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Optimizing the Design of a Neutron Dosemeter with an Extended Energy Range for High Energy Accelerators

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Abstract—Different versions of the design of a neutron dosemeter for high energy accelerators based on a fast scintillation lithium glass detector of thermal neutrons are considered. The detector is placed at the center of a polyethylene moderator shaped as a sphere, a cylinder, or a truncated cylinder with a lead insert used to increase the dosemeter sensitivity to neutrons with energies above 20 MeV. Calculations of the design parameters have been performed to optimize the angular and energy dependences of the response at energies ranging from the thermal energy to 1 GeV. The best results have been obtained for dosemeter versions comprising a boron filter along with the lead insert. In this case, the instrument has the lowest mass. The dosemeter has been developed for use in the radiation monitoring systems of the IHEP U-70 accelerator complex and other accelerators. It can also be used outside shields of reactors and other low-energy facilities.

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INTRODUCTION

Radiation monitoring at nuclear facilities implies measurements of the ambient neutron dose equivalent $H^*(10)$ using, as a rule, thermal neutron detectors enclosed in spherical or cylindrical polyethylene moderators 10–12" in diameter. Such dosemeters have a limited range of measurable energies (<20 MeV), thus causing serious problems when used outside shields of high-energy accelerators, where the contribution of high-energy (>20 MeV) neutrons to the dose may account for 50% and more [1]. Gas-discharge counters filled with ^{3}He or BF_3 are conventionally used as thermal neutron detectors. The time resolution of these counters is in the microsecond range, therefore, they may underestimate the dose due to the counting losses under conditions of pulsed radiation fields and high dose rates outside accelerator shields.

It has been proposed increasing the dosemeter sensitivity in the high-energy range using polyethylene moderators with lead inserts in which neutrons are multiplied and moderated in reactions $(n, 2n)$, $(n, 3n)$, etc. This idea was implemented, e.g., in dossmeters [2, 3]. Their drawbacks are the high anisotropy factor of their response, reaching a value of 2 or more at energies of <0.1 MeV, and a high mass of instruments, which results from the use of cylindrical polyethylene moderators and large-sized boron counters. For example, the mass of the dosemeter in [3] based on a BF_3 counter with dimensions of ∅31 × 115 mm is ~17 kg.

The aim of this work is the calculational optimization of the neutron dosemeter design for high-energy

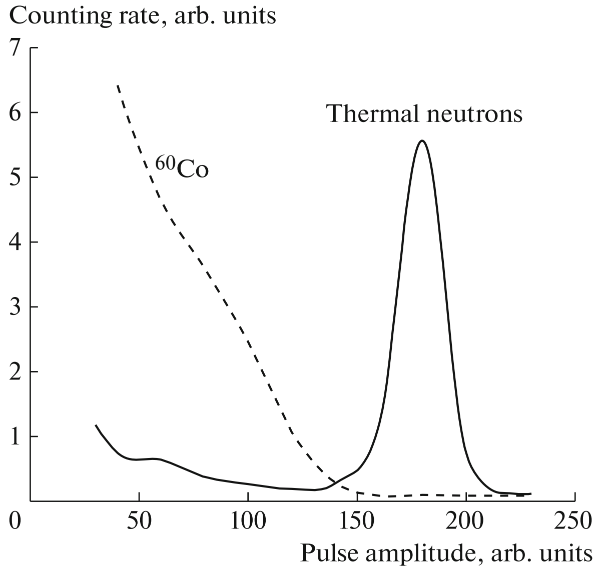

Fig. 1. Apparatus spectra of thermal neutrons and γ rays of ^{60}Co, measured by the GS-20 glass 1 mm thick [4].

accelerators on the basis of a fast scintillation detector with a lithium glass in a polyethylene moderator with a lead converter from the standpoint of the energy and angular dependences of the response and the minimum mass of the instrument. Based on analysis of reference data and calculations, the lithium glass has been selected as the optimum variant owing to a short luminescence decay time (75 ns), a high thermal-neutron detection efficiency, and a good discrimination efficiency for γ rays. All calculations were made for a GS-20 glass from Saint-Gobain Crystals [4] with a ^{6}Li mass content of 6.6% and dimensions of ∅25 × 1 mm. The apparatus spectra of thermal neutrons and γ rays from ^{60}Co in a 1-mm-thick GS-20 glass [4] are presented in Fig. 1.

