IEEE NPSS (Toronto), UOIT, Oshawa, ON, 25 & 26 June, 2010
International Workshop on Real Time Measurement, Instrumentation & Control [RTMIC]

A NEW TYPE OF NEUTRON SPECTROMETER USING NESTED MODERATOR

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Abstract

The design, simulation results and first measurements of a new neutron energy spectrometer are presented. The device, which may be called NNS for Nested Neutron Spectrometer, works under the same principles as a Bonner Sphere Spectrometer system, i.e. whereby a thermal neutron detector is surrounded by polyethylene moderator. However, the moderator is cylindrical in shape. The different thicknesses of moderator are created by inserting one cylinder into another, much like nested Russian dolls. Simulations and measurements show that, despite its shape, the device can be made to offer angular isotropic response to neutrons and that unfolded neutron fission spectra are in agreement with those obtained with the more traditional BSS.

1. Introduction

1.1 Background

Inside a nuclear power reactor building, the neutrons of concern, from the point of view of radiation protection, can have energies ranging from thermal energies to a few MeV. In many instances, the primary tool used by radiation safety officers for the characterisation of the neutron fields is the Andersson-Braun type REM meter [1]. In addition, workers may also carry individual neutron electronic personal dosimeters (EPD) or bubble detectors. A very good review of neutron EPDs is given in [2].

Both the REM meters and EPDs present limitations from the point of view of their dosimetric response. The REM meter is only accurate within a factor of 2 to 5 over the full energy range of interest. In the case of EPDs, reference [2] shows that many of these devices are nearly blind to neutrons in the epithermal region. Another instrument used in neutron field surveys is the tissue equivalent proportional counter (TEPC). Depending on their design, TEPCs may also under-respond to neutrons with less than 50 keV in energy.

A more fundamental way of characterizing the neutron field is to measure the energy differential neutrons fluence. The dose and dose equivalent can then be calculated by folding the measured energy fluence spectrum with fluence to dose equivalent conversion factors such as those found in the ICRP74 report [3]. However, the measurement of the neutron energy spectrum, over 9 orders of magnitude, is not a simple task. Two devices have been available for some time to perform this measurement: the Rotational Spectrometer (or ROSPEC) [4] and the Bonner Sphere Spectrometer (or BSS) [5].

The ROSPEC is a commercial instrument that offers the advantage of being easy to use. In its basic configuration, the ROSPEC consists of 4 spherical detectors filled with different volumes and pressures of hydrogen-rich gas. The incident neutrons are detected via the elastic recoil of protons in the gas. The neutron energy range accessible with this instrument is 50 keV to 4.5 MeV. The device can be augmented with He-3 counters to extend its energy response down to thermal energies. The advantage of the instrument is that the spectrum unfolding is automatic and that its energy resolution is better than the BSS. The disadvantage is that its sensitivity is rather low compared to the BSS. This leads to long data acquisition time in low neutron environments.

1.2 Principles of operation of the BSS

The BSS consists of a thermal neutron counter which is surrounded by a spherical shell of polyethylene moderator. A typical system, such as the one currently in use at the Neutron Irradiation Facility (NIF) of the AECL Chalk River Laboratories, consists of a spherical He-3 proportional counter and a set of high density polyethylene (HDPE) spheres of the following diameters: 10”, 8”, 6”, 5” 4.”, 3.5” and 3” [6]. References [5,6], and others more recent, indicate that the basic design of the BSS has not changed in 50 years.

The measurement with the BSS proceeds as follows. The thermal neutron detector is inserted in one sphere at a time and the neutrons are counted for a set time interval, typically 5 to 30 minutes. This continues until counts are acquired with each sphere and with the bare detector. In the case of the AECL system, 8 data points are thus acquired. The number of counts obtained with the He-3 counter in each sphere depends on the incident energy spectrum and the response function of the sphere. Typical response functions look like the curves shown in Figure 1. They show that for an increasing amount of moderator, the peak in the detector response occurs at higher and higher energies.

