IAEA
International Atomic Energy Agency
Atoms for Peace and Development

Assessment of Occupational Exposure due to External Radiation Sources

Calibration of dosimeters

Calibration of dosimeters - Module outline

- Introduction: what is calibration?
- ISO standards on calibration
- Traceability and hierarchy of standards
- Calibration fields and sources
- Practical calibration procedures

Introduction: what is calibration?

The primary objectives of calibration:

- Ensure that an instrument is working properly and will be suitable for the intended monitoring purpose
- Determine, under a controlled set of standard conditions, the indication of an instrument as a function of the quantity to be measured
- Adjust the instrument calibration, if possible, so that the overall measurement accuracy of the instrument is optimized

What is calibration?

- The *quantitative determination*,
- under a controlled set of *standard conditions*,
- of the indication given by a radiation *measuring instrument*
- as a function of the value of the quantity the instrument is intended to measure

Calibration terminology

- *Conventional true value:* The best estimate of the value determined by a primary or secondary standard, or by a reference instrument that has been calibrated against a primary or secondary standard

- *Reference instrument:* A tool to transfer standard from higher level to lower level

Calibration factor, N

The conventional true value of the quantity the instrument is intended to measure, *H*, divided by the indication, *M* given by the instrument, i.e.

$$N = H/M$$

- Normally only quoted for one reference radiation
- May not be a unique factor for the whole measurement range if instrument has a non-linear response
- Should ideally be dimensionless - instrument’s indication has the same unit as the value to be measured

Instrument response, R

- Quotient of the indication M, and the conventional true value of the measurand (quantity to be measured)
- Type of response should be specified, e.g. ‘fluence response’ (response with respect to fluence, Φ):

$$R_\Phi = M/\Phi$$

- or ‘dose equivalent response’ (response with respect to dose equivalent, H):

$$R_H = M/H$$

Calibration versus Tests

- Calibration - *Quantitative determination*, under a controlled set of *standard conditions*, of the indication given by a radiation *measuring instrument* as a function of the value of the quantity the instrument is intended to measure

- Tests - Measurements intended to confirm that an instrument is *functioning correctly*, and/or the *quantitative determination of the variations* of the indication of the instrument over a range of radiation, electrical and environmental conditions

Routine calibrations

- Used to determine a calibration factor appropriate to the routine application of the dosimeter or dose rate-meter
- May be of a confirmatory nature
  - Performed to check manufacturer’s calibration
  - Check long term calibration stability

Tests

- Type tests - Tests conducted to determine the characteristics of a particular type or model of a production instrument
- Acceptance tests - Contractual tests on all instruments of a particular type to demonstrate conformance to specifications
- Performance tests - Regular tests conducted to demonstrate maintenance of overall dosimetric performance standards

Type Tests

- To determine characteristics of a production instrument
- Involve extensive testing over a wide range of influence quantities, i.e. energy, angle of incidence, dose, dose rate and radiation type
- Performed under a range of environmental conditions
- Performance requirements are specified in national and international standards

ISO standards on calibration

Most important ISO standards for calibration

- ISO 4037 Radiological protection — X and gamma reference radiation for calibrating dosimeters and doserate meters and for determining their response as a function of photon energy
  - Part 1: Radiation characteristics and production methods
  - Part 2: Dosimetry for radiation protection over the energy ranges from 8 keV to 1,3 MeV and 4 MeV to 9 MeV
  - Part 3: Calibration of area and personal dosimeters and the measurement of their response as a function of energy and angle of incidence
  - Part 4: Calibration of area and personal dosimeters in low energy X reference radiation fields
- ISO 18090: Characteristics of reference pulsed radiation
  - Part 1: Photon radiation

Most important ISO standards for calibration

- ISO 8529 Reference neutron radiations
  - Part 1: Characteristics and methods of production
  - Part 2: Calibration fundamentals of radiation protection devices related to the basic quantities characterizing the radiation field
  - Part 3: Calibration of area and personal dosimeters and determination of response as a function of energy and angle of incidence

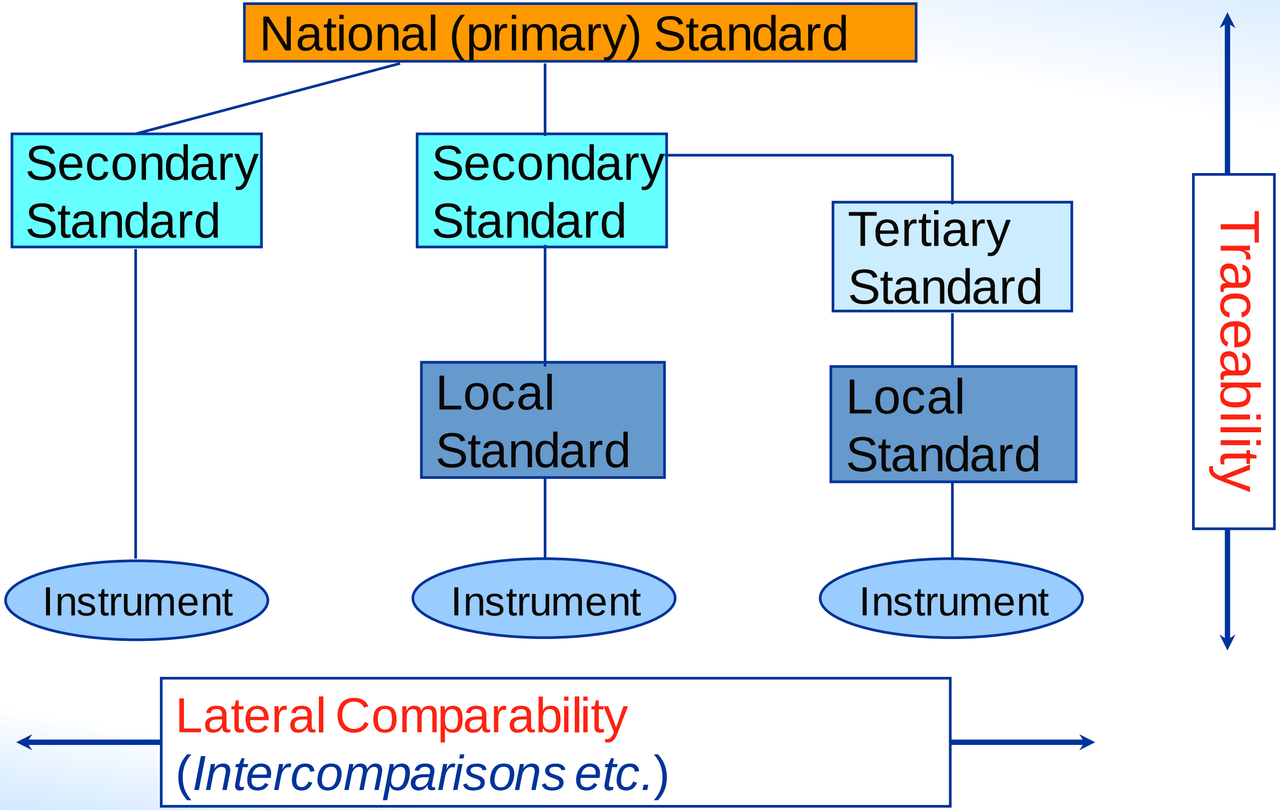
- ISO 6980:2006 Nuclear energy — Reference beta-particle radiation
  - Part 1: Methods of production
  - Part 2: Calibration fundamentals related to basic quantities characterizing the radiation field
  - Part 3: Calibration of area and personal dosimeters and the determination of their response as a function of beta radiation energy and angle of incidence

