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SELECTION OF NEUTRON-ABSORBING MATERIALS TO IMPROVE THE LOW-ENERGY RESPONSE OF A Zr-BASED EXTENDED NEUTRON MONITOR USING MONTE CARLO SIMULATIONS

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Monte Carlo simulations have been carried out using the FLUKA code to improve the neutron ambient dose equivalent [*H(10)] response of the ZReC (zirconium-lined portable neutron counter responding satisfactorily to neutrons up to 1 GeV) by introducing various neutron absorbers in the system such as cadmium, gadolinium, natural boron, enriched ^{10}B and borated polythene. It was found that ZReC can be effectively used as a portable neutron monitor by introducing any one of the following perforated layers: 5 mm thick natural boron, 0.5 mm thick enriched ^{10}B or 1 cm high-density polythene mixed with 50 % boron by weight. The integral response of the instrument was also calculated for some typical reference neutron fields. The relative ambient dose equivalent response of the said system is also found comparable with that of the existing LINUS neutron monitor.**

INTRODUCTION

The neutron spectrum in medium and high-energy ion accelerators usually extend beyond 20 MeV[1]. Routine neutron ambient dose equivalent [*H**(10)] measurements in such facilities are usually carried out using conventional neutron counters without *a priori* knowledge of the energy distribution. Such neutron monitors require to have a response that is similar to the shape of the ICRP fluence to *H**(10) conversion coefficient[2] (ICRP DCC) curve. However, the response of conventional neutron monitors are highly unsatisfactory for neutron energies beyond 15 MeV[3]. To overcome this limitation, extended neutron monitors have been developed to measure high-energy neutron *H**(10) in particle accelerator and in cosmic-ray environments[4–8]. These extended neutron monitors are based on the induction of (n, *x*n) reactions by a suitable metallic shell coupled with high-density polythene (HDPE). However, the introduction of the metallic shells makes it heavy to be used as a portable monitor. In the authors' earlier work[9], a new portable neutron counter (called ZReC) for high-energy neutron measurement was proposed, where a zirconium (Zr) spherical shell [17.8 cm (7 inch) internal diameter, 1 cm thick] was used as the converter. Monte Carlo simulations were carried out to optimise its design so as to reduce the weight without compromising its response to high-energy neutrons. The *H**(10) of ZReC was found to closely follow the ICRP *H**(10) values at high energies, i.e. from 10 MeV to 1 GeV while being portable also (approximate weight 10 Kg). However, the relative ambient dose equivalent response (RDER), defined here as the ratio of *H**(10) indicated by the instrument to ICRP DCC, at lower energies is found to be very high with a maximum value at 5 keV (~56 times over-response). This overestimation needs to be corrected by introducing neutron-absorbing materials in the moderating medium to match the ICRP values as closely as possible so that the instrument can be used to monitor irrespective of the incident neutron energy.

An extensive study has been reported by Leake *et al.*[10] on the overestimation of neutron *H**(10) by a spherical neutron monitor at lower energies and the methods that can be employed to improve it. Andersson-Braun type extended neutron monitors use perforated borated rubber for improving their responses at lower energy[4, 5]. Borated silicone rubber was chosen as the absorber to modify the WENDI-II neutron monitor response at intermediate energies[6] whereas the LB 6411-Pb neutron monitor uses perforated cadmium layer for this purpose[7, 8].

This paper discusses the results of Monte Carlo simulations carried out to reduce the over-response of the ZReC at lower energies, i.e. <10 MeV. Figure 1 presents the RDER of ZReC with respect to the ICRP DCC obtained in the authors' earlier work[9]. However, the RDER depends on the calibration points, and since the ZReC is intended to be used at higher energies, the calibration point was chosen as 14 MeV. As can be seen in Figure 1, the maximum deviation in the RDER occurs at ~5–10 keV and is in agreement with the observations by Leake *et al.*[10] In this work, attempts have been made to reduce the

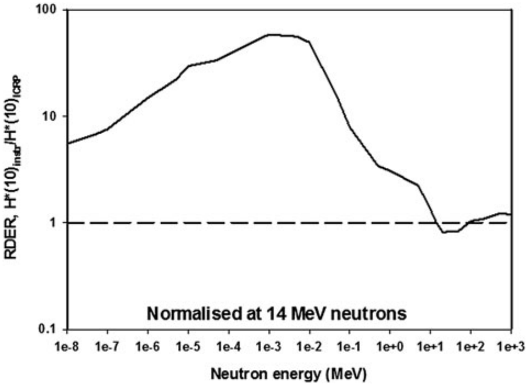

Figure 1. The relative ambient dose equivalent response, RDER, of the ZReC without neutron absorber layer.

