Radiation Protection Dosimetry
Vol. 70, Nos. 1–4, pp. 285–289 (1997)
Nuclear Technology Publishing

IMPROVED NEUTRON SPECTROMETER BASED ON BONNER SPHERES

A. Aroua†, M. Grecescu†, S. Prêtre‡ and J.-F. Valley†
†Institute for Applied Radiophysics, CH-1015 Lausanne, Switzerland
‡Swiss Nuclear Safety Inspectorate, CH-5232 Villigen-HSK, Switzerland

Abstract — A modification of the Bonner spheres neutron spectrometer is proposed in order to improve its energy resolution at low and intermediate energies. The small diameter polyethylene spheres are surrounded by layers of neutron absorbers with suitable composition and thickness. The system design is based on response function calculations with the neutron transport code ANISN. Several absorbers were investigated and, eventually, boron with natural isotopic composition has been retained. The optimal set of detectors consists of the 2″ and 3″ spheres surrounded by boron layers of 0.0628, 0.837 and 2.76 g.cm^{-2}. Narrower response functions have been obtained with one maximum per decade in the energy range 1 eV–100 keV. An experimental calibration has been performed with neutron beams of 0.186, 2, 24 and 144 keV. The computed response functions have been adjusted to the calibration points. Simulations with numeric neutron spectra confirmed the improved energy resolution of the new system.

INTRODUCTION

In recent years, an improved characterisation of neutron fields in the epithermal and intermediate energy range was required in various applications: boron neutron capture therapy (BNCT)[1,2], radiation field measurements inside nuclear power plants[3,4], and production of reference neutron fields for the calibration of neutron monitors[5].

The Bonner spheres neutron spectrometer is suited for radiation protection measurements at nuclear facilities; however, it suffers from its low energy resolution and lack of response functions with maxima at intermediate energies over 4 decades. A better resolution at low energies and a better coverge of the epithermal and intermediate energy range with peaked response functions will improve the accuracy of the system with respect to: the analysis of spectra containing structures in this energy range; the definition of the spectral shape in the region between 100 keV and 1 MeV where the fluence to dose conversion factor h_Φ varies rapidly; and the evaluation of dosimetric quantities for radiation protection.

Wang and Blue[1] developed a neutron spectrometer similar to the Bonner spheres system, designed with an improved resolution in the energy range 1 eV–10 keV. The spectrometer consists of a spherical ^{3}He proportional counter and a set of paraffin spheres surrounded by hemispherical shells loaded with ^{10}B. As this system was developed for a special application (BNCT), it has a limited energy range and an anisotropic response, being unsuitable for general radiation protection use.

Based on the same principle, but using a cadmium shell between two layers of polyethylene, Kryuchkov and Semenova published a set of response functions with improved energy resolution[6].

The present work describes a neutron spectrometer with improved performance in the epithermal and intermediate energy range based on the Bonner spheres system of the Institute of Applied Radiophysics (IAR), Lausanne. The improvement is based on the principle proposed by Wang and Blue[1], namely the use of a suitable neutron absorber around a few spheres, but the previously mentioned limitations have been eliminated by careful design. The system has an isotropic response. Its response functions could be reliably calculated as the spheres are made of polyethylene with a well-defined chemical composition, in contrast to paraffin. The new response functions display one maximum per decade between 1 eV and 100 keV. The modified system has been calibrated with monoenergetic neutron beams.

MATERIAL AND METHODS

Design principles

The IAR Bonner spheres system consists of a set of polyethylene spheres with diameters 2, 2.5, 3, 4.2, 5, 6, 8, 9, 10, 12 and 15 inch. The neutrons moderated in the sphere are detected by a ^{3}He cylindrical proportional counter (1 cm diam. × 1 cm) located at the centre of each sphere and coupled to a suitable electronic system. A detailed description of the construction and performance of this system has been published[7].