Traceability and hierarchy of standards

Hierarchy of standards

- *Primary Standard:* A standard with the highest metrological qualities.
- *Secondary Standard:* A standard whose value is fixed by direct comparison with a primary standard.
- *Tertiary Standard:* A standard whose value is fixed by comparison with a secondary standard

Traceability and lateral comparability



National (primary) Standard

Secondary Standard

Secondary Standard

Tertiary Standard

Local Standard

Local Standard

Instrument

Instrument

Instrument

Traceability

Lateral Comparability
(*Intercomparisons etc.*)

Hierarchy of instrument standards

- Primary Standard: using techniques that determine directly the required quantity
  - Gamma: water calorimeter (absorbed dose to water)
  - X-rays, gamma: plane-parallel ionisation chamber (air kerma)
  - For beta : extrapolation chamber (absorbed dose to tissue)
  - For neutrons: Mn-bath (fluence)
- Mostly maintained by national metrology service
- Recognised by BIPM through intercomparison

Hierarchy of instrument standards

- Secondary or Tertiary Standard: transfer standards, reference instrument
  - For air kerma (X-rays, gamma): ionisation chamber
  - For neutrons: long counter, neutron monitor
- Requirements for transfer standards are given in the ISO standards
- Secondary standard
  - Standard whose value is fixed by direct comparison with a primary standard and which is accompanied by a certificate that documents this traceability

Tertiary and National standards

- Tertiary standard
  - Standard whose valuea is fixed by comparisons with a secondary standard
- National standard
  - Standard recognized by an official national decision as the basis for fixing the value, in a country, of all other standards of the given quantity
  - The national standard in a country is usually the primary standard

Calibration Fields and Sources

Typical photon calibration sources

- Gamma sources:

Source	Energy (keV)	Half life (days)
^{241}Am	59,5	157788
^{137}Cs	662	11050
^{60}Co	1173 and 1333	1925,5

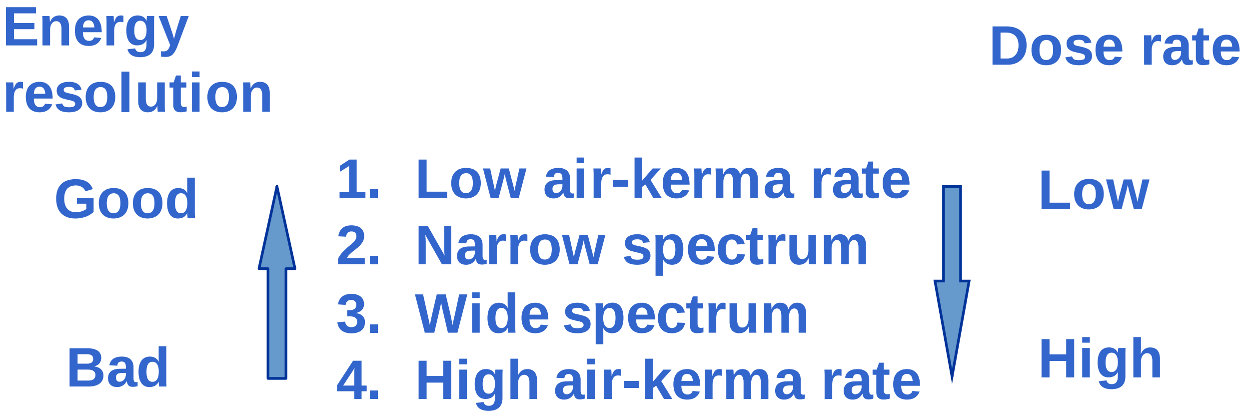
ISO X-ray radiation qualities

- There are 4 different X-ray quality series described in ISO 4037
- Next to this also fluorescent X-rays are described (approaching mono-energetic photons)
- In other standards, more realistic spectra are described, like medical fields (RQR, RQA,…):
  - *IEC 61267:Medical diagnostic X-ray equipment - Radiation conditions for use in the determination of characteristics*

➡ *Can be used for workplace field calibrations*

ISO 4037: X-ray radiation qualities

- ISO 4037 X-ray series: 4 different series
  - *Used for routine calibrations, type testing*

