MeV, gamma radiation produced by reactors and accelerators.

These reference radiations should be selected from table 1.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this part part of ISO 4037. At the time of the publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this part of ISO 4037 are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 197-1:1983, *Copper and copper alloys — Terms and definitions — Part 1: Materials.*

ISO 1677:1977, *Sealed radioactive sources — General.*

ISO 3534-1:1993, *Statistics — Vocabulary and symbols — Part 1: Probability and general statistical terms.*

ISO 8963:1988, *Dosimetry of X and gamma reference radiations for radiation protection over the energy range from 8 keV to 1,3 MeV.*

ICRU Report 10b, *Physical Aspects of Irradiation,* National Bureau of Standards Handbook **85**(1964).

Table 1 — List of X and gamma reference radiation and their mean energies

Values in kiloelectronvolts

Fluorescence X radiation, mean energy	Mean energy, filtered X radiation				Gamma radiation, mean energy
	Low air-kerma rate series	Narrow-spectrum series	Wide-spectrum series	High air-kerma rate series	
8,6	8,5	8		7,5	
9,9					
		12		13	
15,8		16			
17,5	17				
		20		20	
23,2		24			
25,3	26				
	30				
31					
		33			
37,4				37	
40,1			45		
	48	48			
49,1					
59,3	60		57	57	59,5 (^{241}Am)
		65			
68,8					
75,0			79		
98,4	87	83			
		100	104	102	
	109				
		118		122	
	149		137	146	
				147	
		164	173		
	185	208	208		
	211	250			
					662(^{137}Cs)
					1 173 and 1 333 (^{60}Co)
					4 440 (^{12}C)
					6 000 (Ti)
					6 130[1]
					^{16}O* and ^{16}N
					8 500 (Ni)

1) When produced by protons of energy near the reaction theshold, see 7.1).

3 Definitions

For the purposes of this part of ISO 4037, the following definitions apply:

3.1 mean photon energy, $\overline{E}$: Ratio defined by the formula:

$$\overline{E} = \frac{\int_0^{E\max} \Phi_E \, E \mathrm{d}E}{\int_0^{E\max} \Phi_E \, \mathrm{d}E}$$

where Φ_E is the derivative of the fluence Φ_E of the primary photons of energy E with respect to energies between E and $E + \mathrm{d}E$[1], defined as

$$\Phi_E = \frac{\mathrm{d}\Phi(E)}{\mathrm{d}E}$$

In this part of ISO 4037, this definition is abbreviated to "mean energy".

3.2 spectral resolution, R_E (full width at half maximum)**:** Ratio, expressed as a percentage, defined by the formula:

$$R_E = \frac{\Delta E}{E} \times 100$$

where increment ΔE is the spectrum width corresponding to half the maximum ordinate of the spectrum.

NOTE — In the case where fluorescence radiation is present in the spectrum, the spectrum width measured is based upon the continuum only.

In this part of ISO 4037 this definition is abbreviated to resolution.

3.3 half-value layer (air kerma), HVL or HVL_x[2]**:** Thickness of the specified material which attenuates the beam of radiation to an extent such that the air kerma rate is reduced to half of its original value.

In this definition, the contribution of all scattered radiation, other than any which might be present initially in the beam concerned, is deemed to be excluded.

3.4 homogeneity coefficient, h: Ratio of the first half-value layer to the second half-value layer (air kerma):

$$h = \frac{1^{\mathrm{st}}\ \mathrm{HVL}}{2^{\mathrm{nd}}\ \mathrm{HVL}}$$

3.5 effective energy, E_{eff} (of radiation comprised of X-rays with a range of energies)**:** Energy of the monoenergetic X-rays which have the same HVL.

3.6 value of peak-to-peak voltage; ripple: Ratio, expressed as a percentage, defined for a given current by the formula:

$$\frac{U_{\max} - U_{\min}}{U_{\max}} \times 100$$

where U_{max} is the maximum value and U_{min} the minimum value between which the voltage oscillates.

3.7 X-ray unit: Assembly comprising a high-voltage supply, an X-ray tube with its protective housing, and high-voltage electrical connections.

3.8 X-ray tube: Vacuum tube designed to produce X-rays by bombardment of the anode by a beam of electrons accelerated through a potential difference.

3.9 monitor: Instrument used to monitor the stability of the air kerma rate during irradiation or to compare values of air kerma after successive irradiations.

3.10 primary radiation (or beam): Radiation or beam emitted by the X-ray tube.

3.11 secondary [fluorescence] radiation: Radiation or beam emitted by a radiator.

3.12 X-ray tube shielding: Fixed or mobile panel intended to reduce the contribution of scatter X-radiation to the primary or fluorescence (secondary) beam.

4 Continuous reference filtered X radiation

4.1 General

This clause specifies the characteristics of the reference filtered X radiation and the method by which a laboratory can produce a specified reference radiation.

4.1.1 Radiation quality

The quality of a filtered X radiation is characterized in this part of ISO 4037 by the following parameters:

a) mean energy, $\overline{E}$, of a beam, expressed in kiloelectronvolts (keV);

b) resolution, R_E, expressed in percent;

c) half-value layer (air kerma), HVL, expressed in millimetres of Al or Cu;

d) homogeneity coefficient, h.

In practice, the quality of the radiation obtained depends primarily on

— the high-voltage across the X-ray tube,

— the thickness and nature of the total filtration, and

— the properties of the target.

In order to ensure the production of the reference radiation in conformance with the given specifications, the installation shall comply with certain conditions. These are described in 4.2.

4.1.2 Choice of reference radiation

This part of ISO 4037 specifies four series of reference radiation (see table 2), each series being characterized by the resolution of the spectrum:

a) a low air-kerma rate series (see figure 1);

b) a narrow-spectrum series (see figure 2);

c) a wide-spectrum series (see figure 3);

d) a high air-kerma rate series (see figure 4).

The spectra shown in figures 1 to 4 are for the most part based upon theoretical calculations[3] and are only given as examples. Some practical spectra are also included and examples of practical measurements of spectra are given in references [4], [5], [6], [7] and [8].

The narrowest spectra, i.e. those with the lowest resolution, should be used for measurements of the variation of the response of an instrument with proton energy, provided that the air-kerma rates of that series are consistent with the range of the instrument under test. The high air-kerma rate series is suitable for determining the overload characteristics of some instruments.

Details of the operating conditions for each of the four series are given in tables 3, 4, 5 and 6. Table 7 shows an example of the additional filtration required to produce the radiation qualities of the high air-kerma rate series for particular values of the fixed filtration.

For the lower air-kerma rate, the narrow-spectrum and the wide-spectrum series, a "reference laboratory" shall verify, by a spectrometric study, that the value of the mean energy produced is within ± 3 %, and the resolution, R_E, of the spectra is within ± 10 % of the values listed in tables 3, 4 and 5.

For reference radiation for these three series having mean energies lower than 30 keV, the mean energies shall be within ± 5 % and the resolutions within ± 15 % of the values in tables 3, 4 and 5. For reference radiation using additional filtration of 1 mm Al or less, the target angle, target condition and air path strongly influence the values of the mean energies, resolutions and HVLs.

If a laboratory does not have a spectrometry system, the high voltages and filtration characteristics listed in tables 3, 4 and 5 shall be used and the reference radiation produced shall be checked by the simple method described in 4.3.

Table 2 — Specifications of filtered X radiation

Name of series	**Resolution, R_E** %	**Homogeneity coefficient, h** (approximate values)	**Typical air-kerma rates**[1), 2)] Gy·h^{-1}
Low air-kerma rate	18 to 22	1,0	3×10^{-4} [3)]
Narrow spectrum	27 to 37	0,75 to 1,0	10^{-3} to 10^{-2} [3)]
Wide spectrum	48 to 57	0,67 to 0,98	10^{-2} to 10^{-1} [3)]
High air-kerma rate	Not specified	0,64 to 0,86	10^{-2} to 0,5

1) At a distance of 1 m from the X-ray focal spot, with the tube operating at 1 mA.
2) Under conditions of charged-particle equilibrium, the value of air kerma is approximately equal to the absorbed dose to air.
3) At mean energies of less than 30 keV, other values may apply.

Table 3 — Characteristics of low air-kerma rate series

Mean energy, $\overline{E}$ keV	Resolution, R_E %	Tube potential[1] kV	Additional filtration[2] mm				1st HVL[4] mm
			Pb	Sn	Cu	Al	
8,5		10				0,3[3]	0,058 Al
17	21	20				2,0[3]	0,42 Al
26	21	30			0,18	4,0[3]	1,46 Al
30	21	35			0,25		2,20 Al
48	22	55			1,2		0,25 Cu
60	22	70			2,5		0,49 Cu
87	22	100		2,0	0,5		1,24 Cu
109	21	125		4,0	1,0		2,04 Cu
149	18	170	1,5	3,0	1,0		3,47 Cu
185	18	210	3,5	2,0	0,5		4,54 Cu
211	18	240	5,5	2,0	0,5		5,26 Cu

1) The tube potential is measured under load.

2) Except for the three lowest energies, where the recommended inherent filtration is 1 mm of beryllium, the total filtration consists of the additional filtration plus the inherent filtration, adjusted to 4 mm of aluminium (see 4.2.3).

3) The recommended inherent filtration is 1 mm Be, but other values may be used provided that the mean energy is within ± 5 % and the resolution is within ± 15 % of the values given in the table.

4) The HVLs are measured at 1 m from the focal spot. The second HVL is not included for this series, since it is not significantly different from the first HVL.

Table 4 — Characteristics of narrow-spectrum series

Mean energy, $\overline{E}$ keV	Resolution, R_E %	Tube potential[1] kV	Additional filtration[2] mm				1st HVL[4] mm	2nd HVL[4] mm
			Pb	Sn	Cu	Al		
8	28	10				0,1[3]	0,047 Al	0,052 Al
12	33	15				0,5[3]	0,14 Al	0,16 Al
16	34	20				1,0[3]	0,32 Al	0,37 Al
20	33	25				2,0[3]	0,66 Al	0,73 Al
24	32	30				4,0[3]	1,15 Al	1,30 Al
33	30	40			0,21		0,084 Cu	0,091 Cu
48	36	60			0,6		0,24 Cu	0,26 Cu
65	32	80			2,0		0,58 Cu	0,62 Cu
83	28	100			5,0		1,11 Cu	1,17 Cu
100	27	120		1,0	5,0		1,71 Cu	1,77 Cu
118	37	150		2,5			2,36 Cu	2,47 Cu
164	30	200	1,0	3,0	2,0		3,99 Cu	4,05 Cu
208	28	250	3,0	2,0			5,19 Cu	5,23 Cu
250	27	300	5,0	3,0			6,12 Cu	6,15 Cu

1) The tube potential is measured under load.

2) Except for the five lowest energies, where recommended inherent filtration is 1 mm Be, the total filtration consists of the additional filtration plus the inherent filtration, adjusted to 4 mm of aluminium (see 4.2.3).

3) The recommended inherent filtration is 1 mm Be, but other values may be used provided that the mean energy is within ± 5 % and the resolution is within ± 15 % of the values given in the table.

4) The HVLs are measured at 1 m from the focal spot.

Table 5 — Characteristics of wide-spectrum series

Mean energy, $\overline{E}$ keV	Resolution, R_E %	Tube potential[1] kV	Additional filtration[2] mm		1st HVL Cu[3] mm	2nd HVL Cu[3] mm
			Sn	Cu		
45	48	60		0,3	0,18	0,21
57	55	80		0,5	0,35	0,44
79	51	110		2,0	0,96	1,11
104	56	150	1,0		1,86	2,10
137	57	200	2,0		3,08	3,31
173	56	250	4,0		4,22	4,40
208	57	300	6,5		5,20	5,34

1) The tube potential is measured under load.
2) The total filtration consists, in each case, of the additional filtration plus inherent filtration, adjusted to 4 mm of aluminium (see 4.2.3).
3) The HVLs are measured at 1 m from the focal spot.