It is possible to change the shape of the response functions in the low and intermediate energy region by surrounding the small spheres with a layer of absorber having a neutron capture cross section proportional to 1/v such as ^{10}B or ^{6}Li. The effect of the absorber is mainly to cut the low energy tail of the response function, thereby reducing its width and displacing the position of the maximum on the energy scale. For a given sphere, the maximum position can be controlled by varying the absorber thickness; however, a compromise must be achieved with the unavoidable reduction in sensitivity. The procedure is effective for the spheres with diameters up to 6″, whose response functions are predominating in the energy region of interest.

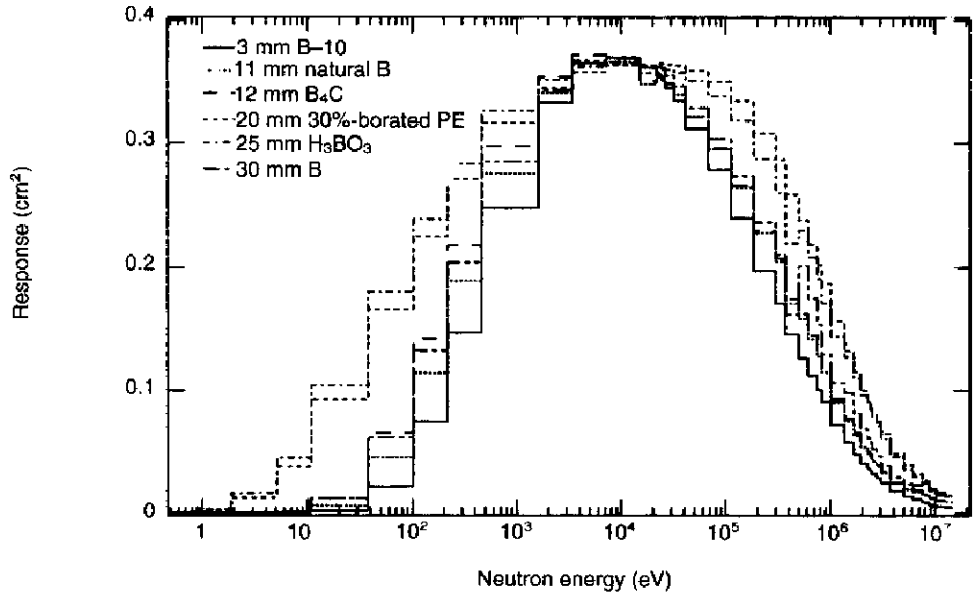

Figure 1. Response functions of the 2″ Bonner sphere covered with spherical shells of different materials containing the same amount of ^{10}B.

