NEUTRON SPECTRUM MEASUREMENTS AT A CANDU REACTOR

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Abstract

Neutron spectrum measurements typically involve sophisticated instrumentation and techniques to characterize the energy distribution of neutrons emitted during fission reactions. These measurements are important for understanding reactor behaviour, fuel performance and safety considerations. Techniques such as foil activation, neutron scattering and spectrometry are used to analyze neutron spectra in CANDU Reactors. Bonner spheres spectrometer is a tool used for measuring neutron spectra in various reactor environments, having a great importance for workers radioprotection. This system is formed by 7 HD polyethylene shells, with different thickness, covering a 5 cm diameter spherical BF3 filled thermal neutron detector. The response matrix was obtained using the MCNP code. In order to obtain the neutron spectrum, the response of the detector to neutrons of different energies is calibrated using a Pu-Be fast neutron source and the shadow cone technique to eliminate the scattered neutrons contribution. The SAND II code was used for spectrum unfolding. Some neutron field characterization measurements have been performed in significant locations at Cernavoda NPP Unit 2.

Keywords: *Bonner spheres, Neutron spectrometry, Unfolding*

Introduction

In certain areas of the reactor building, neutron doses absorbed by workers, although small compared to gamma doses, can still make a notable contribution to the overall radiation exposure. The primary sources are the neutron leaks from the core, including those from moderator and primary reactor coolant.

Existing neutron dosimeters lack the ability to precisely measure dosimetric quantities across a broad neutron energy spectrum. Within the low-energy range, the limited intensity of neutron fields prevents the experimental determination of energy distribution using current methods. Consequently, understanding the neutrons energy distribution is important for correcting dosimeter response for the personnel exposed to neutron radiation.

The Bonner Sphere Spectrometry (BSS) is a technique developed in the 60's by T.J. Bonner [1] for measuring the energy spectrum of neutrons. This technique is used in neutron dosimetry and radiation protection. The spectrometric method covers neutron energies from thermal to high energies, based on the neutron slowing down in polyethylene shells of various thicknesses followed by thermal neutron counting.

Applying the unfolding techniques allows to determinate the energy distribution of incident neutrons and the neutron flux density in the measurement area. An important advantage of the Bonner sphere system is that it covers a large energy range, spanning the thermal neutron domain (10^{-10} MeV) up to 20 MeV.

Bonner sphere spectrometer description

The Bonner sphere spectrometer developed at the Institute for Nuclear Research is formed by 7 polyethylene shells from 60 to 433 mm external diameter [2], covering a LND 2708 spherical thermal neutron detector [3] (see Fig. 1).



Fig. 1. Bonner spheres spectrometer

The response function describes how the instrument detects and measures neutron radiation as a function of neutron energies. It characterizes the spectrometer's sensitivity to neutrons of different energies and influences the accuracy and reliability of neutron dose measurement performed by spectrometer ensuring that the instrument provides accurate readings across a range of neutron energies. In the case of Bonner spheres spectrometer, the response functions are computed for each moderator thickness, and we get the response matrix. Response functions for each experimental configuration (7 shells and the bare detector) have been computed by modelling the neutron slowing down and detection process using the MCNPX code [4].

The neutron spectrum is obtained by unfolding the measured count rates which can be written as:

$$M_i = \int_{E_{min}}^{E_{max}} R_i(E)\Phi(E)dE \quad (1)$$

where R_i (E) is the response function for the i sphere and Φ(E) is the neutron spectrum.

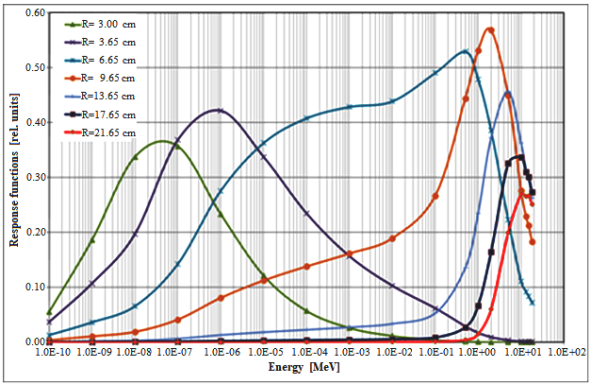


Fig. 2. BSS response functions

The response matrix, as presented in Fig. 2, shows a good coverage of neutron energies, from thermal to high energies. A larger diameter leads to a better moderation and more absorption as well. The energy distribution of the response function to each sphere has a maxim at the incident energy for which the neutrons are best moderated.

For spectrum unfolding the SAND II code, usually used for multi-foil activation techniques, has been adapted. The paper presents the experimental setup, the response matrix, as well as the calibration experiment.

The calibration of Bonner sphere spectrometer

Bonner spheres calibration is the process of determining the response of each individual sphere to neutrons of different energies. This calibration ensures that the spectrometer accurately measures neutron flux across its entire energy range. Calibration involves exposing the spheres to known neutron sources and comparing the measured responses to reference values.

