Response matrix of a multisphere neutron spectrometer with an ^{3}He proportional counter

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The response matrix of a Bonner sphere spectrometer was calculated by use of the MCNP code. As thermal neutron counter, the spectrometer has a 3.2 cm-diameter ^{3}He-filled proportional counter which is located at the center of a set of polyethylene spheres. The response was calculated for 0, 3, 5, 6, 8, 10, 12, and 16 inches-diameter polyethylene spheres for neutrons whose energy goes from 10^{-9} to 20 MeV. The response matrix was compared with a set of responses measured with several monoenergetic neutron sources. In this comparison the calculated matrix agrees with the experimental results. The matrix was also compared with the response matrix calculated for the PTB C spectrometer. Even though that calculation was carried out using a detailed model to describe the proportional counter; both matrices do agree, but small differences are observed in the bare case because of the difference in the model used during calculations. Other differences are in some spheres for 14.8 and 20 MeV neutrons, probably due to the differences in the cross sections used during both calculations.

Keywords: Monte Carlo simulations; neutron transport; gas filled counters.

La matriz de respuesta de un espectrómetro de Esferas de Bonner ha sido calculada mediante el código MCNP. Como detector de neutrones térmicos se utilizó un contador proporcional de 3.2 cm de diámetro que se ubica en el centro de un conjunto de esferas de polietileno. La respuesta, ante neutrones de 10-9 a 20 MeV, se calculó para esferas cuyo diámetro es de 0, 3, 5, 8, 10, 12 y 16 pulgadas. La matriz de respuesta se comparó con un conjunto de respuestas determinado experimentalmente con varias fuentes de neutrones monoenergéticos. En esta comparación la matriz calculada coincide con los resultados experimentales. La matriz también se comparó con la matriz calculada para el espectrómetro PTB C donde el detector se modeló en forma detallada. De esta comparación, se observaron pequeñas diferencias debidas a que en esta investigación el detector se modeló en forma simple. Otras diferencias se observaron para algunas esferas y para neutrones de 14.9 y 20 MeV, la explicación probable de estas diferencias se atribuya a que en ambos cálculos se utilizaron versiones diferentes de los valores de las secciones eficaces.

Descriptores: Monte Carlo; transporte de neutrones; contador proporcional.

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1. Introduction

Since 1932 advances in neutron spectrometry, which has become an important tool in other fields such as nuclear technology, have promoted the development of nuclear physics, fusion plasma diagnostics, radiotherapy, and radiation protection. The introduction of the multisphere spectrometer together with the achievements in computer unfolding methods have produced advances in neutron spectrometry from 1960 to 1979. During this period, other notable developments have been the applications of semiconductor detectors to neutron spectrometry and the introduction of superheated drop detectors [1].

Since its introduction in 1960, the Bonner sphere spectrometer (BSS) [2], also known as multisphere spectrometer, has been the only instrument which enables the measurement of neutron spectra in a wide range of energies, from thermal up to at least 20 MeV [3]. By adding intermediate shells of high mass-number material to the moderator spheres, the spectrometer's response can be raised up to a few GeV [4,5].

The BSS consists of a set of polyethylene spheres of different diameter. At the center of each sphere a thermal neutron detector is located. Fast neutrons impinging on the sphere are moderated as they are transported inside the polyethylene, arriving in the sphere's center as thermal neutrons, where they are detected by the central counter [6].

In the original design, the BSS has a small cylindrical, 0.4 cm $\times$ 0.4 Ø cm ^{6}LiI(Eu) scintillator. However, thermoluminiscent dosimeters (TLD) [7-9], gold [10], and other activation foils [11], track detectors [12], and BF_3 [13] or ^{3}He [14] filled proportional counters have been used as thermal neutron detectors. The counters, that are most commonly used with BSS, detect thermal neutrons through the following exoenergetic nuclear reactions: ^{6}Li(n, α)^{3}H with Q = 4.78 MeV, and cross section 940 barns, ^{10}B(n, α)^{7}Li, which has a Q = 2.31 MeV (93%) or 2.79 MeV (7%) with a cross section of 3837 barns, and ^{3}He(n, p)^{3}H with Q = 0.764 MeV and cross section 5333 barns. In Fig. 1 the cross sections of these nuclear reactions are shown.