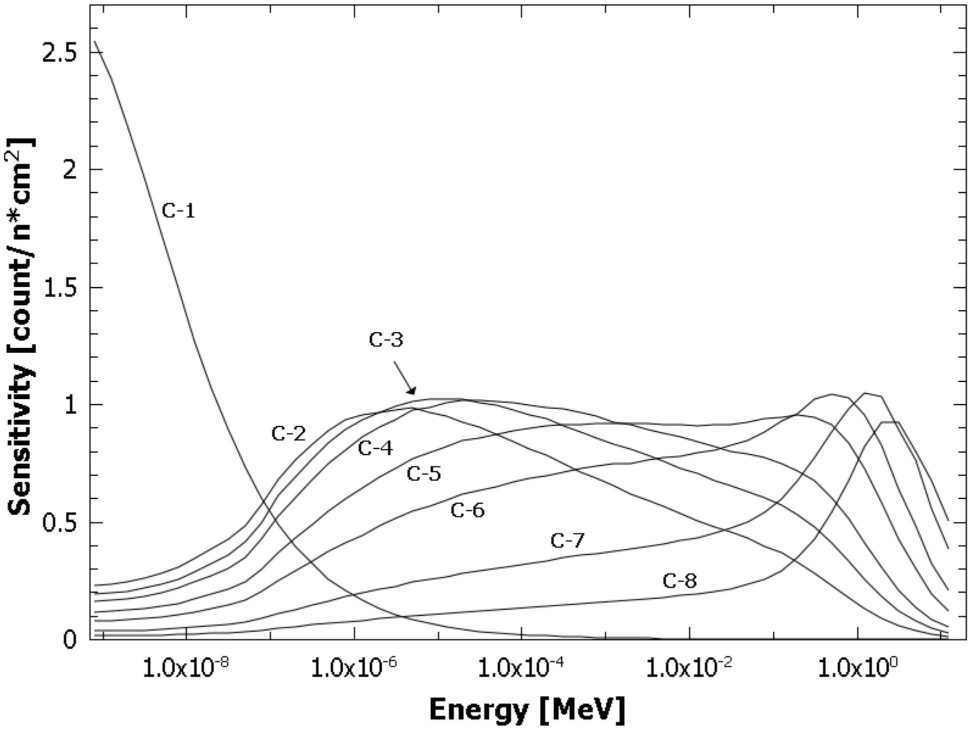

Figure 1: Typical response functions. The curve labelled C-1 corresponds to bare He-3 detector while C-2 to C8 corresponds to increasing amounts of HDPE moderator, from 0.2 to 8 kg.

A complex mathematical unfolding process must be performed in order to obtain a neutron energy spectrum in 52 energy groups from 8 measurements. Various codes are available for this task. The results presented in this paper were obtained by unfolding the data with the StaySL algorithm [7].

The curves in Figure 1 are for the new device described in this paper. However, the spherical counters have much the same shape in response. C-2 would correspond to the smallest sphere, 3”, while C-8 corresponds to the 10” sphere. Typically, the maxima in the response corresponds to 1 to 4 detector counts for unit fluence (counts*cm^2). This yields detector counting rates of 70 to 300 cps in a ^{252}Cf field of 0.1 mSv h^{-1}. Thus, data of very high statistical quality can be acquired in a few minutes. The main advantage of the BSS is its high sensitivity to the whole neutron energy range of interest. The disadvantage of the system is its weight, over 16 kg for the spheres plus the electronics, and its volume, i.e. number of parts that must be carried. In addition, the actual handling of the spheres and detector in an operational setting is tedious.

The new spectrometer described in this paper, preserves the advantages of the BSS while reducing some of the inconvenience. It is hoped that such a device will find more routine use for neutron field characterization than the existing BSS.

2. Nested neutron spectrometer (NSS)

2.1 Design principles

A picture of the new instrument is shown in Figure 2. The design principles were the following. The system is a BSS-type spectrometer where the necessary amount of moderator is built up by adding shells of moderator to produce all the configurations from the smallest moderator volume, to the largest. Thus, the user only needs to carry a moderator of a weight equivalent to that of the largest sphere of the BSS, i.e. about 8 kg. For operational convenience and ease of fabrication, the spherical shape was abandoned in favour of cylindrically shaped moderator. The He-3 counter is also cylindrical in shape.

