Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources

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Lecture contents

- Reference publications
- Quantities
- Metrology framework
- Transfer instruments
- Irradiators
- Scattering correction
Reference publications

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Reference publications

ICRU - International Commission on Radiation Units and Measurements

- ICRU Report 85 (2011): fundamental quantities and units for ionizing radiation

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Reference publications

ISO - International Standardisation Organisation

ISO 8529 Reference neutron radiations

- Part 2 (2000): Calibration fundamentals of radiation protection devices related to the basic quantities characterizing the radiation field
- Part 3 (1998): Calibration of area and personal dosimeters and determination of their response as a function of neutron energy and angle of incidence

ISO 8529 deals with reference neutron radiation fields in the energy range from thermal up to 20 MeV, used for calibrating neutron-measuring devices for radiation protection purposes, and for determining their response as a function of neutron energy.

The reference radiation fields are produced with:
- neutrons from radionuclide sources, including neutrons from sources in a moderator;
- neutrons produced by nuclear reactions with charged particles from accelerators;
- neutrons from reactors.
Reference publications

ISO - International Standardisation Organisation

ISO 8529  Reference neutron radiations

- Part 2 (2000)
- Part 3 (1998)

These standards describe how the neutron fields can be produced, traced to PSDL, and used for calibrations.

These standards are produced and updated by ISO Technical Committee 85 (Nuclear energy) / SC2 (Radiation Protection) / WG2 Working Group 2 (Reference Radiation fields).

ISO 8529-1 is currently under revision. Parts 2 and 3 will be revised in coming 2-3 years.
Reference publications

ISO - International Standardisation Organisation

The ISO 8529 series **does not cover simulated workplace neutron fields** where a range of different issues need to be considered. For these fields a new approach was needed and a new series of two standard, ISO 12789, was written.

**ISO 12789 Reference radiation fields — Simulated workplace neutron fields**

- Part 2 (2008): Calibration fundamentals related to the basic quantities

Passive personal dosemeters are covered by:

**ISO 21909 Passive neutron dosimetry systems**

- Part 2 (2019): Methodology and criteria for the qualification of personal dosimetry systems in workplaces

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Reference publications

IEC - International Electrotechnical Commission

The International Electrotechnical Commission have produced standards on test methods for radiation protection devices, e.g.

IEC 61005 (2014) covering area survey instruments
IEC 61526 (2010) covering active personal dosemeters
Reference publications

IAEA - International Atomic Energy Agency


TRS 285 included the technical bases that led to the production of the ISO 8529 Series of Standards.


Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Quantities

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Basic physical quantities

Fluence

\[ \Phi = \frac{dN}{da} \]

unit: m\(^{-2}\) or cm\(^{-2}\)

Φ is quotient between the number of particle dN incident on the elemental sphere having cross sectional area da, and the cross sectional area da; unit cm\(^{-2}\).

• All particles are equally weighted, independently on their direction.
• An instrument with isotropic response is needed to accurately measure the quantity.

In Monte Carlo codes the fluence in a cell having volume ΔV is often calculated as

\[ \Phi = \frac{\sum l_i}{\Delta V} \]

Where \(l_i\) are the particle path lengths in the volume ΔV.

Fluence rate

\[ \dot{\Phi} = \frac{d\Phi}{dt} \]

m\(^{-2}\) s\(^{-1}\)

more frequently cm\(^{-2}\) s\(^{-1}\)

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
The distribution $\Phi_E$ of the fluence with respect to energy (spectrum)

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

$m^{-2} J^{-1}$, more frequently $cm^{-2} MeV^{-1}$

- Plotting $d\Phi/dE$ vs. $E$ is not practicable, as $E$ varies over many orders of magnitude
- Plotting $d\Phi/dE$ vs. $\log(E)$ does not preserve the proportions (we desire that to equal areas correspond equal neutron fluence values)
- If the lethargy distribution of the fluence, $E \frac{d\Phi}{dE}$, is plotted vs. $\ln(E)$, the proportions are preserved, as

$$\int d(\ln(E)) E \frac{d\Phi}{dE} = \int \frac{dE}{E} E \frac{d\Phi}{dE} = \Phi$$

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Particle radiance (or angle / direction distribution of the fluence)

\[ \Phi_\Omega = \frac{d\Phi}{d\Omega} \quad \text{m}^{-2} \text{sr}^{-1}, \text{more frequently cm}^{-2} \text{sr}^{-1} \]

The direction is often specified in terms of cosine(\(\theta\)), where \(\theta\) is the polar angle with respect to a reference direction in space.

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Fluence-to-dose equivalent conversion coefficients

The type of dose-equivalent must be specified. For neutrons the following are relevant:

- $H^*(10)$ for ambient monitoring
- $H_p(10,\alpha)$ for individual monitoring

The dose equivalent is derived by energy-integrating the product of the spectrum and the energy- (and angle-) dependent conversion coefficient tabulated in ICRP74 / ICRU57.

$$H = \int h(E) \cdot \frac{d\Phi}{dE} \cdot dE$$

A convenient concept is the **unit spectrum**, defined as the spectrum per unit fluence. The unit spectrum has unit integral and only contains the “shape” of the spectrum.

$$H = \int h(E) \cdot \frac{d\Phi}{dE} \cdot dE = \Phi \cdot \int dE \cdot h(E) \cdot \varphi_E$$

$$h_\Phi = \frac{H}{\Phi} = \int dE \cdot \varphi_E \cdot h(E)$$

If an ISO standard field is used, $\varphi_E$ and $h_\Phi$ are tabulated in ISO 8529-1.
Neutrons

Free-field Fluence Response \[ R_\Phi \quad ISO\ 8529-2(2000) \]

\[ R_\Phi = \frac{G_{corr}}{\Phi} \]

\( \Phi \) is the conventional quantity value of the “free-field” fluence from the source:

NOT including the neutrons scattered by the room (walls, floor, ceiling), surrounding structures and materials, and the air.