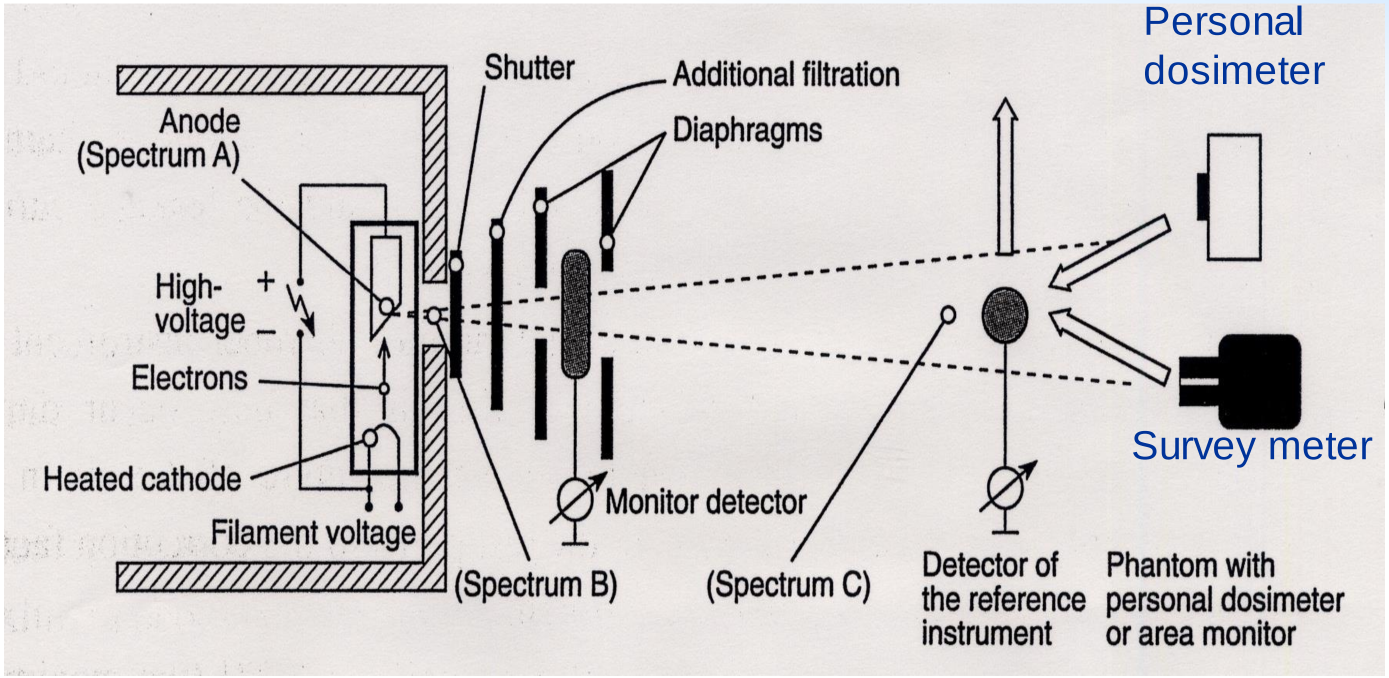


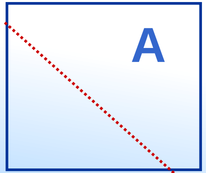
Energy resolution

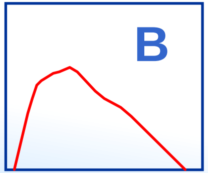
Dose rate

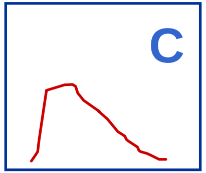
1. **Low air-kerma rate**
2. **Narrow spectrum**
3. **Wide spectrum**
4. **High air-kerma rate**

X-ray machine for instrument calibration









Characteristics of X-ray qualities

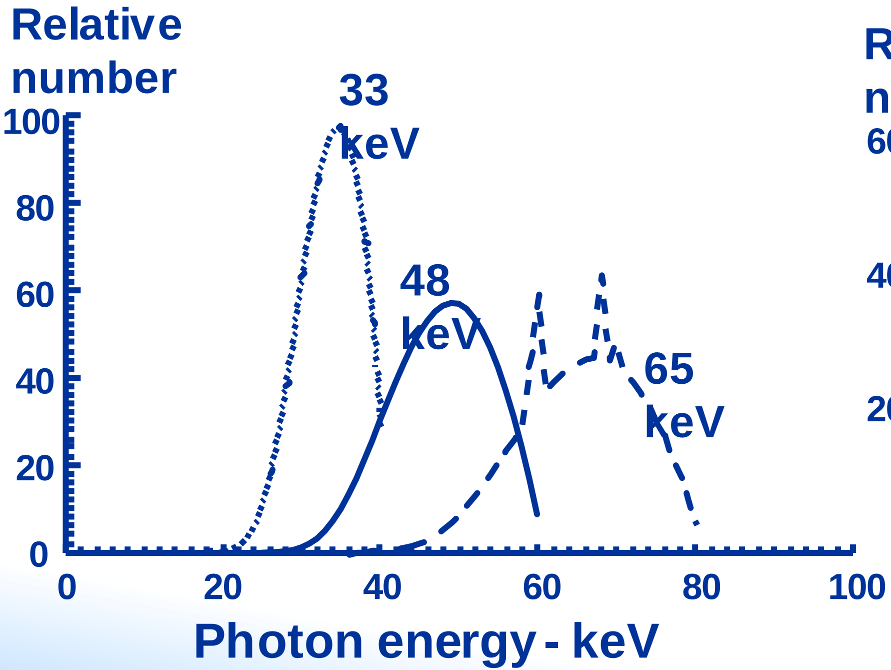
- Determined by
  - Average energy (in keV)
  - Resolution (in percentage)
  - Half value layer, HVL (in mm Al or Cu)
  - Homogeneity coefficient

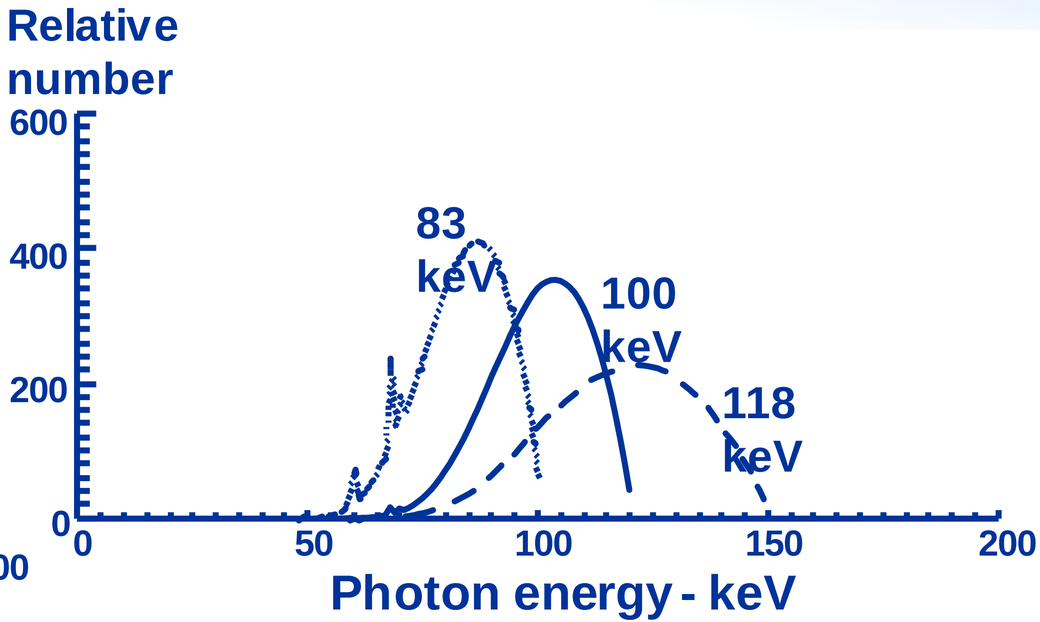
- In practice: the spectra are determined by the
  - Voltage of the tube
  - Type and thicknesses of the filters
  - Characteristics of the target

Narrow series specifications

Short Name	Mean energy (keV)	Resolution (%)	Tube potential (kV)	Inherent filtration	Additional			
					Pb mm	Sn mm	Cu mm	Al mm
N-10	8.5	28	10	1 mm Be				0.1
N-15	12.4	33	15	1 mm Be				0.5
N-20	16.3	34	20	1 mm Be				1.0
N-25	20.3	33	25	1 mm Be				2.0
N-30	24.6	32	30	1 mm Be				4.0
N-40	33.3	30	40	4 mm Al			0.21	
N-60	47.9	36	60	4 mm Al			0.6	
N-80	65.2	32	80	4 mm Al			2.0	
N-100	83.3	28	100	4 mm Al			5.0	
N-120	100.4	27	120	4 mm Al		1.0	5.0	
N-150	118.2	37	150	4 mm Al		2.5		
N-200	164.8	30	200	4 mm Al	1.0	3.0	2.0	
N-250	207.3	28	250	4 mm Al	3.0	2.0		
N-300	248.4	27	300	4 mm Al	5.0	3.0		
N-350	288	29	350	4 mm Al	7.0	4.5		
N-400	328	27	400	4 mm Al	10.0	6.0		