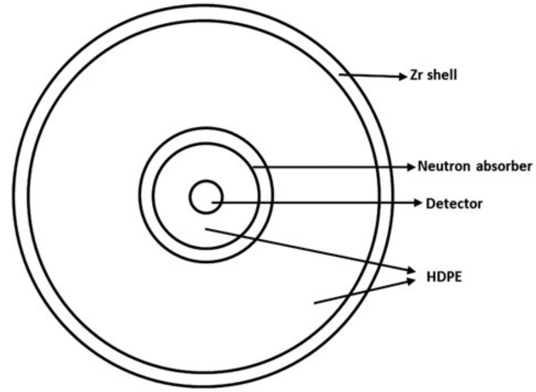

Figure 2. The simulated geometry of the ZReC with layer of neutron absorber.

RDER of the ZReC, particularly around this energy region, by using neutron-absorbing materials such as natural boron (B), cadmium (Cd) and gadolinium (Gd). The position of these absorbers inside the HDPE sphere and their thicknesses are systematically investigated. Since boron can be used in various forms often dictated by the ease of fabrication and cost, three different forms of it such as natural boron (B), enriched ^{10}B and boron-loaded HDPE (borated HDPE) were investigated in combination with perforations in it.

MONTE CARLO SIMULATIONS

The simulations were carried out using the Monte Carlo-based computer code FLUKA[11, 12]. The geometric configuration used in the simulation is presented in Figure 2. The simulated system consisted of the following four parts: (1) a spherical detector volume of 1 cm radius filled with air at the centre, (2) inner HDPE spherical shell moderator around the detector volume, (3) a neutron absorber surrounding the inner HDPE moderator shell and (4) an outer HDPE moderator shell and (5) the outermost 1 cm thick Zr shell. The position of the neutron absorbers (B, Cd and Gd) was changed by varying the thickness of the inner HDPE moderator, keeping the same value (19.8 cm) of the total diameter of instrument, to determine the optimal location.

Annular monoenergetic parallel beams of neutrons were applied normally incident on the detector system with the diameter of beam equal to the diameter of the HDPE sphere with Zr shell (19.8 cm). Neutron energy spectrum was scored inside the detector volume using track length estimator for incident neutron energies varying from 10^{-8} MeV to 1 GeV. The ^{6}Li detector response, R, was obtained as follows:

$$R = A \int \varphi(E)\sigma(E)\,\mathrm{d}E \qquad (1)$$

where $\varphi(E)\mathrm{d}E$ is the mean fluence (cm^{-2}) inside the volume at energy E and $E + \mathrm{d}E$, $\sigma(E)$ is the cross section (cm^{2}) and A is the area of the neutron beam (cm^{2}).

The value of the RDER at 5 keV, being always maximum[10], was chosen as the major indicator for the optimisation of the material, location, thickness and the number of perforations on the neutron absorber. As the absorber was introduced, the response at very low neutron energies also reduced and the RDER at 0.025 eV of neutron energy was calculated for every configuration. However, the absorber drastically reduced the response near thermal region, and simulations were performed with perforations (1 cm diameter) embedded uniformly throughout the absorber to improve the RDER near thermal energy region. Once the configuration was optimised in terms of the material, the location, the thickness and the number of perforations on it, the integral response (integral RDER) of the modified ZReC was obtained for five different types of neutron spectra covering a wide energy range and different shapes. This is because the integral response of a neutron monitor depends on the shape of the neutron spectrum[3], as the under- and over-responses tend to compensate each other depending upon the shape and fluence rate of the incident spectrum. In this work, neutron spectra from a bare ^{252}Cf spontaneous fission source, a D_2O-moderated ^{252}Cf spontaneous fission source, ^{241}Am-Be source and neutrons emitted from copper targets bombarded with 50 MeV and 1 GeV protons were used to study the RDER of the modified ZReC.

RESULTS AND DISCUSSIONS

Optimising the location of the absorber

To determine the optimal position of the absorber, the RDER at 5 keV was obtained by varying its location inside the moderator. This was done by changing the thickness of inner HDPE from 0 cm (i.e. absorber layer closest to detector volume) to 7 cm. The thickness of the absorber was kept as 0.05 cm. Figure 3 presents the RDER at 5 keV as a function of the thickness of inner HDPE moderator. From the figure, it is seen that the RDER value is the lowest when boron is placed after 2 cm of HDPE moderator. For Cd and Gd, the lowest RDER values were obtained by keeping them closest to the detector volume. With these absorber locations, the RDER of the ZReC extending from 0.025 eV to 1 GeV is shown in Figure 4. The RDER obtained at 5 keV, for all the absorbers, shows approximately the same value. Cd and Gd cut off the response drastically for very-low-energy neutrons (<10 eV) as compared with B. Therefore, it appears that B is a better choice for an overall improved response at very low energies. Furthermore, it is found that even after introducing the neutron absorbers, RDER value remains maximum at ~5–10 keV. This is similar to what has been observed by Leake *et al.*[10]

Selection of absorber material and thickness

Once the location of the absorber has been optimised, the effect of absorber thickness on the RDER was studied. In addition, Boron was chosen in three different forms, viz, natural boron layer (B), enriched ^{10}B layer and different borated HDPE (in terms of B percentage).

