Neutron Fluence and Dose Standards:
Thermal
Well characterised thermal neutron fields are available at NPL for the calibration of neutron measuring devices e.g. area survey instruments or personal dosemeters, and for irradiation purposes.

These standard thermal neutron fields are produced by bombarding two beryllium targets, set into a large graphite moderator, with a beam of deuterons from the NPL 3.5 MV Van de Graaff accelerator.

The thermal neutron fluence rate at the centre of the ‘pile’ is controlled by signals from three boron coated ionisation chambers placed within the graphite, below the beam line. These signals are used to set the voltages on pairs of horizontal and vertical deflection plates which in turn determine the number of deuterons striking each beryllium target in order to give a stable, uniform neutron field.

A small cavity at the centre of the pile provides for the irradiation of artefacts of modest size in a standard thermal neutron field.

Devices such as neutron monitors for reactors can be calibrated in the central access hole provided their diameter is less than 12.5 mm. Allowance for the variation of the fluence with height can be made by using gold foils to measure the fluence along the active length of the instrument.

Larger samples, e.g. area survey instruments, can be irradiated in a beam of thermal neutrons extracted through an evacuated tube or ‘thermal column’. Corrections for epi-cadmium neutrons are derived from the results of irradiations under cadmium cover.

The value of the fluence rate is determined in terms of known thermal neutron capture cross sections by the activation of gold foils. The fluence rates near the central region and below the thermal column are continuously monitored with small fission chambers.

Dose quantities, e.g. ambient or personal dose equivalent, can be derived from the fluence values using standard conversion coefficients.

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### Standard Thermal Neutron Facility

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of a central access hole</td>
<td>12 cm</td>
</tr>
<tr>
<td>Range of fluence rate</td>
<td>10^4 to 3 x 10^7 cm^-2 s^-1</td>
</tr>
<tr>
<td>Uncertainty of value (95 % confidence limit)</td>
<td>±2 %</td>
</tr>
<tr>
<td>Long term stability</td>
<td>Better than ±0.25 %</td>
</tr>
<tr>
<td>Spatial uniformity</td>
<td>±0.2 %</td>
</tr>
<tr>
<td>Epithermal fluence component</td>
<td>1 %</td>
</tr>
<tr>
<td>Epithermal spectrum</td>
<td>E^-105</td>
</tr>
<tr>
<td>Cadmium ratio for a thin 1 / v detector</td>
<td>270</td>
</tr>
<tr>
<td>Gamma absorbed dose (in tissue) in cavity</td>
<td>0.6 Gy per 10^12 cm^-2</td>
</tr>
</tbody>
</table>

### Thermal Column

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross sectional area</td>
<td>1000 cm^2</td>
</tr>
<tr>
<td>Length</td>
<td>1 m to 1.5 m</td>
</tr>
<tr>
<td>Maximum dose equivalent rate at 1.0 m</td>
<td>about 1.4 mSv h^-1</td>
</tr>
<tr>
<td>Neutron fluence component &gt; 0.5 eV</td>
<td>19% of total fluence</td>
</tr>
<tr>
<td>Photon dose rate Air Kerma / thermal personal dose equivalent</td>
<td>4.0 Gy / Sv</td>
</tr>
<tr>
<td>Maximum steady fluence rate</td>
<td>4 x 10^4 cm^-2 s^-1</td>
</tr>
<tr>
<td>Minimum steady fluence rate</td>
<td>about 2 x 10^2 cm^-2 s^-1</td>
</tr>
</tbody>
</table>

### Uncertainties

Our reported uncertainties are based on a standard uncertainty and multiplied by a factor $k=2$, providing a coverage probability of approximately 95 %.
Transfer Standards for Thermal Neutron Fields

The transfer standard for thermal neutron fluence is based on the activation of gold foils and the subsequent measurement of the induced activity. The activity is directly proportional to the fluence but also depends on the neutron spectrum.

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The thermal neutron fluence rate associated with a nuclear reactor, a radioactive neutron source or any other neutron-producing equipment can be measured at the customer's premises using gold foils as the transfer standard.

