DOI: 10.15669/pnst.4.400

Progress in Nuclear Science and Technology
Volume 4 (2014) pp. 400-403

ARTICLE

Development of a neutron standard field using a heavy-water moderated ^{252}Cf source at NMIJ-AIST

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A neutron standard field using a heavy-water moderated ^{252}Cf source has been developed at the National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology. It can produce an energy distribution consisting of a remaining spontaneous fission spectrum and a slowing-down continuum to the low-energy region, which is similar to that present in real workplaces at nuclear facilities. The heavy-water moderated ^{252}Cf source and irradiation system includes shadow cones for measurements of scattered neutrons, and was designed using Monte-Carlo simulations based on the MCNPX code. The field was characterized using detector measurements and the results were compared to calculations. A fluence measurement was performed using a 6” Bonner sphere detector and the result agreed with the calculation to within the experimental uncertainty. In addition, a spectral measurement was carried out using a Bonner sphere spectrometer and the unfolding method and the unfolded spectrum was found to be in good agreement with the calculated spectrum.

Keywords: neutron standardization; calibration; ISO 8529; heavy-water moderated ^{252}Cf source; radiation protection equipment

1. Introduction

Neutron survey meters used for radiation protection in nuclear related facilities need to be adequately calibrated in a well-characterized calibration field. The spectra of neutron fields in actual workplaces at nuclear related facilities are different from those of calibration fields produced by the common bare radionuclide sources ^{241}Am-Be and ^{252}Cf. The former consists of a remaining spontaneous fission spectrum and a slowing-down continuum to the low-energy region. In contrast, ^{241}Am-Be and ^{252}Cf radionuclide sources produce a peak at 4.16 and 2.13 MeV, respectively. To overcome this problem, a heavy-water-moderated ^{252}Cf neutron source is specified in ISO 8529 [1] and has been developed at a number of calibration laboratories [2-4]. The neutrons emitted from a bare ^{252}Cf source placed at the center of a heavy-water tank are scattered and moderated by the heavy-water, and a neutron spectrum similar to that in a nuclear-related workplace is produced outside the source assembly. The National Metrology Institute of Japan, National Institute of Advance Industrial Science and Technology (NMIJ-AIST) has developed a neutron standard field using such a heavy-water moderated ^{252}Cf source for use in addition to existing fields produced by bare ^{241}Am-Be and ^{252}Cf sources.

2. Construction of heavy-water moderated neutron field

2.1. Source assembly

The heavy-water moderated ^{252}Cf source consists of a standard ^{252}Cf source with an aluminum sustaining rod and an enclosed stainless steel heavy-water tank covered with a cadmium outer cover. A schematic of the source is shown in **Figure 1**. The cadmium cover is used to eliminate thermal neutrons. The ^{252}Cf source itself is encapsulated in a type-X1 stainless steel capsule with a nominal activity of 200 MBq. Its neutron emission rate was calibrated by means of a relative measurement against a standard ^{241}Am-Be source calibrated by the National Physical Laboratory in the UK [5]. The tank is 30 cm in diameter and weighs approximately 20 kg when it is filled with heavy water. It has a heavy-water inlet and a penetrating tube to load the ^{252}Cf source. The isotropic enrichment of the heavy water is more than 99.9 %.

The cadmium cover was assumed to have a uniform thickness of 0.6 mm. The hemispherical cadmium shell was cast from flat sheets and its average thickness was estimated based on thickness measurements at several different positions.

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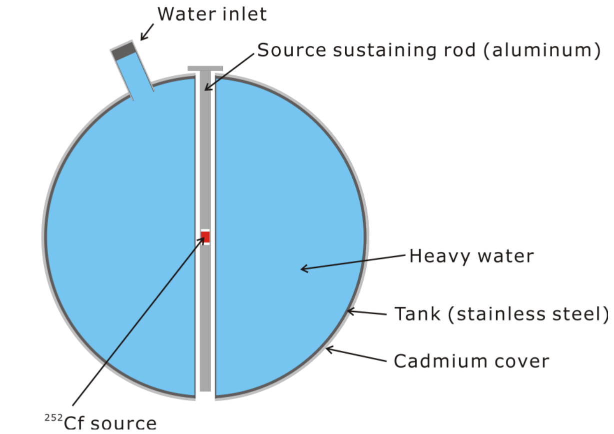

Figure 1. Heavy-water moderated ^{252}Cf source assembly at NMIJ-AIST.