The RDER of modified ZReC at 5 keV with the thicknesses of various B absorbers is shown in Figure 5. The RDER at 5 keV with B layer shows a decreasing trend with increasing thickness whereas for Cd and Gd, they remain more or less unchanged. For a thickness of 0.5 cm of B, RDER is 4.6 at 5 keV incident neutron energy whereas the lowest RDER with Cd or Gd remains at 11.5. These results indicate the suitability of using B as absorber in ZReC. From the figure, it can be seen that the equivalent thickness of 0.5 cm B can be either 0.05 cm of ^{10}B or 1 cm thick borated HDPE of 50 % boron.

Effect of perforations in the Boron layer

The results presented in the previous section have shown the effectiveness of boron as the absorber. However, it can be seen that as the thickness of B absorber increases, response at very low energies reduces drastically. To compensate for this reduction, simulations were carried out with perforations embedded uniformly throughout the absorbers so that a fraction

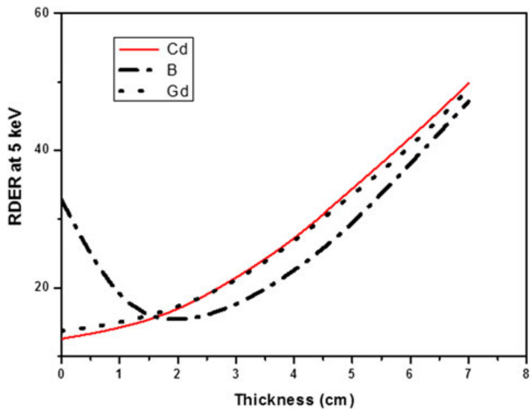

Figure 3. The relative ambient dose equivalent response, RDER at 5 keV incident neutron energy with 0.05-cm Cd, B and Gd absorber layer as a function of the various thickness of inner moderator (HDPE) from the central detector volume to the absorber layer.

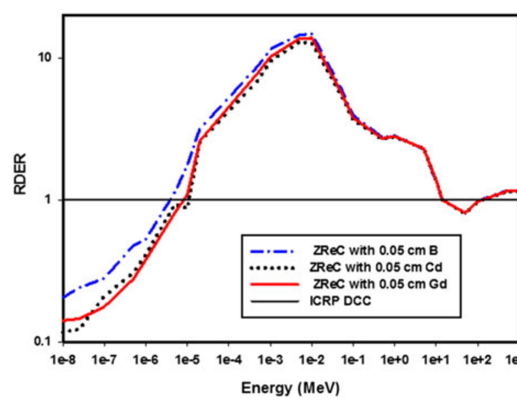

Figure 4. The RDER as a function of incident neutron energy of the original ZReC with 0.05 cm thick B, Cd and Gd layer.

of low-energy neutrons are allowed to reach the detector without interacting with the B layer. The simulations were made with 6, 12 and 24 holes of 1 cm diameter in the absorber, covering ~3, 5 and 12 percentage of the surface area, respectively. Table 1 shows the modified RDER with different number of perforations on (a) 0.5 cm thick B, (b) 0.05 cm thick ^{10}B and (c) 1 cm thick borated HDPE with 50 % B by weight. As can be seen in the table, with six perforations on 0.5 cm B layer, the RDER for thermal neutrons has increased to 0.4 (from nearly zero) and to 8.0 (from 4.6) at 5 keV. That is, 0.5 cm B layer with six holes provides eight times overestimation of $H^*(10)$ at 5 keV and 2.5 times underestimation at thermal

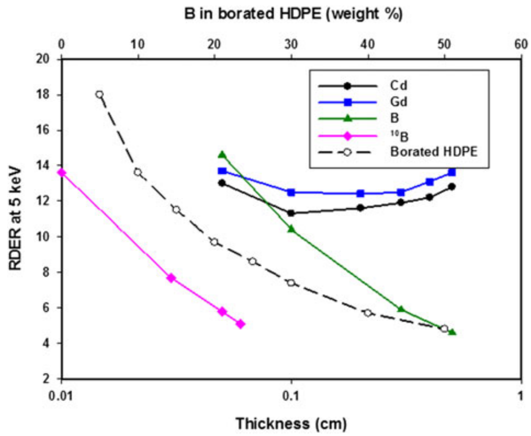

Figure 5. The variation of RDER at 5 keV incident neutron energy with varying thickness of Cd, B (natural boron) and Gd absorber layer and also 1 cm thick borated polythene with various percentage of natural boron.