When the detector is located inside the polyethylene sphere the response is modified. This gives rise to an overall response function for each set of thermal neutron detector and moderating sphere; the response function is also known as response matrix [5].

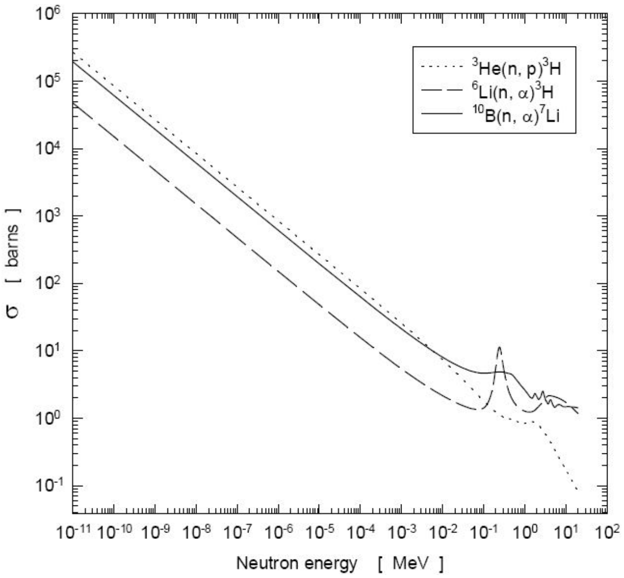

FIGURE 1. Cross sections of the most commonly nuclear reactions used in BSS to detect thermal neutrons.

The detector's count rate (C), response matrix (R_Φ (E)), and the neutron spectrum (Φ_E(E)) are related through the Fredholm integral equation of the first kind

$$C = \int_{E_i}^{E_f} R_\Phi(E)\ \Phi_E(E)\ dE \qquad (1)$$

Once the neutron spectrum is obtained, the dose equivalent, H, is calculated using equation (2)

$$H = \int_{E_i}^{E_f} h_\Phi(E)\ \Phi_E(E)\ dE \qquad (2)$$

Here h_Φ (E) represents the fluence-to-dose equivalent coefficients [15]. Other kind of doses are obtained using proper fluence-to-dose coefficients.

It is highly desirable to determine the response matrix experimentally by use of monoenergetic neutrons. However, this is only practical for few monoenergetic neutrons with energies greater than a few keV, and for thermal neutrons [6]. Therefore the responses have been determined by means of calculations using the one-dimensional discrete ordinates transport code (ANISN) calculations [16], or Monte Carlo methods with the MCNP code [17,18] and high-energy codes [4,5].

In this investigation, the response matrix of a Bonner spectrometer with a ^{3}He filled proportional counter has been calculated using Monte Carlo methods with updated cross section libraries. This matrix was compared with experimental and calculated responses.

2. Methods

The model SP90 is a commercially available 3He-filled spherical proportional counter that is used as thermal neutron detector in BSS. It is 3.2 cm in diameter, and is made by Centronic Ltd, UK. The response matrix of a BSS with this particular counter has been experimentally determined [19].

Using the Monte Carlo code MCNP 4C [20], the thermal neutron detector and polyethylene spheres were modeled and the response matrix was calculated. The proportional counter was modeled as a hollow sphere filled with ^{3}He at 200 kPa with 4.9431 x 10^{19} ^{3}He atoms per cm^3. The gas enclosure was modeled as a spherical shell with 1.60 cm inner radius and 1.65 cm outer radius, made of stainless steel. The counter wall composition was 70.5% Fe, 19.5% Cr and 10% Ni. Cross sections were obtained from the ENDF/B-VI library [21].

Moderating spheres were modeled as 0.946 g-cm^{-3} polyethylene-spheres. Chemical binding and crystalline effects of polyethylene during thermal neutron scattering were taken into account using the S(α , β) treatment [20]. A disk-shaped source term with the same diameter as the moderating sphere was used to represent a monoenergetic neutron source whose neutrons were directed towards the polyethylene sphere.

During the neutron transport calculation, three nuclear reactions, (n, total), (n, n') and (n, p), occurring inside the active volume of the detector, were determined. The spectrometer's response was defined only through the (n, p) reactions per neutron emitted by the source term. Polyethylene spheres were modeled as a series of concentric polyethylene shells, each with a different neutron importance, increasing as the sphere center was approached. This was the only variance reduction technique used in the calculations. Throughout the MCNP calculations, the number of histories used for each sphere was long enough to have uncertainties less than 1%.