The experimental calibration process is based on the comparison of apparatus readings with the known value of the physical quantity (i.e. neutron flux density), followed by the response function adjustment with a suitable scaling factor. This process needs different arrangements for thermal or fast neutrons. The calibration procedure presented in the paper uses a Pu-Be neutron source and shadow cone measurements in order to eliminate the scattered neutron effects. The 50 cm length shadow cone is made by borated polyethylene to perform a complete absorption of the neutrons. The experimental arrangement (see Fig. 3) is suitable for calibration measurements on configurations with thick polyethylene shell, responding to intermediate and fast neutrons. The shadow cone efficiency has been checked by installing the experimental setup in two different locations having low and high contribution of scattered neutrons, respectively.



Fig. 3. Calibration experiment arrangement

By subtracting the measured values obtained using the shadow cone from those acquired without the shadow cone, the direct exposure is obtained. Because there was a single cone, the measurements have been performed at different distances, as required by the sphere dimension.

The results have been normalized to a reference distance (e.g. 1 m) according to the $1/r^2$ law, considering the point like source approximation. The corresponding flux density was 16.7 neutrons/cm^{2}s. A Pu-Be isotopic neutron source with an intensity of 1.05 x 10^7 neutrons/sec has been used. It is a source for industrial applications without certified uncertainty of the reported intensity. Isotropic emission has been assumed. For the calibration experiment, only five spheres from seven have been used, the cone base being larger than the 60 mm and 73 mm diameter spheres. The results are summarized in the table below.

Table 1. Calibration experiment results

Sphere ID	Diameter [mm]	Count rate (without cone) [cps]	Count rate (with cone) [cps]	Count rate (direct exposure) [cps]	Corrected count rate (at 1m) [cps]
3	133	250.69	68.385	182.305	69.21
4	193	177.879	52.125	125.754	121.83
5	273	75.477	22.268	53.209	115.77
6	353	29.641	10.044	19.597	75.73
7	433	11.787	3.1375	8.6495	52.20

The scaling factor is obtained by imposing the value of the neutron flux density at 1 m from the source (based on the known value of 1.05×10^7 n/sec for the source strength according to the manufacturer recommendations). The recommended Pu-Be spectrum [5] has been considered as guess spectrum, the unfolding solution being obtained after four iterations, with a standard deviation of the measured count rates less than 5%. The scaling factor applied to the count rates was of 2.18×10^{-26}.

Experimental results

From the point of view of the existing neutron fields during the reactor operation, at the CANDU NPP there are a number of significant locations. Several studies have been carried out at different CANDU units [6], in rooms R-009, R-104, R-110, R-405 and R-501. In our study, the research was limited to three locations at the Unit 2 from Cernavoda NPP, namely rooms R-009, R-405 and R-501, respectively (see Fig. 4).

Neutron spectra can vary significantly depending on location, making it challenging to replicate reported values even in similar installations. Comparisons are typically limited to the neutron flux order of magnitude.

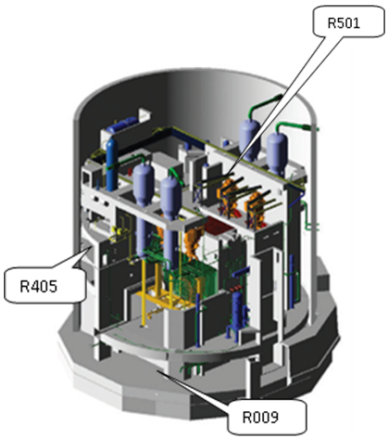


Fig. 4. Positioning of the interest locations in the CANDU Reactor Building [7]

All seven polyethylene spheres and the bare detector have been used. They were positioned one after another, at the same elevation, using appropriate aluminium supports.

The monitor detector (Fig. 5) has been placed at about two meters from the spheres in order to avoid perturbations. The monitor count rate does not vary more than 5% during the measurements performed in R-405, and has been almost constant during the measurements in R-009 (0.7% standard deviation).



Fig. 5. Monitor detector

The unfolding procedure for Bonner sphere spectrometer involves deconvolving the measured count rates with the response functions of the spheres to determinate the neutron energy spectrum. To start this procedure, the iterative process requires knowledge of a guess spectrum.

The tests carried out on laboratory setups with isotropic neutron sources allowed the promotion of alternative methods that can be applied without prior knowledge of the energy distribution. The initial attempts using constant or 1/E neutron spectra highlighted the necessity of including the specific neutron source component. For this reason, a spectrum composed of a fast component (Watt spectrum) connected to a 1/E component was generated. Tests performed have shown the necessity to more precisely define the source component, since attributing a fission form is not consistent with reality.

To account for the of photoneutrons produces in heavy water, which is specific to CANDU reactors, an alternative to the spectra mentioned above would be a spectrum formed by the photoneutron spectrum produced in heavy water connected to a 1/E spectrum below 100 keV energy. The photoneutron spectrum has been combined with the characteristic spectrum of 24Na-D_2O from reference [5].