Table 1. RDER values of ZReC at 5 keV and 0.025 eV with different perforated absorber layers.

Absorber material and thickness	Number of perforations	Fraction of area removed (%)	RDER at 5 keV	RDER at 0.025 eV
B, 0.5 cm	6	3.1	8.0	0.4
	12	6.1	11.9	0.8
	24	12.2	17.4	1.3
^{10}B, 0.05 cm	6	4.0	10.5	0.6
	12	8.0	15.9	1.3
	24	16.1	23.5	2.2
Borated HDPE, 50 %	6	2.3	7.0	0.3
	12	4.7	9.3	0.5
	24	9.4	14.3	0.7

energy. Similarly, with 0.05 cm thick ^{10}B, the response is 10.5 times higher at 5 keV and 1.6 times lower at thermal energy whereas 1 cm thick 50 % borated HDPE gives seven times overestimation at 5 keV and 3.3 times underestimation at thermal energy. As the number of perforations increases, more thermal neutrons enter the detector volume and the RDER at 5 keV shows an undesirable increase.

Figure 6 presents the modified RDER of the ZReC as a function of neutron energy with 1 cm thick 50 % borated HDPE, 0.5 cm B and 0.05 cm of ^{10}B absorbers, each with six perforations. In the figure, the RDER of the LINUS neutron monitor is included for comparison. It is found that the response of modified ZReC agrees well with the LINUS system, except for an under-response at neutron energies of <1 eV.

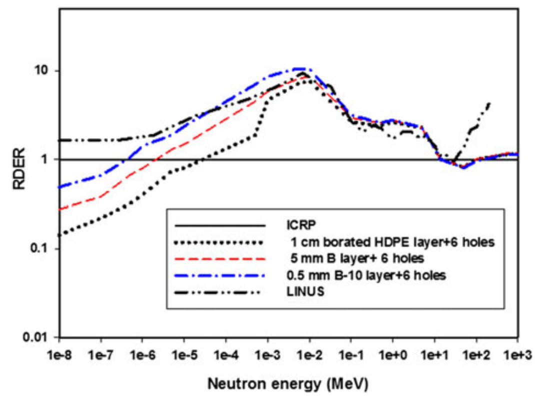

Figure 6. Modified RDER of ZReC with different perforated absorber layers and the Linus RDER for comparison.

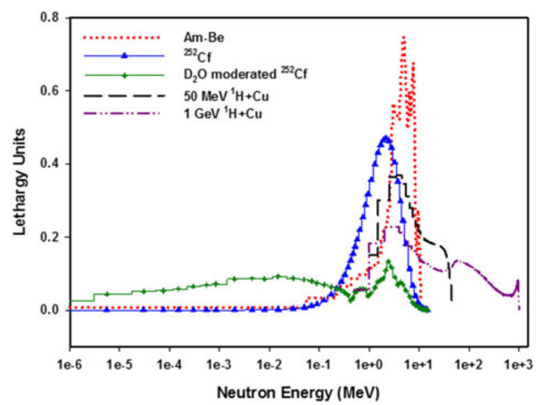

Figure 7. The neutron spectra used to generate the response of the original and modified ZReC.

Response of the instrument to various neutron spectra

The integral RDER of the modified ZReC was studied with the neutron spectra as mentioned previously. The neutron spectra from a bare ^{252}Cf source, D_2O-moderated ^{252}Cf source and ^{241}Am-Be source were obtained from ISO 8529-1[13]. The neutron spectrum from 50-MeV proton incident on a Cu target was calculated using the PRECO nuclear reaction model code[14] whereas the emission neutron spectrum from 1-GeV proton incident on a Cu target has been calculated as the emerging yield using the FLUKA code. These are shown in Figure 7. The emission from a D_2O-moderated ^{252}Cf-based source extends from thermal neutrons to ~11 MeV whereas the ^{241}Am-Be and the bare ^{252}Cf spectra are predominant above 0.1 MeV and up to 11 MeV. The neutron

Table 2. The integral responses of the original and modified ZReC for various neutron fields.