Fifty years ago, the original BSS was built around spherically shaped moderators in order to ensure that the instrument would have a response independent of the direction of incidence of the neutrons. The new cylindrical instrument was designed using numerous Monte Carlo simulations until a diameter to length ratio for each cylinder was found to provide nearly angular independent responses. Finally, small air gaps of 0.5 to 1 mm were allowed between the vertical sides of nested cylinders to facilitate the insertion and extraction of the cylindrical shells into each other. This allows for a quick modification of the configuration during field measurements.

Figure 2: Pictures of the cylindrical shells (left) and the He-3 counter inserted into the 0.2 kg cylinder (right).

2.2 Simulation results and device details

A prototype was built around the model 25185 Helium-3 counter by LND Inc. The main characteristics of the detector are a gas pressure of 2 atm, and a sensitive diameter and length of 15.5 and 23.9 mm, respectively. The cylindrical moderating shells were of such thickness as to reproduce approximately the mass of the spheres of a traditional BSS when nested one into the other. Pictures of some of the cylinders are shown in Figure 2. The smallest cylinder, with an aperture large enough for the He-3 counter, has a mass of plastic of ~200 g. When all shells are inserted one into the other, the whole assemble has a mass of ~8 kg. Hence, by removing shells, a moderating assembly with variable moderator in the range of about 0.2 to 8 kg can be assembled. The fully assembled detector has both heights and diameter of 22 cm. The response functions of this system were shown in Figure 1. The labels on the curves refer to the configurations listed in the first column of Table 1.

The most important feature of the sets of shell is that, for each configuration, the diameter and height have been optimized to offer angular isotropic response to the neutrons. This was realized by modeling each configuration using MCNP$^{\text{TM}}$ [8]. For each external cylindrical volume, multiple Monte Carlo runs were performed for 52 energies and 5 angles of incidence. After each set, the outer diameter and length of the cylindrical moderator was adjusted iteratively until the best angular independence was achieved. The counts were tallied in the He-3 gas as the number of $He^3(n,p)H^3$ reactions. As an example, Figure 3 gives the final response for the configuration where the He-3 counter is surrounded by the first 3 smallest cylinders. This configuration is approximately equivalent to the 4" sphere of the BSS. The angle of incidence is measured with respect to the axis of the cylinder. We observe that only for an incidence directly on the flat part of the cylinder is the response depressed. Note that for angles of 22.5° or greater, equivalent to 93% of the solid angle of incidence, the response is nearly independent of angle. Similar results are found for all moderator thicknesses. The various moderator configurations for this new instrument are listed in the columns 1 and 2 of Table 1. The aspect ratios, i.e. the diameter to length ratio, of the cylinders that lead to isotropic responses are near unity.