Room R-009 is located in the basement of the Reactor building. The neutrons reach this room by scattering from the room above, i.e. from the reactor wall. The solution spectra obtained is presented in the figure below.

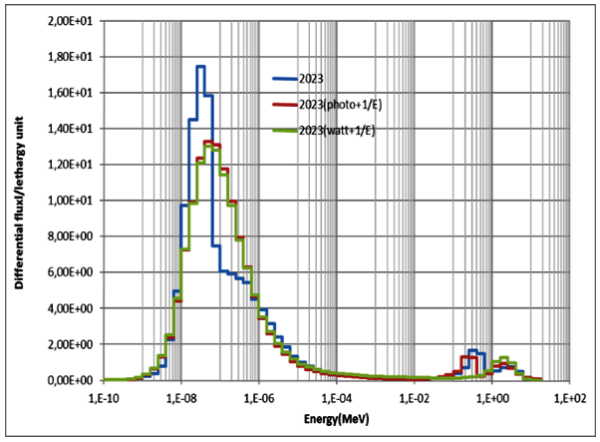


Fig. 6. Solution spectra in R-009

Room R-501 is the Heat Transport Pump room. The measurements have been performed near to the pump no. 3 instead of pump no. 4 (as in the most published data). There are no reasons to expect major differences between these positions, at least as spectrum shape. Figure 7 presents the solution spectra obtained.

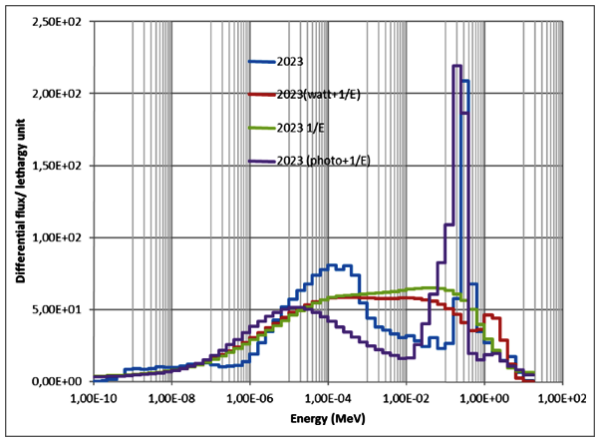


Fig. 7. Solution spectra in R-501

Room R-405 is the heat transport auxiliary room. The measurements have been performed by the door leading to Pressurized Valve Gallery and in the centre of the room. The neutrons reaching the room by scattering from the valve gallery and the field is strongly affected by the Fuelling Machine status (in operation or not). The solution spectra are shown in Figs. 8 and 9 for measurements at the door and in the centre of the room, respectively.

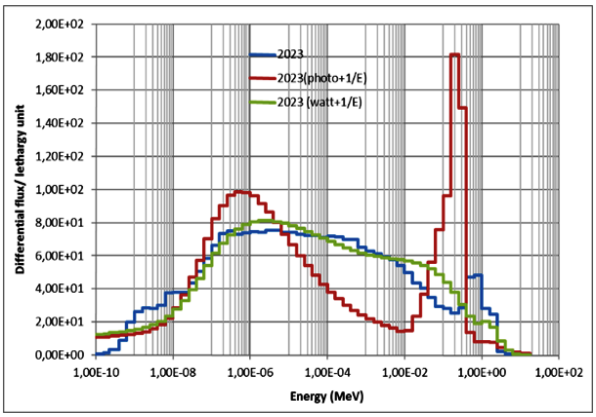


Fig. 8. Solution spectra in R-405 (at the door)

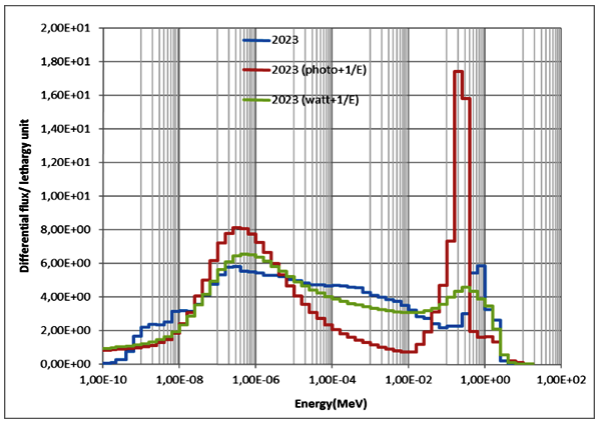


Fig. 9. Solution spectra in R-405 (centre of the room)

Conclusions

The Bonner sphere spectrometer developed at RATEN ICN can be used in different applications, including workplace dosimetry, environmental monitoring and research in nuclear facilities, as well as for other nuclear facilities which could lead to the neutron exposure of the workers (neutron generators, beam tubes).

Experimental results from neutron spectrum measurements performed in key locations at Cernavoda NPP are outlined in this work. They align with previously published data obtained from comparable facilities, by using similar instruments or alternative measurement techniques (such as proportional counters, dose rate monitors).

Acknowledgments

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