The measurements involve activating gold foils both bare and under 1 mm thick cadmium covers and measuring the induced \(^{198}\text{Au}\) activity. The fluence rate is determined from the thermal neutron cross section for gold.

The quantity measured is the conventional thermal neutron fluence rate \(n_{th} v_o\) where \(n_{th}\) is the neutron density below the cadmium cut-off for 1 mm thick cadmium covers, and \(v_o\) is the neutron velocity, 2200 m s\(^{-1}\) (corresponding to an energy of 0.0253 eV), conventionally used when specifying thermal fluences.

The fluence rate is given by:

\[
n_{th} v_o = \frac{F(D - D_{Cd} F_{Cd})}{N g \sigma}
\]

Where:

- \(F\) is a correction factor for self-shielding and perturbation of the neutron field,
- \(D, D_{Cd}\) are the saturation disintegration rates per gram of foil for the bare and cadmium-covered foils respectively,
- \(F_{Cd}\) is a correction factor for attenuation of neutrons in the cadmium cover,
- \(N\) is the number of gold atoms per gram,
- \(g \sigma\) is the effective value of the neutron capture cross section for gold for the thermal component of the spectrum where \(s\) is the cross section at 2200 m s\(^{-1}\) and \(g\) is the Westcott factor for the departure of the cross section from the 1/v law.

The activated foils must be returned to NPL for measurement of the induced \(^{198}\text{Au}\) activity using \(4\pi\beta\gamma\) counting, the counting efficiency of each foil having been determined previously following irradiation in the NPL thermal neutron field.

If the foils have been irradiated in a fairly intense thermal neutron fluence, such as that in a reactor, the activity may be determined more directly using the \(4\pi\beta\gamma\)-\(\gamma\) coincidence counting technique.

Gold foils of different areas and thicknesses are available e.g. 0.3 cm\(^2\) foils with thicknesses around 30 mg cm\(^{-2}\), 1 cm\(^2\) foils with thicknesses between 20 mg cm\(^{-2}\) to 100 mg cm\(^{-2}\), 4 cm\(^2\) foils with thicknesses around 350 mg cm\(^{-2}\).

Irradiation times necessary for an adequate activity vary from about 15 minutes, for a high fluence rate, up to a maximum useful period of about a week for a fluence rate of 100 cm\(^{-2}\) s\(^{-1}\).

Foils must be returned to NPL within two days of irradiation.

### Uncertainties

<table>
<thead>
<tr>
<th>Type B</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Range of fluence rate</td>
<td>10(^4) to 3 (\times) 10(^7) cm(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>Uncertainty of value (95% confidence limit)</td>
<td>±2%</td>
</tr>
<tr>
<td>Long term stability</td>
<td>Better than ±0.25%</td>
</tr>
<tr>
<td>Spatial uniformity</td>
<td>±0.2%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type A</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium ratio for a thin 1/v detector</td>
<td>270</td>
</tr>
</tbody>
</table>
Neutron Fluence Standard Mono-Energetic: 50 keV to 17 MeV

At NPL, well-characterised mono-energetic neutron fields covering the greater part of the energy range 50 keV to 17 MeV are routinely available for the calibration of neutron sensitive devices or for irradiation purposes. Energies just above and below this range can also be produced for special applications.
Mono-energetic neutrons with energies between 50 keV and 17 MeV are produced, via a variety of nuclear reactions, by employing beams of protons or deuterons from a 3.5 MV Van de Graaff accelerator to bombard appropriate targets. The charged particle beam energy and energy spread are determined using a calibrated analysing magnet and the mean energy is defined to within ± 2 keV.

The neutron-producing targets are located at the centre of a low scatter facility, at a point at least 6 m from the walls, floor or ceiling of the room. This arrangement minimises corrections for scattered neutrons when performing calibrations.

Lightly constructed supports are provided for neutron detectors, which may be positioned automatically at the desired angle to the incident charged particle beam (this angle determines the neutron energy) and at the required distance from the neutron-producing target.