\( G_{corr} \) is the “corrected indication”.

✓ Scattered neutrons are an influence quantity of type S (ISO 29661)
✓ The natural background is also an influence quantity of type S
✓ Non linearity is an influence quantity type F

Dose equivalent response \[ R_H \quad ISO\ 8529-2(2000) \]

\[ R_H = \frac{G_{corr}}{H} = \frac{R_\Phi \cdot \Phi}{H} = \frac{R_\Phi}{h_\Phi} \]

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Primary and Secondary Standards

In neutron metrology the following are primary standards, intended as established by primary reference measurement procedure (i.e. using measurement standards for magnitudes of different type):

• Activation techniques based on elements with well-known radiative capture cross sections
  
  ✓ emission rate of radionuclide sources can be determined accurately through the thermal neutron activation of $^{55}$Mn (sulphate in aqueous solution) in the so-called “manganese moderating bath”
  
  ✓ thermal neutron fluence rates are measured through thermal neutron activation of $^{197}$Au (gold activation foils)

• Nuclear reactions with very well-known Xs, such as n–p scattering in Hydrogenated materials
  
  ✓ Neutron fluence in the 0.5 MeV - 10 MeV region can be measured with recoil Proton Telescopes or Recoil proton proportional counters (counting the recoil protons from a known hydrogenated volume)

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Thermal fluence rate measurements

Measuring thermal fluence rate with Au foils and Cd subtraction technique

$^{197}\text{Au}(n,\gamma)\ 1^{98}\text{Au}$ radiative capture cross section in thermal domain is well known and can be used as primary standard for Thermal neutron fluence rate.

$^{198}\text{Au}$ beta decays (2.694 d) and yields 411.8 keV $\gamma$ (95.6%)

\[
D_{E<0.5\text{eV}} = \frac{1}{G_t} (D_{\text{bare}} - FD_{\text{Cd}})
\]

\[
= \frac{N_{\text{Av}} \cdot \sigma_0 \cdot g}{M_{\text{at}}} \cdot \Phi_w
\]

In Au – Au/Cd technique:

$G_t$ thermal neutron self-shielding factor (typ. 1.02 for 10 um foils)

$F$ Correction factor for attenuation of epithermal neutrons in Cd (typ. 1.01)

$\sigma_0$ conventional thermal Xs (at 25 meV) = 98.69 b

$g$ Westcott factor (for Au) = 1.0046 (departure from $1/v$)

$\Phi_w$ is the “conventional thermal neutron fluence rate” or “sub-Cd cut off fluence rate in the Westcott convention”: the 25 meV fluence rate that would produce the observed activation.
Monoenergetic reference fields between 1 keV and 20 MeV

ISO 8529-1:2001 recommends a set of energies for standards of monoenergetic fluence, based on a number of different neutron-producing reactions, from accelerator or reactors.

<table>
<thead>
<tr>
<th>Neutron energy MeV</th>
<th>Method of production</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,5 × 10^-8 (thermal) a</td>
<td>Moderated-reactor or accelerator-produced neutrons</td>
</tr>
<tr>
<td>0,002</td>
<td>Scandium-filtered reactor neutron beam or accelerator-produced neutrons from reaction (^{46}\text{Sc}(p,n)) (^{45}\text{Ti})</td>
</tr>
<tr>
<td>0,024</td>
<td>Iron/aluminium-filtered reactor neutron beam or accelerator-produced neutrons from reaction (^{46}\text{Sc}(p,n)) (^{45}\text{Ti})</td>
</tr>
<tr>
<td>0,144 a</td>
<td>Silicon-filtered reactor neutron beam or accelerator-produced neutrons from reactions (T(p,n)) (^3\text{He}) and (\checkmark\text{Li}(p,n)) (^7\text{Be})</td>
</tr>
<tr>
<td>0,25 a</td>
<td>Accelerator-produced neutrons from reactions (T(p,n)) (^3\text{He}) and (\checkmark\text{Li}(p,n)) (^7\text{Be})</td>
</tr>
<tr>
<td>0,665 a</td>
<td>Accelerator-produced neutrons from reactions (T(p,n)) (^3\text{He}) and (\checkmark\text{Li}(p,n)) (^7\text{Be})</td>
</tr>
<tr>
<td>1,2</td>
<td>Accelerator-produced neutrons from reaction (T(p,n)) (^3\text{He})</td>
</tr>
<tr>
<td>2,5 a</td>
<td>Accelerator-produced neutrons from reaction (T(p,n)) (^3\text{He})</td>
</tr>
<tr>
<td>2,8 a, b</td>
<td>Accelerator-produced neutrons from reaction (D(d,n)) (^4\text{He})</td>
</tr>
<tr>
<td>5,0</td>
<td>Accelerator-produced neutrons from reaction (D(d,n)) (^4\text{He})</td>
</tr>
<tr>
<td>14,8 a, b</td>
<td>Accelerator-produced neutrons from reaction (T(d,n)) (^4\text{He})</td>
</tr>
<tr>
<td>19,0</td>
<td>Accelerator-produced neutrons from reaction (T(d,n)) (^4\text{He})</td>
</tr>
</tbody>
</table>

• Small accelerators providing protons and deuterons up to an energy of 3,5 MeV are enough to generate neutrons of all recommended energies.