The responses were calculated for 27 neutron energies ranging from 10^{-9} to 20 MeV. Diameters of moderating spheres were 0, 7.62, 12.70, 15.24, 20.32, 25.40, 30.48, and 40.64 cm, *i.e.* 0, 3, 5, 6, 8, 10, 12 and 16 inches, respectively.

3. Results and Discussion

In Fig. 2, the response functions for 0, 3, 5, 6, 8, 10, 12, and 16 inches-diameter polyethylene spheres as a function of neutron energy are shown. The bare detector (^{3}He proportional counter without moderator) has the maximum response for 10^{-9} MeV neutrons and the minimum response for 20 MeV neutrons; between these two extremes the response is approximately 1/v. As the sphere's diameter increased the response tends to decrease for thermal and epithermal neutrons. On the other hand, the maximum in the responses is shifted to higher energies for large spheres. This, agrees with the work of Thomas [25], and Wigel, and Alevra [14]. The calculated discrete set of responses is shown in Table I.

TABLE I. Responses, in reactions per unit fluence, for each sphere in function of neutron energy.

Energy [MeV]	0 [cm]	7.62 [cm]	12.70 [cm]	15.24 [cm]	20.32 [cm]	25.40 [cm]	30.48 [cm]	40.64 [cm]
1.000E-09	6.289E+00	5.876E-01	2.807E-01	1.850E-01	7.607E-02	2.922E-02	1.068E-02	1.207E-03
4.140E-07	1.029E+00	2.443E+00	1.312E+00	8.666E-01	3.501E-01	1.337E-01	4.972E-02	6.011E-03
6.826E-07	8.161E-01	2.597E+00	1.466E+00	9.698E-01	3.946E-01	1.497E-01	5.515E-02	6.914E-03
1.445E-06	5.730E-01	2.731E+00	1.667E+00	1.114E+00	4.543E-01	1.728E-01	6.428E-02	7.957E-03
3.059E-06	4.000E-01	2.779E+00	1.846E+00	1.246E+00	5.096E-01	1.944E-01	7.203E-02	9.052E-03
6.476E-06	2.781E-01	2.780E+00	2.004E+00	1.374E+00	5.648E-01	2.158E-01	7.943E-02	9.834E-03
1.371E-05	1.929E-01	2.689E+00	2.118E+00	1.475E+00	6.118E-01	2.336E-01	8.481E-02	1.056E-02
2.902E-05	1.336E-01	2.566E+00	2.211E+00	1.561E+00	6.573E-01	2.516E-01	9.258E-02	1.171E-02
6.144E-05	9.278E-02	2.424E+00	2.278E+00	1.638E+00	6.978E-01	2.671E-01	9.778E-02	1.237E-02
1.301E-04	6.442E-02	2.267E+00	2.327E+00	1.710E+00	7.391E-01	2.847E-01	1.051E-01	1.360E-02
2.754E-04	4.488E-02	2.106E+00	2.367E+00	1.769E+00	7.800E-01	3.021E-01	1.113E-01	1.417E-02
5.929E-04	3.115E-02	1.952E+00	2.386E+00	1.825E+00	8.211E-01	3.192E-01	1.176E-01	1.510E-02
1.234E-03	2.211E-02	1.805E+00	2.402E+00	1.875E+00	8.548E-01	3.375E-01	1.236E-01	1.551E-02
2.613E-03	1.571E-02	1.658E+00	2.408E+00	1.920E+00	8.995E-01	3.583E-01	1.321E-01	1.629E-02
5.531E-03	1.126E-02	1.523E+00	2.404E+00	1.963E+00	9.472E-01	3.782E-01	1.405E-01	1.768E-02
1.171E-02	8.227E-03	1.394E+00	2.406E+00	2.011E+00	9.947E-01	4.053E-01	1.502E-01	1.915E-02
2.479E-02	6.151E-03	1.269E+00	2.423E+00	2.087E+00	1.074E+00	4.439E-01	1.655E-01	2.072E-02
5.247E-02	4.569E-03	1.148E+00	2.464E+00	2.197E+00	1.193E+00	5.023E-01	1.905E-01	2.441E-02
1.111E-01	3.418E-03	1.011E+00	2.529E+00	2.381E+00	1.391E+00	6.114E-01	2.373E-01	3.024E-02
2.237E-01	2.736E-03	8.468E-01	2.582E+00	2.605E+00	1.694E+00	8.115E-01	3.301E-01	4.296E-02
4.508E-01	2.425E-03	6.466E-01	2.529E+00	2.786E+00	2.149E+00	1.182E+00	5.381E-01	8.505E-02
9.072E-01	2.397E-03	4.355E-01	2.251E+00	2.757E+00	2.593E+00	1.755E+00	9.738E-01	2.192E-01
1.872E+00	2.731E-03	2.481E-01	1.704E+00	2.346E+00	2.763E+00	2.323E+00	1.640E+00	6.212E-01
3.679E+00	2.323E-03	1.277E-01	1.075E+00	1.611E+00	2.213E+00	2.187E+00	1.815E+00	9.658E-01
7.408E+00	1.630E-03	5.789E-02	6.015E-01	9.934E-01	1.621E+00	1.931E+00	1.924E+00	1.519E+00
1.492E+01	9.629E-04	2.768E-02	3.072E-01	5.323E-01	9.642E-01	1.255E+00	1.389E+00	1.370E+00
2.000E+01	7.411E-04	1.884E-02	2.174E-01	3.832E-01	7.219E-01	9.799E-01	1.122E+00	1.188E+00