The calculations were performed using a new universal FAN12 version of the FANEUT program simulating transport of photons and neutrons with energies below 20 MeV [5, 6] combined with the HADRON program simulating transport of high-energy hadrons (version HADR99 [7]) into a unified complex H99F12. The main distinction of the FAN12 program from the previous version is in the wide use of modern databases on the total and differential cross sections for neutron–nucleus interactions (ENDF/B-VI [8]) and photon interactions with atoms (EPDL97 [9]). The statistical error of all results of calculations presented in this paper is <1.5% in all cases.

A NEUTRON DOSEMETER WITH A LITHIUM GLASS SCINTILLATOR IN A SPHERICAL POLYETHYLENE MODERATOR WITH A LEAD CONVERTER

Figure 2 presents the response function (RF) of the detector with a lithium glass placed at the center of a polyethylene sphere ∅10" (25.4 cm), calculated by the H99F12 program under conditions of isotropic irradiation, in comparison with the energy dependence of ambient dose equivalent per unit neutron fluence $h^*(10)$ [10, 11]. In the calculations, the polyethylene density was assumed to be 0.95 g/cm^3. From now on, RFs $R(E)$ shown in the figures have been normalized, as a rule, to value $h^*(10)$ at an energy of 2 MeV for ease of comparison of RFs for various dosemeters. The results of our calculations agree well with the calculation data in [12] for a ^{6}LiI detector with dimensions ∅4 × 4 mm in the same geometry, which were obtained using the MCNP program [13]. It is apparent that, unlike the energy dependence of the ambient dose equivalent, both RFs sharply decline at a neutron energy of >10 MeV.

To increase the detection probability for high-energy neutrons, a cylindrical lead layer (a Pb converter) was inserted in the moderator, and the influence of its thickness and outer dimensions on the RF was investigated. The radius of the polyethylene sphere was increased by the value of the lead layer thickness. The diagram of the dosemeter with a lead insert is shown in Fig. 3. Three variants of the Pb converter with outer dimensions of ∅8 × 8, ∅10 × 10, and ∅12 × 12 cm were investigated. The RF was calculated for each of these variants at different lead thicknesses.

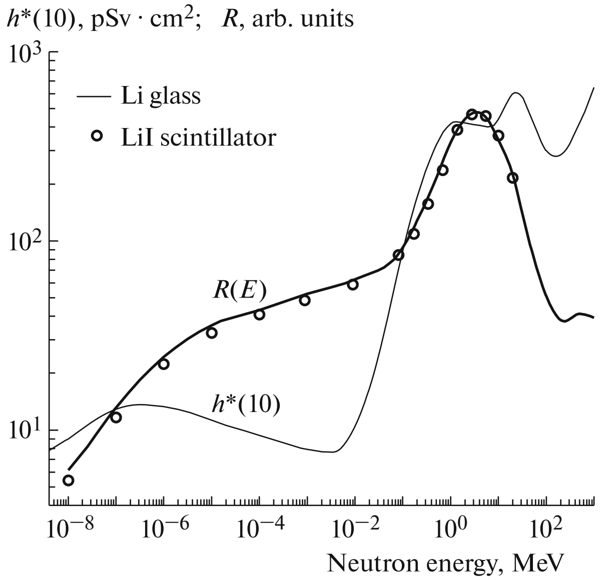

Fig. 2. Response function $R(E)$ of the scintillation neutron detectors based on lithium glass with dimensions of ∅25 × 1 mm (this study) and ^{6}LiI (∅4 × 4 mm) [12] in the spherical polyethylene moderator ∅10". Both RFs were normalized to value $h^*(10)$ at an energy of 2 MeV.