• For 2,8 MeV and 14,8 MeV, however, a small accelerator with a potential of up to few hundred kilovolts, is sufficient.

• Parameters to be known: charged particle energy, angle, fluence measurement and monitoring, neutron spectrum, sources of scattered and contaminant neutrons, target age and thickness.

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
The manganese sulphate bath

- Absolute determination of the 4\pi sr neutron emission rate from **radionuclide neutron sources**.

- A spherical vessel (50 to 150 cm diameter) is filled with aqueous solution of pure Mn SO\(_4\) (about 20 g/l).

- The neutron source is placed at the centre of the bath.

- Neutrons are thermalized in water and induce radiative capture in \(^{55}\text{Mn}\) (100\% of the Mn atoms).

- Capture in Oxygen is negligibly small and neutron capture by hydrogen and sulphur produces stable isotopes.

\[ ^{55}\text{Mn}(n,\gamma) ^{56}\text{Mn} \]

\(^{56}\text{Mn}\) beta decays (2.58 h) and yields 847 keV \(\gamma\) (100\%).

- The specific Mn saturated activity is measured (4\pi\(\beta\)-\(\gamma\) or NaI(Tl) counting) and the source emission rate \(Q\) is obtained (1-2\% standard unc.) by:

\[
Q = \frac{A_m M}{f (1 - \delta)}
\]

- \(A_m\) \(^{56}\text{Mn}\) specific saturated activity (reached after one irradiation day)
- \(M\) mass of the solution
- \(f\) capture probability in Mn / total capture probability
- \(\delta\) removal probability by \((n,\alpha)\) and \((n,p)\) in S, \((n,\alpha)\) in O, re-capture from source, escape from vessel.

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
The preferred one is the spontaneous fission $^{252}$Cf source, as it is very small, has well known spectrum, low photon field, and is available with any emission rate. The time-dependent emission rate depends on decay of all the constituents, including $^{250}$Cf and $^{248}$Cm. If more than 5% of the emission is due to $^{250}$Cf + $^{248}$Cm, frequent recalibration should take place. The short half life (2.65 a) requires frequent replacements.

(α,n) Am-Be sources are considerably bigger than Cf. As the spectrum depends on capsule size and amount of active material, they are affected by format-to-format spectral variations that should be taken into account.

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Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Recommended Radionuclide neutron sources ISO 8529:2001

Anisotropy

✓ Neutron sources generally show anisotropic neutron emission
✓ The angular emission rate \( dB/d\Omega = B_\Omega \text{ (sr}^{-1}) \) is specified in terms of the direction \( \Omega \) that is specified by the angles \( \alpha \) and \( \theta \).
✓ The anisotropy factor \( F_\Omega \) in a given direction \( \Omega \) is defined as: considered that \( B/4\pi \) is the angular emission rate for an isotropic source.

\[
F_\Omega = \frac{B_\Omega}{B/4\pi}
\]

✓ For **cylindrical sources** the symmetry implies that \( B_\Omega \) mainly depends upon angle \( \theta \).
✓ For practical reasons the \( \theta=90^\circ \) direction is used for calibrations and the source should be put in slow rotation about the cylindrical axis to eliminate the residual anisotropy around angle \( \alpha \).
Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources

$^{252}\text{Cf source spectrum}$
Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources

10 μg $^{252}$Cf source in X1 encapsulation (A)

$^{252}$Cf source anisotropy (X1 capsule)

\( \text{D}_2\text{O moderated }^{252}\text{Cf source} \)

\( ^{252}\text{Cf at the centre of 15 cm radius} \)

\( \text{D}_2\text{O sphere with 1 mm thick external Cd shell 11.5\% neutrons captured in the sphere} \)
$^{241}\text{Am-Be source spectrum}$

Spectrum derived for $3.0 \times 10^6$ n/s,
4 cm$^3$ cavity volume
25.2 (height) x 25.2 (diam), 3.7 mm (cylinder wall), 3.2 mm (end walls)

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
$^{241}$Am-Be source anisotropy (X3 capsule)


Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Establishing secondary standards at SSDL

Primary standards in neutron metrology:

- Source emission rate (Mn bath)
- Thermal neutron fluence (gold foils)
- Neutron fluence in the 0.5 MeV - 10 MeV region: Recoil Proton Telescope or Recoil proton proportional counters (counting the recoil protons from a known hydrogenated volume)

Secondary standards at SSDL should be established using neutron sources with ideally:

- Emission rate determined at a PSDL using the Mn bath
- Anisotropy determined at a PSDL using a long-counter
- Known spectrum

If the source has

- Unknown emission rate, or
- Unknown anisotropy, or
- Spectrum different than those reported in ISO 8529:1 (2001)

Then the secondary standard should be established by means of a transfer instrument.