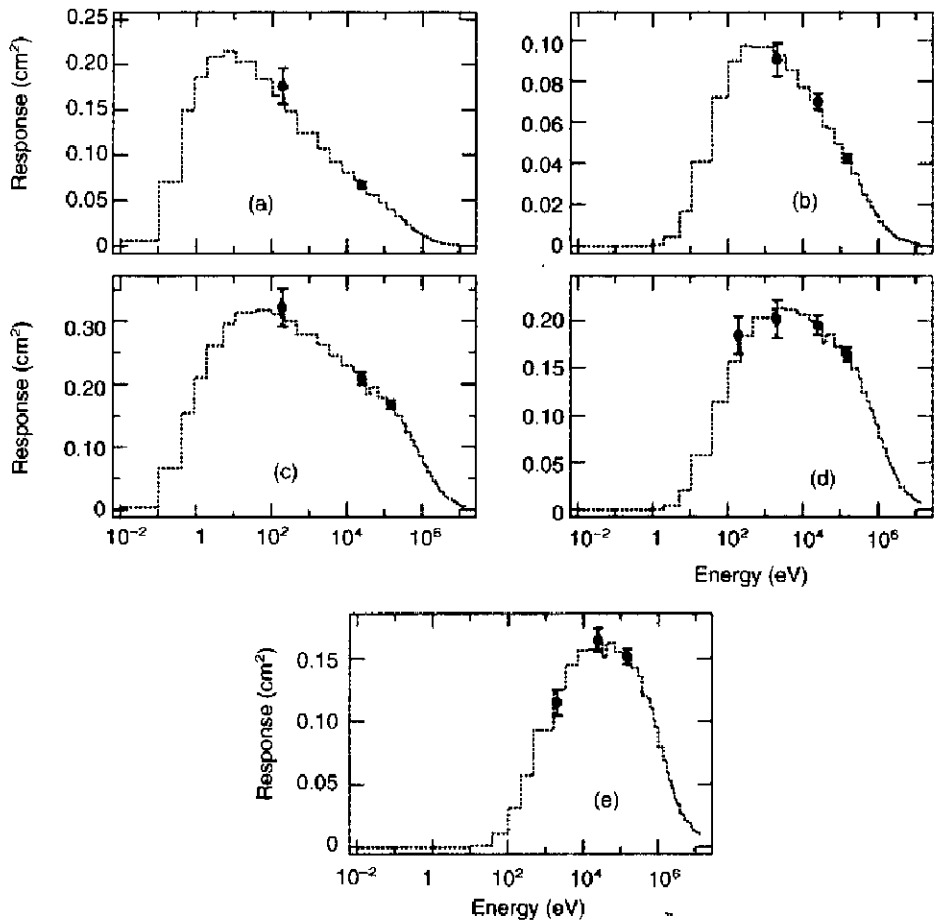

Figure 2. Response functions calculated by ANISN and adjusted to the experimental calibration points: (a) 2″ + 0.0628 g.cm^{-2} boron; (b) 2″ + 0.837 g.cm^{-2} boron; (c) 3″ + 0.0628 g.cm^{-2} boron; (d) 3″ + 0.837 g.cm^{-2} boron; (e) 3″ + 2.76 g.cm^{-2} boron.

The system design is based on the calculation of the response functions with various combinations of materials and geometries, in order to choose the best solution in terms of energy resolution, sensitivity, cost and dimensions.

Calculation of the response matrix

The calculation of the response matrix was performed using the one-dimensional transport code ANISN[8] which had been used previously for calculating the response functions of the IAR Bonner spheres system[9]. The cylindrical proportional counter is filled with ^{3}He at a nominal pressure of 8×10^5 Pa according to the manufacturer, and the polyethylene density is 0.916 ± 0.003 g.cm^{-3}. The effective pressure in the proportional counter may be different from the nominal one and an adjustment of the calculated response functions to experimental calibration points is necessary.

The neutron absorber has the shape of a spherical shell surrounding a polyethylene sphere. In order to determine its optimal composition, simulations with several materials were performed. The ^{10}B has been preferred to ^{6}Li and cadmium because of the monotonous 1/v shape and the higher value of its neutron absorption cross section. Calculations showed that the design goals could be reached with suitable ^{10}B thicknesses. However, highly enriched ^{10}B is expensive and subsequent simulations were performed with various chemical compounds containing boron with natural isotopic composition (20% ^{10}B and 80% ^{11}B): elemental boron, B_4C, B_2O_3, H_3BO_3, borated polyethylene (30% B). Equivalent thicknesses containing the same amount of ^{10}B have been used. Typical results are presented in Figure 1, showing that elemental boron gives the closest response function to that obtained with ^{10}B. The response functions obtained with hydrogen-containing compounds (borated polyethylene and boric acid) are significantly wider.

Table 1. Characteristics of the boron layers.

Thickness (mm)	Volume (cm^3)	Mass (g)	Density (g.cm^{-3})	Mass thickness (g.cm^{-2})
1	31.8	19.97	0.628	6.28×10^{-2}
11	442	336	0.761	8.37×10^{-1}
35	2288	1803	0.788	2.76

An additional investigation was carried out using a 3″ diameter sphere made entirely of borated PE. Its response function is similar to that of the 3″ polyethylene sphere covered with 4.5 mm boron, but its response is 50 times lower, which precludes the use of this material.

