Public Health England

Determination of Neutron Dose Rates for the Public Health England Neutron Facility

About Public Health England

Public Health England's mission is to protect and improve the nation's health and to address inequalities through working with national and local government, the NHS, industry and the voluntary and community sector. PHE is an operationally autonomous executive agency of the Department of Health.

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CONTENTS

1 INTRODUCTION

Public Health England (PHE) provides a calibration service for both passive and active neutron monitors using $^{241}Am(Be)$ neutron sources. A ^{252}Cf neutron source is also available. This report details the design and construction of the neutron laboratory, the traceability of the neutron dose rates, derivation of the scatter correction and an uncertainty budget associated with the dose rates used during the calibration or irradiation.

2 FACILITY CONSTRUCTION

Prior to installation, the suitability of this room as a neutron facility was investigated to ensure the requirements of safety and low leakage radiation levels in adjacent laboratories could be met. A detailed theoretical study was carried out on neutron scattering levels in the room, which indicated the need for some remedial measures to be taken. The aim was to conform to the specifications for neutron calibration laboratories laid down by the National Measurement Accreditation Service (NAMAS) and International Organisation for Standardisation (ISO). In addition, the room—not having appropriate shielding on the walls and door—would have caused unacceptable levels of background radiation in adjacent areas. The computation of the scattering conditions within the room predicted that significant improvements could easily be made if the scattering surfaces were lined with hydrogenous materials doped with lithium as this would capture low energy neutrons without emission of appreciable gamma radiation.

3 IMPROVEMENTS EFFECTED

The neutron facility (originally measured 8.1 m x 5.2 m x 2.7 m high) has solid concrete walls approximately 30 cm thick with no windows. The work of lining the facility surfaces was carried out in two stages: lining of the ceiling and floor was carried out in 1984, with the second stage of development taking place in 1991. The hydrogenous material used for the lining was a material originally developed for shielding neutron source containers and has since found wider applications in shielding. It is marketed by Premise Engineering Ltd under the trademark 'Premadex'. Soft wood frames were fixed onto the concrete surfaces of the walls, floor and ceiling and 7.5 cm thick Premadex blocks were placed in the framework. This formed a lining throughout the entire surfaces of the room. The surfaces were then finished off in plywood. A new door was also installed, measuring 170 cm wide x 195 cm high x 13.5 cm thick. It consists of a mild steel frame with a 3 mm mild steel plate covering the outside surface. A 1 cm thick lead sheet was added on the inner surface followed by 7.5 cm thick Premadex lining. Both surfaces of the door were finished in plastic laminates. In order to improve shielding the door hangs from an overhead track with the bottom of the door within a channel cut into the floor.

Measurements were carried out to determine the reduction in neutron scattering levels within the facility. Scattering levels were measured, with and without a shadow cone intercepting the primary beam, before and after the installation of lining on the ceiling and floor. Following the lining of the walls and installing the new door, a second series of measurements of room scatter was carried out. The leakage of both neutron and gamma radiations to the adjoining areas was also measured at five monitoring points: four at various locations on the outside walls of the laboratory and one on the door.

The scatter component as a fraction of the primary component (in terms of the reading of a rem counter) at the calibration position has been reduced by 52% as a result of changes from the original to the present state of the facility. The NAMAS/ISO requirement for an acceptable room scattered component of the measured quantity has been met.

The lining of the walls and door also significantly reduced the dose equivalent rate from leakage radiation in adjacent areas, particularly in the access corridor where previously dose rate levels were unacceptable from safety considerations.

4 RADIONUCLIDE SOURCES

The neutron fields are produced from ^{241}Am(Be) by (α, n) reactions and from ^{252}Cf by spontaneous fission.

Radionuclide sources have the advantages that the sources are physically small and easy to use. The output, so long as the source is used in the same orientation, is constant allowing for radioactive decay, which can easily be corrected for.

The emission of neutron sources, however, is not isotropic (uniform in all directions) and the spectra are distributed rather than mono-energetic. The variation, however, of emission relative to the axis of the source can be determined in a low-scatter area using a De Pangher long counter.

The spectra distribution means these sources are useful for simulating distributed operational spectra, but they are not particularly suitable for energy response measurements.

5 TRACEABILITY TO NATIONAL STANDARDS

5.1 Calibration of the source

The total neutron emission rate of our radioactive neutron sources were measured by the National Physical Laboratory (NPL).

The method used by NPL is to place the source at the centre of a spherical bath containing an aqueous solution of manganese sulphate. Within this solution the emitted neutrons are slowed down to thermal energies and subsequently captured by the ^{55}Mn(n,γ)^{56}Mn reaction. The amount of radioactive manganese produced is measured by pumping the solution past two scintillation detectors, the γ-counting efficiencies of which have been determined by absolute counting techniques.