The neutron fluence rate depends upon factors such as target thickness, charged particle beam current, geometry and required neutron energy resolution. These factors may be varied within certain limits to meet the requirements of individual customers.

The various standard fields are characterised in terms of neutron fluence rate, neutron energy and energy resolution.

Neutron fluences are measured using a carefully calibrated long counter. Fluence uncertainties depend on the particular arrangements but are typically in the range 3 to 5 %.

Values for quantities of interest for dosimetry, e.g. ambient or personal dose equivalent, can be derived by making use of internationally agreed conversion coefficients.

ISO recommended energies:

- Neutrons can be produced with energies almost anywhere within the range 50 keV to 17 MeV, and to some extent outside this range for special applications. However, certain energies are recommended by the International Organisation for Standardization, ISO, as being particularly appropriate for performing calibrations. For example, at 565 keV a relatively high fluence of neutrons can be produced because this energy corresponds to a peak in the \(^{7}\text{Li}(p,n)^{7}\text{Be}\) reaction cross section. The relevant ISO energies are listed in the table below together with rough indications of the maximum fluence and ambient dose equivalent rates achievable at 1 m from the target. Personal dose equivalent rates are very similar.

Notes

- In the determination of neutron fluence rate, corrections are applied for in-scatter (measured with shadow cones), and out-scatter (calculated from the known cross-sections for oxygen and nitrogen).
- When dosimetric quantities are of interest, the gamma-ray contribution to the total dose can also be determined, using energy compensated Geiger-Müller counters.

Uncertainties

- Uncertainties are treated as recommended by UKAS, publication M3003.
- Our reported uncertainties are based on standard uncertainties multiplied by a factor \(k=2\), providing a coverage probability of approximately 95 %.

### ISO recommended energies:

<table>
<thead>
<tr>
<th>Neutron energy (MeV)</th>
<th>Reaction</th>
<th>Appropriate maximum rates at 1 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fluence (cm(^{-2}) s(^{-1}))</td>
</tr>
<tr>
<td>0.144</td>
<td>(^{7}\text{Li}(p,n)^{7}\text{Be})</td>
<td>(1 \times 10^3)</td>
</tr>
<tr>
<td>0.250</td>
<td>(^{7}\text{Li}(p,n)^{7}\text{Be})</td>
<td>(6 \times 10^2)</td>
</tr>
<tr>
<td>0.565</td>
<td>(^{7}\text{Li}(p,n)^{7}\text{Be})</td>
<td>(1.6 \times 10^3)</td>
</tr>
<tr>
<td>1.2</td>
<td>(T(p,n)^{4}\text{He})</td>
<td>(2 \times 10^2)</td>
</tr>
<tr>
<td>2.5</td>
<td>(T(p,n)^{4}\text{He})</td>
<td>(6 \times 10^2)</td>
</tr>
<tr>
<td>5.0</td>
<td>(D(d,n)^{4}\text{He})</td>
<td>(6 \times 10^2)</td>
</tr>
<tr>
<td>17.0</td>
<td>(T(d,n)^{4}\text{He})</td>
<td>(5 \times 10^2)</td>
</tr>
</tbody>
</table>

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Transfer Standards for d-T Neutron Fields

Activation foils can be used to determine d-T neutron fluences at customer sites. The foils must be returned to NPL for the activity to be counted and a knowledge of the precise neutron energy is required.
Fluences in d-T fields can be derived by activation of aluminium or iron foils. The neurons should be monoenergetic with an accurately known energy, or have an accurately known spectrum in the region from about 4 MeV to 20 MeV. Neutrons with energies below the thresholds of the reactions (about 4 MeV for the $^{27}$Al($n, \alpha$) reaction and about 5 MeV for the $^{56}$Fe($n, p$) reaction) will not be detected.