Table 6 — Characteristics of high air-kerma rate series

Tube potential[1] kV	First HVL[3] mm	
	Al	Cu
10	0,04	
20	0,11	
30	0,35	
60	2,4	0,077
100		0,29
200		1,7
250		2,5
280[2]		3,4
300		3,4

1) The constant potential is measured under load.
2) This reference radiation has been introduced as an alternative to that generated at 300 kV, for use when 300 kV cannot be attained under conditions of maximum load.
3) The HVLs are measured at 1 m from the focal spot.

Table 7 — Approximate characteristics of high air-kerma rate series

Tube potential kV	Additional filtration[1] mm			Half-value layer[2] mm				Mean photon energy, $\overline{E}$ keV
				First		Second		
	Al	Cu	Air	Al	Cu	Al	Cu	
10			750	0,036	0,010	0,041	0,011	7,5
20	0,15		750	0,12	0,007	0,16	0,009	12,9
30	0,52		750	0,38	0,013	0,60	0,018	19,7
60	3,2		750	2,42	0,079	3,25	0,11	37,3
100	3,9	0,15	750	6,56	0,30	8,05	0,47	57,4
200		1,15	2 250	14,7	1,70	15,5	2,40	102
250		1,6	2 250	16,6	2,47	17,3	3,29	122
280		3,0	2 250	18,6	3,37	19,0	3,99	146
300		2,5	2 250	18,7	3,40	19,2	4,15	147

NOTE — The values listed in this table have been taken from Seelentag *et al.*[5] tables B4 and B5 and the spectra shown in figure 4 were calculated using the conditions listed in the tables [3]. The length of air path employed, which has been included in the additional filtration, is significant for the lower energy radiation. The actual spectral distributions obtained for a given X-ray facility will depend significantly upon the target angle and roughness.

1) For tube potentials above 100 kV, the total filtration consists, in each case, of the additional filtration plus the inherent filtration, adjusted to 4 mm of aluminium (see 4.2.3). For tube potentials at 100 kV and below, the examples given above refer to an inherent filtration of approximately 4 mm Be.

2) The HVLs are measured at 1 m from the focal spot.

For the high air-kerma rate series, the quality of the reference radiation is specified in terms of the X-ray tube potential, and the first HVL. The method for producing the high air-kerma rate series is described in 4.4.

4.2 Conditions and methods for producing reference radiation

4.2.1 Characteristics of the X-ray units

X radiation shall be produced by an X-ray unit whose tube potential shall have a ripple of less than 10 %. It is preferable to use an X-ray unit having a ripple as low as possible. X-ray units are commercially available which have a ripple of <1 %. It should be possible to display the value of this tube potential to whithin ± 1 %.

The target of the X-ray tube shall be made of tungsten, shall be of the "reflection" type and shall be orientated at an angle of not less than 20° to the direction of the bombarding electrons.

During irradiation, the mean value of the tube potential shall be stable to within ± 1 %.

NOTE — The X-ray tube should be operated in such a way that ageing effects are minimized, since these effects increase the inherent filtration (see 4.2.3).

4.2.2 Tube potential

The reference laboratory shall calibrate, at several points and under operating conditions, the equipment used to indicate the tube potential. The best methods employ an appropriately calibrated resistor chain or involve the measurement of the maximum photon energy by high resolution spectrometry. If the calibration is determined by spectrometry, the tube potential shall be found from the intersection of the extrapolated linear high-energy part of the spectrum with the energy axis. The conventionally true value of the tube potential shall be known to within ± 2 %.

For laboratories without these facilities, it is possible to set the tube potential to produce any of the radiation described in tables 3, 4 and 5.

This may be accomplished in one of the following ways.

a) For radiation generated at potentials below 116 kV (i.e. below the K-absorption edge of uranium at 115,6 keV), the voltage-measuring equipment or meter can be calibrated using techniques based on the excitation of the characteristic radiation from a selected element.

b) Alternatively, and for tube potentials above 116 kV, using the method described in 4.3. The inherent filtration shall be determined as described in 4.2.3 and the fixed filtration shall be adjusted to the required value with an additional aluminium filter (the total being regarded as constituting the new fixed filtration). The tube potential calibration shall be determined by achieving the reference HVL by the method specified in 4.3.

4.2.3 Filtration

NOTE — The total filtration is made up of the fixed filtration and the additional filtration. For radiation having the three lowest mean energies of 8,5 keV, 17 keV and 26 keV of the low air-kerma rate series and for radiation having the five lowest mean energies of 8 keV, 12 keV, 16 keV, 20 keV and 24 keV of the narrow-spectrum series, the fixed filtration comprises the recommended inherent filtration of the tube of 1 mm Be. Other values of the tube filtration may be used [see footnote 3) of tables 3 and 4].

4.2.3.1 For all other reference X radiation, the fixed filtration comprises:

a) the inherent filtration of the tube, plus that due to the monitor ionization chamber, if applicable, plus the aluminium filters which are added to obtain a total fixed filtration equivalent to that of 4 mm of aluminium at 60 kV. These aluminium filters shall be placed after the additional filtration (i.e. furthest from the X-ray focal spot) in order to reduce fluorescence radiation from the additional filtration;

b) the inherent filtration of the tube is due to the various constituent elements (glass of the bulb, oil, window, etc.) and is expressed, for a given voltage, as the thickness of an aluminium filter which, in the absence of hte constituent elements of the tube, would supply a radiation having the same first HVL. A tube whose inherent filtration exceeds 3,5 mm of aluminium should be not used;

c) the inherent filtration shall be checked periodically in order to ensure that this limit is not reached (because of tube ageing) and to proceed to the adjustment of the fixed filtration.

4.2.3.2 Determination of the inherent filtration shall be made by measuring, with aluminium absorbers of 99,9 % purity, the first HVL of the beam produced by the tube without additional filtration, at 60 kV, in the following way.

a) The method of measurement of the HVL should be in accordance with ICRU Report 10b and reference [9].

b) If a monitor ionization chamber is used during the measurement of inherent filtration, it should be placed between the two sets of beam collimators and be followed by the aluminium absorbers in such a manner that it does not correspond to radiation backscattered from the absorbers.

c) The first HVL shall be determined using an ionization chamber with a known response per unit air-kerma rate over the energy range of interest. Corrections shall be applied for any variation in detector response with changes in the photon spectrum as the thickness of the aluminium absorber is increased.

d) The inherent filtration measurements shall be made in a manner such that negligible scattered radiation from the aluminium absorbers reaches the detector, since such radiation would increase the measured HVL. For radiation produced at potentials above 100 kV, extrapolation to infinitely small field size should be made.

e) The aluminium absorbers should be located equidistant from the X-ray tube focus and from the detector. The diameter of the beam at the detector location shall be just sufficient to irradiate it completely and uniformly. The distancae from the aluminium absorbers to the detector should be at least five times the diameter of the beam at the detector.

f) The attenuation curve in aluminium shall be plotted, the first HVL shall be determined and a deduction made from it of the value of the inherent filtration on the basis of table 8. The results shall be rounded to the nearest 0,1 mm.

Table 8 — Inherent filtration

First HVL mm Al at 60 kV	Inherent filtration mm Al
0,33	0,25
0,38	0,3
0,54	0,4
0,67	0,5
0,82	0,6
1,02	0,8
1,15	1
1,54	1,5
1,83	2
2,11	2,5
2,35	3
2,56	3,5
2,75	4
2,94	4,5
3,08	5
3,35	6
3,56	7

NOTE — Results used were obtained from reference [10].

In the case of filtered X radiation, the values determined on the basis of table 8 at 60 kV may be used for other high-voltage values, since changes in the inherent filtration, expressed in millimetres of aluminium, are small compared with the added filtration.

NOTE — The inherent filtration value, expressed in millimetres of aluminium, varies as a function of the energy in a manner which depends upon the constituent elements of the inherent filtration.

4.2.3.3 The additional filtration comprises:

a) for the low air-kerma rate series, the narrow spectrum series and the wide spectrum series: lead, tin and copper filters as specified in tables 3, 4 and 5;

b) for the high air-kerma rate series: aluminium.

Table 9 — Metal properties

Metal	Quality	Nominal density g/cm^3
Aluminium	Minimum purity: 99,9 %	2,70
Copper[1)]	Minimum purity: 99,9 %	8,94
Tin	Minimum purity: 99,9 %	7,28
Lead	Extra fine Minimum purity: 99,9 %	11,3

1) See ISO 197/1.

c) For tube potentials < 100 kV or copper and aluminium (≥ 100 kV): as specified in table 7.

For each metal adopted, the filters used shall have a thickness which is specified with an accuracy of ± 5 % and be as homogeneous as possible (without air-holes, flaws, cracks and macroscopic grains) and the metals should have the purities shown in table 9.

The individual elements of the additional filtration shall be arranged, from the focus, in decreasing order of atomic number.

4.3 Alternative method of establishing reference radiation

This method enables a laboratory that does not have the capability to measure the value of the tube potential to determine the adjustments that shall be made to the tube potential in order to produce a radiation which is as close as possible to the reference radiation. This method is not applicable to the high air-kerma series, which is dealt with in 4.4.

4.3.1 Criterion

If the first and second HVLs in a given material agree within ± 5 % for two X-ray beams, then these two beams shall be considered to be essentially of the same quality. For tube potentials greater than 100 kV, the HVL shall be obtained from the extrapolation to infinitely small field size (see 4.2.3.2).

4.3.2 Apparatus

The apparatus consists of the detector itself and the measuring equipment, permitting a repeatability of at least 0,3 %, in accordance with ISO 3534-1.

The detector shall be an ionisation chamber whose variation in response per unit air kerma is small and known as a function of photon energy, over the energy range in question.

The measuring equipment and the methods of its use shall comply with the recommendations of ISO 8963.

A monitor chamber shall be used in order to permit application of corrections for fluctuations in the air kerma rate.

4.3.3 Measurement procedure

For selected reference radiation corresponding to the conditions specified in tables 3, 4 and 5, the following procedure shall be carried out.

Plot the attenuation curve $\log_e (I_d) = f(d)$ where I_d is the value of the air-kerma rate which is transmitted through a filter having a thickness d.

From the attenuation curve, determine the first and second HVLs.

If values of these layers agree within ± 5 % with those listed in tables 3, 4 and 5, it shall be assumed that the quality of the reference radiation complies with this part of ISO 4037. Note for the low air-kerma rate series only the first HVLs need comply with the values given in table 3.

If this is nost the case, the voltage used shall be adjusted and the measurements repeated until the ± 5 % criterion is met.

4.4 Production of high air-kerma rate series

4.4.1 Fixed filtration

For tube potentials up to and including 60 kV, the total filtrations (inherent + additional) are less than the equivalent of 4 mm of aluminium, so an X-ray tube with low inherent filtration is required to generate the lower energy radiation. At potentials of 60 kV and above, the fixed filtration shall be adjusted to the equivalent of 4 mm of aluminium. The aluminium filter used to supplement the inherent filtration of the tube shall be placed after the copper filter in order to reduce any fluorescent radiation arising from the copper. The thickness of aluminium employed shall not be less than 0,5 mm.

4.4.2 Additional filtration

At a given potential, the thickness of the additional filtration shall be adjusted so that the measured first HVL lies within ± 10 % of that specified, for radiation generated up to and including 30 kV and within ± 5 % for the higher energy radiation. The minimum purity of the additional filters and the absorbers used to determine the HVL shall be 99,9 %, except in the case of aluminium used at and below 20 kV when the minimum shall be 99,99 %. Examples of additional filtration for the high air-kerma rate series are given in table 7.

4.5 Field uniformity and scattered radiation

4.5.1 Field diameter

The diameter of the field shall be sufficient to completely and uniformly irradiate the detector at the point of test closest to the focus, usually not closer than 50 cm. The field may remain unchanged for all other experimental points of test or may be reduced to be just sufficient to irradiate the detector uniformly.