Examples of N-series spectra

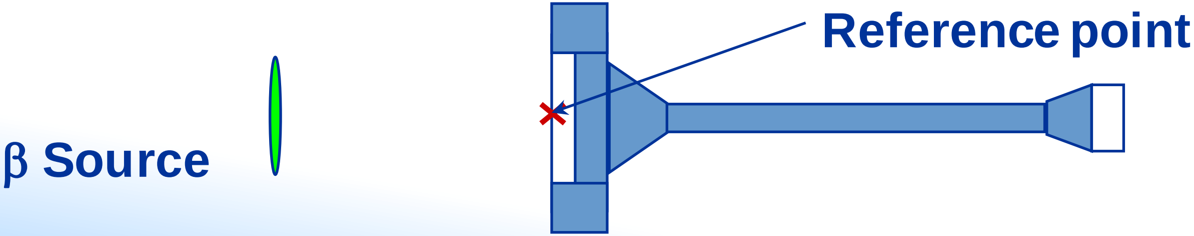




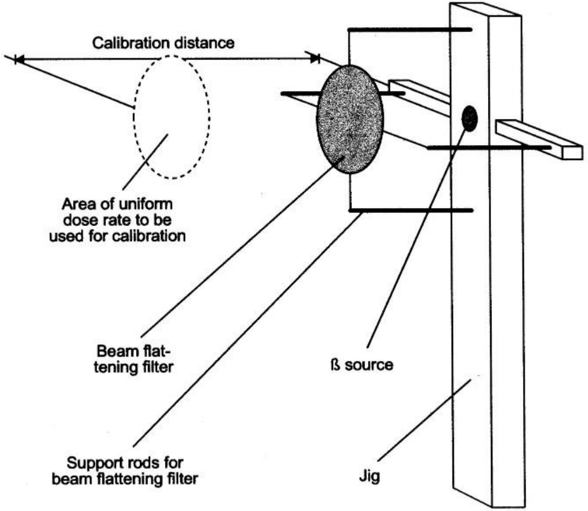
Typical beta sources and characteristics

Nuclide	E_{max} (keV)	T1/2 (days)
^{14}C	156	2093000
^{147}Pm	225	958
^{85}Kr	687	3915
^{204}Tl	763	1381
^{90}Sr-Y	2274	10523
^{106}Ru-Rh	3541	373

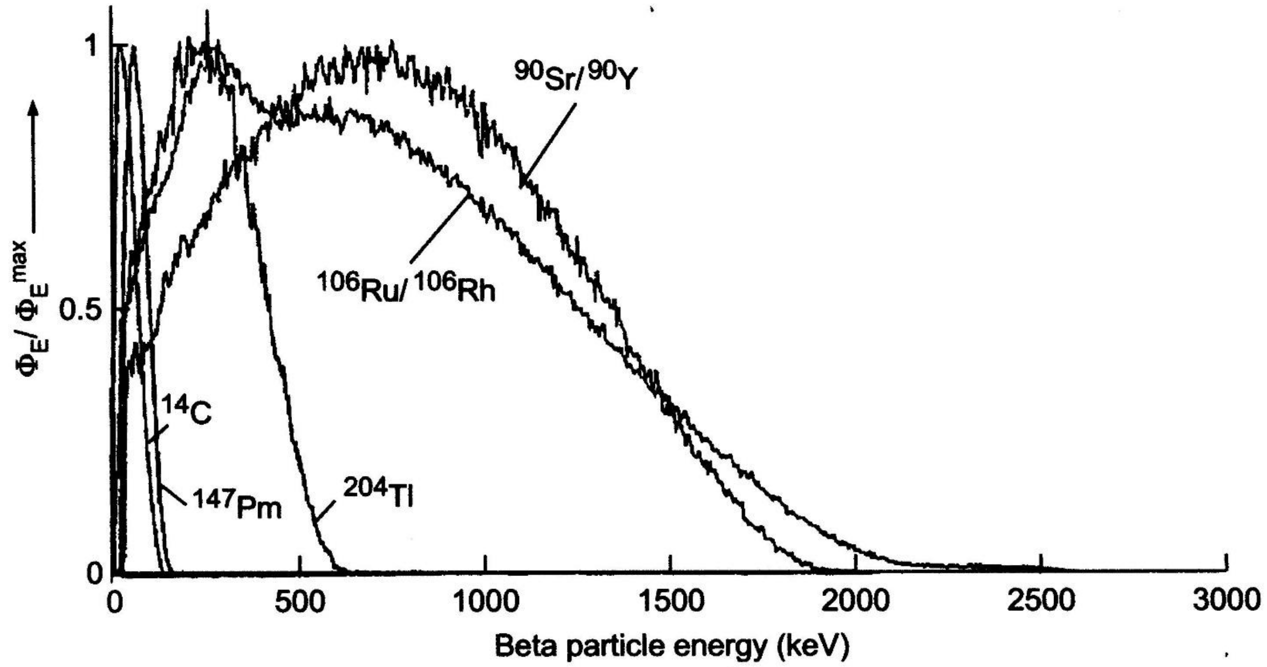
Beta reference dosimetry is done with an extrapolation chamber in terms of tissue absorbed dose rate.