The higher the energy of the emitted neutrons, the larger the size of the bath required to ensure almost complete capture: at NPL two sizes of bath are used, of 0.5 m diameter for (γ,n) sources and of 1 m diameter for (α,n) and spontaneous fission sources.

5.2 Calculation of fluence rate from neutron emission rate

Neutron fluence can be defined as the quotient of dN by da, expressed in neutrons per square metre (m^{-2}), where dN is the number of neutrons incident on a sphere of cross-sectional area:

$$\Phi = \frac{dN}{da}$$

The neutron fluence rate in neutrons $cm^{-2}\ s^{-1}$ can easily be calculated from the neutron emission rate as follows:

$$\text{Fluence rate} = \frac{\text{total neutron emission rate}}{4\pi \times 10000}$$

5.3 Calculation of dose equivalent from fluence

The mean neutron fluence to dose equivalent conversion factor can be found within ISO 8529. For ^{241}Am(Be) this is currently 391 pSv cm^2.

Values of neutron fluence to dose equivalent conversion factors in this international standard are taken from ICRP publication 21. These values refer to irradiation by a unidirectional broad beam of mono-energetic neutrons and are evaluated at the maxima of the depth-dose equivalent curves. The calculations have been mainly made in 300 mm diameter, 600 mm high cylinder, equivalent to soft tissue, with the broad beam incident perpendicular to the cylinder axis.

A further correction factor of 1.036 should be applied for the field in a plane through the centre of, and perpendicular to, the long axis.

6 DERIVATION OF NEUTRON SCATTER

6.1 Scatter

In addition to the direct neutrons from the source, the radiation field used for calibration will include neutrons that have been scattered from the walls, floor and ceiling of the room, from objects in the room and from the surrounding air.

The scattered neutrons at the point of measurement will have a different energy spectrum to that of the direct source neutrons. Consequently, unless the instrument under test has a flat energy response it will have a different response to scattered neutrons compared to that from the direct neutrons.

6.2 Derivation from historical data

The calibration of active neutron monitors for nearly 30 years has resulted in a large amount of data for a number of different types of monitors. Twenty sets of data for each type of instrument was analysed after ensuring that each data set was typical of type and contained no outliers.

Historically, the response factor of each instrument was determined using linear regression of the instrument reading at a number of different dose rate points; where the dose rate was calculated from NPL's calibration of the source. Applying the equation of a straight line:

$$Y = mx + c$$

resulted in a gradient equal to the instrument response. However, this did not take account of the scatter or give an increased weighting to dose rate point closer to the source and therefore further from the facility walls where the scatter component would be less.

The original response factor for each neutron monitor was used to calculate an apparent dose rate at each position of test. The dose rate at each position as determined from NPL's source calibration was then subtracted from the apparent dose rate. This value was taken to be the scatter component at each position.

The scatter percentage at each position was obtained by dividing the scatter component at each position by the dose rate calculated from NPL's calibration of the source.

The value at each position for true dose rate including scatter was determined by multiplying the dose rate calculated from NPL's calibration of the source by one plus the percentage scatter component expressed as a decimal.

Finally, each instrument's response was re-calculated using the true dose rate including scatter value and the instrument's indication.

No individual instrument's response varied across its range of measurement by more than 4% or varied from the originally determined single point response factor by more than 7%.

A comparison was performed of the scatter component predicted by each type of instrument. Each scatter value calculated is contained in Table 1.

TABLE 1 Scatter contribution derived from analysis of historical data

	Distance (mm)						
Instrument type	**2700**	**2000**	**1500**	**1500**	**1000**	**500**	**300**
Ludlum 12-4	36.9%	26.6%	12.1%	10.3%	10.6%	1.7%	
NMS 17 Digital	28.5%	32.0%	24.7%		10.1%	3.5%	0.6%
NMS analogue	37.3%	32.5%	23.7%		10.9%	10.6%	0.4%
NM2 Digital	36.7%	24.2%	15.0%		8.1%	1.9%	
NM2 Analogue	40.7%	24.5%	15.7%		6.04%	4.2%	1.0%
Studsvik 2202D	42.8%	30.5%	23.2%		10.7%	8.7%	0.8%
Prescila digital	33.0%	25.3%	13.7%		7.6%	4.8%	0.5%
Prescila analogue	39.2%	31.7%	19.4%		9.3%	11.1%	0.5%
Mean	36.9%	28.4%	18.5%	10.3%	9.2%	5.8%	0.6%
SD	4.5%	3.6%	5.0%		1.8%	3.8%	0.2%

6.3 Scatter measurements using a shadow cone

Measurements of scatter were made using a shadow cone. Recommendations on the required cone construction and the method of measurement are published in ISO 8529-2. The diameter of the front end of the cone depends on the size of the source, while the diameter of the rear end of the cone depends on the size of the detector, and should just shadow the detector completely. The length of the shadow cone should be sufficient to completely absorb the direct neutrons incident on its front face.