4.5.2 Field uniformity

The air-kerma rate at each point of test shall not vary by more than 5 % over the entire sensitive volume of the detector under test.

4.5.3 Scattered radiation

Both the following tests shall be carried out to check that, at the experimental distances the contribution due to scattered radiation is less than 5 % of the total air-kerma rate. These tests shall be carried out with the aid of a secondary standard ionisation chamber of adequate sensitive whose variations in response per unit air kerma as a function of photon energy and direction are small within the spectrum range considered.

4.5.3.1 Test 1

Measure the air-kerma rates on the central axis of the beam at the various points of test. The air-kerma rates, after corrections for air attenuation and for chamber size if applicable, shall be proportional within 5 % to the inverse square of the focus to detector distance.

4.5.3.2 Test 2

At each distance employed in test 1, measure the air kerma rate after displacing the chamber, in a plane perpendicular to the axis of the beam, by a distance which is equal to twice the radius of the beam plus its penumbra. The air-kerma rates of the scattered radiation outside the direct beam shall be less than or equal to 5 % of the corresponding air-kerma rates on the central axis.

5 Fluorescence X radiation

5.1 Principle

The calibration of dosemeters and doserate meters by means of fluorescence radiation makes use of the K fluorescence lines of certain materials having energies between 8,6 keV and 100 keV and which are given, as a first approximation, by that of their $K_{\alpha 1}$ line (see figure 5). The contribution of the K_β lines is made negligible with the aid of secondary filters whose K-absorption edges lie between the K_α and K_β lines (see table 10).

Table 10 — Radiators and filters used for K-fluorescence reference radiation

No.	Theoretical energy, $K_{\alpha 1}$ keV	Radiator			Tube potential[1] kV	Total primary filtration	Secondary filtration	
		Element	Recommended chemical form	Recommended areic mass of relevant chemical form g/cm²		Minimum thickness areic mass g/cm²	Recommended chemical form	Recommended areic mass of relevant chemical form g/cm²
1	9,89	Germanium	GeO_2	0,180	60	Al 0,135	GdO	0,020[3]
2	15,8	Zirconium	Zr	0,180	80	Al 0,27	$SrCO_3$	0,053
3	23,2	Cadmium	Cd	0,150	100	Al 0,27	Ag	0,053
4	31,0	Caesium	Cs_2SO_4	0,190	100	Al 0,27	TeO_2	0,132
5	40,1	Samarium	Sm_2O_3	0,175	120	Al 0,27	CeO_2	0,195
6	49,1	Erbium	Er_2O_3	0,230	120	Al 0,27	Gd_2O_3	0,263
7	59,3	Tungsten	W	0,600	170	Al 0,27	Yb_2O_3	0,358
8	68,8	Gold	Au	0,600	170	Al 0,27	W	0,433
9	75,0	Lead	Pb	0,700	190	Al 0,27	Au	0,476
10	98,4	Uranium	U	0,800	210	Al 0,27	Th	0,776
11	8,64	Zinc	Zn	0,180	50	Al 0,135	Cu	0,020
12	17,5	Molybdenum	Mo	0,150	80	Al 0,27	Zr	0,035
13	25,3	Tin	Sn	0,150	100	Al 0,27	Ag	0,071
14	37,4	Neodymium[2]	Nd	0,150	110	Al 0,27	Ce[2]	0,132
15	49,1	Erbium	Er	0,200	120	Al 0,27	Gd	0,233
16	59,3	Tungsten	W	0,600	170	Al 0,27	Yb	0,322

NOTE — For radiation numbered 1 to 10, the radiators and filters consist of either metallic foils or suitable chemical compounds. Alternative radiation covering the same energy region but consisting solely of metallic radiators and filters can be used and is formed by replacing radiators 1 to 7 with the radiators and filters numbered 11 to 16.

1) The optimum tube potential for maximum purity of the reference. Radiation is approximately twice the K-absorption edge energy for the relevant radiator. If higher air-kerma rates are required, it is possible to use higher values for high voltage, but this will result in a lower purity of radiation.

2) These foils should be properly sealed to prevent oxidation.

3) The value 0,020 g/cm² applies to the gadolinium only.

5.2 Fluorescence X-ray installation

The installation comprises an X-ray unit and a fluorescence device made up of a radiator, filters, a primary diaphragm, a secondary diaphragm and a trap (see figure 6).

5.2.1 X-ray unit

The same X-ray unit as that described in 4.2.1 may be used. The high voltage shall be stabilized so that variations do not exceed ± 5 % of the preset voltage.

In order to take account of possible fluctuations in the air-kerma rate, use shall be made of a monitor chamber irradiated by the secondary radiation beam, the chamber being constructed or placed so that it does not increase the secondary filtration significantly.

5.2.2 Fluorescence device (see figure 6)

5.2.2.1 Radiators

The radiators shall be chosen from among those listed in table 10. The radiator materials shall have a minimum purity of 99,9 %. The radiators may be in the form of thin metal foils or in the form of a powdered compound (oxide, carbonate or sulfate) dispersed in a plastic binder which contains only materials having atomic numbers low compared with those of the fluorescence elements (i.e. $Z_{eff} \leqslant 8$). The radiator support should also be constructed from materials having atomic numbers low compared with those of the radiator element.

5.2.2.2 Filters

A primary filter (or filters) shall be used to limit the low-energy components of the primary beam that do not contribute to the production of fluorescence radiation. A filter (or filters) shall be used in the secondary beam to eliminate the L lines and reduce the intensity of the K_β lines relative to the K_α lines. Their characteristics are given in table 10.

5.2.2.3 Primary diaphragm

A primary diaphragm, situated at the output of the X-ray tube, shall limit the area of the exciting beam to that of the radiator, in order to minimize any extraneous scatter from the radiator supports and from the walls of the fluorescence device.

5.2.2.4 Secondary diaphragm

This diaphragm limits the angle of the beam of fluorescence radiation and thus reduces the magnitude of the radiation scattered by the environment[1].

5.2.2.5 Trap

A trap shall be placed in the path of the primary radiation to prevent any scattered radiation produced by the primary radiation from contaminating the fluorescence radiation. It may consist of a room having large dimensions, if possible, into which the primary beam is released.

5.2.2.6 X-ray shielding

The zone reserved for experiments shall be isolated with the aid of an X-ray screen or other protective device.

1) Here the environment is taken to consist of the walls, the supports and other accessories of the installation.

5.3 Operating conditions

5.3.1 Geometry

The radiator shall be angled at 45° ± 5° relative to the axis of the primary X-ray beam, and fluorescence radiation whose direction forms an angle of 90° with that of the primary beam shall be used (see figure 6).

To provide sufficiently high air-kerma rates in the secondary beam, the tube should be brought as close as possible to the radiator and the primary beam should irradiate the greatest possible area of the radiator.

The point of test should be at a distance from the radiator compatible with the air-kerma rate desired, and the variation in the air-kerma rate of the secondary beam over the area of the detector employed shall not be greater than 5 %. The beam cross-section at the point of test shall always be greater than the cross-sectional area of the instrument being calibrated.

The contribution of the radiation due to scattering of the primary and secondary beams from the environment shall not exceed 5 % of the air-kerma rate due to the fluorescence radiation measured at the point of test. The purity of the radiation shall be checked by spectrometry.

5.3.2 Characteristics of reference radiation

Table 11 gives, as a guide, for an X-ray tube current of 10 mA and a distance of 30 cm from the radiator centre, the percentage of air kerma due to extraneous radiation (see note below) and the air-kerma rates which were measured in an X-ray beam having the characteristics given in table 10.

The air-kerma rates may be reduced by varying the following parameters:

a) tube current: reduction to approximately 1 mA (subject to preserving the reference radiation characteristics);

b) area of the fluorescence source: use of a smaller diameter primary diaphragm, which must not be les than the focus diameter;

c) radiator-detector distance: use of distances up to approximately 1 m. If distances > 1 m are used it will be necessary to recheck the spectral purity of the reference radiation.

NOTE — Extraneous radiation includes characteristic emissions other than the K_α radiation of the radiator and the scattered radiation originating from the radiator itself and its support, from the diaphragms and from the filters. It does not include the radiation scattered from the environment, mentioned later.

Table 11 — Examples of air-kerma rates and extraneous radiation measured 30 cm from the radiator centre with a tube current of 10 mA

Energy obtained keV	**Air-kerma rate 30 cm from centre of radiator** $mGy \cdot h^{-1}$	**Air kerma due to extraneous radiation**[1)] %
From 10 to 25	60 to 130	⩽ 10
From 25 to 98,4	26 to 60	⩽ 10

1) Defined in note to 5.3.2 and given by the formula:

$$\frac{\text{Air kerma of extraneous radiation} \times 100}{K_\alpha \text{ radiation air kerma} + \text{air kerma of extraneous radiation}}$$

5.4 Measurement of scattered radiation

An appropriately calibrated ionization chamber, selected for the energy and air-kerma rate ranges in question, shall be used to determine the contribution due to scattered radiation at the points of test.

The contribution due to scattered radiation shall be less than 5 % of the air-kerma rate due to the fluorescence radiation.

The ionization chamber's variations in response per unit air kerma as a function of the spectral quality and direction of the radiation shall be small and known over the energy range in question.

The values of the air-kerma rate at the point of test shall be measured. Then the ionization chamber shall be displaced in a plane perpendicular to the axis of the beam by a distance equal to twice the radius of the beam plus its penumbra. Two diametrically opposite measurements shall be carried out in this plane. The results of either of these measurements shall not exceed 5 % of the air-kerma rate measured at the point of test. If this limit is exceeded, the effectiveness of the X-ray shielding shall be checked. For this purpose, the residual air-kerma rate at the point of test shall be measured with the secondary beam completely absorbed. The measured air-kerma rate should be less than 0,5 % of that due to the fluorescence radiation.

5.5 Guidance on the use of the reference radiation

It should be noted that the extraneous radiation referred to in table 11 is specified in terms of the quantity air kerma. For quantities that refer to the measurement at a depth in a material, where the attenuation of the fluorescent X-ray lines may be significant the spectral distribution of Compton scattered impurities may have a dominant influence upon the device being calibrated. As a consequence of such spectral impurities, it is extremely difficult to quantify the dose and effective mean energy of penetrating quantities and necessitates precise spectral information of the radiation beams, weighted in terms of the appropriate dosimetric quantity. Also, for comparative purposes, measurements performed using different tube potentials would produce ambiguous results. Therefore the radiation qualities numbered 1 and 11 in table 10 shall not be used for determining an instrument's response with respect to a dosimetric quantity at a depth of 1 cm. For the same reason, caution should be exercised in using other low-energy fluorescence radiation.

6 Gamma radiation emitted by radionuclides

6.1 Radionuclides used for the production of gamma radiation

Calibrations of dosemeters and rate dosemeters by means of gamma radiation emitted by radionuclides shall be carried out with radiation from the radionuclides listed in table 12.

Table 12 — Radionuclide properties

Radionuclide	Radiation energy keV	Half-life days	Air-kerma rate constant[1)] $\mu Gy \cdot h^{-1} \cdot m^2 \cdot MBq^{-1}$
^{60}Co	1 173,3 1 332,5	1 925,5	0,31
^{137}Cs	661,6	11 050[13]	0,079
^{241}Am	59,54	157 788	0,003 1

1) The air-kerma rate constant (see ICRU Report 33[14]) is valid only in the case of an unshielded point source. It is therefore given only as a guide and not as a means of determining the air-kerma rates.

6.2 Specification of radiation sources

6.2.1 Sources

Since the source should be as small as possible, it is essential that use be made of a radioactive substance having sufficient activity per unit mass. The air-kerma rate due to the principal radioactive impurity shall be less than 1 % of the air-kerma rate due to the radiation of the isotope to be utilized.

Table 13 gives examples of specific activities and recommended chemical forms of the specified radioactive nuclides.