**Aluminium Activation:**
- Thin aluminium discs are used to measure monoenergetic neutron fluence in the energy range from 14 MeV to 20 MeV using the $^{27}$Al($n, \alpha$)$^{24}$Na reaction.
- The 15 hour half life of $^{24}$Na requires the irradiated samples to be returned to NPL within a day for measurement of the induced beta activity.
- This reaction is insensitive to low energy neutrons. The use of highly efficient beta counting enables relatively thin discs to be used. These can be positioned for example, on objects being irradiated.

**Iron Activation:**
- Thin iron discs are used to measure 14 MeV to 20 MeV neutron fluence using the $^{56}$Fe$(n, p)^{56}$Mn reaction.
- The 2.56 hour half life of $^{56}$Mn requires the irradiated samples to be returned to NPL within a few hours.
- This reaction has a similar excitation function to that for aluminium activation and the technique also employs beta counting.

**d-T Neutron Field Transfer Standards:**

<table>
<thead>
<tr>
<th>Range of application:</th>
<th>Al or Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluence</td>
<td>$10^8$ cm$^{-2}$ and above</td>
</tr>
<tr>
<td>Energy</td>
<td>14 MeV to 20 MeV</td>
</tr>
</tbody>
</table>

| Statistical accuracy for the fluence*: | 2 % or better |
| Overall fluence accuracy*:            | 2 % is possible |

**Uncertainties:**
*Uncertainties are treated as recommended by UKAS, publication M3003. Our reported uncertainties are based on a standard uncertainty and multiplied by a factor $k=2$, providing a coverage probability of approximately 95 %.
HSE Performance Testing of Personal Dosimetry Services for Fast Neutron Radiation

NPL is one of the few laboratories in the UK that can offer performance testing of dosimetry services for fast neutron radiation. As a result of changes in the Health and Safety Executive’s ‘Requirements for the Approval of Dosimetry Services under the Ionising Radiations Regulations 1999’, all dosimetry services are now required to undertake performance tests, if there is a relevant HSE performance test for the type of dosimetry for which they seek approval. The tests are carried out under well defined irradiation conditions enabling the basic performance of a service to be assessed for approval.
Sources used for Performance Tests:

- $^{241}$Am-Be or $^{252}$Cf.
- NPL can provide all the dose equivalent ranges required by the HSE, the highest range being between 30 to 50 mSv for both $^{241}$Am-Be and $^{252}$Cf.
- Irradiations are usually performed at 75 cm from the neutron source, but are also possible at 50 cm if required.

Neutron Fluence:

- The neutron fluence rate at the reference point of the dosemeter is calculated from the absolute neutron emission rate of the source, as measured in the NPL manganese bath. Dose equivalent rates are derived from the fluence rate using internationally agreed conversion coefficients.
- When specifying the fluence, allowance is also made for the source emission anisotropy.

Calibration Facilities for Performance Testing:

- Irradiations of personal dosemeters are performed in a low scatter facility (18 m × 18 m × 25 m). The source is mounted 6 m above the floor keeping the scattered neutron component to a minimum.

<table>
<thead>
<tr>
<th>Source type</th>
<th>Fluence - averaged mean neutron energy (MeV)</th>
<th>Fluence rate at 75 cm (cm$^{-2}$ s$^{-1}$)</th>
<th>Personal dose equivalent rate at 75 cm (µSv h$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Am-Be (α, n)</td>
<td>4.2</td>
<td>up to 475</td>
<td>up to 700</td>
</tr>
<tr>
<td>$^{252}$Cf (sf)</td>
<td>2.1</td>
<td>up to 1800*</td>
<td>up to 2600*</td>
</tr>
</tbody>
</table>

* Figures as of January 2016

- Personal dosemeters are usually mounted on an ISO recommended water phantom but can also be mounted free-in-air if necessary.