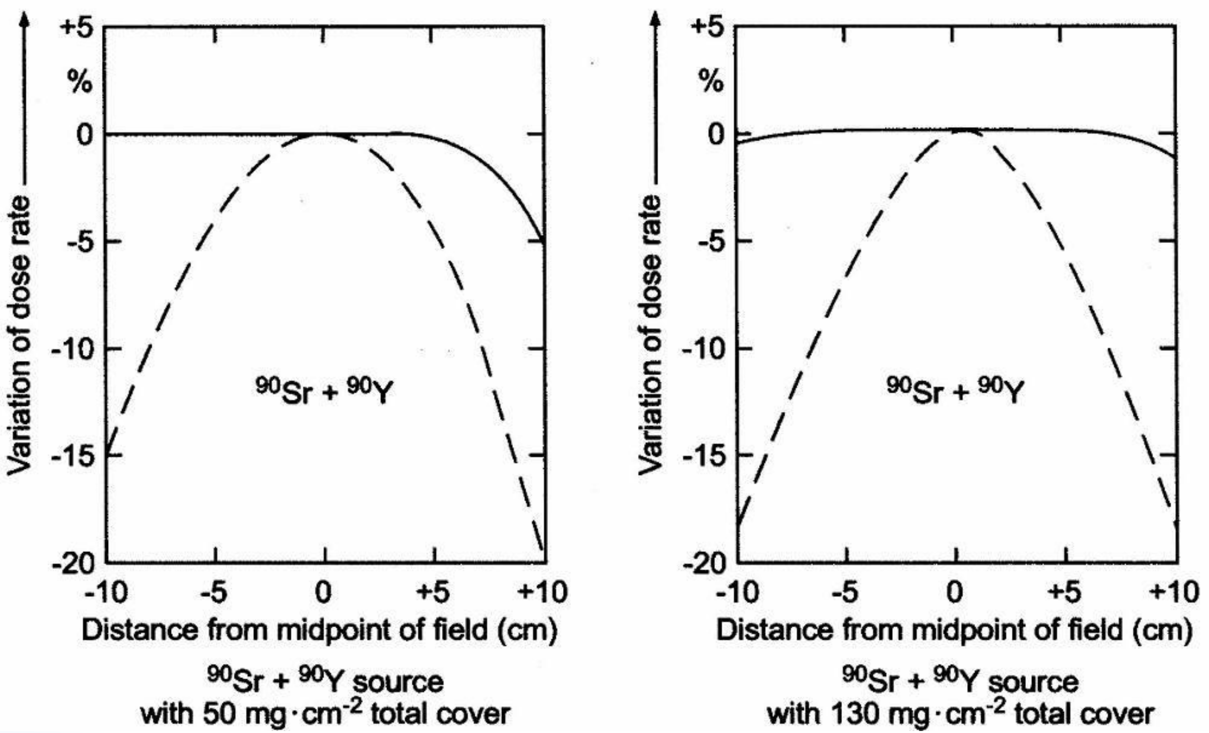
Beta calibration standard



Beta particle spectra



Effect of beta beam flattening filters



^{90}Sr + ^{90}Y source
with 50 mg·cm^{-2} total cover

^{90}Sr + ^{90}Y source
with 130 mg·cm^{-2} total cover

— — — Without filter ——— With filter

Neutron sources

Neutron radionuclide sources

Source	Half - life $T_{½}$	Average Energy[a] (MeV)	Neutron yield (s^{-1} x MBq^{-1})	Neutron dose equivalent rate constant (Sv x h^{-1} x m^2 x MBq^{-1})
$^{252}Cf + D_2O$	968 d	0.54	2×10^{12} [b,c]	5.2 [d]
^{252}Cf	968 d	2.4	2.3×10^{12} [c]	22 [d]
^{241}Am – B (α,n)	432.7 y	2.8	16	1.8×10^{-10}
^{241}Am – Be (α,n)	432.7 y	4.4	66	7×10^{-10}

a) Dose equivalent average energy, E
b) In $n \cdot s^{-1} \cdot g^{-1}$ for ^{252}Cf
c) Neutron yield for a source in a moderating sphere, shielded with 1 mm Cd
d) In $Sv \cdot h^{-1} \cdot m^2 \cdot g^{-1}$ for ^{252}Cf

Neutron spectra

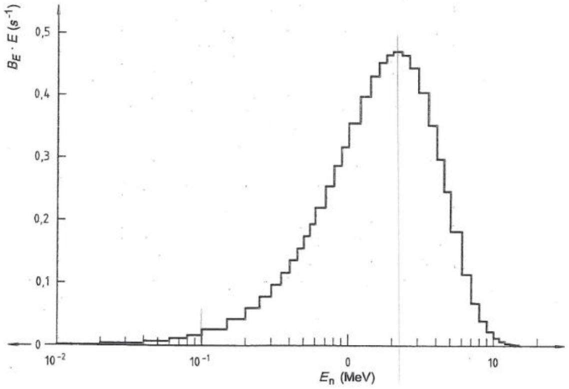


Figure A.2 — Neutron spectrum from a ^{252}Cf spontaneous fission source

^{252}Cf spectrum

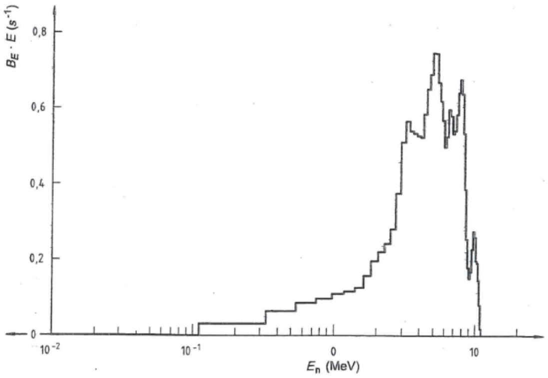
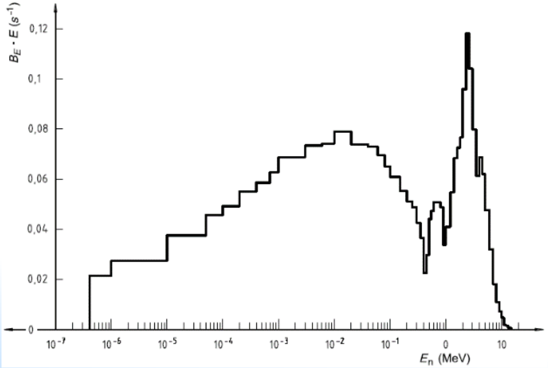


Figure A.4 — Neutron spectrum from a ^{241}Am-Be(α,n) source

Am-Be spectrum



^{252}Cf (D_2O) spectrum

Isotopic source considerations

- ^{241}Am-Be (α,n) and/or ^{252}Cf sources are preferred for routine calibration
- ^{252}Cf sources have a high specific source strength and are comparatively small
- Because of their half-life of 2.65 years, ^{252}Cf sources need occasional replacement
- Should be spherical or cylindrical ($l \cong r$)
- Encapsulation should be uniform and thin
- 1 mm thick Pb shielding reduces the photons from ^{241}Am-Be(α,n) sources < 5 %
- Anisotropy correction can be needed

Accelerator produced neutrons

- Accelerator neutrons are not readily available
- Advantage □ usually nearly monoenergetic, and useful to determine energy response
- Most reactions use proton and deuteron beams of energies up to 3.5 MeV to produce neutrons up to 19 MeV
- Small deuteron accelerator with a few 100 kV allows to produce neutrons with 2.8 and 14.8 MeV in respectively deuterium and tritium targets

Reactor produced neutrons

- Produced with modified fission spectra
- Thermal neutrons available at few reactors
- A few locations have filtered beams for nearly monoenergetic neutrons - 2, 24 and 144 keV
- Useful to determine the intermediate energy response of instruments and dosimeters
- Hardly used in practice…. (costs, access, availability)

Neutrons for determining energy response

Neutron energy (MeV)	Method of production	Reaction
2.5×10^{-8}(thermal)	Moderated-reactor or accelerator-produced neutrons	Fission
0,002	Scandium-filtered reactor neutrons or accelerator-produced	$^{45}Sc(p,n)\ ^{45}Ti$
0,024	Iron/aluminum-filtered reactor neutrons or accelerator produced	$^{45}Sc(p,n)\ ^{45}Ti$
0,144	Silicon-filtered reactor neutrons or accelerator produced	$T(p,n)^{3}He$ and $^{7}Li(p,n)^{7}Be$
0,25	Accelerator	$T(p,n)^{3}He$ and $^{7}Li(p,n)^{7}Be$
0,565	Accelerator	$T(p,n)^{3}He$ and $^{7}Li(p,n)^{7}Be$
1,2	Accelerator	$T(p,n)^{3}He$
2,5	Accelerator	$T(p,n)^{3}He$
2,8	Accelerator	$D(d,n)^{3}He$
5,0	Accelerator	$D(d,n)^{3}He$
14,8	Accelerator	$T(d,n)^{4}He$
19,0	Accelerator	$T(d,n)^{4}He$