Table 13 — Specific activity and recommended chemical form of radioactive nuclides

Radioactive nuclide	Specific activity $Bq \cdot kg^{-1}$	Recommended chemical form
^{60}Co	$3,7 \times 10^{15}$	Metal
^{137}Cs	$8,51 \times 10^{14}$	Chloride
^{241}Am	$1,11 \times 10^{14}$	Oxide

NOTE — ^{60}Co is particularly suitable for providing sources having high activity per unit mass.
Since newly made sources of ^{137}Cs may contain a significant amount of ^{134}Cs, decay corrections should allow for the different half-lives of these two caesium isotopes. The use of aged ^{137}Cs sources is therefore recommended, but specifications of the impurities shall be given by the source manufacturer.

6.2.2 Encapsulation

The encapsulation of the sources shall comply with the requirements of ISO 1677.

The capsules shall be sufficiently thick to absorb the beta radiation from the sources, i.e. they shall have an areic mass of 0,2 g/cm^2 in the case of ^{60}Co and 0,5 g/cm^2 for ^{137}Cs. For ^{241}Am it should have an areic mass of at least 0,32 g/cm^2 of stainless steel to attenuate the 26 keV gamma radiation and the characteristic L radiation to less than 1,0 % of the 59,5 keV gamma radiation.

6.3 Irradiation facility and influence of scattered radiation

The secondary standard ionization chamber used for all measurements shall be of adequate sensitivity.

Its variation in response per unit air kerma as a function of the energy and direction of radiation should be small and known for the energy range in question.

The air-kerma rate due to radiation scattered by the environment shall not exceed 5 % of that due to direct radiation.

This can be obtained either:

— with uncollimated geometry, using a room with sufficiently large dimensions (see 6.3.1), or

— with collimated geometry, an example of which is given in 6.3.2.

6.3.1 Uncollimated geometry installation

The source should be used in a shielded room having minimum internal dimensions of 4 m × 4 m × 3 m high.

The source and detector (ionization chamber) should be used on supports that are constructed from the minimum amount of low-atomic number materials such as polymethylmethacrylate or aluminium. They should be positioned at half the height of the room. Only source-to-point-of-test distances for which the departures from the inverse square law do not exceed 5 %, after correction has been made for air attenuation, should be used.

NOTE — This will be the case for distances from about 30 cm to 130 cm.

6.3.2 Collimated geometry installation

The principal characteristics and a schematic diagram of an example of an acceptable collimator device, particularly applicable in the case of ^{60}Co and ^{137}Cs[2] are shown in figure 7.

The safety enclosure shall be made of lead of sufficient thickness to reduce the fluence of the extraneous beam passing through the enclosure to one-thousandth of the useful beam. For ^{60}Co, this thickness is 12,5 cm and for ^{137}Cs, it is 6,5 cm. These values may have to be increased in order to limit radiation exposure of users to acceptable levels.

A collimator shall be employed to define the shape and size for the photon beam. The collimated installation shown in figure 7 has a collimator that is conical in shape with the source at the apex. It is made up of a succession of at least six apertures, having a total thickness of about 90 mm and separated from each other by 20-mm interstices which serve as traps for the photons scattered by the edges of the preceding aperture. The final aperture has a thickness of 3 mm and a diameter which is slightly greater than the cross-section of the beam a that point. These apertures are made of tungsten alloy. An example for the composition of such an alloy is given in table 14.

NOTE — In an improved method of operation, the collimator is extended by an output tube. The tube/collimator assembly, which is closed at its ends by thin windows made of ethylene glycol polyterephthalate, forms an enclosure in which a vacuum can be created, thereby reducing air scatter whithin this assembly.

Table 14 — Example of composition of aperture alloy used in the collimator of figure 7

Element	Content %
Tungsten	89
Nickel	7
Copper	4

The beam cross-section shall be larger than that of the detectors to be irradiated. The distance d_1 (see figure 7) shall be greater than or equal to 30 cm. The distance d_2 shall be sufficiently great for the contribution to the total air-kerma rate of photons backscattered by the walls of the room to be compatible with the requirements given in 6.4.

6.3.3 Variation of air-kerma rate by means of lead attenuators

Instead of using sources with different activities, the air-kerma rate may also be varied by means of lead attenuators for collimated beams of ^{137}Cs and ^{60}Co. The attenuators shall be placed in close vicinity to the diaphragm. A sequence of lead attenuators with thicknesses of about 20 mm, 40 mm, 60 mm, etc. and 38 mm, 76 mm, 114 mm etc. leads to a reduction in air-kerma rate by successive orders of magnitude for Cs and Co, respectively. The above figures serve merely as a guideline. The exact extent of the attenuation depends on geometrical parameters such as field size. Therefore the value of the air-kerma rate at the point of test shall be determined by dosimetric measurements.

The range of attenuation may cover six orders of magnitude or more. Despite an increased fraction of photons which have undergone a scattering event with increasing attenuator thickness, the spectral purity of the radiation is maintained as the fluence spectra of all photons become progressively narrower, i.e. the mean energy approaches more and more that of the emission line(s)[15, 16].

In order to eliminate the influence of a possibly distorted electronic equilibrium at the point of test the distance between the lead attenuator and point of test should be at least 100 cm. Alternatively, the lead attenuator may be covered by a layer of graphite of at least 0,5 cm thickness.

2) This kind of installation produces at most 5 % scattered photons for ^{137}Cs and less for ^{60}Co.

6.4 Checking installation conformity

The following test shall be carried out in order to check that, at the various experimental distances, the contribution due to scattered radiation extraneous to that from the source capsule does not exceed 5 % of the total air-kerma rate.

The air-kerma rates shall be measured on the axis of the beam at the various points of test. After correcting for air attenuation, the air-kerma rates shall be proportional within 5 % to the inverse square of the distance from the source centre to the detector centre.

7 Photon radiation with energy between 4 MeV and 9 MeV

7.1 General

Reference radiation in the energy range between 4 MeV and 9 MeV is provided because of the 6 MeV photon fields produced by many nuclear power stations and other nuclear reactor systems, as well as by other high-energy photon sources. Further energies are not specified, since the variation in response of most dosemeters and rate dosemeters with photon energy shows no discontinuity over this energy range.

7.2 Production of reference radiation

Photon reference radiation shall be produced by one of the following reactions:

a) de-excitation of ^{16}O in the ^{19}F (p, $\alpha\gamma$) ^{16}O reaction, (see 7.2.1)[17, 18, 19, 20];

b) de-excitation of ^{12}C (see 7.2.2) [20];

c) thermal neutron-capture gamma radiation (see 7.2.3)[21];

d) decay of ^{16}N (see 7.2.4)[24, 25].

Examples of photon fluence spectra for these reference radiations are shown in figures 10, 11, 12 and 13.

7.2.1 Photon reference radiation from de-excitation of ^{16}O in the $^{19}F(p, \alpha\gamma)^{16}O$ reaction

This reference radiation shall be produced using a particle accelerator to bombard a fluorine target (usually CaF_2) with protons using the $^{19}F(p, \alpha\gamma)^{16}O$ reaction.

The energy levels and the relative emission probabilities resulting from this reaction for 340,5 keV protons incident on a thin target are shown in figure 8. At this proton energy, the probability for the decay of the excited ^{16}O state by emission of 6,13 MeV photons is 97 %, 2,5 % for the 7,717 MeV level and 0,5 % for the 6,917 MeV level, while the 6,05 MeV photon emission is negligible. The deviation from isotropic emission of these photons is less than 3,5 %. At the higher proton energies the relative contribution of the 6,13 MeV photons decreases in favour of the higher energy photons, and there is an increase in the contribution by contaminant reactions, for example (p, p'γ) and pair production.

Relative photon emission rate (yield) as a function of proton energy is illustrated in figure 9. As target thickness (and thus proton energy loss in the target) is increased, the yield increases and the photon spectrum changes, as the protons undergoing interactions with the fluorine have decreasing energies with increasing depth. The energy of the photons emitted is high enough for their attenuation in the target to be considered negligible.

Depending on the required yield, the proton energy chosen for the production of the reference radiation shall be either one of the resonance energies (340,5 keV or 872,1 keV) or a convenient energy between 2 MeV and 3 MeV. If a high yield is required and a contamination contribution to the air kerma of approximately 4 % can be tolerated, protons, of energy close to 2,7 MeV, incident on a target of approximately 6 $mg \cdot cm^{-2}$ in thickness, should be used (see also 7.4.3). For the purest possible reference radiation, 340,5 keV protons should be used, provided that the lower air-kerma rates are acceptable. For the 340,5 keV proton resonance, calibration shall be carried out both on-resonance and off-resonance by −10 keV in order to allow for the effect of any low-energy and non-resonant

radiation originating from the accelerator. The difference between the on-resonance and the off-resonance calibrations shall be taken as due only to the 6,13 MeV photon radiation and to associated knock-on electrons.

Care should be taken to prevent fluorine other than that of the target from being introduced into the accelerator.

Typical yields and air-kerma rates are given in table 15 for four different incident proton energies, for a proton current of 1 μA and a target thickness of approximately 6 $mg \cdot cm^{-2}$.

NOTE — The proton energy loss in such a target is approximately 600 keV for a 2,7 MeV incident proton.

A typical photon fluence spectra produced with 2,7 MeV protons and a target thickness of approximately 6 $mg \cdot cm^{-2}$ is shown in figure 10[8].

Table 15 — Typical photon yields and air-kerma rates for specified proton energies and 1 μA proton current

Proton energy MeV	Photon yield s^{-1}	Typical air-kerma rate at 1 m from target $\mu Gy \cdot h^{-1}$
0,340 5 (resonance)	10^5	0,05
0,872 1 (resonance)	10^6	0,5
2,05	6×10^7	30
2,7	2×10^8	100

7.2.2 Photon reference radiation from de-excitation of ^{12}C

This reference radiation shall be produced by using a particle accelerator to bombard a carbon target with protons, resulting in the population of the lowest excited level of ^{12}C at 4,44 MeV followed by a de-excitation using the $^{12}C(p,p'\gamma)^{12}C$ reaction:

The target shall consist of a layer of high-purity carbon. If natural carbon is used, two further reactions will compete with the $^{12}C(p,p'\gamma)^{12}C$ reaction:

a) $^{13}C(p,p'\gamma)^{13}C$, resulting in 3,09 MeV photon radiation;

b) $^{13}C(p,n)^{13}N$, resulting in 0,511 MeV annihilation photons, stemming from the positron decay of ^{13}N which has a half-life of 9,96 min. A steady state between production and decay of ^{13}N is reached about 20 min after the reaction is started (i.e. after the proton beam is switched on). During this period the reference radiation shall not be used.

The ratios of the yields of the 4,44 MeV and 3,09 MeV lines and of the 4,44 MeV and 0,511 MeV lines are independent of proton energy.

At a proton current of 1 μA, a proton energy of 5,5 MeV at a distance of 1 m from the target, the photon fluence rates are about 160 $cm^{-2} \cdot s^{-1}$, 12 $cm^{-2} \cdot s^{-1}$ and 1 800 $cm^{-2} \cdot s^{-1}$, and the corresponding air-kerma rates are about 1,4 $\mu Gy \cdot h^{-1}$, 0,046 $\mu Gy \cdot h^{-1}$ and 85 $\mu Gy \cdot h^{-1}$ for the lines at 0,511 MeV, 3,09 MeV and 4,44 MeV respectively. A typical photon fluence spectra is shown in figure 11[8].

7.2.3 Reference radiations produced by thermal neutron-capture gamma reactions in titanium or nickel

These beams shall be produced by the (n,γ)-capture reaction in a titanium or nickel target using a reactor as the neutron source. An example of an irradiation facility is shown in figure 14[21]. Multiline spectra are produced with both the target materials. Examples of photon yields of the main spectral components, i.e. above 3 photons per 100 neutron captures are given in table 16[22].