Eventually boron with natural isotopic composition and in powder form was chosen for the absorber shells. Different metals were tested for the walls of the powder container (1 mm of aluminium, steel or copper); their effects on the response functions are negligible and aluminium was retained for mechanical reasons.

The response functions were calculated for the small diameter spheres (2″ to 6″) covered with different thicknesses of natural boron between two sheets of 1 mm aluminium. An optimal set of sphere – absorber combinations was established as a compromise between the following factors: reduced width of the response func-

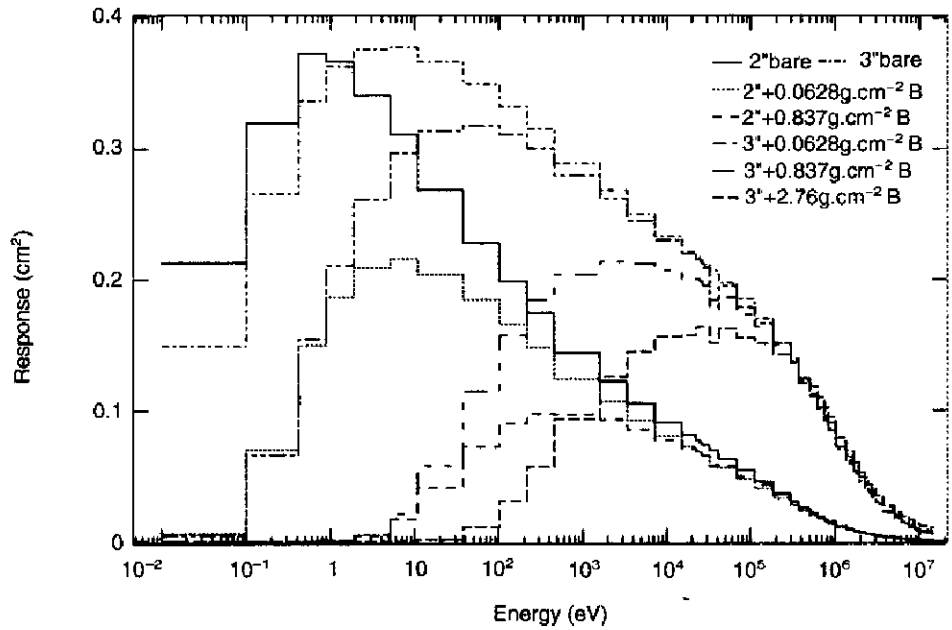

Figure 3. Response matrix of the improved Bonner spheres spectrometer.

tions, their uniform distribution (one peak per decade in the energy range 1 eV to 100 keV), acceptable sensitivity reduction, reasonable complexity (number of combinations) and cost. The set consists of the 2″ and 3″ polyethylene spheres used together with three boron absorbers of different thicknesses.

RESULTS

Response functions

For practical reasons, the absorbers were manufactured as cylindrical aluminium boxes filled with boron powder (purity 97%, maximum grain size 1 μm). The inner dimensions of the boxes are 82 mm in diameter and height, suitable for accommodating the 3″ sphere. The necessary boron layer thickness was determined by taking into account the density of compacted boron powder. The effective boron quantity was eventually obtained by weighing the manufactured boxes (Table 1). A definitive set of response functions was computed with the experimental boron mass thickness by taking into account the impurities specified by the chemical analysis.

An adjustment of the ANISN calculations to experimental calibration points is necessary to correct for whatever detail may be missed in the simulation, which is based upon the assumption that the detector has a perfect spherical symmetry and upon the value of the ^{3}He pressure in the proportional counter specified by the manufacturer. The system was calibrated with quasi-monoenergetic neutron beams (0.186, 2, 24 and 144 keV) at the research reactor of the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig[10].

The calculated response functions have been adjusted to the experimental calibration points, using a least squares fit. The results of the adjustment are presented in Figure 2. It is remarkable that the individual adjustment factors are quite close to each other (within ±2.3%), the mean value being 0.577. This points to a common origin of the difference between the calculated and the experimental responses, undoubtedly the true value of the ^{3}He density.