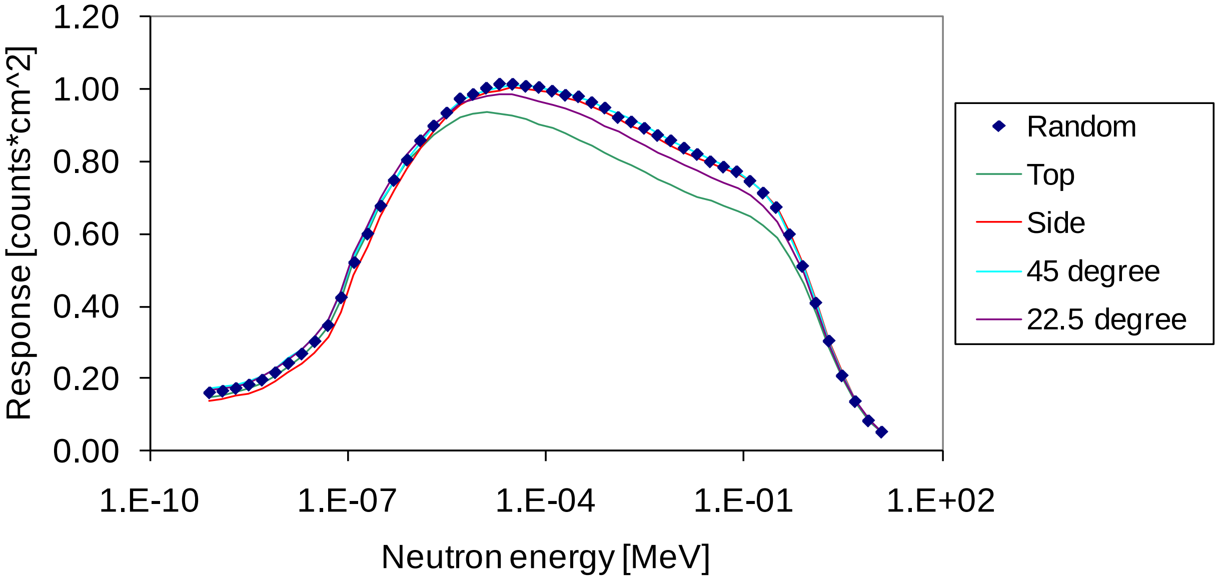

Figure 3: Energy and angular response for the He-3 counter surrounded by the 3 smallest cylinders.

3.0 Experimental measurements

The response of the Nested Neutron Spectrometer was tested using the bare ^{252}Cf source of the Neutron Irradiation Facility at AECL Chalk River. These early tests consisted in the probing of the isotropy of the response of the NNS for the available field and a direct comparison to the

AECL spherical system for the available field. Measurements were taken with standard low noise spectroscopy electronics and with a Ludlum 2241 hand held meter and scaler.

3.1 Response of the NSS for two angles of incidence

The NSS was positioned at 2m from the ^{252}Cf source and 8 counts were acquired for each of the 8 cylindrical moderator configurations (see column 1 of Table 1). The data was acquired for the neutrons incident on the curved side of the cylindrical moderator, i.e. with the instrument upright on its flat end. Next, the measurements were repeated for the detector lying on its side in order for the neutrons to be primarily incident on the flat bottom part of the cylindrical moderator. The raw count rates, due to the source with a neutron output rate of $4.33\text{x}10^7$ n s^{-1}, are displayed in Table 1. We observe that the count rates are the same for both orientation are in agreement to better than 0 to 2%.

Table 1: Count rates at 2 m for all NSS configurations for two directions of incident

Configuration	Neutrons incident on curved side [cps]	Neutrons incident on flat side [cps]	Response ratio curve/flat
C-1: Bare detector	20 ± 0.9%	20 ± 0.9%	1.01
C-2: 1st cylinder	57 ± 0.5%	56 ± 0.5%	1.01
C-3: Cyl. 1 into 2	72 ± 0.5%	72 ± 0.5%	1.00
C-4: Cyl 1, 2 and 3	86 ± 0.4%	86 ±0.4%	1.01
C-5: Cyl. 1 to 4	106 ± 0.4%	104 ± 0.4%	1.02
C-6: Cyl. 1 to 5	114 ± 0.4%	114 ± 0.4%	1.01
C-7: Cyl. 1 to 6	101 ± 0.4%	100 ± 0.4%	1.00
C-8: Cyl. 1 to 7	75 ±0.5%	75 ± 0.5%	0.99

3.2 Comparison of the NSS to the BSS

The data of Table 1 for the NSS and similar data for the BSS were used to generate the unfolded ^{252}Cf fission spectra as measured 2 m away from the source. Both unfolded spectra are shown in Figure 4 and they are compared to the theoretical ^{252}Cf spectrum. Both instruments are in agreement. They both show the unscattered component of the spectrum as well as a continuum of degraded energies. This second component is present because the NIF is not a low scatter facility and that both the source and the spectrometers were located 1.2 m from the floor.