2.2. Irradiation room and settings

The heavy-water moderated ^{252}Cf source assembly was set at the center of a concrete-walled cubic irradiation room (11.5 m × 11.5 m × 11.5 m). An aluminum grating floor is used for reducing the amount of scattered neutrons. This irradiation room is also used for calibrations and experiments related to radionuclide-sourced neutrons and accelerator-produced monoenergetic neutrons.

The mount for the source assembly was designed to minimize the effects of neutron scattering, within design limits imposed by the need of matching with an existing base mount used for experiments with bare neutron sources.

The shadow-cone method was adopted to estimate the effect of scattered neutrons. The accuracy of this method strongly depends on the geometry of the shadow cones. Three types of shadow cones were carefully designed and fabricated for use with representative detectors. There are also issues related to the size, weight and cost of shadow cones because of the large diameter of the source assembly. High-density polyethylene was used for the shadow cone material after verifying its shielding ability using MCNPX calculations [6].

3. Characterization of heavy-water moderated neutron field

3.1. Calculation by MCNPX

3.1.1 Calculation conditions

The spectral fluence of the heavy-water moderated ^{252}Cf source was calculated using the MCNPX code with various settings. The geometric model of the source assembly used in the calculations is shown in **Figure 2.** The spectral fluence was determined using point tally that were a distance of 150 cm from the geometrical center of the source assembly. In an actual calibration, the response of the detector is defined as its count rate divided by the neutron fluence at the effective center of the detector. **Figure 3** shows the calculated moderated spectral fluence compared with the bare ^{252}Cf source spectrum. The effect of thickness variation in the cadmium shell was also investigated but this was found to have little effect on the calculated spectrum for shell thicknesses greater than 0.3 mm.

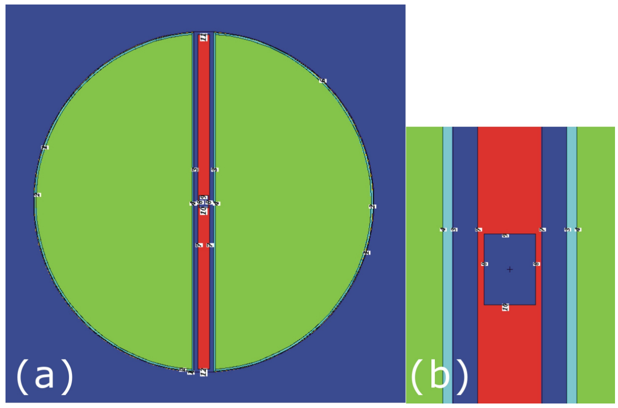

Figure 2. Geometric model of the source assembly for MCNPX calculations; (a) overall geometry and (b) close-up of the ^{252}Cf source. The components are the ^{252}Cf neutron source, aluminum sustain rod, heavy water, stainless steel tank and cadmium shell.

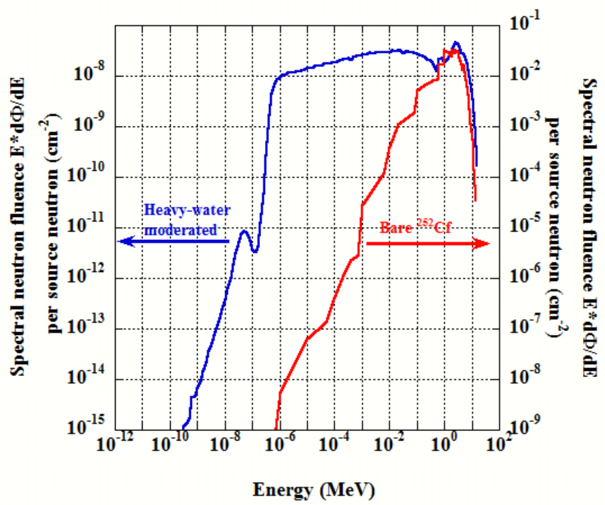

Figure 3. Calculated heavy-water moderated neutron spectrum (blue line). Red line shows the bare ^{252}Cf source spectrum.