The adjusted matrix of the manufactured spectrometer is represented in Figure 3 and shows that the design goals have been achieved. The maxima of the response functions are evenly spread (roughly one per decade) between 1 eV and 100 keV, reduced widths have been obtained for the response functions of the new detectors and their reduction in sensitivity does not exceed a factor of 4.

A comparison between the measurement duration for the set of 7 detectors considered in Figure 3 and a set of 6 conventional Bonner spheres (2″, 2.5″, 3″, 4.2″, 5″ and 6″) covering the same energy range has been performed. In a typical neutron field encountered in radiation protection, with a moderate dose equivalent rate of 100 μSv.h^{-1}, the effective counting time required to have less than 1% statistical error is of the order of 74 min for the first set and 19 min for the second one. The increase of the measuring time by a factor of about 4 is still acceptable.

Spectrometric performance

The spectrometric performance of the new system has been evaluated by simulation using four synthetic neutron spectra consisting of a single peak in the epithermal energy region, situated at 1, 10, 100 and 1000 eV respectively. For each of these spectra the counting rate

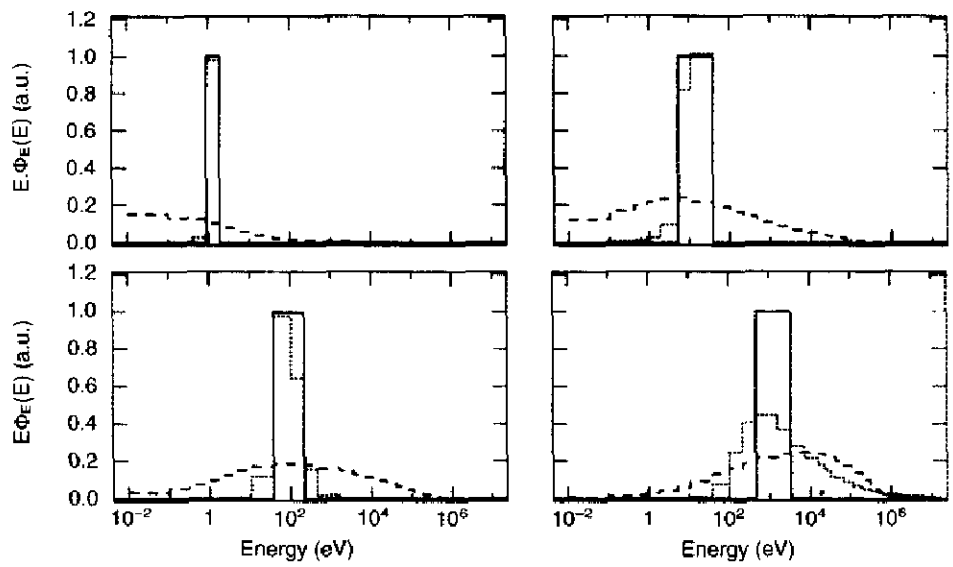

Figure 4. Comparison of results obtained on test spectra with a standard Bonner spheres set and with the improved spectrometer: (——) test spectrum; (– – – –) unfolded spectrum with standard matrix; (. . . .) unfolded spectrum with improved matrix. For details, see text.

expected from a given detector has been determined by convolution of the spectrum with the response function of this detector. The two sets of detectors previously considered have been used. The unfolding has been performed with a version of the SAND code[11] using 47 energy groups. For all the unfolding trials a 1/E spectrum over the whole energy range was used as a 'first guess', without any *a priori* information about the presence of a peak.

The spectrometric results obtained with the two sets of detectors are compared in Figure 4. They show a significant improvement of the resolution. Clearly the boron-based set gives better spectrometric information in the epithermal region; indeed, it always correctly locates the peak (in most cases also with a correct amplitude), while the spectrum determined by the conventional spectrometer shows only a very broad structure.