For use of the resulting radiation as reference radiation between 4 MeV and 9 MeV, its low energy components shall be reduced or eliminated by appropriate added filtration. The individual contribution of the various spectral lines to total air kerma depends on the amount of added filtration. With suitable filtration, the effective energy of the reference radiation may be increased, for instance with a 30 cm thick aluminium filter from 4,5 MeV to 6,4 MeV for a titanium target and from 7 MeV to 8,1 MeV for a nickel target[23].

Typical photon fluence spectra obtained by deconvolution of pulse height distributions from a bismuth germanate (BGO) detector are shown in figure 12 for a titanium target and in figure 13 for a nickel target. The corresponding fluence weighted mean energies are 5,14 MeV and 6,26 MeV respectively[21]. In both cases the total filtration is about 75 $g \cdot cm^{-2}$.

Examples of air-kerma rates and reference energies obtained with targets of nickel and titanium under the specified experimental conditions are given in table 17[21].

7.2.4 Photon reference radiation from decay of ^{16}N

These beams shall be produced by activation of water in a reactor core by fast neutrons using the $^{16}O(n, p)\ ^{16}N$ reaction.

The subsequent beta-decay of ^{16}N (see also 7.2) with a half-life of 7,1 s leads to the excited states of ^{16}O, in this case yielding 6,13 MeV and 7,12 MeV photons, with relative emission probabilities of 68 % and 5 % respectively, and 10,4 MeV beta-radiation. Photon energies and relative emission probabilities are shown in figure 8

In a practical set-up, water is pumped continuously through the reactor core in a closed loop at a flowrate of 30 $l \cdot s^{-1}$. This loop is brought out through the biological shield of the reactor and acts as the radiation source[24]. The photon emission rate per megawatt of thermal power and per kilogram of water is of the order of $1 \times 10^8\ s^{-1}$ and the associated air-kerma rate is approximately 50 $mGy \cdot h^{-1}$ at 1 m.

7.3 Beam diameter and uniformity of radiation field

The requirements shall be identical to those specified in 4.5, except that the term "tube focus" shall be replaced by "target". If the area of the field is not sufficient to irradiate the dosemeter or phantom completely and uniformly, they should be scanned across the beam. This technique is not always applicable to air-kerma rate instruments.

7.4 Contamination of photon reference radiation

7.4.1 General

Contamination of the reference radiation by neutrons, electrons and by photons of energy other than the reference energy shall be assessed, and its influence on the readings of the dosemeters and rate dosemeters being calibrated shall be determined.

Table 16 — Principal photon yields of titanium and nickel per 100 neutron captures

Titanium		Nickel	
Photon energy keV	Number of photons[1)]	Photon energy keV	Number of photons[1)]
342	26,3	283	3,3
1 381	69,1	465	13
1 498	4,1	878	3,9
1 586	8,9	6 837	10,8
1 762	5,6	7 537	4,5
4 882	5,2	7 819	8,2
4 969	3,6	8 121	3,1
6 418	30,1	8 533	17
6 557	4,7	8 999	37,7
6 761	24,2		

1) Above 3 photons per 100 neutron captures.

Table 17 — Capture gamma radiation — Examples of targets, air-kerma rates and reference energies obtained [26]

Target				Reference energy	Air-kerma rate[1)]
Material	Dimensions mm	Mass kg	Purity %	MeV	Gy·h^{-1}
Titanium	550 × 100 × 15	3,7	98	6,0 ± 0,5	0,8
Nickel	550 × 100 × 10	4,9	98	8,5 ± 0,5	1,2

1) Air-kerma rate at a distance of 5 m for a thermal neutron fluence rate of $1,5 \times 10^{13}$ cm^{-2}·s^{-1}. These values are given only as a guide; they were obtained using beam filtration comprising 102 g·cm^{-2} of polyethylene plus 14 g·cm^{-2} of aluminium. Different filtrations will produce different air-kerma rates.

Both the photon reference radiation and the associated photon contamination may be assessed from measurements of the pulse-height distributions (see figures 10, 11, 12 and 13). Since the variation in response of most dosemeters and rate dosemeters with photon energy is small and shows no discontinuities over the energy range from 4 MeV to 9 MeV, contamination by photon energies differing by up to around 1 MeV from the reference beam energy may be tolerated. In instruments containing beryllium, tin or lead, the effects caused by photonuclear reactions in these materials will be negligible. Methods of reducing the contamination of the reference beam are described in references [17], [18], [21], [24] and [25]. The most prevalent forms of contamination of the reference radiation produced by the methods specified are given in 7.4.2 to 7.4.4.

7.4.2 Contamination of reference radiation common to all methods of production of reference radiation

7.4.2.1 Photons with energies of 0,511 MeV are produced by positron annihilation after pair production events in the target chamber and in the walls of the calibration room and in filter materials, if used.

7.4.2.2 Beta particles created in the target as a consequence of a nuclear reaction, or secondary electrons created by photons at or near the target and in the intervening air space, cause considerable contamination of the reference radiation. Further contamination can arise from associated bremsstrahlung.

7.4.2.3 Scattering of photons of the reference radiation in the target and the material in its vicinity produces lower-energy photons contributing at least 1 % to the air-kerma rate.

7.4.3 Additional contamination of accelerator produced reference radiation from de-excitation of ^{16}O (see 7.2.1)

In addition to the forms of contamination listed in 7.4.2, which can be reduced by decreasing the target chamber mass, discrete gamma radiations from nuclear reactions are induced in the target by the proton beam. At proton energies between 2 MeV and 3 MeV, photons with energies between about 0,1 MeV and 1,5 MeV are produced by the [$^{19}F(p, p'\gamma)^{19}F$] reaction, with yields increasing with proton energy. At a proton energy of 2,7 MeV, this reaction contributes about 4 % of the air-kerma rate from the 6 MeV to 7 MeV reference radiation. The use of a filter constructed of a high atomic-number material, e.g. lead, around the target to eliminate the low-energy photon contamination increases contamination by secondary electrons and annihilation radiation.

7.4.4 Additional contamination of reference radiation produced by reactor neutrons

7.4.4.1 Contamination of reference radiation produced by thermal neutron-capture gamma reactions in titanium or nickel (see 7.2.3)

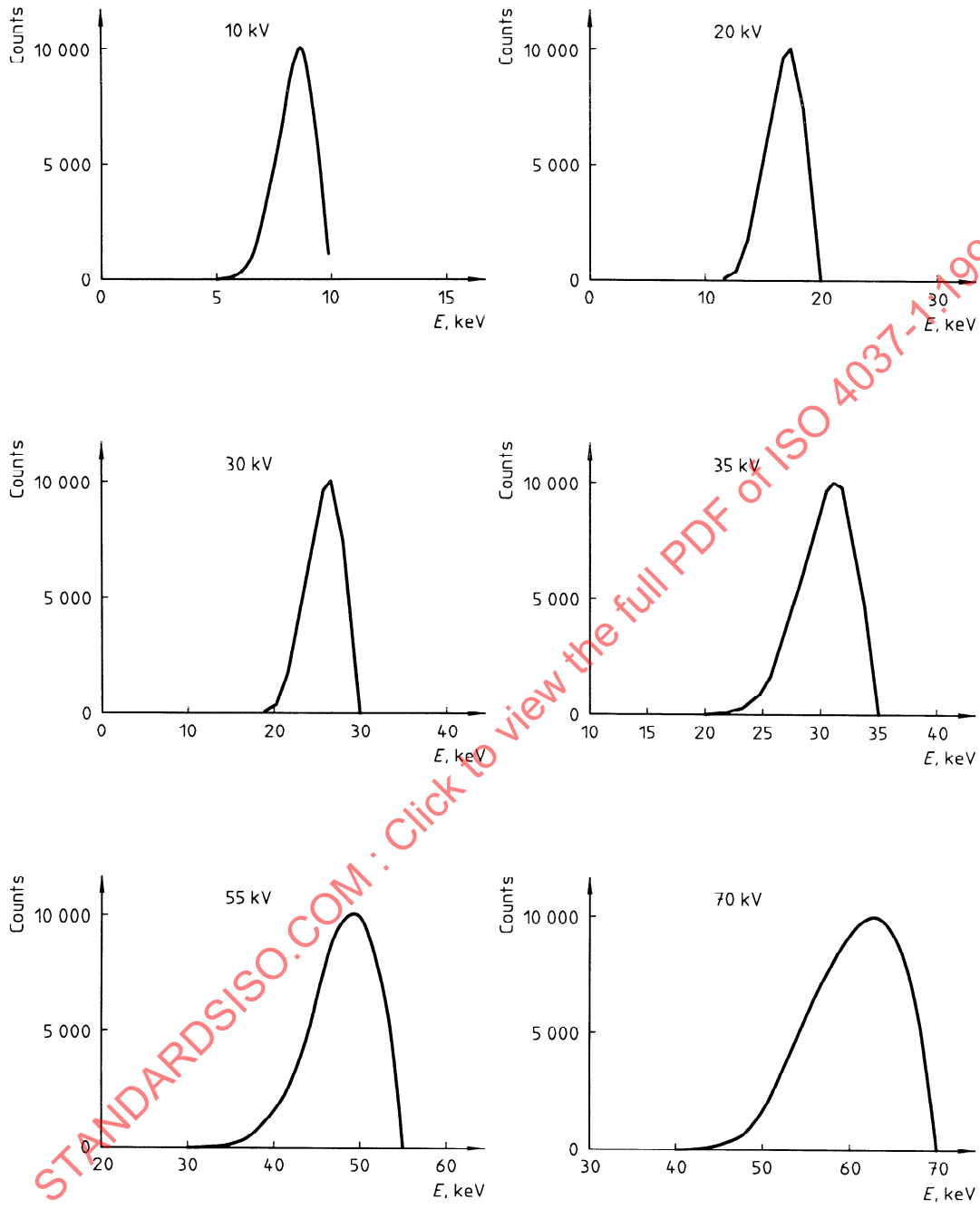
In addition to the forms of contamination listed in 7.4.2, the reference beams contain discrete radiation of low-energy photons (see table 16) and photons produced by Compton scattering, especially in the filters added to reduce the low-energy photon contamination. The discrete radiation of photons of energies below 5 MeV in the reference radiation produced by titanium and below 6,8 MeV in the reference radiation produced by nickel shall be reduced by means of added filtration, such that the kerma rate from photons below these energies shall not exceed 10 % of the total air-kerma rate.

In the examples given in reference [23], using additional filtration of 30 cm aluminium reduces the air-kerma rate due to such photon contamination, so that the effective mean energy increases from 4,5 MeV to 6,4 MeV for titanium and from 7,0 MeV to 8,1 MeV for the nickel target reference beam.

There also is contamination of the reference radiation by neutrons produced by photodisintegration; this shall be determined from measurements made with a neutron detector (e.g. a neutron dose equivalent ratemeter).