Uncertainties are $\leq 1\%$

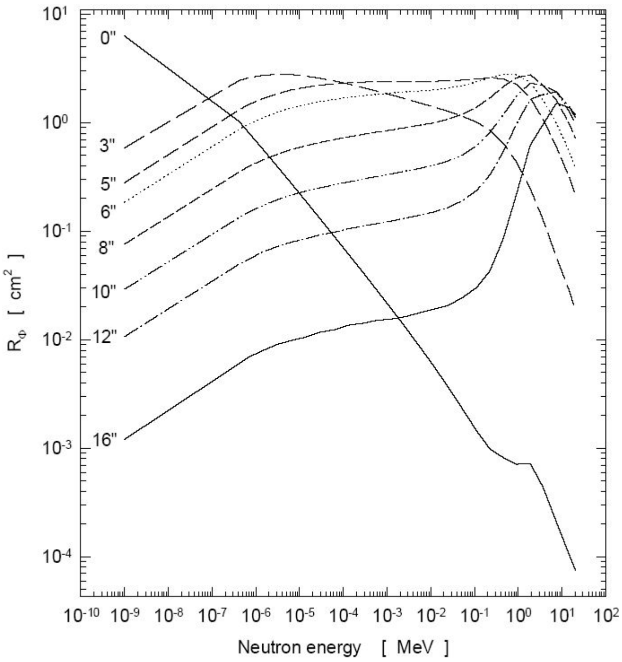

FIGURE 2. Calculated response matrix for BSS with ^{3}He detector.

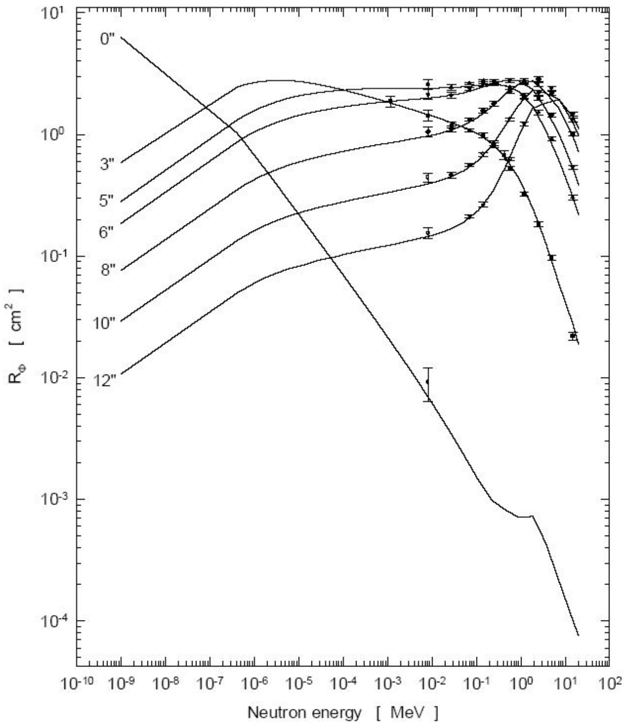

FIGURE 3. Calculated and measured responses for the BSS with ^{3}He detector.