CONCLUSIONS

An improved version of the multisphere neutron spectrometer has been developed. The simulations showed the possibility of improving the spectrometer performance (energy resolution, more uniform distribution of the response functions) in the epithermal and intermediate energy region by using neutron absorbers of different thicknesses around the small spheres. They led to the choice of natural boron and allowed the selection of an optimised set of sphere diameter–boron thickness combinations. The prototype boron-based spectrometer, with practical dimensions and weight, was calibrated with monoenergetic neutron beams between 0.186 and 144 keV and its response matrix was determined by adjusting the computed response functions to the calibrated points. The investigation of its performance by simulation confirmed the improvement of the energy resolution in the epithermal region, with no dramatic decrease in sensitivity.

ACKNOWLEDGEMENTS

The present work has been performed under contract No 94.0039 with the Swiss Federal Office for Education and Science; the authors are grateful for this financial support. The cooperation of Dr E. Dietz (PTB) during the experimental calibration of the system is gratefully acknowledged.

REFERENCES

1. Wang, C. K. and Blue, T. E. *A Neutron Spectrometer for Neutrons with Energies between 1 eV and 10 keV*. Nucl. Instrum. Methods A**290**, 237–241 (1990).
2. Perks, C. A. and Gibson, J. A. B. *Neutron Spectrometry and Dosimetry for Boron Neutron Capture Therapy*. Radiat. Prot. Dosim. **44**(1/4), 425–428 (1992).
3. Aroua, A., Boschung, M., Cartier, F., Grecescu M., Prêtre, S., Valley, J.-F. and Wernli, C. *Characterisation of the Mixed Neutron–Gamma Fields Inside the Swiss Nuclear Power Plants by Different Active Systems*. Radiat. Prot. Dosim. **51**(1), 17–25 (1994).
4. Lindborg, L. and Klein, H. (eds) *Determination of Neutron and Photon Dose Equivalent at Work Places in Nuclear Facilities of Sweden: An SSI-EURADOS Comparison Exercise*. SSI-Report 95-15 (Stockholm: SSI) (1995).
5. Chartier, J.L., Posny, F. and Buxerolle, M. *Experimental Assembly for the Simulation of Realistic Neutron Spectra*. Radiat. Prot. Dosim. **44**(1/4), 125–130 (1992).
6. Kryuchkov, V. P. and Semenova, G. I. *Neutron Responses for Sphere Spectrometer*. (in Russian) IHEP Reprint 87-191 (Serpukhov: IHEP) (1987).
7. Aroua, A., Grecescu, M., Lerch, P., Prêtre, S, Valley, J.-F. and Vylet, V. *Evaluation and Test of the Response Matrix of a Multisphere Neutron Spectrometer in a Wide Energy Range, Part 1. Calibration*. Nucl. Instrum. Methods A**321**, 298–304 (1992).
8. Engle, W. W., Jr *A User Manual for ANISN, A One Dimensional Discrete Ordinates Transport Code with Anisotropic Scattering*. AEC Research and Development Report K 1693 (1967).
9. Aroua, A., Grecescu, M., Lanfranchi, M., Lerch, P., Prêtre, S. and Valley, J.-F. *Evaluation and Test of the Response Matrix of a Multisphere Neutron Spectrometer in a Wide Energy Range, Part 2. Simulation*. Nucl. Instrum. Methods A**321**, 305–311 (1992).
10. Guldbakke S., Dietz, E., Kluge, H. and Schlegel, D. *PTB Neutron Fields for the Calibration of Neutron Sensitive Devices*. In: Strahlenschutz: Physik und Messtechnik, Band 1, pp. 240–247 (Fachverband für Strahlenschutz e.V.) (1994)
11. McElroy, W. N., Berg, S., Crockett, T. and Hawkins, R. *A Computer-Automated Iterative Method for Neutron Flux Spectra Determined by Foil Activation*. Report AFWL-TR-67-41, Vols I–IV (US Air Force Weapons Lab., Kirtland, AFB, New Mexico) (1967).