Plans for neutron metrology at NPL

Michael Bunce, David Thomas, Neil Roberts, Graeme Taylor and Alberto Boso
National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, UK

michael.bunce@npl.co.uk

Abstract. The National Physical Laboratory has provided industry and research with neutron fluence and dose standard neutron fields since the 1960’s. Sectors such as civil nuclear power, defence, radiation-protection and fusion generation rely on NPLs facilities to operate safely and ensure traceability back to an internationally recognised UK primary standard. A central part of the capability is the 3.5 MV Van de Graaff accelerator which, using light ions, generates monoenergetic fields of neutrons ranging from a few keV to 19 MeV and intense thermal neutron fields. This accelerator is reaching the end of its operational life and a project to replace it is underway.

1. Current capability in neutron metrology
The nuclear metrology group at NPL has a broad range of expertise in radioactivity, radiochemistry and neutron metrology that is used to underpin key sectors such as civil nuclear power and nuclear medicine. Neutron metrology at NPL has several dedicated facilities to ensure high quality measurements and traceability to internationally recognized standards.

1.1. Radionuclide source characterization
Radionuclide neutron sources are used in laboratories globally to calibrate equipment and make measurements; it is therefore important to be able to characterize the properties of these sources that are important in the calibration process [1]. To measure the neutron emission rate the technique employed by NPL (and several other NMIs) is the manganese bath method. A radionuclide source is placed in a spherical tank of manganese sulphate solution. The $^{55}$Mn in the solution captures a neutron to form radioactive $^{56}$Mn which subsequently decays ($t_{1/2} \approx 2.6$ h) to $^{56}$Fe and emits gamma and beta radiation. The activated liquid is pumped from the spherical bath to a NaI detector arrangement where the gamma radiation is measured. From this the neutron emission rate can be determined. For further details see references [1] and [2].

Emission anisotropy is another key variable requiring characterization to enable the use of radionuclide neutron sources. The facilities and expertise exist at NPL to determine source anisotropy and are often carried out in conjunction with a measurement of the emission rate.

1.2. Radionuclide source-based fluence and dose standards
NPL has a range of radionuclide neutron sources to produce neutron fluence and dose standards for use in the testing, characterization, calibration of neutron sensitive devices. The devices range from personal dosemeters to area survey monitors to bespoke research instrumentation. Device exposures are typically performed in the NPL low scatter facility which reduces the unwanted lower energy scatter component of the neutron field. Radionuclide sources available for use are $^{252}$Cf, D$_2$O.
moderated $^{252}\text{Cf}$, $^{241}\text{Am-Be}$, $^{241}\text{Am-B}$, $^{241}\text{Am-F}$ and $^{241}\text{Am-Li}$ with source emission rates up to $10^7\text{ s}^{-1}$. For further details see reference [3].

1.3. Accelerator-based fluence and dose standards

NPL has a 3.5 MV Van de Graaff accelerator that is used to produce thermal and monoenergetic neutron fields. Beams of protons or deuterons are accelerated to energies between 0.88 and 3.5 MeV and directed onto various targets to produce neutrons.

Thermal neutrons are produced by accelerating deuterons to 3 MeV (up to $80\mu\text{A}$) and directing them onto two thick beryllium targets to produce a broad-spectrum fast neutron field. The field is thermalized in a large graphite assembly ($279 \times 144 \times 156 \text{ cm}^3$). The two targets are located symmetrically equidistant from a central bore hole (12 cm diameter), in which instruments can be placed to receive a neutron fluence rate of up to $1.2 \times 10^7\text{ cm}^{-2}\text{s}^{-1}$. Larger instruments can be irradiated using an extracted column of neutrons (30 cm diameter) where a fluence rate of $4.0 \times 10^4\text{ cm}^{-2}\text{s}^{-1}$ can be achieved. For further details see reference [5] and [5].