Workplace field calibrations

- Calibration fields described in ISO standards are not always the same as in real workplace
  - Real workplace: influence of room and air scatter
  - Calibration: without scatter
- Sometimes better to calibrate in spectra that resemble workplace field
  - Especially for neutron dosimeters with bad energy response
  - More difficult to have good reference
  - ISO standard for neutrons workplace fields (ISO 12789)

Practical calibration procedures

General requirements for calibration fields

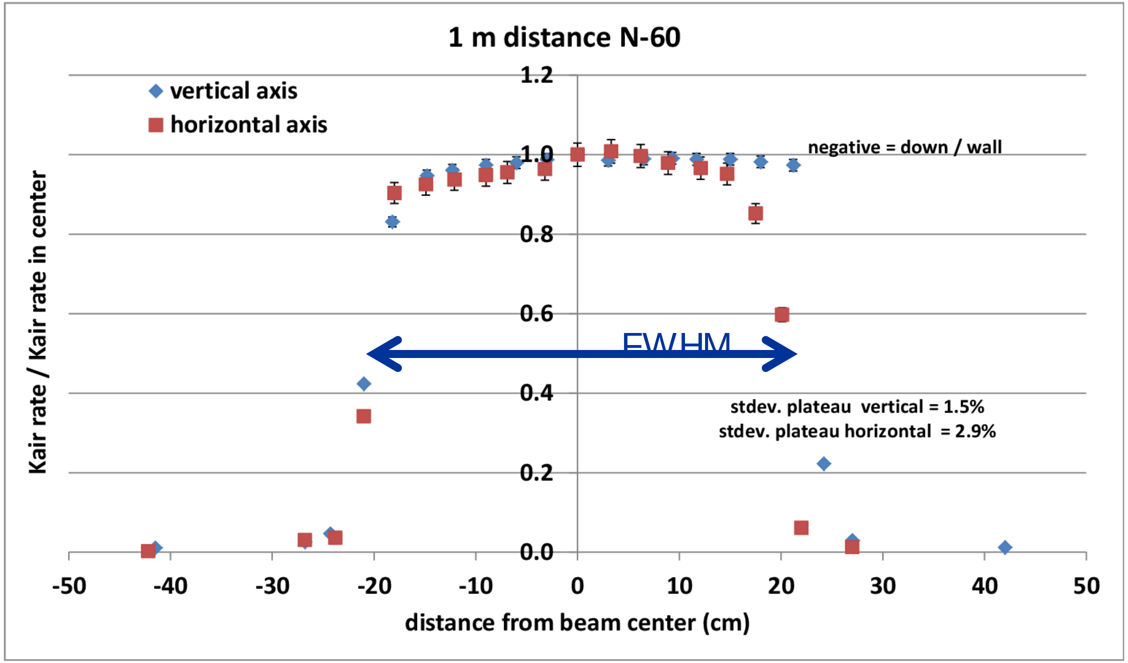
- Characterize the calibration field’s uniformity
- Stability with time should be checked
- Room scatter effects should be investigated
- Background levels should be low compared to calibration radiation
  - Record and correct background readings of the instrument if necessary.

Calibrations - Geometrical considerations

- Recommended irradiation distances are listed in ISO 4037
  - For gamma sources: between 1 to 4 m
  - For X-ray, dependent on spectrum form 1 to 2 or 3 meter
- To prevent significant changes in spectrum
- Scatter contribution should be less than 5% (gamma, X-rays)
  - Determine deviation from $1/r^2$ (after correction from air scatter)
- Most neutron calibrations are made with irradiation distances less than 1 m to minimize the scatter contribution (dependent on room size)
- Beta irradiations are made at distances of 20 – 50 cm because of the electron short range
- The air kerma rate outside the collimated beam shall not exceed 5 % of that inside the collimated beam

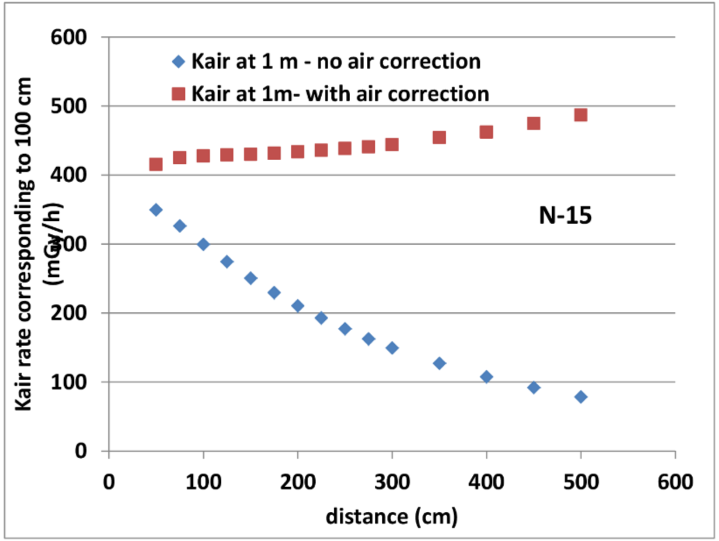
Beam diameter and profile

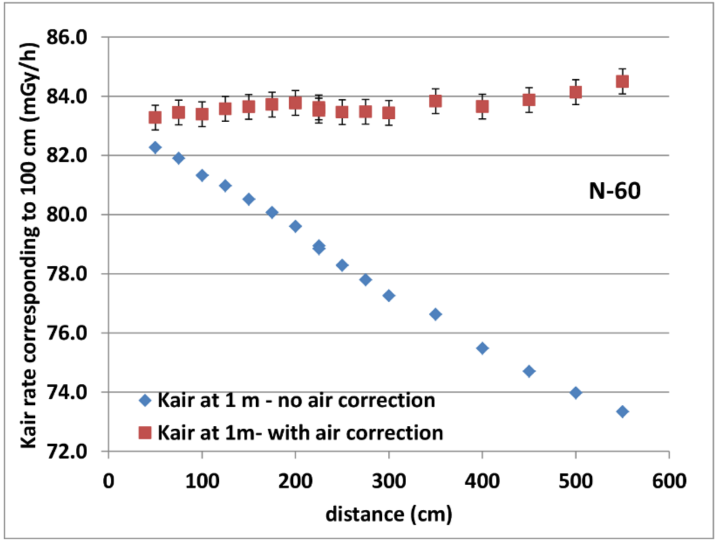
The air kerma rate at each point of test shall not vary by more than 5 % over the entire cross sectional area of the sensitive volume of the detector under test or over the entire area of the phantom.(ISO-4037)



Distance dependence and attenuation in air

- $K_{air} \sim \frac{1}{distance^2}$ for a point-like source
- attenuation in air ($e^{-\mu \cdot distance}$) and μ is larger for small energies