ISO Recommendations:

- The $^{241}$Am-Be and $^{252}$Cf sources are both ISO recommended calibration standards. (See ISO 8529 Reference neutron radiations – Part 1: Characteristics and methods of production (2001))

Calibration Quantities:

- Calibrations are performed in terms of the quantity personal dose equivalent. A test report is provided detailing the customer and conventional true values for the dose equivalents, and the bias and relative standard deviation for each of the personal dosemeters, as required in the HSE protocol. (Health and Safety Executive Measurement Protocol for Performance Testing of Dosimetry Services for External, Whole Body Fast Neutron Radiation. (June 2001))
- Conversion coefficients used are those recommended in ISO 8529 Reference neutron radiations – Part 3: Calibration of area and personal dosimeters and determination of their response as a function of neutron energy and angle of incidence, ISO 8529-3 (1998). These are based on the latest conversion coefficient tables published jointly by the ICRP, in ICRP Publication 74, and by the ICRU, in ICRU Report 57.
Source Based Neutron Fluence Standards

At NPL a variety of radionuclide neutron sources are used to provide well characterised neutron fields for calibrating neutron sensitive devices or for irradiating samples. Typical applications include the calibration and radiological type testing of area survey instruments, personal dosemeters, neutron spectrometers and measurements of the response of neutron sensitive devices as a function of energy. NPL is one of the few national standards laboratories worldwide that can offer radiological type testing facilities to determine device response functions.
Calibration Quantities

Calibrations are performed in terms of neutron fluence, ambient dose equivalent, or personal dose equivalent.

The dose equivalent quantities used are normally according to the recommendations of ICRP Publication 60.


Range of sources available:

- $^{241}$Am-Be, $^{241}$Am-B, $^{241}$Am-F, $^{241}$Am-Li, $^{252}$Cf, and heavy water moderated $^{252}$Cf.
- Mean energies of the fluence spectra are between 0.5 MeV and 4.1 MeV.
- Total neutron emission rates vary for the different source types, ranging from $3 \times 10^3$ to $2 \times 10^8$ s$^{-1}$, corresponding to fluence rates between 0.02 and 1800 cm$^{-2}$s$^{-1}$ at 1 m (Figures as of January 2014). See table for further details.

Neutron Fluence:

- The neutron fluence rate at an irradiation position is calculated from the absolute neutron emission rate of the source, as measured in the NPL manganese bath. Dose equivalent rates can be derived using internationally agreed conversion factors.
- When specifying the fluence, allowance is made for source emission anisotropy and, if necessary, for scattered neutrons.

ISO Recommendations:

- The $^{241}$Am-Be, the $^{241}$Am-B, the 'bare' $^{252}$Cf and the heavy water moderated $^{252}$Cf sources are all ISO recommended calibration standards. (See International Standard ISO 8529 Reference neutron radiations – Part 1 Characteristics and methods of production (2001).

Calibration Facilities

- Calibrations of neutron sensitive devices can be performed in the NPL low scatter facility. The source is placed at the centre of the room thus keeping the scattered neutron component as small as possible. Techniques are available to correct for this component if necessary.

<table>
<thead>
<tr>
<th>Sources available, with typical fluence and dose equivalent rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source type</td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td>$^{241}$Am-Be ($\alpha$, n)</td>
</tr>
<tr>
<td>$^{241}$Am-B ($\alpha$, n)</td>
</tr>
<tr>
<td>$^{252}$Cf (sf)</td>
</tr>
<tr>
<td>Moderated $^{252}$Cf</td>
</tr>
<tr>
<td>$^{241}$Am-F ($\alpha$, n)</td>
</tr>
<tr>
<td>$^{241}$Am-Li ($\alpha$, n)</td>
</tr>
</tbody>
</table>

† Figures as of January 2016

* Based on fluence to ambient dose equivalent conversion factors published in ICRP publication 74 and ICRU Report 57

Personal dosemeters can be mounted on an ISO recommended water phantom, an ICRU recommended perspex phantom, or free-in-air. The normal irradiation distance for this type of device is 75 cm from the source, unless otherwise specified by the customer.

Heavy water moderated $^{252}$Cf irradiations are performed by placing the 'bare' $^{252}$Cf source capsule at the centre of a 30 cm diameter sphere of heavy water. This results in a neutron spectrum, which contains a significant low energy neutron component.