Neutron source	Initial RDER of original ZReC	Modified RDER [$H^*(10)_{instr}/H^*(10)_{ICRP}$]		
		50 % borated HDPE with six perforations	0.5 cm natural B with six perforations	0.05 cm ^{10}B with six perforations
0.025 eV	6	0.3	0.4	0.6
5 keV	56	7	8	10.5
^{252}Cf (D_2O moderated)	29.2	3.3	4	5.2
^{252}Cf	3.2	2.5	2.6	2.6
^{241}Am-Be	3.2	2.2	2.6	2.6
50 MeV ^{1}H + Cu	2.1	2.0	2.0	2.1
1 GeV ^{1}H + Cu	1.9	1.7	1.8	1.8

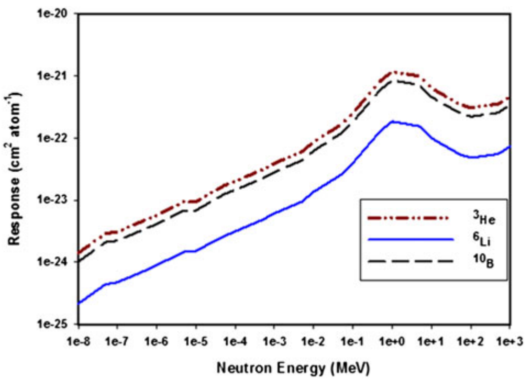

Figure 8. Comparison of response of ZReC with perforated 1 cm thick 50 % borated HDPE absorber layer when used with various detectors.

emissions from 50 MeV and 1 GeV protons incident on a Cu target starts from ~1 MeV. The integral RDER of the modified ZReC, obtained by folding the RDER with these normalised spectra, is shown in Table 2 along with the original un-modified ZReC response.

From the table, it can be seen that with the incorporation of the absorber, the RDER has improved significantly for incident neutrons of 0.025 eV, 5 keV and the D_2O-moderated ^{252}Cf spectra whereas a moderate improvement is observed for ^{252}Cf and ^{241}Am-Be sources. It is also observed that the modification has negligible effect on the spectra obtained from 50 MeV and 1 GeV protons incident on copper, irrespective of the shape of the spectra as both these extend above 1 MeV. This is because the initial RDER of the unmodified ZReC matches reasonably well with the shape of the ICRP DCC above ~1 MeV while deviating substantially below it. The modifications described here will allow the instrument to function as a universal neutron monitor. It is also seen that after incorporating the modifications in ZReC, the over-response of the instrument is almost constant by a factor of ~2 for neutrons in the range 100 keV–1 GeV. Also for the neutron fields with significant neutron component closer to thermal energy, similar to a moderated fission spectrum, the correction factor has to be ~3–4. These corrections can always be implemented externally, thus enabling the instrument to measure the neutron $H^*(10)$ more accurately.

The effect of transferability of detector medium on RDER of the instrument

The detailed analysis of the RDER of the ZReC was made using the ^{6}Li response at the centre of the instrument. However, calculations were also made by replacing ^{6}Li detector with ^{10}B as well as ^{3}He detectors to study the effect on the RDER of the instrument. Figure 8 presents a comparison of the calculated response of ZReC with ^{6}Li, ^{10}B and ^{3}He detectors by folding of the fluence with the cross sections. From the figure, it is seen that they follow a similar pattern. The RDER of the instrument was estimated by keeping the normalisation point (i.e. 14 MeV) constant for all the detectors and found the same irrespective of the detector medium.

CONCLUSION

The following conclusions can be drawn as a result of the Monte Carlo simulation studies carried out to modify the $H^*(10)$ response of a portable high-energy neutron monitor (ZReC) to match the shape of the ICRP fluence to ambient dose equivalent conversion factors especially for low-energy neutrons by introducing neutron absorbing materials inside the moderator.

The optimised position for Cd and Gd inside the moderator is found to be closest to the central detector volume, whereas for the B layer, it is 2 cm away. Also, B is found to perform better to improve the response at lower energies, as it gives the lowest RDER at 5 keV neutrons. It is seen that the modified response of the ZReC with 1 cm thick borated HDPE or

0.5 cm natural B or 0.05 cm ^{10}B, each with six circular perforations of 1 cm diameter, is found to be the optimised configurations and agrees well with the $H^*(10)$ response of the LINUS neutron monitor. The integral response of the modified ZReC studied with typical reference neutron spectra spanning from thermal neutrons up to 1 GeV shows significant improvement at lower neutron energies while remaining more or less unchanged when the incident spectrum is >1 MeV. The instrument has already been designed and is being fabricated based on the theoretical simulations performed. The validation of the present simulations shall be carried out at different available facilities as and when the instrument is in place.

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