Scatter corrections are important for neutron calibrations

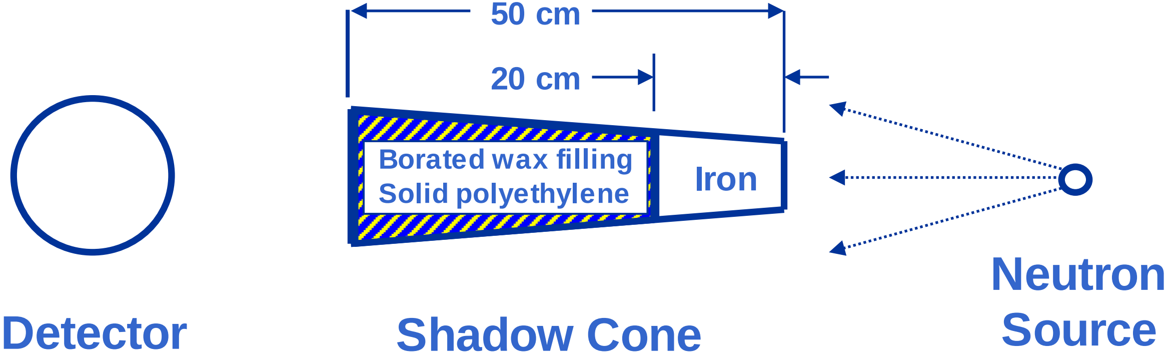
- Instruments and dosimeters respond to direct and scattered neutrons
- Neutrons are scattered from walls, floor, objects in the room, and even air
- Scatter contribution depends on distance to the source, room size and other factors
- Calibration coefficient should not be dependent on room, so scatter contribution should be subtracted
- Scatter contribution can be estimated from calibration room geometry, or measured with a shadow cone (see ISO 8529)

Shadow cone for scatter correction

$R_1(r) = R_o(r) + R_s(r)$ Without shadow cone

$R_2(r) = R_s(r)$ With shadow cone

$R_o(r) = R_1(r) - R_2(r)$ + correction for air scatter (in- and out-)



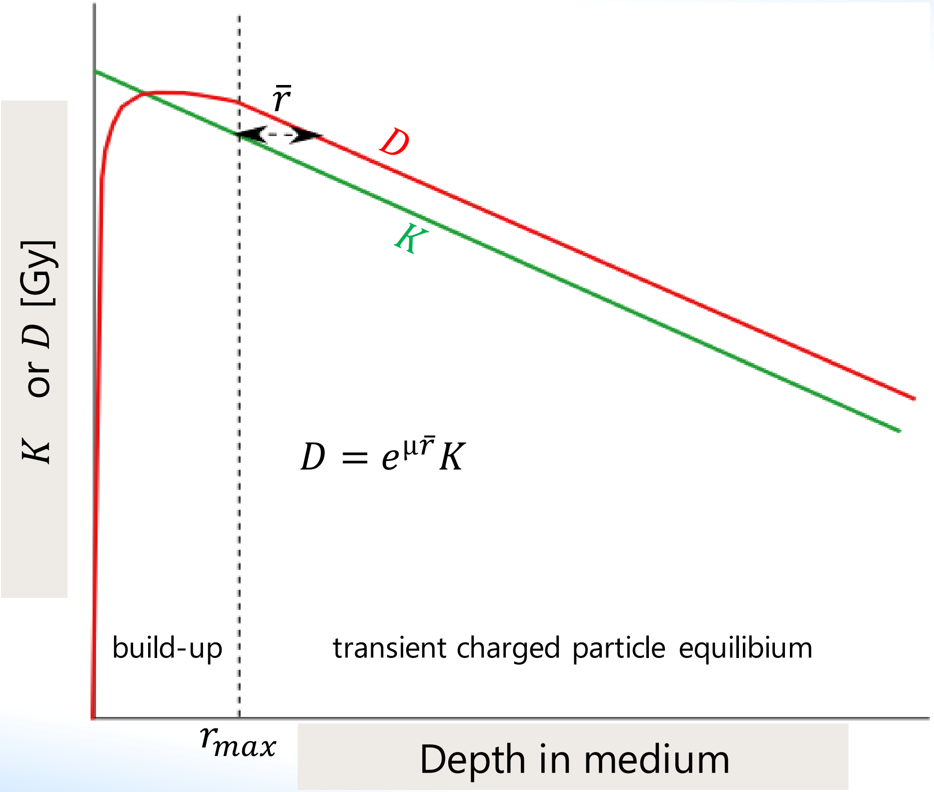
Reference conditions for calibration

Influence quantities	Standard conditions
Temperature	18 – 22 °C
Humidity	30 – 75 %
Air pressure	86 – 106 kPa

Secondary charged particle equilibrium

- Electrons with energies above 65 keV and 2 MeV can penetrate respectively 0.07 mm and 10 mm ICRU tissue. This can affect measurements of Hp(0.07) for photons with energies above 65 keV and Hp(10) for photons with energies above 2 MeV
  - Charged particle equilibrium is important
  - Build up plates to be used
- In the standard ISO 4037-3 the required thicknesses for the different reference fields are given for PMMA as build-up material.
- Up to 250 keV build up is guaranteed by air and other materials in the beam
- For ^{137}Cs and ^{60}Co gamma radiation 3 mm PMMA build up plates are required

Secondary charged particle equilibrium



Different steps in calibration

Calibration of radiation monitors: 4 steps

Radiation monitors must measure the operational quantities

1°. Basic quantity is determined free in air at point of reference
Reference dosimetry is made in *Air Kerma* for photons, *Fluence* for neutrons and *Tissue (or Air) Absorbed Dose* for beta rays

2°. Operational quantity is calculated with dose conversion coefficients
Listed in ISO standards

3°. Reading of the monitor is determined at the point of reference, with or without phantom

4°. Compare the readings with the reference value to obtain the response or calibration factor

Reference dosimetry

Reference values for calibration can be determined by three different methods:

1) Alternating instrument method

2) Source method

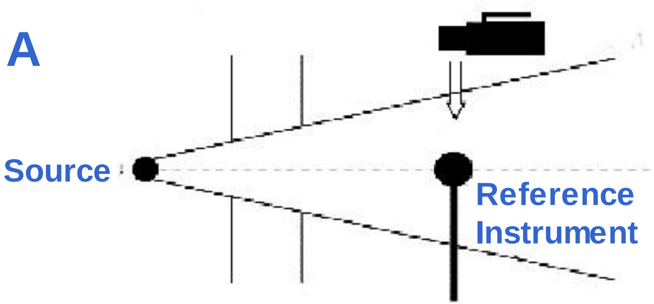
3) Inverse-square law method

Reference dosimetry

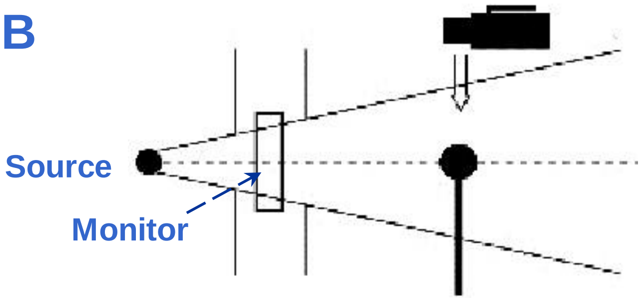
Alternating instrument method

- Reference dosimetry is made with a reference instrument just before irradiation
- The test instrument is placed at the same point after removal of the reference instrument
- The test instrument is irradiated
- After the calibration exposure, a 2nd measurement can be made with reference instrument
- Monitor can be used to control stability (X-rays)