7.4.4.2 Contamination of reference radiation produced by decay of ^{16}N (see 7.2.3)

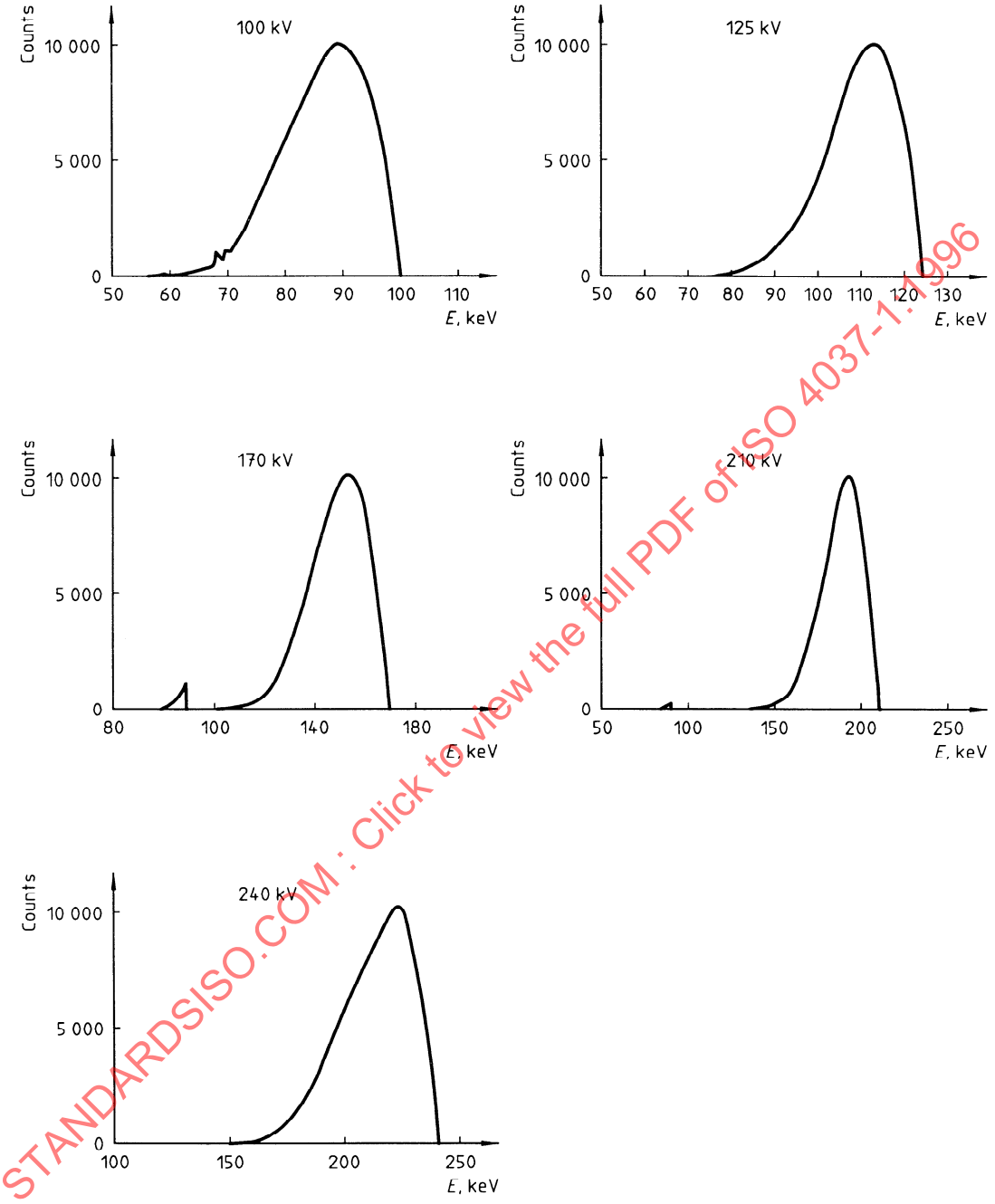
In addition to the forms of contamination listed in 7.4.2, this reference radiation contains low-energy photons emitted by the various activation products from the contaminants in the cooling medium, the main contribution arising from ^{24}Na with energies at 2,754 MeV and 1,369 MeV.



a) 10 kV to 70 kV

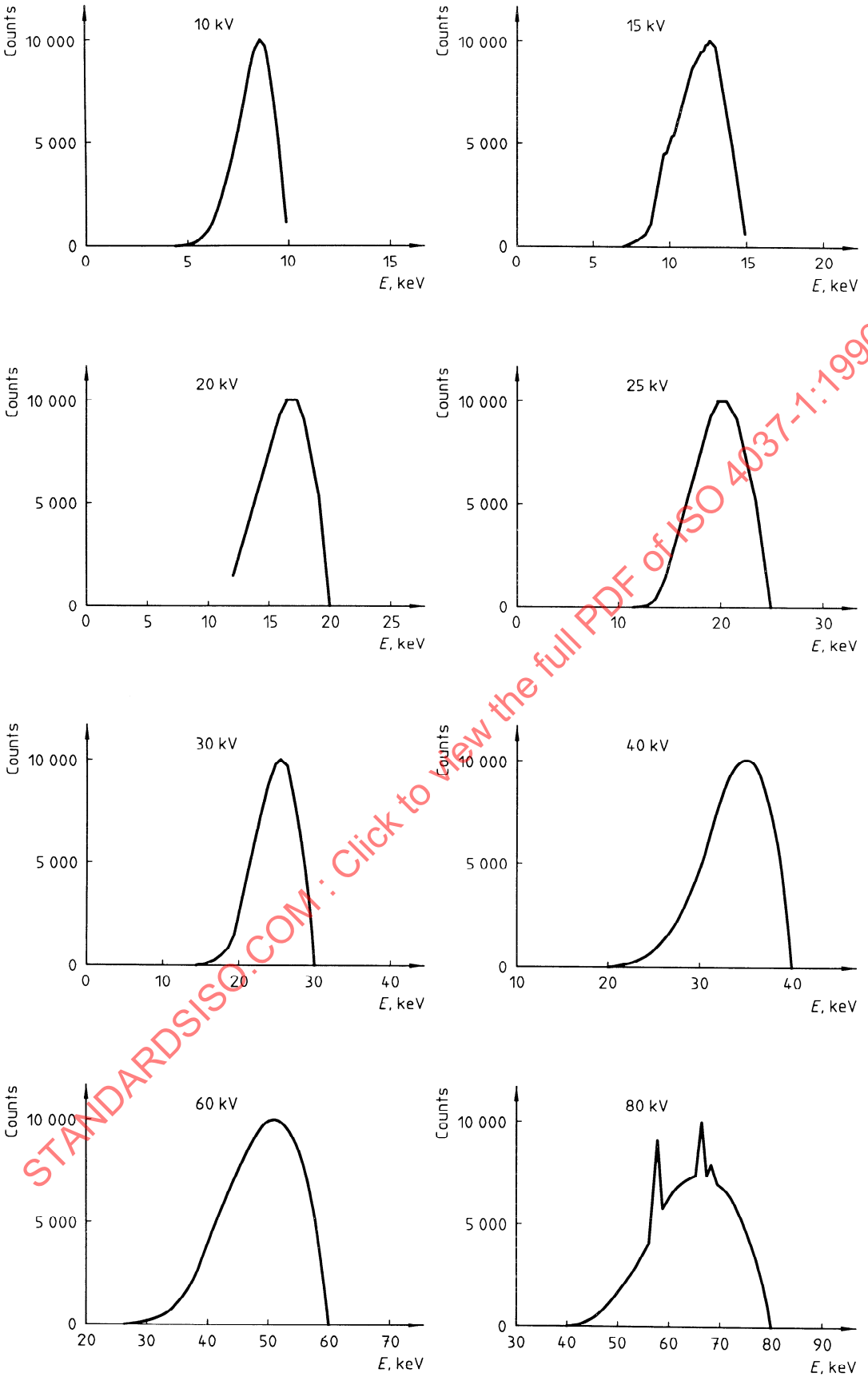
(10 kV spectrum is a practical unfolded spectrum, the remainder are theoretical)

Figure 1 — Low air-kerma rate series spectra



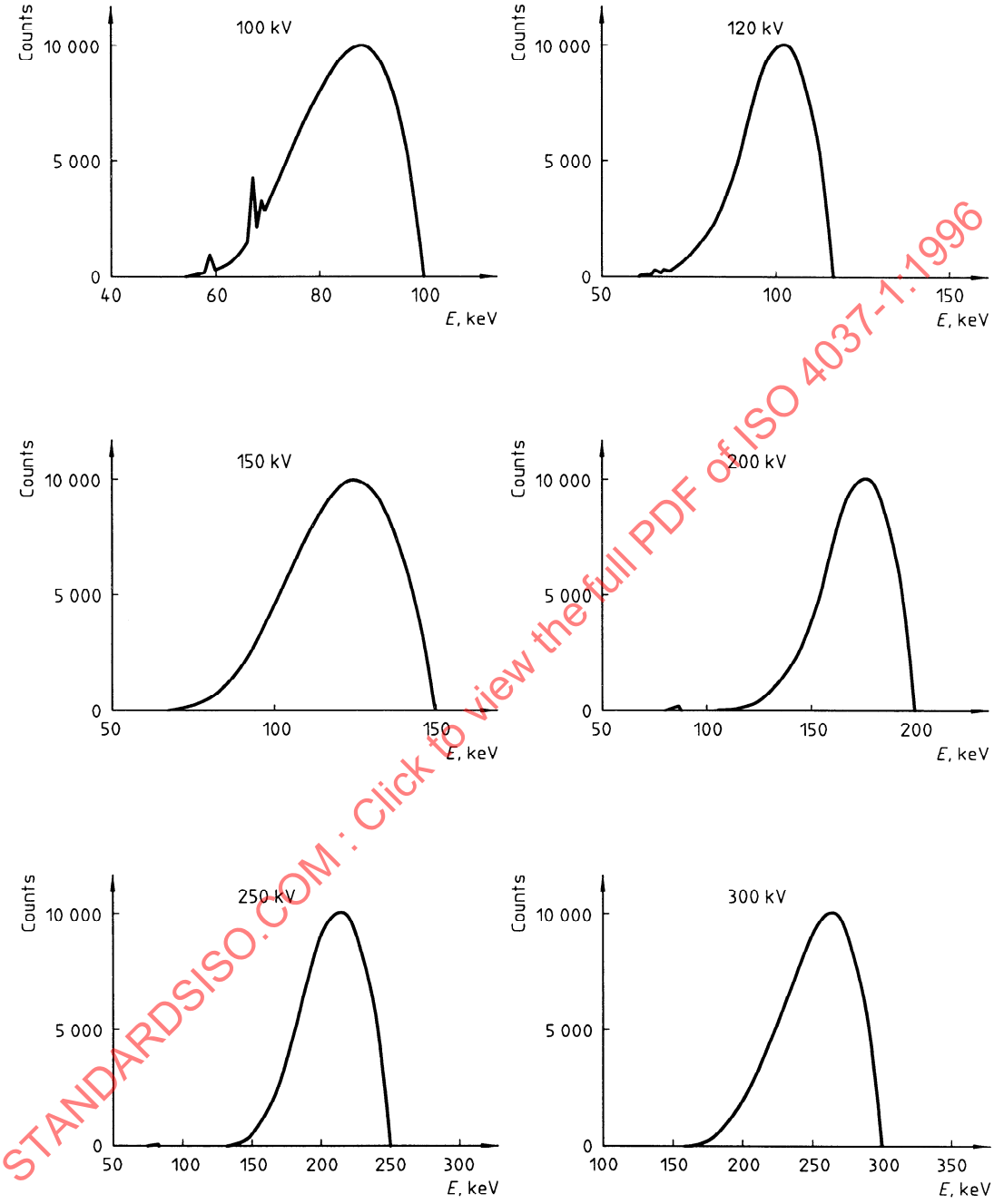
b) 100 kV to 240 kV (theoretical)

Figure 1 *(concluded)*



a) **10 kV to 80 kV** (10 kV and 15 kV spectra are practical and unfolded, the remainder are theoretical)

Figure 2 — Narrow-spectrum series



b) **100 kV to 300 kV** (theoretical)