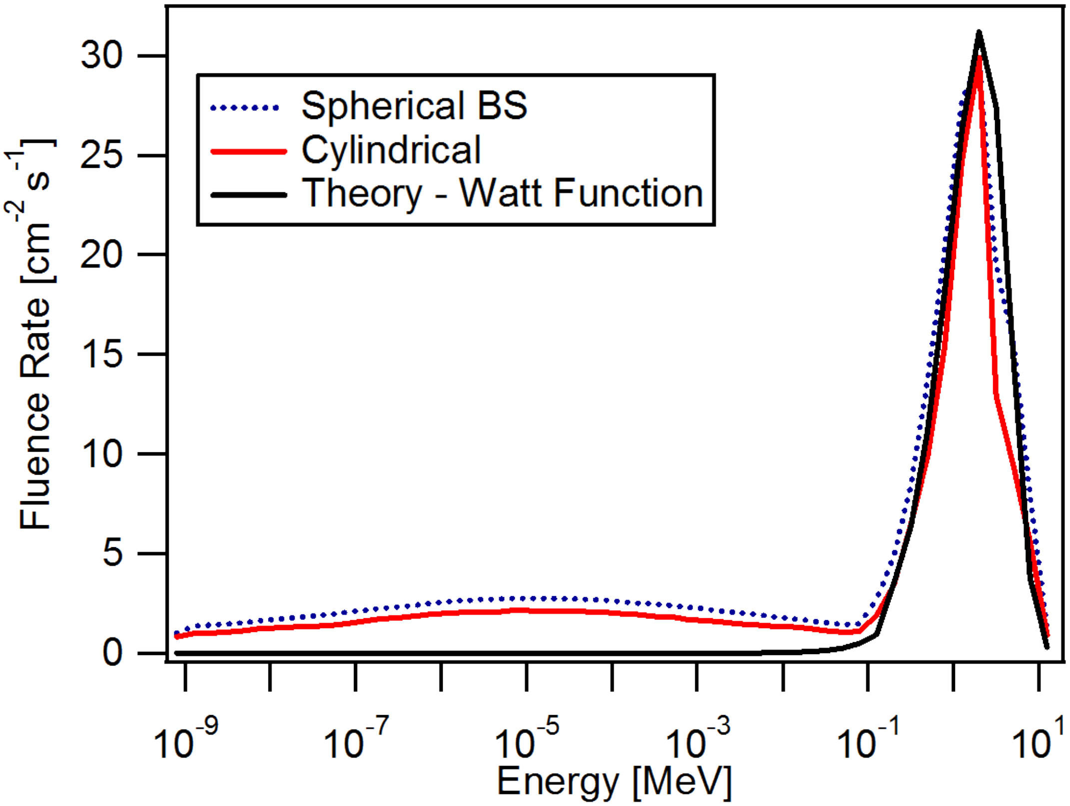

Figure 4: ^{252}Cf fission neutron spectrum measured by the NNS and the BSS located 2 m away from the source. The measurements are compared to the theoretical spectrum.

4.0 Discussion

The results for the new spectrometer are promising. It apparently exhibits the required angular independence in response. However, the measurement conditions may have been "optimistic" due to the presence of a scattered component of the neutrons.

The new NSS is a spectrometer in a convenient single unit package and the cylinders can easily be positioned upright on a flat stand. The successive handling to the NSS and the tradition BSS quickly revealed to the authors that the configuration of the NSS can be modified quickly and that a complete set of 8 measurements could be realized more quickly in the demanding environment inside the containment building of a nuclear power plant. In addition, the whole spectrometer, when used in conjunction with handheld counting electronics, becomes as simple to carry around as a REM meter while offering much more information.

5.0 Conclusion

The design principles, simulated response and first measurements of a new moderated neutron spectrometer were presented. The new instrument should be much more convenient to use than a traditional Bonner Sphere System in an operational setting. It is hoped that this advance in portable neutron spectrometer will result in a more widespread use of the technique. Work will continue to characterize the instrument in other neutron environments.

6.0 References

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