Custom radionuclide source irradiations are available on request. The maximum ambient dose equivalent rate achievable with an $^{241}$Am-Be source is in the region of 3.7 mSv h$^{-1}$ at ~ 30 cm.

The maximum ambient dose equivalent rate achievable with a $^{252}$Cf source is in the region of 25 mSv h$^{-1}$ at ~ 30 cm. (figure as of January 2014)

Uncertainties

- Reported uncertainties are based on a standard uncertainty multiplied by a coverage factor $k=2$, providing a coverage probability of approximately 95%.

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Measurement and Hire of Radionuclide Neutron Sources

NPL is one of the few national standards laboratories worldwide that offers an absolute measurement of the total emission rate of a radionuclide neutron source into $4\pi$ steradians. Comparative measurements of the total emission rate can also be performed. A further service offered is a measurement of the variation in emission rate relative to the axis of the source (anisotropy). NPL also has available for hire a number of sources with accurately known neutron emission rates and anisotropy factors.
Calibration facilities:

- Absolute emission rate measurements are performed using the manganese bath technique. The neutron source is placed at the centre of a spherical bath, 1 m in diameter, containing an aqueous solution of manganese sulphate. The amount of radioactive manganese produced is measured by pumping the solution past two scintillation detectors, the \(\gamma\)-counting efficiencies of which are determined by absolute counting techniques. The neutron emission rate is calculated from the \(\gamma\)-count rate at saturation, applying appropriate correction factors.

- A moderating assembly incorporating BF\(_3\) proportional counters is used to make comparative emission rate measurements. The source emission rate is obtained by comparison with a source of the same type which has been measured in the manganese bath.

- Anisotropy measurements are made in a low-scatter area using a long counter to measure the output in steps of 10°.

Measurement capabilities:

- The calibration limits are determined by the emission rate of a source. Lower and upper limits are outlined in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Manganese bath</th>
<th>Moderating assembly</th>
<th>Anisotropy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower limit</td>
<td>(2.0 \times 10^5) s(^{-1})</td>
<td>(10^5) s(^{-1})</td>
<td>1.0 %</td>
</tr>
<tr>
<td>Upper limit</td>
<td>(2.4 \times 10^5) s(^{-1})</td>
<td>(2.4 \times 10^5) s(^{-1})</td>
<td>1.8 %</td>
</tr>
</tbody>
</table>

Note: \(2.4 \times 10^5\) s\(^{-1}\) is the nominal emission rate from a 37 GBq (1 Ci) \(^{241}\)Am-Be source or a 1 mg \(^{252}\)Cf source.

- Calibrations are UKAS accredited.

- The measurement of a source is generally completed within two weeks of receipt, and the calibration certificate issued within six weeks.

Uncertainties:

- Uncertainties are treated as recommended by UKAS, Publication M3003 which is consistent with the approach recommended in the 'Guide to the Expression of Uncertainties in Measurements' (GUM) published by the International Organisation for Standardisation (ISO).

- Our reported uncertainties are based on a standard uncertainty, multiplied by a coverage factor \(k=2\), providing a coverage probability of approximately 95 %.

- Uncertainties depend on source emission rate and type. Typical values are summarised in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Emission rates</th>
<th>Anisotropy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Manganese bath</td>
<td>Moderating assembly</td>
</tr>
<tr>
<td>Lower limit</td>
<td>1.0 %</td>
<td>1.4 %</td>
</tr>
<tr>
<td>Upper limit</td>
<td>1.8 %</td>
<td>2.0 %</td>
</tr>
</tbody>
</table>

Recalibration frequency:

- It is recommended that \(^{252}\)Cf sources are recalibrated at least every 2.5 years, and \(^{241}\)Am-based sources at least every 10 years.