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Transfer instruments

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
The moderated ambient dose equivalent meter (rem counter)

- It shows "flat" energy dependence of the $H^*(10)$ response (in principle)
- If the meter is well-designed:
  - $M = q \cdot H^*(10)$
  - The **Fluence response** is proportional to the energy-dependent fluence-to-ambient-dose equivalent conversion coefficient (ICRP74 / ICRU57)

$$R_\Phi = \frac{M}{\Phi} = \frac{q \cdot H^*(10)}{\Phi} = q \cdot h^*(10, E)$$

- Hankins (LA-2717 (1962)) realized that the fluence response of a 25.4 cm sphere with a thermal counter in its centre was curiously similar to “dose equivalent” conversion coefficient, in the energy range from 100 keV to few MeV.

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
The moderated ambient dose equivalent meter

- If compared with the h*(10) conversion coefficients, the response of the 25 cm sphere shows large overestimation in the epithermal region.
- Improvements to this concepts lead to different designs, all of them aimed at depressing the epithermal response while keeping the MeV response.
- Interrupting the moderator with a neutron absorber (a perforated cadmium foil or a borated rubber shell) proved to have some effect..

Leake counter
$^3$He 200 kPa
21 cm diam.
Anderson-Braun NM2B
BF3
24 h x 21 cm diam.
Studsvik 2202D
BF3
24 h x 21 cm diam.
Berthold LB6411
3.5 bar $^3$He+1 bar CH$_4$
25 cm diam.

Taken from Report HPA (UK) HPA-RPD-016 (2006)
The long counter

• A long counter is a **directional meter with “flat” fluence response from 1 keV to 15 MeV (<10% dependence)**. It was designed in the 1950-60s by Hanson, De Pangher, McTaggart.

• Usually formed by a thermal neutron tube counter (usually BF3) in a cylindrical moderator with typical size 44 cm x \( \varnothing \)38 cm

• The fluence response (\( \approx 10 \, \text{counts cm}^2 \)) is determined within about 1.5%-2% using sources with known emission rate (via Mn-bath)

• Design principles
  - Lateral shield (PE + boron)
  - Holes for low-energy streaming

• Effective centre depends on energy and shifts deeper with increasing energy. It can be known with unc. \( \approx 0.6 \, \text{cm} \).

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Bonner spheres

- HDPE spheres of multiple diameters (5-30 cm), sequentially exposed with the same thermal neutron detector in their centre.

The tracks in figure correspond to:

- (a) high-energy neutron escaping from the assembly,
- (b) neutron reaching the detector with thermal energy, producing a count,
- (c) low-energy neutron absorbed in the polyethylene.

- The probability for a neutron to be moderated and give a “count” in the detector is uniquely related to its energy.

- The energy that maximizes such probability is uniquely related to the sphere diameter: the response of a sphere has a peak at an energy value that is uniquely related to the sphere diameter.
Bonner spheres

- Response matrix = counts per unit fluence as a function of the energy and the sphere diameter, under uniform irradiation condition. Derived by Monte Carlo with at least 5 bins per decade.
  \[
  C_i = \Phi \int_{E_{\text{min}}}^{E_{\text{max}}} R_i(E) \varphi(E) \, dE
  \]

- \( \Phi \) is the neutron fluence in cm\(^{-2} \);
- \( \varphi(E) \) is the energy distribution of the neutron fluence normalized to 1 cm\(^{-2} \) and its unit is MeV\(^{-1} \) (also termed “unit spectrum”)
- \( R_i(E) \) is the response function of the sphere (in cm\(^2 \)).
- \( C_i \) are the counts in the i-th spheres.

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Bonner spheres

- The counts of different spheres exposed to the same fluence of a given spectrum form a plot as a function of the diameter (count profile). These are smooth curves, fitted by 5-6 points.
- The profiles contain the totality of the spectrometric information.
- 5-6 well chosen spheres are enough to describe all possible variation in the profile.
- The spectrum is inferred via “unfolding” starting from the response matrix, the count profile, the uncertainties, and a given amount of pre-information (a MC simulation for ex.) needed to make up for the lack of information (the problem is underdetermined, because with ten measurements or less we infer a continuous spectrum over maybe 100 bins).

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Bonner spheres – central detectors

<table>
<thead>
<tr>
<th>Central detector model</th>
<th>Sensitive volume and shape</th>
<th>$R$ (1 MeV, 200 mm) cm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>05NH1</td>
<td>8 kPa, $^3$He</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Cylindrical, 10 mm × 9 mm</td>
<td></td>
</tr>
<tr>
<td>SP9</td>
<td>200 kPa, $^3$He</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>Spherical, 32 mm diameter</td>
<td></td>
</tr>
<tr>
<td>$^6$Li(Eu)</td>
<td>Scintillator</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Cylindrical, 4 mm × 4 mm</td>
<td></td>
</tr>
<tr>
<td>$^6$Li(Eu)</td>
<td>Scintillator</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Cylindrical, 11 mm × 3 mm</td>
<td></td>
</tr>
</tbody>
</table>
Transfer instruments for establishing secondary Standards