Alternating instrument method



With reference instrument and no monitor



With reference instrument and a monitor

Reference dosimetry

Source method

- Reference dose rate measurements are made at pre-selected calibration points
- Instrument calibrations are then made at these points with comparison to the reference values
- Taking into account decay of source (if applicable)

Reference dosimetry

Inverse square law method:

- The dose rate at a reference point is made by calculation using source activity and distance
- Will lead to higher uncertainties

Conversion coefficients

- To go from primary quantity (fluence, air kerma) to operational quantity
- Conversion coefficients are calculated through Monte Carlo simulations
- All relevant conversion coefficients are listed in the ISO standards, for all sources recommended for calibration
- Conversion coefficients depend on spectral, and, for personal dose equivalent, the directional distributions.

Instrument calibration - Illustration

- ^{137}Cs source
- Air kerma rate at 2 meters = 0.5 Gy/h
- Conversion coefficient for $H_p(10)$ = 1.21 Sv/Gy
- $H_p(10)$ rate at 2 meters = 1.21×0.5 = 0.605 Sv/h
- Expose a dosimeter on a slab phantom at 2 m for 10 minutes

Instrument calibration - Illustration (Cont.)

- $H_p(10) = 0.605 \text{ Sv/h} \times 0.167 \text{ h} = 0.101 \text{ Sv}$
- dosimeter reading, M = 55 units
- Response, R = 55/0.101 = 544 units/Sv
- Calibration factor, N = 0.101/55 = 0.00184 Sv/unit

Phantoms

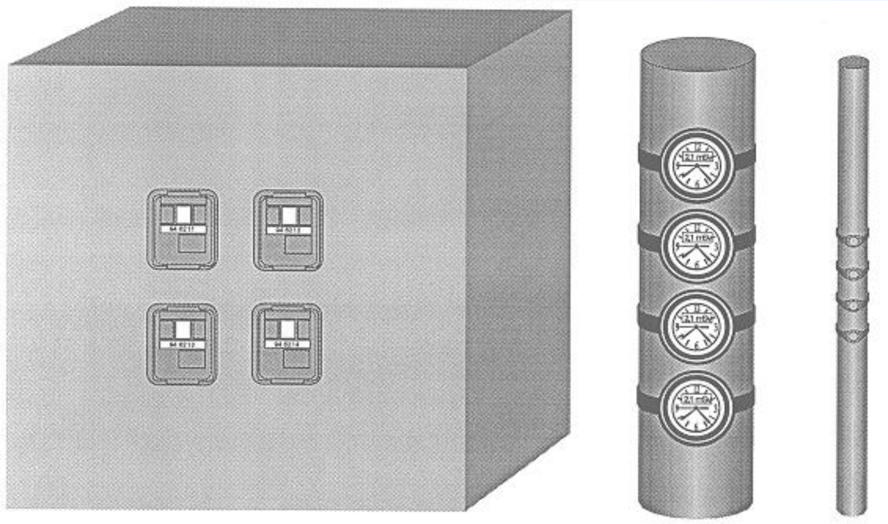
Calibration for the operational quantities

- Ambient monitors: calibration free in air
- Personal monitors: calibration on phantom

Calibration of personal dosimeters

- The ISO has specified three phantoms that should be used for dosimeter calibration
  - A water filled PMMA phantom represents the human torso
  - The water filled pillar phantom is recommended as an arm or wrist phantom
  - Full PMMA or plexi phantoms sometimes used
  - ISO rod phantom serves as a finger phantom
  - Cylindrical phantom: (20cm diameter) for $H_p(3)$

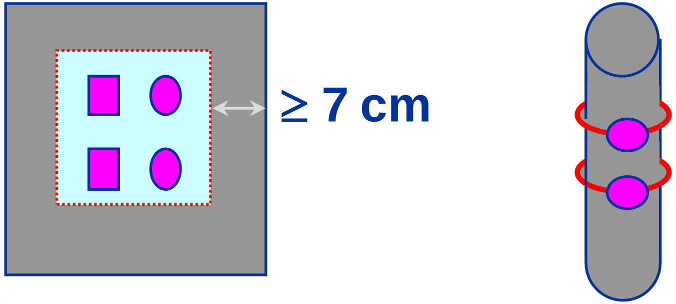
ISO calibration phantoms



Slab: 30 ×30 ×15 cm with 2.5 mm PMMA front wall
Pillar: 73 mm diameter × 30 cm with 2.5 mm PMMA wall
Rod: Solid PMMA rod, 19 mm diameter × 30 cm

Dosimeter Placement

- Single dosimeters should be placed on the center of the phantom surface
- Multiple dosimeters should be arranged to avoid radiation interaction between dosimeters
- Avoid placing dosimeters closer than 7 cm for the slab phantom edge



Reference point for dosimeter calibration

- The reference point of a measuring instrument is the point to be used in order to position the instrument at the point of test
- The manufacturer should mark the reference point on the instrument, or it should be indicated in the accompanying documentation
- Reference point is dosimeter, not phantom
- But is also important for determining angular dependences

Uncertainties of measurements

- Every measured value from a calibration laboratory must be reported together with the corresponding uncertainty (according to ISO 17025)
- The uncertainties are calculated according to the GUM
  - JCGM –“Evaluation of measurement data- Guide to the expression of uncertainty in measurements”
- All sources of uncertainties must be considered

Uncertainties on the reference measurements

- **Uncertainties in the calibration of a secondary standard**
- Random uncertainties of the measurements
- zero shift
- leakage and ambient radiation
- measuring assembly scale and range non-linearity
- differences in energy between the radiation used for calibrating the secondary standard instrument itself and the reference radiation used for calibrating the radiation protection instrument
- variations in air temperature, pressure and humidity
- calibration distance
- beam non-uniformity
- stem scatter
- shutter transit time
- long-term stability of the complete instrument
- resolution of scale indication

Uncertainties on the calibration measurement

- Uncertainty of the conventional quantity value
- Uncertainty in the exact positioning of standard and test instrument
- Uncertainty resulting from different irradiation distances
- Uncertainty of the conversion coefficient
- Uncertainty due to field inhomogeneity over the cross-sectional area of the beam
- Uncertainty due to the simultaneous irradiation of several dosimeters
- Uncertainties due to simplified procedures
- Uncertainty introduced by using a build-up plate
- Uncertainty due to long-term variation of response of standard instrument
- Random uncertainties of the measurements