Response functions are similar in shape independently of the thermal neutron detector, except for the bare case whose response is strongly influenced by the cross section. Thus for ^{6}LiI(Eu) and TLDs, there is a resonance between 0.1 and 0.5 MeV [17,18] due to the ^{6}Li cross section. Even though these are solid detectors, their responses go from 10^{-5} up to 0.2 cm^2, being smaller than those for the BSS with ^{3}He detector, whose responses go from 10^{-4} up to approximately 7 cm^2. This is mainly due to the differences between the ^{6}Li(n, α)^{3}H and ^{3}He(n, p)^{3}H cross section.

The calculated matrix was compared with a set of experimental values reported for a BSS with ^{3}He [19]. This comparison is shown in Fig. 3. Here the 16 inches-diameter sphere was not included because no experimental data are reported for it. For the bare detector, there is only a single response experimentally reported. By analyzing the calculated and measured responses, a good agreement was found. This matrix is better than the set of calculated responses used originally by Alevra *et al*. [19] to compare their experimental data.

The International Atomic Energy Agency has published two technical reports [22,23] in which the updated data about detector responses, using a consistent energy structure, were compiled. In this data set the response of a BSS with ^{3}He, known as PTB C, is shown. This response was calculated in 1993-1994 using a realistic detector model, and was taken here to compare it with the responses obtained in this work. In Fig. 4 continuous lines are the calculated responses compiled by the IAEA and discrete dots are the responses calculated in this study.

It can be seen from Fig. 4, that there are small differences between both calculated responses in the case of the bare detector. For other spheres there is a good agreement between both responses except for the two last neutron energies. In the case of the bare detector, the differences may be attributed to the details included in the model used in the PTB C cal-

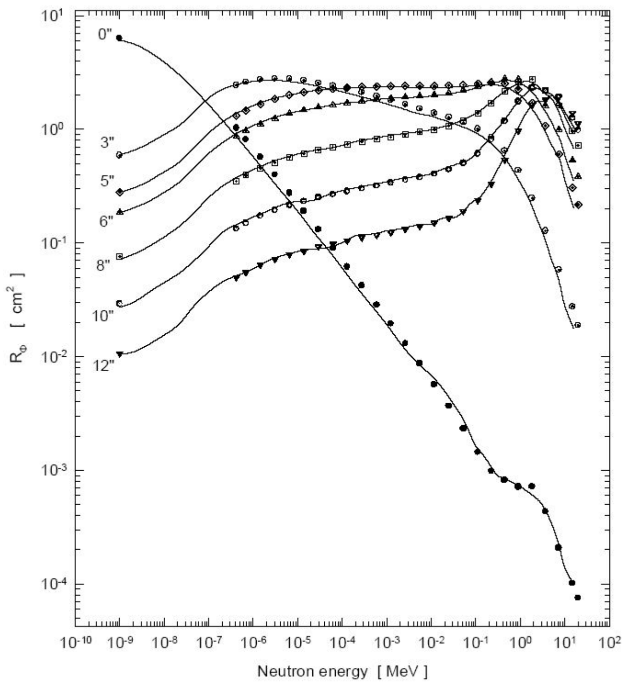

FIGURE 4. Calculated response matrices. Continuous lines are the calculated responses compiled by the IAEA and discrete dots are the responses calculated in this study.