Using a spherical survey meter of a long counter

If the source at SSDL is a $^{252}$Cf:
• The spectrum can be assumed to be identical to the ISO tabulation
• Uncertainty in the fluence-to-H*(10) conversion coefficient is only 1%
• The free-field quantity at the calibration distance in the used direction can be determined precisely (unc. 3-4%)

If the source at SSDL is a $^{241}$Am-Be
• The spectrum is probably different than the ISO tabulation
• The $^{241}$Am-Be source used at the PSDL to calibrate the transfer instrument is probably different than the source at the SSDL.
• Additional uncertainties are needed to account for the differences (how to evaluate them?)
• Additional 4% uncertainty in the fluence-to-H*(10) conversion coefficient

Using Bonner spheres

The free-field fluence or H*(10) at the calibration distance in the used direction can be determined precisely (3-4%) for any source type and capsule type.

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Calibration room

In general, irradiation rooms have thick concrete walls. Inside dimensions should be as large as practically possible.

Large buildings with low scattering walls (aluminium) have been built to reduce scattering.

The magnitude of the correction for room- and air-scattered neutrons, and the resulting uncertainty in the free-field quantities, depend critically on the size of the room.

In all cases, the effects of scattered neutrons shall be determined. Details of the recommended calibration procedures are dealt with in ISO 8529-2

“ The room should be such that scatter contributions are as low as possible, but in any case they should not cause an increase in instrument reading of more than 40% at the calibration point ”

<table>
<thead>
<tr>
<th>Source</th>
<th>(^{252}\text{Cf}+\text{D}_2\text{O})</th>
<th>(^{252}\text{Cf})</th>
<th>AmBe or AmB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Cubical room ((L=W=H))</td>
<td>4.2</td>
<td>7.5</td>
<td>8.2</td>
</tr>
<tr>
<td>small sphere or albedo dosimeter</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>large sphere or survey meter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Half-cubical room ((L=W=2H))</td>
<td>6.1</td>
<td>10.9</td>
<td>12.1</td>
</tr>
<tr>
<td>small sphere or albedo dosimeter</td>
<td>4.4</td>
<td>4.4</td>
<td>4.3</td>
</tr>
<tr>
<td>large sphere or survey meter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Open ceiling ((L=W=2H))</td>
<td>4.2</td>
<td>7.1</td>
<td>8.0</td>
</tr>
<tr>
<td>small sphere or albedo dosimeter</td>
<td>3.0</td>
<td>2.9</td>
<td>2.9</td>
</tr>
<tr>
<td>large sphere or survey meter</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Panoramic irradiators

A panoramic irradiator is, ideally, a neutron source suspended in air in the centre of a very large room.

For a room with size 10 x 10 x 3 m$^3$ the scattering can produce a +40% (ISO criterion) in a rem ball reading at 2 m. Useful calibration range < 2 m.

Collimated-beam are commercially available with different degree of automation (shutter motion is the most important). These are not recommended, as the spectrum in the calibration line significantly differs from that of the bare source.
Automated irradiators

Automated irradiators nearly eliminate Individual exposure (except for loading and unloading sources).

- Source in shielded bank (1 m³)
- Multiple source selection
- Automated source extraction and motion
- Work position far from bank to reduce scattering
- Irradiation bench up to about 3 m
- Remotely controlled instrument holder
- Ancillary equipment (cones, D₂O sphere) can also be automated

Manufacturers also provide safety systems:

- Signalization lights (source in bank, source in motion, source out)
- Emergency buttons
- Search buttons
- Counting photocells, interlocked doors
- Motorized doors (typ. 20 cm HDPE + boron or Cd + lead)
- Video monitoring and/or intercom

Disadvantages: cost, troubleshooting, bulky structures

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Manual irradiators

As they do not have automations, manual irradiators have the advantage of being as light as practically achievable.

- Source in a shielded bank
- Manually transferred to work position
- Manipulator (1.5 m)
- Irradiation bench up to 2-3 meters
- Ancillary equipment (cones, D2O sphere) manually operated

Example: a light-structure manual irradiator in a 8 x 8 x 5 (h) m³ underground bunker with light aluminium roof may provide +10% scattering increase in a rem ball reading placed at 1 m.

For radiation protection reasons, sources up to about 2E+6 n/s can be handled.
Calibration equipment

Calibration room equipment includes rigid structures, designed to minimize scattered radiation, with the purposes of

- suspending the source at a proper height (minimum scatter from ground and roof)
- positioning the instrument in distance and height from ground.
  It should be possible to vary the source-to-detector distance.
- Suspending the shadow cone and regulating its position
- Allocating the D_2O moderating sphere

Laser liners are useful to:
- Mark the source-detector-line on horizontal and vertical planes
- Useful distances from the source (1 m, 1.5 m)

IAEA

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Simulated room and equipment

- The simulated room has size 6 x 6 x 3 (h) m³, 20 cm concrete walls, floor and roof.
- The irradiator structure is built with steel profiles with linear mass 2.7 kg/m
- The holder suspends the source at 1.8 m from ground
- The typical spherical meter is a 25 cm diameter HDPE sphere with a spherical $^3$Heproportional counter in its centre (3.2 cm diameter, 5E+19 atoms/cm³)
- The instrument is leaning on a 30 x 30 x 1 cm³ aluminium plate
- The source is a cylindrical volume source (3.1 cm (h) x 2.24 cm diameter) X3 like with emission rate 2E+6 s⁻¹ and Am-Be spectrum