Afterward, the optimization procedure included the RF convolution with spectra from the available neutron spectrum library and calculation of the dose sensitivity ratios r_i for each ith spectrum and r_{cal} for the calibration spectrum:

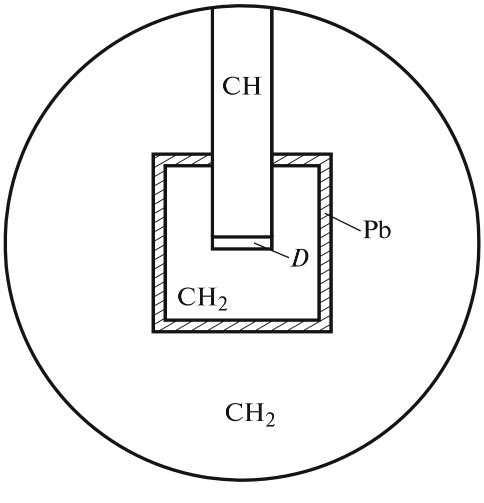

Fig. 3. Diagram of the neutron dosemeter with the lead converter: (D) lithium glass scintillator, (CH$_2$) polyethylene moderator, (CH) Plexiglas light guide, and (Pb) cylindrical lead insert.

Table 1. Dimensions (cm) of the spherical CH_2 moderators and the cylindrical Pb converters, the RFs for which are presented in Fig. 4

Designation in Fig. 4	Pb converter			CH_2 moderator diameter
	diameter	height	thickness	
Without Pb	0	0	0	25.4
Pb(∅8 × 8 × 0.7)	8	8	0.7	26.8
Pb(∅8 × 8 × 1.3)	8	8	1.3	28.0
Pb(∅10 × 10 × 0.8)	10	10	0.8	27.0
Pb(∅12 × 12 × 0.7)	12	12	0.7	26.8
Pb(∅12 × 12 × 1)	12	12	1	27.4

$$k_i = r_i/r_{\rm cal} = \frac{\int R(E)\Phi_i(E)dE}{\int h^*(10)(E)\Phi_i(E)dE} \Bigg/ \frac{\int R(E)\Phi_{\rm cal}(E)dE}{\int h^*(10)(E)\Phi_{\rm cal}(E)dE}, \qquad (1)$$

where $\Phi_{\rm cal}(E)$ is the neutron spectrum [14] obtained with a ^{239}Pu–Be source on the UKPN-1M calibration facility used at IHEP. The neutron spectrum library includes low-energy neutron spectra outside reactor shields, filtered and unfiltered spectra of radionuclide sources [14–17], and high-energy spectra outside shields of the IHEP and CERN accelerators [1, 18]. In this case, only spectra with the thermal neutron component were selected from available sources. Spectra behind steel shields that are not characteristic of the work of personnel have not been used.

The lead thickness has been optimized for three variants of the outside dimensions of the Pb converter, so that the deviation of the k_i values from unity is minimal for high-energy neutron spectra, while the relative response in the low-energy region is retained. The optimum variants of the Pb converter are as follows: ∅8 × 8 × 1.3, ∅10 × 10 × 0.8, and ∅12 × 12 × 0.7 cm. The geometrical dimensions of some of the dosemeter design variants are presented in Table 1.

The RFs obtained for these variants are shown in Fig. 4 in comparison with the RF for the moderator without the lead (a thick solid line). When normalized to $h^*(10)$ at an energy of 2 MeV, the RFs for three selected variants are almost identical over the whole energy range from the thermal energies to 1 GeV. The differences in the absolute values are also small.