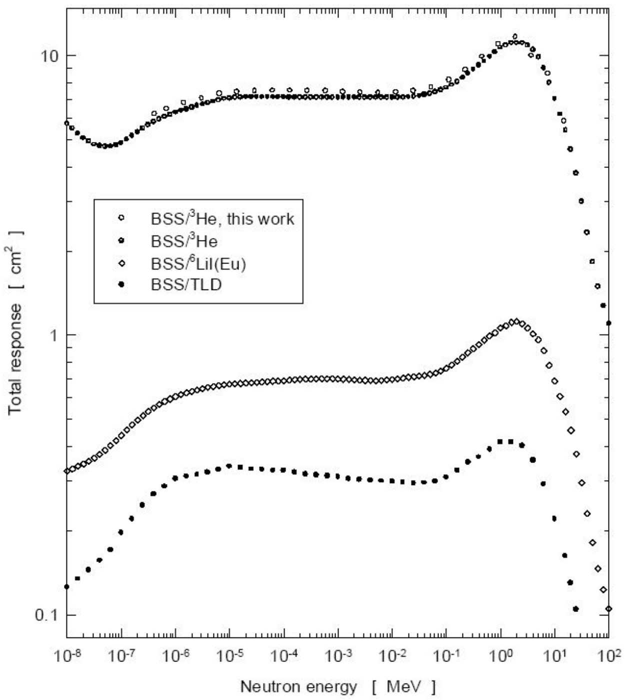

FIGURE 5. Total response of BSS with different thermal neutron detectors.

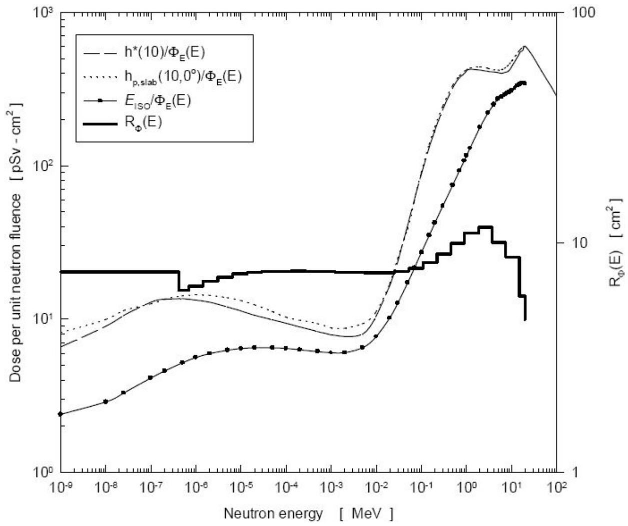

FIGURE 6. Neutron fluence-to-dose conversión coefficients and the BSS/^{3}He total response.

culations. For other spheres the differences observed are attributable to the differences in the polyethylene density and to the neutron cross sections used here in comparison with those used in the PTB C calculations, because between the ENDF/B-V and ENDF/B-VI cross section libraries there are significant changes [21].

The total response of BSS with ^{3}He [23], ^{6}LiI(Eu) [17] and TLD [18] as a function of neutron energy is shown in Fig. 5. Here it can be noticed that the total responses have similar shapes. However their amplitudes are different, being larger for ^{3}He and lower for TLD. This difference is due to the cross section and to the nuclei density. Regardless the neutron detector, the total BSS response is larger for neutrons between 1 and 10 MeV. These neutrons have the largest fluence-to-dose (personal and ambient) coefficients and are found in actual situations [9,10,24,26,27], as can be noticed in Fig. 6.

Here, the total response is plotted with the Ambient (h*(E)), Personal ($h_{p,slab}(10, 0^o)$) and Effective (E_{ISO}) dose per unit neutron fluence.[28]

4. Conclusions

The fluence responses for eight Bonner spheres have been calculated for neutrons from 10^{-9} to 20 MeV. The calculations have been performed using the MCNP 4C code and the ENDF/B-VI cross-section library. The $S(\alpha, \beta)$ scattering model was utilized during the transport of low energy neutrons.

The response matrix has been compared with a set of experimentally determined responses. From this comparison a good agreement was found.

Good agreement was also observed between our response matrix and the matrix calculated by other scientists, even when a simple model of the ^{3}He proportional counter was used in this work. However, small differences are observed for the bare detector in both calculated responses; differences are also noticed for 14.9 and 20 MeV neutrons, attributed to the cross sections used during the calculations and to the differences in the neutron detector model. Therefore, it is advisable that every time a cross-section library is updated, the response matrix of the BSS must be calculated in order to have data that allow measuring neutron fields with greater accuracy.

The total response for the BSS with different thermal neutron detectors was also determined. Approximately, the response has the same shape regardless the thermal neutron detector. This shape shows larger efficiency for those neutrons that have larger fluence-to-dose conversion coefficients. However, the total response's amplitude strongly varies with the type of thermal neutron detector due to the difference in the cross sections and the nuclei density.

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