FIGURE 1 Shadow cone set up in the Neutron Laboratory at PHE

For two instruments, Studsvick and Harwell 0075, a number of measurements were made both with and without the appropriate shadow cone in place. The scatter contribution was derived by noting the measurement without the scatter cone in place and subtracting the value obtained with the shadow cone. The results obtained are contained in Table 2.

TABLE 2 Scatter contribution derived from shadow cone measurements

	Distance (mm)			
	2700	**2000**	**1500**	**1000**
Studsvik	34.0%	28.0%	21.0%	12.0%
Harwell 0075	41.0%	27.0%	18.0%	11.0%
Mean	34.3%	26.2%	19.5%	11.5%
SD	5%	1%	2%	1%

The scatter contribution calculated at a number of distances using the two different methods were compared. Although the instrument types used in the two methods differed, there is good agreement in the results obtained using either method.

TABLE 3 Comparison of scatter contribution using both methods

		Distance (mm)			
		2700	**2000**	**1500**	**1000**
Scatter data analysis	Mean	36.9%	28.4%	18.5%	9.2%
Scatter cone measurement	Mean	34.3%	26.2%	19.5%	11.5%
% difference		107.6%	108.5%	94.6%	79.8%

Since it has been demonstrated that the analysis of historical data gives a value for the scatter contribution which is in good agreement with the values obtained using a shadow cone, PHE has used this method to determine traceable dose rates including the contribution from scatter for all the distances used for neutron monitor calibrations.

7 UNCERTAINTY BUDGET

The neutron field is produced using an Am/Be source with a known emission rate and anisotropy factor. These values and associated uncertainties are contained within the source calibration certificate issued by the National Physical Laboratory. Instrument calibrations are usually performed in terms of ambient dose equivalent rate; this is derived by the application of a conversion factor defined in ISO 8529. A number of other factors also give rise to an uncertainty in the ambient dose equivalent rate at any point in the neutron field. These have been considered and an uncertainty budget derived.

PHE considers that the true ambient dose equivalent rates quoted in all calibrations performed in the neutron facility have an associated expanded uncertainty of ± 11%.

Using the example above PHE reports a typical value of the response factor of a neutron dose rate monitor measured at 2700 mm as:

> R = 0.98 ± 20%. The reported uncertainty is based on a standard uncertainty multiplied by a coverage factor of k=2, which provides a level of confidence of approximately 95%.

TABLE 4 Uncertainty budget for ambient dose equivalent rate at a distance of 2700mm in an Am/Be neutron field

Quantity	Value	Uncertainty (δx_i)	Probability distribution	Divisor	(df/dx)/y	c_i/y	$u_i(y)$ %
Emission rate, E	1.02E+07	7.12E+04	Normal	2	1/E	9.83E-06	0.350
Anisotropy, A	1.04E+00	0.008	Normal	2	1/A	9.62E+01	0.400
Attenuation correction,AC	0.992	0.001	Normal	2	1/AC	1.01E+02	0.050
Room scatter, RS	1.35	10%	Normal	2	1/RS	7.41E+01	3.704
Conversion factor,Cf	391	4%	Normal	1	1	1	4.000
Position of effective centre, rc	2700	1	Rectangular	1.732	2/rc	0.074	0.043
Centre of detector to source ,rds	2700	2	Rectangular	1.732	2/rds	0.074	0.086
							5.48
							k = 2.00
				Expanded uncertainty			**11.0**

TABLE 5 Uncertainty budget for calibration of a portable neutron dose rate monitor

Quantity	Value	Uncertainty (δx_i)	Probability distribution	Divisor	(df/dx)/y	c_i/y	$u_i(y)$ %
Ambient dose equivalent rate,E	2.20E+01	2.42E+00	Normal	2	1/E	4.55E+00	5.500
Mean reading of monitor,M	2.17E+01	2.170	Normal	2	1/(M-Mb)	4.65E+00	5.047
Mean Background reading,Mb	0.2	0.100	Normal	2	1/(M-Mb)	4.65E+00	0.233
Position of effective centre, rc	2700	1	Rectangular	1.732	2/rc	0.074	0.043
Parrallax, P	--	5%	Rectangular	1.732	M/(M-Mb)	1.009	0.029
centre of detector to source ,rds	2700	2	Rectangular	1.732	2/rds	0.074	0.086
							7.47
							k = 2.00
				Expanded uncertainty			**14.9**