Monoenergetic neutron fields are produced at NPL using the following nuclear reactions: $^{45}\text{Sc(p,n)}^{45}\text{Ti}$, $^{7}\text{Li(p,n)}^{7}\text{Be}$, $^{7}\text{Li(p,n)}^{3}\text{He}$, $^{3}\text{He}$, $^{3}\text{He}$ and $^{4}\text{He}$. Monoenergetic neutrons can be produced covering most of the ISO recommended energies from 27 keV to 19 MeV with varying neutron fluence and dose equivalent rates across the range (see Table 1). The beam current used for monoenergetic production is typically limited to reduce the heat load on the targets with maximum currents of 3, 20 and 40 $\mu\text{A}$ for hydrogen targets (deuterium and tritium absorbed into a titanium matrix), lithium targets (LiF) and scandium targets respectively. The neutron producing targets are located on the end of the accelerator beam line at the centre of the low scatter facility which reduces the scatter component of the neutron field. Thick aluminium-lithium targets are also available to produce high fluence rate, broad energy, neutron fields. For more information see references [6] and [7].

Table 1. Details of the monoenergetic neutron fields that are routinely produced at NPL.* Based on fluence to ambient dose equivalent conversion coefficients published in ICRU Report 57, Conversion coefficients for use in radiological protection against external radiation, (ICRU, Bethesda) August 1998. Values are only for indication so can be taken to apply for both ambient or personal dose equivalent.

| Neutron Energy (MeV) | Incident ion-beam energy (MeV) | Nuclear reaction | Target thickness ($\mu\text{g cm}^{-2}$) | Maximum rates at 1 m Fluence ($\text{cm}^2\text{s}^{-1}$) | Maximum rates at 1 m Dose equivalent ($\mu\text{Sv h}^{-1}$)* |
|----------------------|-------------------------------|-----------------|--------------------------------------|---------------------------------|---------------------------------|
| 0.027                | 2.926                         | $^{45}\text{Sc(p,n)}^{45}\text{Ti}$ | 60                                    | 8                               | 0.6                             |
| 0.144                | 1.935                         | $^{7}\text{Li(p,n)}^{7}\text{Be}$ | 60                                    | 1000                            | 450                             |
| 0.250                | 2.016                         | $^{7}\text{Li(p,n)}^{7}\text{Be}$ | 60                                    | 600                             | 440                             |
| 0.65                | 2.293                         | $^{7}\text{Li(p,n)}^{7}\text{Be}$ | 60                                    | 1600                            | 2000                            |
| 1.2                  | 1.998                         | $^{7}\text{Li(p,n)}^{7}\text{He}$ | 355*                                 | 100                             | 150                             |
| 2.5                  | 3.282                         | $^{7}\text{Li(p,n)}^{7}\text{He}$ | 355*                                 | 850                             | 1300                            |
| 2.5                  | 3.282                         | $^{7}\text{Li(p,n)}^{7}\text{He}$ | 355*                                 | 200                             | 300                             |
| 5.0                  | 1.773                         | $^{7}\text{Li(p,n)}^{7}\text{He}$ | 355*                                 | 1500                            | 2000                            |
| 16.5                 | 0.979                         | $^{7}\text{Li(p,n)}^{7}\text{He}$ | 355*                                 | 600                             | 870                             |

*Based on fluence to ambient dose equivalent conversion coefficients published in ICRU Report 57. Values are only for indication so can be taken to apply for both ambient or personal dose equivalent.
1.4. Neutron spectrometry
NPL has a suite of spectrometers that can be used to characterize neutron fields present at nuclear sites and provide spectral information of standard neutron fields used for calibration. The instruments available include active and passive Bonner sphere sets [8], SP2 hydrogen recoil counters and scintillators.

2. Future capability in neutron metrology
As discussed above, a central facility for neutron metrology at NPL is the Van de Graaff accelerator used to produce neutron fluence and dose standards. However, this accelerator has been operational for over 50 years and requires replacing.