3.1.2 Evaluation of shadow cones

Calculations were carried out to evaluate the shielding abilities of shadow cones. The geometric setup for the calculations is shown in **Figure 4**. The penetrating neutron spectral fluence behind a simple shadow cone made from 50-cm-thick high-density polyethylene (curve (b) in **Figure 5**) was compared with that behind a common shadow cone with a 20-cm-long section made from iron and a 30-cm-long section made from boron-doped high-density polyethylene (curve (a) in Figure 5), as recommended in ISO 8529 [7]. With the former design, an increase in the number of thermal neutrons was observed. Although the number of thermal neutrons was reduced by the boron doping of the polyethylene (curve (c) in Figure 5), this increases the cost. As an alternative, the addition of a 1-mm-thick sheet of cadmium on the downstream edge of the 50-cm-thick polyethylene (curve (d) in Figure 5) was considered, but found to be ineffective. However, in terms of the effect on a calibration, the contribution of thermal neutrons behind the 50-cm-thick high-density polyethylene shadow cone was only 1 % in terms of dose. Therefore, as mentioned in section 2.2, a shadow cone made from this material was used.

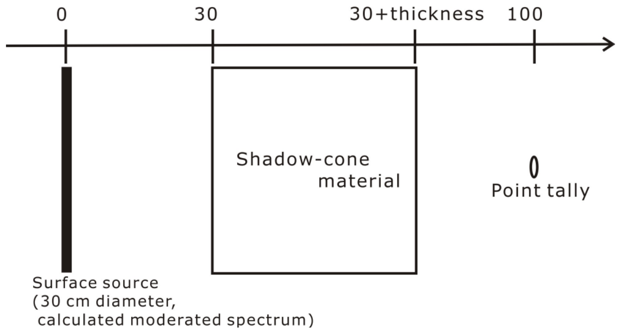

Figure 4. Calculation conditions for evaluating shielding ability of shadow cones.

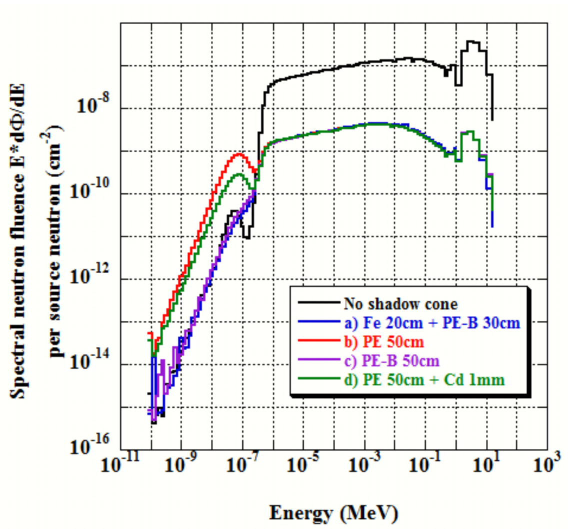

Figure 5. Penetrating spectral neutron fluence behind different shadow cones with a heavy-water moderated ^{252}Cf source.