Top view. The source in in the room centre and the sphere is the rem ball

Lateral view. The yellow lines are the Structure (horizontal line) and source holder (vertical line)

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Neutrons

Free-field Fluence Response  \( R_\Phi \)
Dose equivalent response  \( R_{H} \)

\[
R_\Phi = \frac{G_{corr}}{\Phi} \quad \text{and} \quad R_H = \frac{G_{corr}}{H} = \frac{R_\Phi \cdot \Phi}{H} = \frac{R_\Phi}{h_\Phi}
\]

\( \Phi \)  “conventional quantity value” of the “free-field” fluence from the source, i.e. NOT including the neutrons scattered by the room (walls, floor, ceiling), surrounding structures and materials, and the air.

\( G_{corr} \)  “corrected indication” for non-linearity, background, and especially scattering

Scattered neutrons are due to the room, the surrounding materials and the air. Not correcting would make \( R_\Phi \) and \( R_H \) dependent on the calibration room.

ISO 8529-2 provides methods to determine the part of indication coming from scattered neutrons, \( G_s \)

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“free-field” fluence rate $\Phi$

$\Phi$ (or its rate) is derived by propagating the source emission rate in the calibration direction, taking air attenuation into account.

$$\Phi = \frac{B \cdot F_\theta}{4 \cdot \pi \cdot l^2} \cdot e^{-\Sigma \cdot l}$$

Where

- $B$ source emission rate
- $F_\theta$ anisotropy factor for the used direction
- $l$ distance from source centre and instrument centre
- $\Sigma$ Air linear attenuation coefficient for the specific spectrum

<table>
<thead>
<tr>
<th>Neutron source</th>
<th>Linear attenuation coefficient $\Sigma$ $(10^{-7}$ cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{252}$Cf with $\text{D}_2\text{O}$ moderator 15 cm in radius</td>
<td>2.964</td>
</tr>
<tr>
<td>$^{252}$Cf spontaneous fission</td>
<td>1.055</td>
</tr>
<tr>
<td>$^{241}$AmB($\alpha$,n)</td>
<td>833</td>
</tr>
<tr>
<td>$^{241}$AmBe($\alpha$,n)</td>
<td>890</td>
</tr>
</tbody>
</table>

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
**Scattering model**

\[ M_T(l) \text{ (total indication)} \approx k/l^2 + A/l + S \]

**Room:**
scattering from walls, floor, ceiling. Room scatter is typically the most important source of scattered neutrons.

**Support structures**
Support structures should be as light as possible, with little or no hydrogenated materials. Special care should be taken to minimize the mass of support structure nearest the source or detector.

**Air**

**Air out-scatter**
Neutrons emitted by the source are absorbed and deflected in the air.

**Air in-scatter**
The instrument detects neutrons that are originally emitted in other directions, but are deflected by the air towards the instrument.

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
**Scattering**

*Instrument indication Vs distance in the idealized Monte Carlo model*

- Free-field
- Air only – note: Air only > free field (in-scatter prevails over out-scatter)
- Air and room

![Graph showing instrument indication vs distance with three lines representing free field, air only, and air and room conditions.](image)
Scattering

Scatter-related Increase in indication Vs distance - idealized Monte Carlo model

- Maximum useful calibration distance 1.25 m
Scattering

Four methods are proposed to determine the scattered contribution to the instrument indication:

**Shadow-cone method:**
- requires a minimum of two measurements at the same distance

**Generalized fit,**
**semi-empirical,**
**Reduced fitting methods**
- Require an initial set of careful measurements as a function of the distance.
- A lot of points near the source are fundamental in the Gen-fit method, to get low uncertainties

As different methods may give slightly different results (within few %), the choice of the method depends on room characteristics.

**Usually the shadow-cone method is the quickest and more accurate method for calibrations**
Geometry correction

$F_1(l)$
takes into account the non uniform illumination of the instrument at short distances

Formulas in ISO 8529-2 were determined using analytic approximations. If even a very simplified Monte Carlo model of the device is available, it would probably provide better correction.

$$F_1(l) = 1 + \delta \left[ \frac{2l^2}{r_D^2} \left[ 1 - \left( 1 - \frac{r_D^2}{l^2} \right)^{1/2} \right] - 1 \right]$$

Point source and spherical detector
$F_1(l)$ depends on

- $l$  source to detector distance
- $r_D$ detector radius
- $\delta$ constant

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Generalised fit

Requires a lot of data points, less spaced (1-2 cm) near the source, more spaced at larger distances (5-10 cm at 1 m and beyond). Points near the source are CRUCIAL for getting low uncertainties.

a) room size, shape and source/detector size: no limitation;

b) source-detector distance: minimum distance 1 cm between the surfaces of the source and the detector, maximum distance is set by the requirement that the increased reading from room scatter should be less than 40 %;

Advantages: May be used with any of the ISO sources;

Disadvantages: A complete set of measurements needed for each instrument. Non-linear or drifting readings should be carefully corrected, since they can be masked by the fitting procedure. Good positioning and counting statistics required.