2.1. Replacement and expansion of capability
To continue the provision of neutron fluence and dose standards a replacement machine must be able to accelerate DC beams of light ions to several MeV, variable across the required energy range. The accelerator of choice for this application is a low energy electrostatic accelerator, such as a Van de Graaff accelerator (similar to the extant machine) or a Cockroft-Walton type accelerator.

The accelerator identified as an ideal replacement is a tandem-type machine which requires a lower terminal voltage as the accelerating voltage is used twice, i.e. negatively charged hydrogen or deuterium ions are accelerated from ground to +2 MV, stripped of their electrons (making them positively charged) and then accelerated from +2 MV to ground potential, resulting in 4 MeV ions. In addition, the ion sources in a tandem system are located outside the accelerator tank allowing for easy maintenance and upgrade.

The benefits of the new machine will be:
- Lower beam energies, closer to the T(d,n)³He cross section peak, making it easier to produce 14.7 MeV neutrons
- Higher beam current, hence higher neutron output with certain targets
- A new thermal pile facility to exploit the higher beam current
- Increased reliability, hence increased operational time
- Pulsed capability, allowing time-of-flight measurements/experiments
- More space for new beam-lines and a shielded irradiation room (i.e. the well-shielded accelerator room housing the current accelerator)

Figure 1 shows the proposed layout of the accelerator and associated facilities. An extension will be built to house the new tandem accelerator and a new thermal pile which will occupy a separate shielded room. A dipole magnet will enable the beam to be diverted into the main experimental area to produce monoenergetic neutron fields. Additional beam lines will be accommodated in the remaining space.

This scheme will allow the continuation of operations during the works and ultimately a side-by-side comparison of the current and new accelerator systems.

2.2. Further expansion of capability
The extension will also allow the addition of a second accelerator: a cyclotron (see Figure 1). This will open new areas of research for the nuclear metrology group such as: the production of high energy quasi-monoenergetic neutron fields (i.e. from the ⁷Li(p,n)⁷Be reaction); high energy broad spectrum (white) neutron fields; the production of novel radiopharmaceuticals for research and standardization.
Figure 1. Illustration of the extension (shaded blue) to the extant facilities showing the new tandem accelerator, thermal pile and potential new cyclotron.

3. Conclusion
NPL has a long history of providing fluence and dose equivalent standard neutron fields for industry and research. A plan to replace the ageing accelerator at the heart of the facility has been formulated and submitted to government. The new facility will ensure continued operations, extend capability and provide a vital service for the nuclear sector by providing underpinning measurements and traceability to internationally agreed standards.

4. Acknowledgements
The authors would like to acknowledge the support of the National Measurement System of the UK government’s Department for Business, Education and Industrial Strategy.

References
[1] Roberts N J, Moiseev N N and Kralik M *Radionuclide neutron source characterization techniques* Metrologia 48 (2011) S239-253
[2] Roberts N J and Jones L N *Recent developments in radionuclide neutron source emission rate measurements at the National Physical Laboratory* Appl. Radiat. Isot. 68 (2010) 626–30
[3] Gressier V and Taylor G C *Calibration of neutron-sensitive devices* Metrologia 48 (2011) S213-327
[4] Thomas D J and Kolkowski P *Thermal fluence and dose equivalent standards at NPL* NPL Report DQL RN008, March 2005.
[5] N P Hawkes, P Kolkowski, N J Roberts, P Salvador-Castiñeira, G C Taylor and D. J. Thomas *Additional characterisation of the thermal neutron pile at the national physical laboratory, UK* Rad. Prot. Dos. (2017) pp.1-4
[6] Nolte R and Thomas D J *Monoenergetic fast neutron reference fields: I. Neutron production* Metrologia 48 (2011) S263-S273
[7] Nolte R and Thomas D J *Monoenergetic fast neutron reference fields: II. Field characterization* Metrologia 48 (2011) S274-S291

[8] Roberts N J, Thomas D J and Visser T *Improved Bonner sphere neutron spectrometry measurements for the nuclear industry* Rad. Phys. Chem. 140 (2017) 319-321.