Sources available for hire:

<table>
<thead>
<tr>
<th>Source type</th>
<th>Mean neutron energy (MeV)</th>
<th>Neutron emission rate (s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{252})Cf(sp.f.)</td>
<td>2.1</td>
<td>(3.5 \times 10^8) to (1.3 \times 10^9)</td>
</tr>
<tr>
<td>(^{241})Am-Be ((\alpha,n))</td>
<td>4.1</td>
<td>(7.7 \times 10^4) to (3.2 \times 10^5)</td>
</tr>
<tr>
<td>(^{241})Am-B ((\alpha,n))</td>
<td>2.8</td>
<td>(4.3 \times 10^3)</td>
</tr>
<tr>
<td>(^{241})Am-F ((\alpha,n))</td>
<td>1.5</td>
<td>(1.3 \times 10^5)</td>
</tr>
<tr>
<td>(^{241})Am-Li ((\alpha,n))</td>
<td>0.5</td>
<td>(2.1 \times 10^5)</td>
</tr>
</tbody>
</table>

† Figures as of January 2016

Shielded transport containers are also available for use with these sources.

Contact details

<table>
<thead>
<tr>
<th>Further information</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Physical Laboratory</td>
</tr>
<tr>
<td>Hampton Road</td>
</tr>
<tr>
<td>Teddington</td>
</tr>
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<td>Middlesex</td>
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<tr>
<td>United Kingdom</td>
</tr>
<tr>
<td>TW11 0LW</td>
</tr>
<tr>
<td>Switchboard: 020 8977 3222</td>
</tr>
<tr>
<td>Website: <a href="http://www.npl.co.uk">www.npl.co.uk</a></td>
</tr>
</tbody>
</table>

For further information contact: neil.roberts@npl.co.uk
Neutron Spectrometry for Radiation Protection

The use of spectrometry to provide information for neutron radiation protection has become an increasingly important activity over recent years. The need for spectral data arises because neither area survey instruments nor personal dosemeters give the correct dose equivalent results at all neutron energies. It is important therefore to know the spectra of the fields in which these devices are used. The spectra can be used either to provide information on the reliability of the results from devices used to measure the dose equivalent, or as a direct and accurate measurement of the dose equivalent. This is particularly valuable where doses approach statutory limits.
NPL can undertake on-site spectrometry measurements which, in addition to providing information for radiation protection applications, can also be used, for example, to determine the neutron output from a range of devices (e.g. cyclotrons or LinAcs) which produce neutrons either as the primary radiation or as an unwanted contaminant.

Available spectrometers

The spectrometers available at NPL can be divided into two types: firstly, Bonner sphere sets which cover a very broad energy range, albeit with rather poor resolution; secondly, devices with high resolution but which only cover a limited energy range. The particular instruments available are listed below:

- An ‘active’ Bonner sphere system, based on a sensitive $^3$He proportional counter. This set can be used for dose equivalent rates from several hundred Sv per hour down almost to natural background.
- A ‘passive’ Bonner sphere system, based on gold activation foils as sensor elements. This system is less sensitive than the $^3$He-based set, but can be used in areas where the neutron field is pulsed, where there is an intense photon field, or where radioactive contamination is a potential problem.
- Two high resolution NE213 scintillator spectrometers, which cover the energy range from 1 MeV to 20 MeV approximately.
- A set of SP2 high resolution spherical hydrogen recoil counters, which cover the energy range from about 50 keV to above 1 MeV.

Measurement timescales

- Timescales for making a measurement depend on the intensity (dose rate) of the neutron field, and on the number of measurement sites.
- For the active instruments it can take several hours to set up the instrumentation, and for the passive Bonner sphere set the efficiency is rather low so long measurement times may be required.
- Although maximum and minimum dose rates depend on the spectrum being measured, the passive Bonner sphere set can measure from about 10 mSv h$^{-1}$ upwards, while the active set can measure, in a reasonable timescale, down to several tens of nSv h$^{-1}$. The NE213 scintillator requires a dose equivalent rate in the tens of mSv h$^{-1}$ range, while the hydrogen recoil counters need dose equivalent rates in the region of a hundred mSv h$^{-1}$ or higher.