3.2. Characterization experiment

3.2.1 Fluence measurement

The results of a fluence measurement using a 6” Bonner sphere consisting of a ^{3}He spherical proportional counter (Centronic Ltd., SP9) and a 6-inch-diameter high-density polyethylene moderator are shown in **Table 1**. The Bonner sphere was set 150 (149.57) cm from the center of the source. The measured value agrees with the value determined from the calculated spectral fluence of the field and the response function of the Bonner sphere using MCNPX code. The absolute value of the response of the Bonner sphere was adjusted to agree with the results of calibrations performed using standard bare ^{241}Am-Be and ^{252}Cf sources. The uncertainty in the measurement arises mainly from the estimated response of the 6” Bonner sphere (5.2 %), the emission rate of the ^{252}Cf source (1.6 %), geometrical settings such as the distance between the source and the detector (0.4 %), the reliability of the shadow-cone method (5.3 %) and statistical uncertainties (0.9 %). Uncertainties for the calculated value in the geometrical modeling and of the cross-section data are currently under evaluation.

The ratio of the neutron emission rate of the moderated source assembly and the bare ^{252}Cf source is an important parameter for characterizing the moderated neutron field and it depends on the details of the source assembly. In this study, the ratio was 0.911, which is in reasonably good agreement with previously reported values [8]. Additional measurements using a flat-response detector [9] are also planned.

Table 1. Result of the fluence measurement.

	Neutron fluence Φ per source neutron (cm^{-2})
Experiment	$(3.08\pm0.24)\times10^{-6}$
Calculation	3.23×10^{-6}

3.2.2 Spectral measurement

Spectral evaluation using a Bonner sphere spectrometer and the unfolding method was also performed at the distance of 150 cm from the center of the source. In this study, bare, 3”, 3.5”, 4”, 4.5”, 5” and 6” spheres were used. The default spectrum was the spectral fluence calculated using MCNPX. The MAXED code [10] included in the UMG package version 3.3 was used for the unfolding procedure. **Figure 6** shows the unfolding results together with the default spectrum, and it can be seen that there is good agreement between the two. We also investigated the differences between the measured count rates and those expected based on the default spectrum and the response function for each sphere. The difference tended to be larger the smaller sphere. The highest difference was 7.8 % for the case of the bare SP9. A possible cause for this discrepancy is the thermal neutrons remaining behind the polyethylene shadow cone. For the bare SP9 detector, based on the calculated penetrating neutron spectral fluence and the response function, the effect of such thermal neutrons is 5 %. Further corrections for scattered neutrons that cannot be properly subtracted by the shadow-cone method is under consideration.

4. Conclusion

A heavy-water moderated neutron calibration field has been developed at NMIJ-AIST. The moderated neutron field was simulated using MCNP code. Shadow cones used for estimating the effect of scattered neutrons were designed and their shielding abilities were evaluated by MCNPX calculations. A fluence measurement was performed using a 6” Bonner sphere and the result agreed with the calculation to within the experimental uncertainty. Spectral measurement was performed using a Bonner sphere spectrometer and the unfolding method. Good agreement was found between the unfolded and calculated spectra. However, the effect of scattered neutrons that cannot be perfectly estimated using the shadow-cone method should be considered and corrected. Additional measurements will be performed in the near future. Uncertainties arising while calibrating commercial survey meters should also be considered.

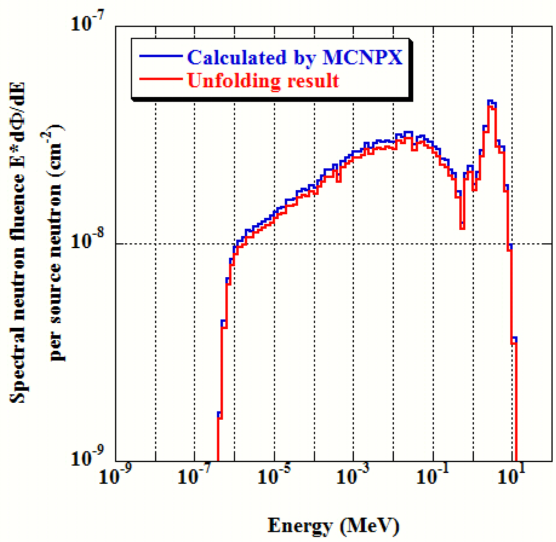

Figure 6. Result of the spectral fluence measurement using a Bonner sphere spectrometer.

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