\[ M_T(l) = \frac{k}{l^2} \left[ \frac{F_1(l)}{F_A(l)} + A_{in} \cdot l + s \cdot l^2 \right] \]

k free-field indication at unit distance
l centre to centre distance
\( F_1(l) \) geometric correction
\( F_A(l) \) air out-scatter correction = e \( ^\Sigma l \)
\( A_{in} \) Air in-scatter coefficient
s Room scatter coefficient

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Generalised fit

\[ M_T(l) = \frac{k}{l^2} \left[ \frac{F_1(l)}{F_A(l)} + A_{in} \cdot l + s \cdot l^2 \right] \]

\[ \frac{F_1(l)}{F_A(l)} = \alpha_6 \cdot l^6 + \alpha_5 \cdot l^5 + \alpha_4 \cdot l^4 + \alpha_3 \cdot l^3 + \alpha_2 \cdot l^2 + \alpha_1 \cdot l + \alpha_0 \]

\[ M_T(l) \cdot l^2 = k \cdot \alpha_0 + \text{polynomials (6th) without constant term} \]

(1) Fit \( F_1/F_A \) with a 6\textsuperscript{th} degree polynomial and find \( \alpha_0 \)

(2) Fit \( M_T(l) \cdot l^2 \) with a 6\textsuperscript{th} degree polynomial and find \( k \cdot \alpha_0 \) \( \rightarrow \) get \( k \) (\( G_{corr} @ 1 \text{ m} \))

a lot of points near the source are needed to get low uncertainty!

(3) Fit \( 1/l \cdot (M_T(l)/k \cdot l^2 - F_1/F_A) \) with a line and find \( A_{in} \) and \( S \)

Advantage: you can use the same \( A_{in} \) and \( S \) for next instrument of the same type

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Generalised fit

What if you do not have a lot of points near the source? – idealized room model

Fitting $M_T(l) \times l^2$ with a 6th degree polynomial provides $k \times \alpha_0$ with 20% uncertainty!!

$k = 32 \pm 6 \text{ cps} \cdot \text{m}^2$

**True value** (simulation without room and air) $k_{\text{true}} = (33.67 \pm 0.12) \text{ cps} \cdot \text{m}^2$

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**Semi-empirical method**

\[
M_r(l) = \frac{k}{l^2} \cdot F_1(l) \cdot (1 + A \cdot l) \cdot (1 + S \cdot l^2)
\]

- **k** free-field indication at unit distance
- **l** centre to centre distance
- **F_1(l)** geometric correction
- **A** **Air scatter** coefficient (in – out)
- **S** Room scatter coefficient

Room size: no limitation;
Room shape: cubical or close to cubical;
Source/detector size: no limit;
Distance: from source plus detector diameters to 40% limit

**Advantages:** Same Room-scatter correction can be used for all instruments of the same type

**Disadvantages:**
1. Can be used if the main source of neutron scatter is the room
2. Forcing a “physical model” for the scatter may lead to slightly bias the results
Semi-empirical method

\[ M_T(l) = \frac{k}{l^2} \cdot F_1(l) \cdot (1 + A \cdot l) \cdot (1 + S \cdot l^2) \]

\[ \frac{M_T(l) \cdot l^2}{F_1(l)} = k \cdot (1 + A \cdot l + S \cdot l^2 + A \cdot S \cdot l^3) \]

1. Fit \( M_T(l) \cdot l^2 / F_1 \) with a 3\textsuperscript{rd} degree polynomial and find \( k = G_{\text{corr}} \) @ 1 m

2. Determine \( A \) and \( S \)

Application to the idealized room model

\( k = (34.45 \pm 0.74) \) cps\textcdot m\textsuperscript{2}

\( k_{\text{true}} = (33.67 \pm 0.12) \) cps\textcdot m\textsuperscript{2}

\( S = 0.28 \pm 0.06 \)

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Reduced fitting method

\[ M_T(l) = \frac{k}{(d + a)^2} + S \]

- \( k \): free-field indication at unit distance
- \( d \): distance from source to surface of meter
- \( a \): “effective” position of the detector centre
  
  For symmetric devices use \( l = d + a \)

- \( S \): Scatter coefficient

Room size: no limitation;
Room shape: no limitation;
Source/detector size: no limitation;
Distance: from 1.5 x size of instrument to 40% limit

Advantages:
1. does not require long series of data points
2. Allows estimating “effective centre”

Disadvantages:
1. Neglect geometry correction
2. Does not work in low-scatter rooms as it assumes constant scattering
3. Forcing a “physical model” for the scatter may lead to slightly bias the results
Reduced fitting method

\[ M_T(l) = \frac{k}{(d + a)^2} + S \]

1. Linearly Fit \( M_T(l) \) as a function of \( 1/l^2 \) and get \( S \) and \( k \) (\( k = G_{corr} @ 1 \text{ m} \))

Application to the idealized room model

\[
\begin{align*}
    k &= (35.36 \pm 0.32) \text{ cps m}^{-2} \\
    k_{true} &= (33.67 \pm 0.12) \text{ cps m}^{-2} \\
    S &= 7.57 \pm 0.42
\end{align*}
\]
**Shadow-cone**

The shadow-cone is a shielding made of two parts: a front end, 20 cm long made entirely of iron; and a rear end, 30 cm long made of polyethylene, with 5 % or more boron loading.