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**Spectrometer Characteristics**

<table>
<thead>
<tr>
<th>Spectrometer</th>
<th>Energy range</th>
<th>Typical minimum dose equivalent rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Bonner sphere set</td>
<td>Thermal to 20 MeV</td>
<td>Tens of nSv h$^{-1}$</td>
</tr>
<tr>
<td>Passive Bonner sphere set</td>
<td>Thermal to 20 MeV</td>
<td>Tens of µSv h$^{-1}$</td>
</tr>
<tr>
<td>NE213 scintillators</td>
<td>1 to 20 MeV</td>
<td>Tens of µSv h$^{-1}$</td>
</tr>
<tr>
<td>Hydrogen recoil counters</td>
<td>50 KeV to 20 MeV</td>
<td>About 100 µSv h$^{-1}$</td>
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</tbody>
</table>

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Field Measurement of Dose Quantities using Microdosimetry

Microdosimetry is a useful tool in the measurement of radiation levels in the workplace and has one distinct advantage over other techniques: it records a spectrum that can be analysed to give separate photon and neutron dose rates and dose equivalent rates in a single measurement.
Principles of the microdosimetric measurement system:

- The tissue equivalent proportional counter (TEPC) is designed to mimic the response of human tissue to irradiation.
- It uses a low pressure gas (with an atomic composition similar to that of muscle tissue) to fill a cavity roughly 12 cm in diameter.
- The cavity lies at the centre of a sphere of conducting plastic (also with an atomic composition similar to that of muscle tissue).
- This similarity of composition means that the TEPC satisfies the Bragg-Gray criterion of cavity-ionisation theory, and allows the absorbed dose to be measured precisely.
- The TEPC tends to ‘sample’ a charged particle’s track rather than stop it completely and, in the majority of cases, the energy deposited in the gas is related to how densely the particle ionises the tissue, a property usually called linear energy transfer or LET.
- This relation to LET enables microdosimetry to distinguish between recoil electrons, protons, alpha particles and heavy ions. This, in turn, enables the determination of neutron and gamma ray absorbed doses, quality factors and dose equivalents.

Instruments available for hire:

The original NPL microdosimetric measurement system relies on three MCA cards housed in a PC, together with the associated modular units of electronics required to process the detector signals, and remains the best-characterised, highest-resolution, but most labour-intensive, system.

NPL possesses a self-contained battery powered microdosimetric measurement system that is as easy to use as a neutron area survey meter.

Benefiting from miniaturised, low power electronics, this detector trades off spectral resolution to gain portability and ease of use. Logging data every minute, this TEPC can be hired out to customers who can perform mixed field radiation surveys in a number of workplace areas including on board commercial aircraft, with its LCD display giving the user an approximate indication of the dose rates in situ.

The instrument needs to be returned to NPL for detailed analysis; all the customer need do is provide timing information for the TEPC when used in several locations.

Measurement times for both systems vary from a few minutes for high dose rates (up to ~50 mSv h\(^{-1}\)) to (ideally) several hours for low dose rates (< 1 mSv h\(^{-1}\)).

<table>
<thead>
<tr>
<th>Quantities measured</th>
<th>Derived Quantities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron dose rate</td>
<td>Neutron dose equivalent rate</td>
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<tr>
<td>Photon dose rate</td>
<td>Photon dose equivalent rate</td>
</tr>
<tr>
<td></td>
<td>Quality factors</td>
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</tbody>
</table>

Quantities:

- all with a single measurement.
- Dose equivalent values are calculated using the Q(L) relationship of ICRP Publication 60.

Instrument Calibration:

- The instruments are nominally self-calibrating, but the calibration is checked by \(^{241}\text{Am-Be}\) irradiations.

Correction Technique:

- Although TEPCs have poor efficiencies for intermediate energy neutrons, corrections can be applied, derived from the shape of the spectrum.

(See NPL Report CIRM 26, Neutron Response Characteristics of the NPL Tissue-Equivalent Proportional Counter. Taylor, G.C., (March 1999)).

Comparison of ionising density spectra measured for x-rays, neutrons from a heavy-water-moderated californium source and cosmic radiation measured in-flight, illustrating why x-rays are considered lightly ionising.