Figure 2 *(concluded)*

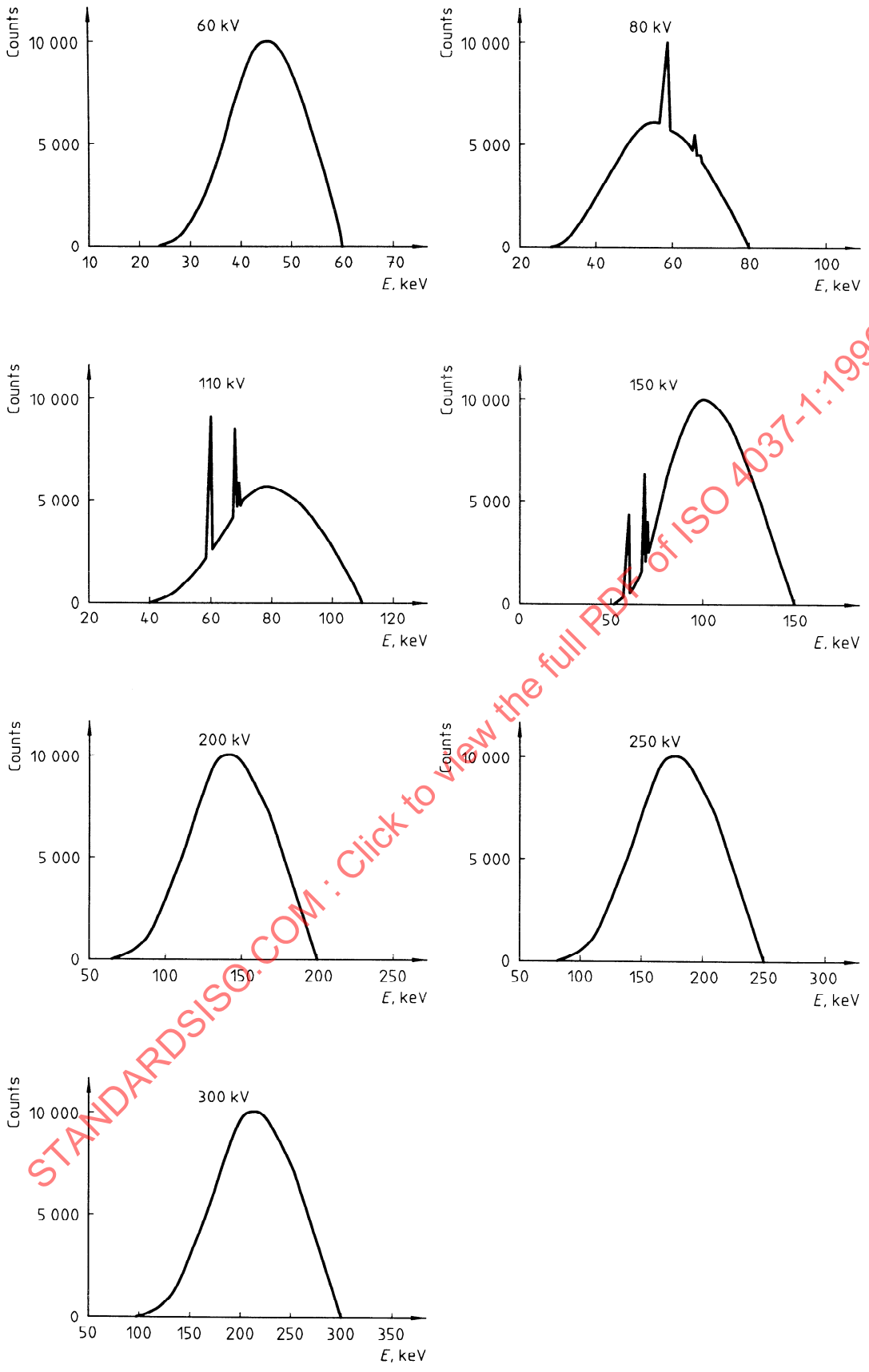
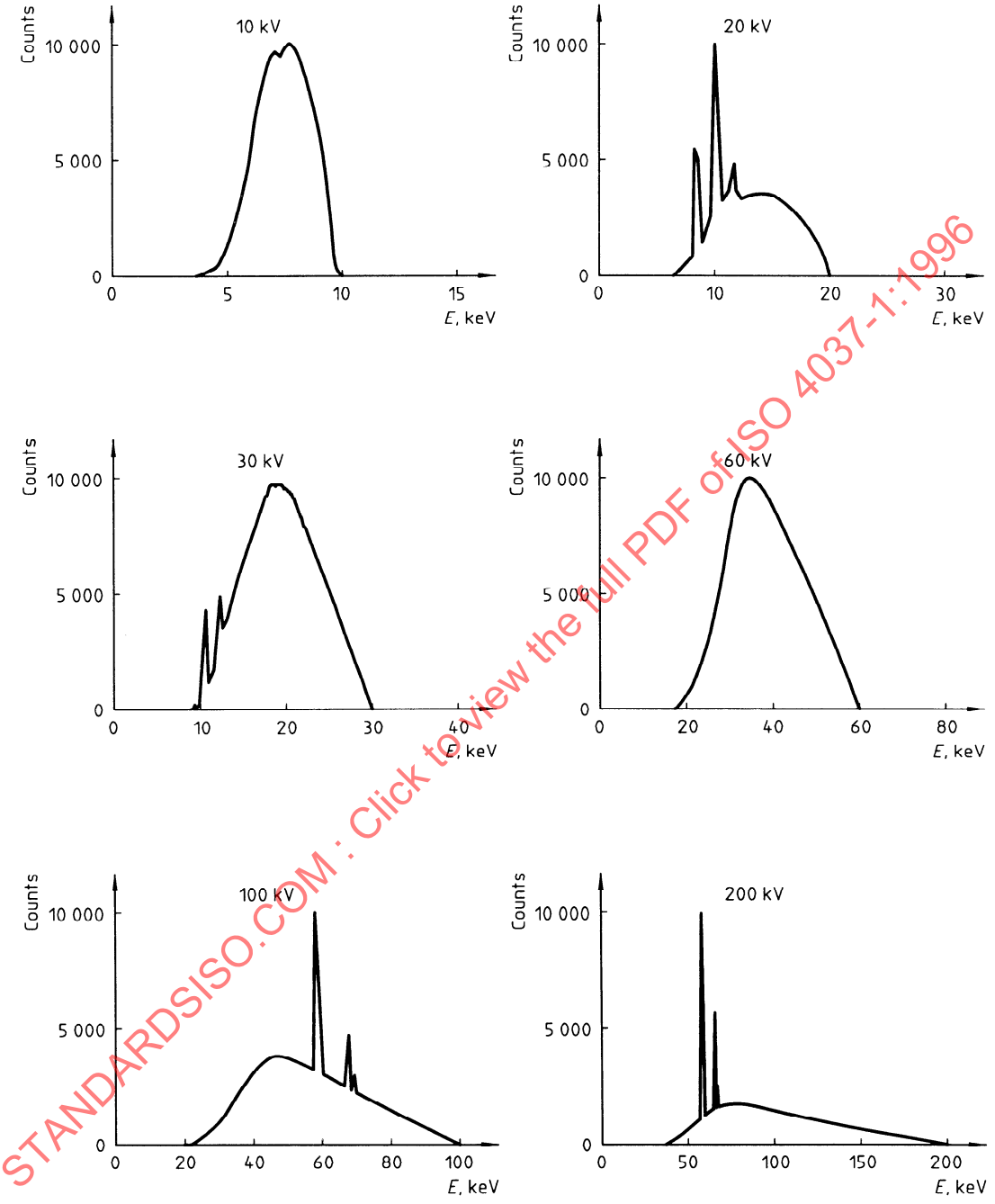
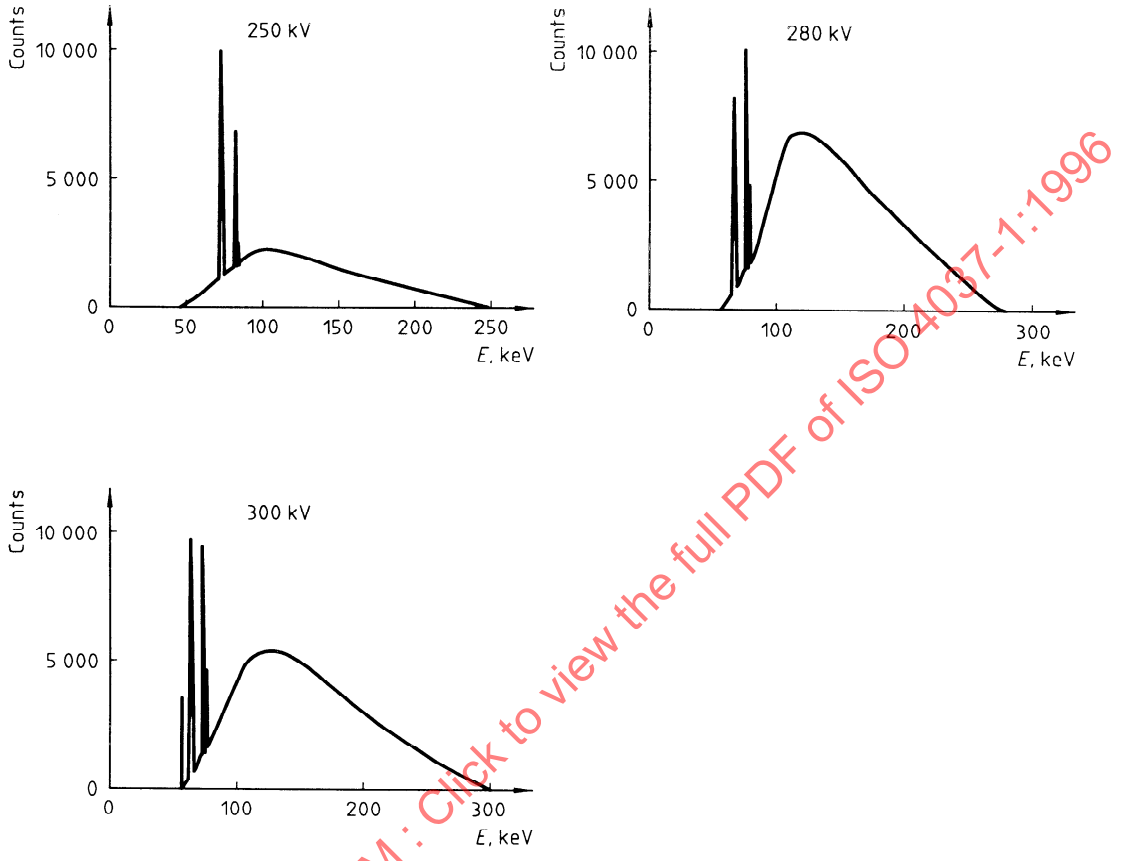


Figure 3 — Wide-spectrum series (theoretical)



a) **10 kV to 200 kV** (10 kV to 30 kV practical and unfolded spectra, the remainder are theoretical)

Figure 4 — High air-kerma rate series spectra



b) **250 kV to 300 kV** (theoretical)