The choice of the front-end diameter has to be based on the size of the available neutron sources.

The shadow cone should:
- have a negligible transmission for the direct neutrons
- Cover the solid angle of the device.

Pairs of measurements at the same distance:

\[ M_c(l) \] (shadow-cone) device exposed to the in-scattered radiation only (room, air).

\[ M_T(l) \] (total field) device exposed to the total field (free-field, in-scatter, air out-scatter).

\[ F_A(l) \] air out-scatter correction = \( e^{\Sigma_1} \)

\[ [ M_T(l) - M_c(l) ] \cdot F_A(l) = G_{corr} = \frac{k}{l^2} \]

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
Shadow-cone

Accurate estimation of the in-scattered contribution (with cone):

- SCD to be experimentally optimized
- CDD > 50 cm (SDD > 1 m + SCD);
- Max SDD limited to the 40% scattering criterion
- The cone aperture should be such to overshadow the device by max. a factor of 2
- Several shadow-cones needed to cover different SDD and device sizes

General criteria
- Room size: large room preferred
- Room shape: no limitation
- Source size: preferably small. D$_2$O-$^{252}$Cf requires a large cone

Advantage: direct measurement of effect of in-scattered neutrons;
Disadvantage: a set of shadow cones is required.
**Shadow-cone**

Idealized room model (MC simulations)

Parametric study to investigate the accuracy of the measurement when changing:
- SCD
- Cone minimum diameter
- Cone shadowing ratio
- SDD is fixed to 1.25 m

$G_{corr}$ value is determined by running a simulation without room and without air

\[ G_{corr} = (21.91 \pm 0.08) \text{ cps} \]

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**Shadow-cone**

Effect of changing SCD
Green lines denote ±1% boundary
\[ d_{\text{min}} = 5 \text{ cm}, \quad d_{\text{max}} = 15 \text{ cm} \]
**Shadow-cone**

Effect of changing cone $d_{\text{min}}$

SCD = 20 cm. Shadowing ratio always between 1.1 and 2. Green lines denote ±1% boundary.

\[ [M_T(l) - M_c(l)] = \frac{G_{\text{corr}}}{F_A(l)} \]

SCD = 20 cm

$d_{\text{min}} = 1$

$d_{\text{max}} = 15$

SCD = 20 cm

$d_{\text{min}} = 9$

$d_{\text{max}} = 18$

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources.
**Shadow-cone**

Effect of changing the shadowing ratio (SR), by varying $d_{\text{max}}$.

$SCD = 20 \text{ cm}, d_{\text{min}} = 5 \text{ cm}$

Green lines denote $\pm 1\%$ boundary

$\frac{[M_T(l) - M_c(l)]}{F_A(l)} = \frac{G_{\text{corr}}}{F_A(l)}$

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources
**Methods comparison**

Idealized room model (MC simulations)

$G_{\text{corr}}$ value is determined by running a simulation without room and without air

**True value** (simulation without room and air) \[33.67 \pm 0.12\]

Generalized fit \[32 \pm 7\]

Semi-empirical \[34.45 \pm 0.74\]

Reduced fit \[35.36 \pm 0.32\]

Shadow-cone (SCD 20 cm, $d_{\text{min}}=5$ cm, $d_{\text{max}}=15$ cm) \[34.0 \pm 0.5\]
Uncertainties

- Source emission rate (< 2% in Mn bath)
- Anisotropy factor (typ. < 1% for measured values)
- Calibration distance
- Geometry factor $F_1(l)$
- Uncertainty of the conversion coefficient; by convention taken to be zero for monoenergetic neutrons, for broad spectra see also ISO 8529-2 (1% for Cf and 4% for other spectra)
- Instrument reading
- Scattering correction (elaborated from fit / cones procedures)
Considerations for personal dosemeters

✓ The quantity to be measured for individual monitoring is the personal dose equivalent, Hp(10).
✓ Conversion coefficients from fluence to $H_p(10)$ in the ICRU tissue slab phantom (ICRU 47)

<table>
<thead>
<tr>
<th>Neutron source</th>
<th>$h_{p0} (10; \alpha)$ in pSv cm$^2$, for angles of incidence, $\alpha$, of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$0^\circ$</td>
</tr>
<tr>
<td>$^{252}$Cf(D$_2$O-moderated)</td>
<td>110</td>
</tr>
<tr>
<td>$^{252}$Cf</td>
<td>400</td>
</tr>
<tr>
<td>$^{241}$Am-B ($\alpha,n$)</td>
<td>426</td>
</tr>
<tr>
<td>$^{241}$Am-Be($\alpha,n$)</td>
<td>411</td>
</tr>
</tbody>
</table>

✓ ISO recommends distance from phantom face to source centre 75 cm.
✓ Scatter contribution need to be determined (once per dosemeter type)
✓ Simplified procedure (no phantom) is allowed (phantom backscatter once per dosemeter type)
✓ Simultaneous calibration of several dosemeters: consider the effective distance for every dosemeter (do not exceed 15 cm from centre of phantom face)

Uncertainties

✓ Source emission rate and anisotropy
✓ positioning
✓ Unc. on conversion coefficient (1% for Cf and 4% for other spectra)
✓ uncertainties due to simplified procedures or scatter correction
✓ uncertainty due to simultaneous irradiation of several dosimeters;

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