Figure 4 *(concluded)*

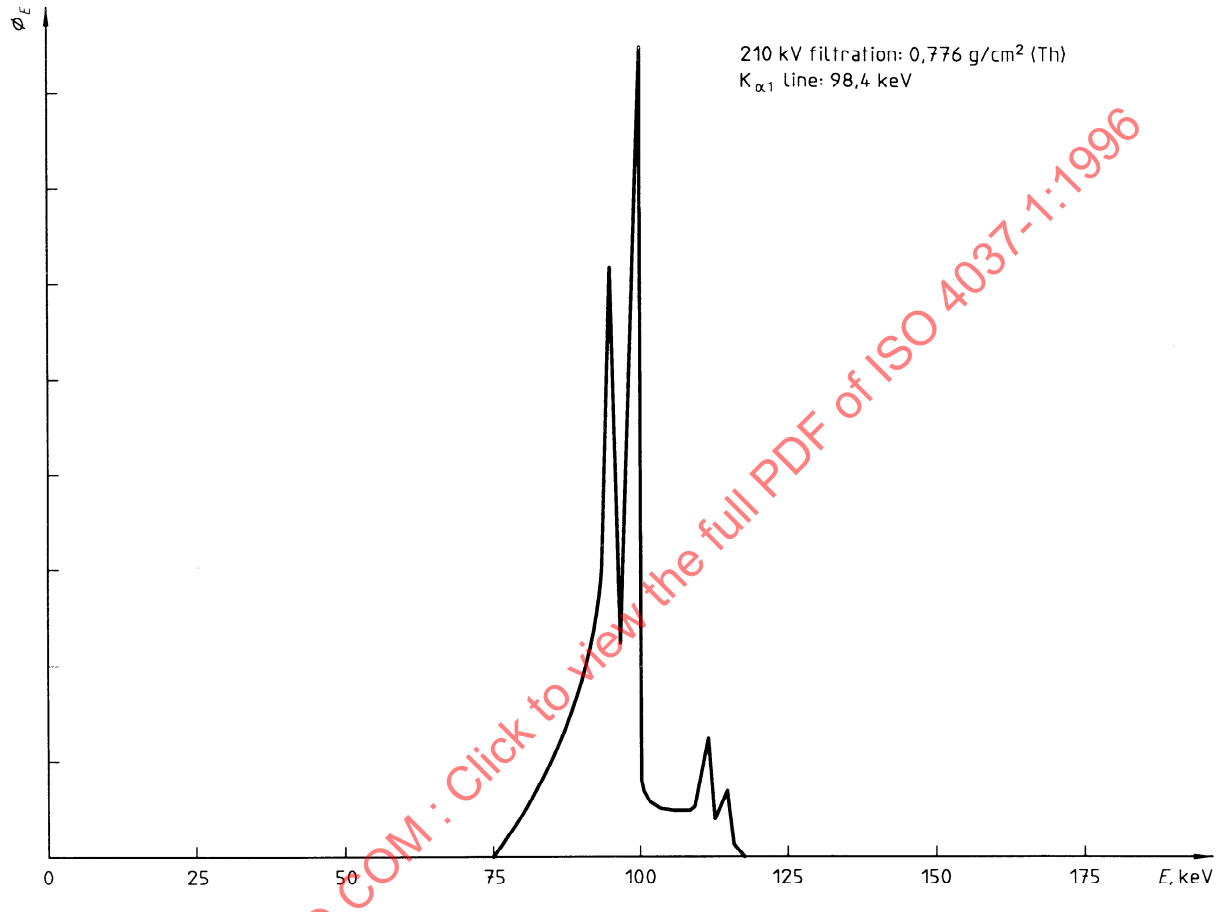


Figure 5 — Uranium spectrum

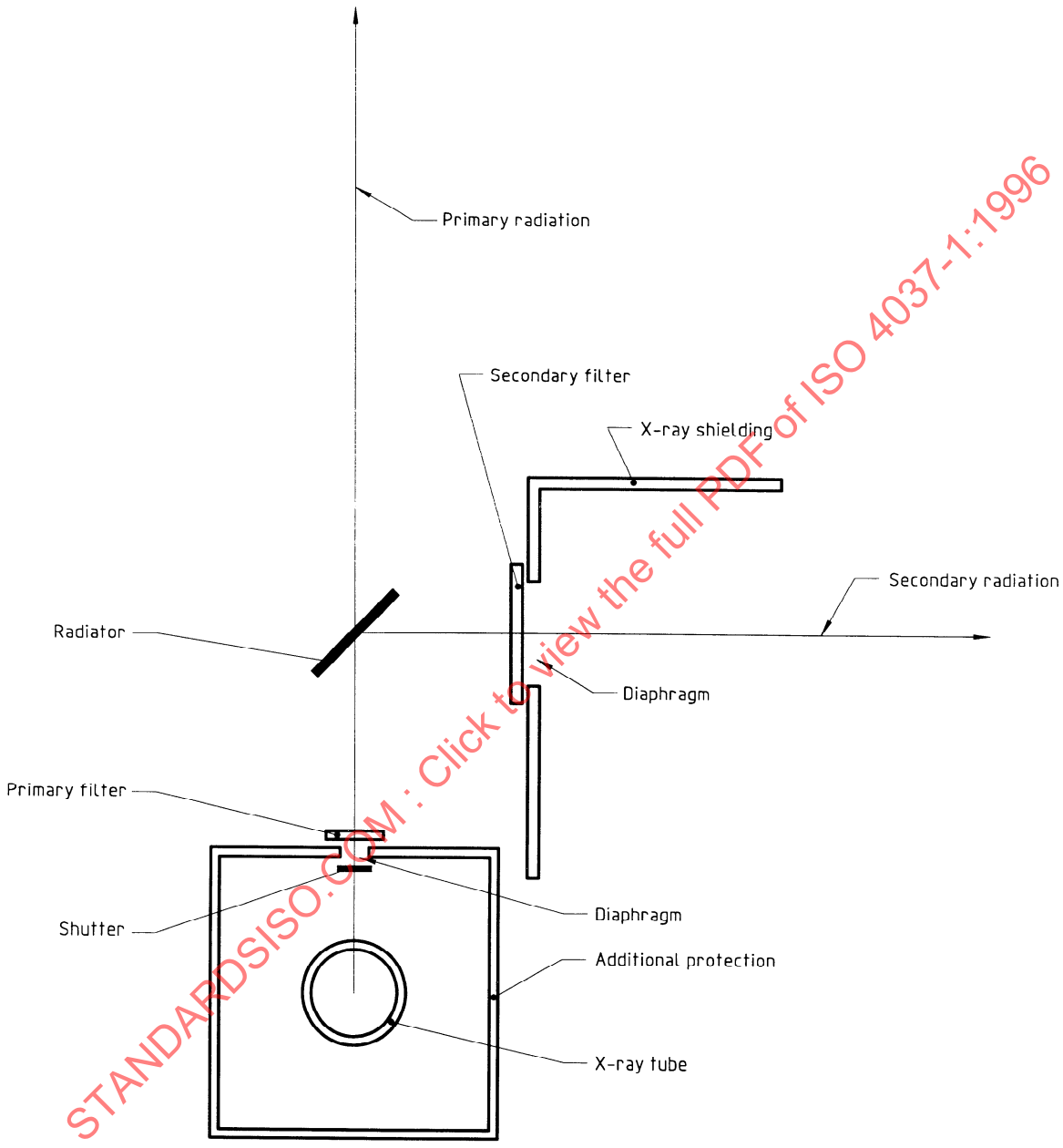


Figure 6 — Schematic diagram of a K-fluorescence X-ray installation

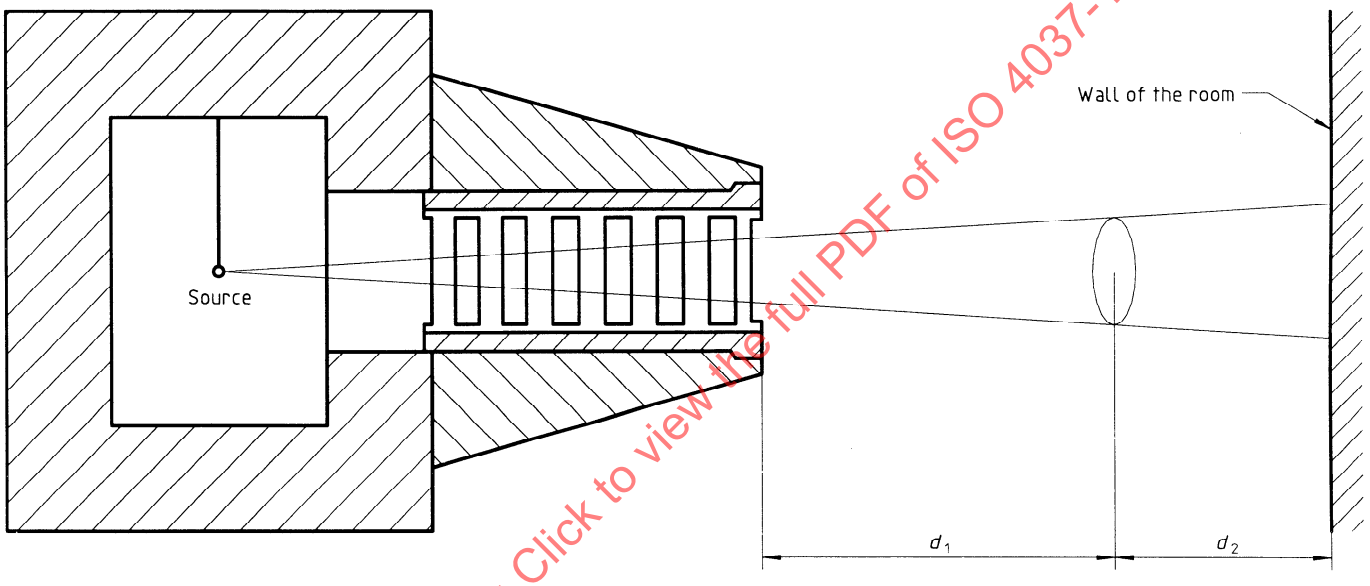


Figure 7 — Example of a collimated installation

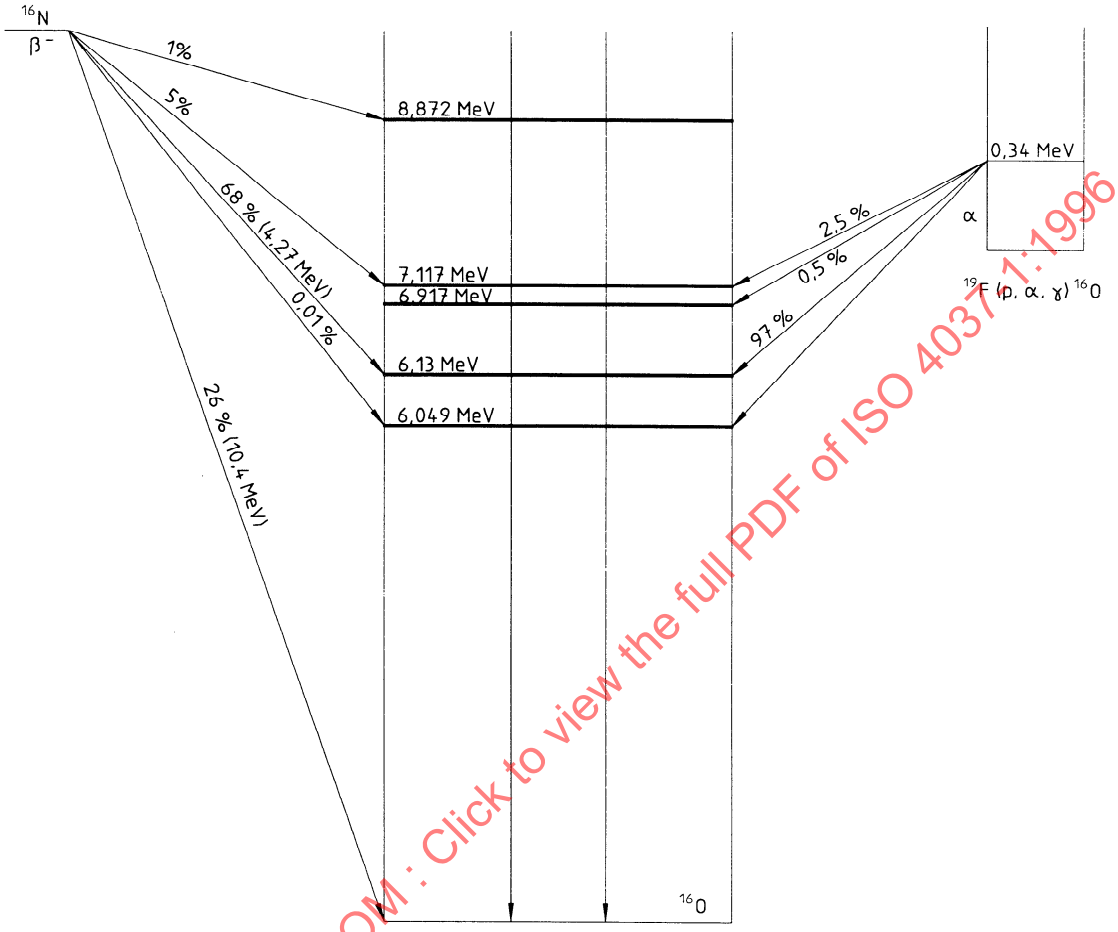


Figure 8 — Energy levels and emission probabilities of photon radiation from the decay of ^{16}N (left) and from the de-excitation of ^{16}O for an incident proton energy of 340,5 keV on ^{19}F (right)[22]