Relative dose sensitivity $k_i = r_i/r_{\rm cal}$ of the dosemeter having a Pb converter with dimensions of ∅10 × 10 × 0.8 cm in a spherical CH_2 moderator ∅27 cm (from now on, it is designated Pb_s) is shown in Fig. 5 as a function of the mean energy of the epicadmium neutron spectrum in comparison with the data for the CH_2 moderator ∅25.4 cm free from the lead insert. In the second case, the underestimation of the neutron dose in the hardest spectrum is as high as 60%. The deviation of the k_i values from unity for the dosemeter with the Pb converter does not exceed 15% over a wide range of the neutron spectrum hardness with mean energies from 0.1 to 60 MeV. Table 2 presents the characteristics of the optimum variants of the lead insert, which demonstrate that the Pb_s dosemeter has an advantage of the lower mass (the mass was calculated in the geometry of Fig. 3, i.e., ignoring the photomultiplier tube housing, the voltage divider, and other external details of the design).

A NEUTRON DOSEMETER WITH A SPHERICAL POLYETHYLENE MODERATOR, A LEAD CONVERTER, AND A BORON FILTER

For the energy dependence of the response of a thermal-neutron detector in a polyethylene moderator in the intermediate energy range, Andersson and Braun proposed placing a cadmium or boron thermal-neutron absorber inside the polyethylene moderator at some distance from the detector [19]. Such dosemeters, particularly, with cadmium absorbers, are widely used in radiation monitoring. Use of cadmium in a dosemeter based on a lithium-glass scintillation detector is inexpedient, since absorption of neutrons by (n, γ) capture in cadmium creates a powerful γ-ray source with energies of up to a few MeV. Let us take an ABH dosimeter (Andersson–Braun High-energy) [3] containing a boron absorber as a basis.

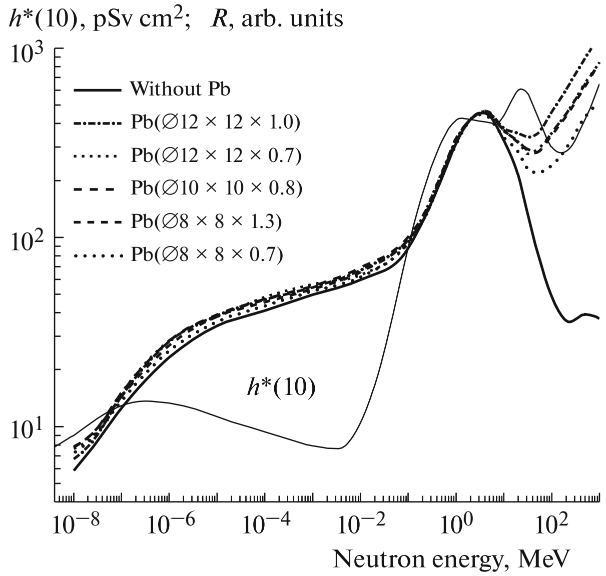

Fig. 4. RF of the dosemeter based on the lithium glass with lead inserts and CH_2 moderators with different sizes. All RFs were normalized to value $h^*(10)$ at an energy of 2 MeV.

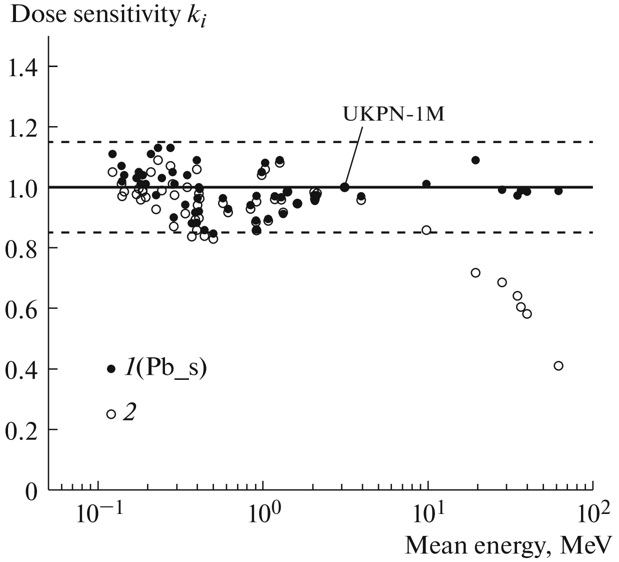

Fig. 5. Dose sensitivity of the dosemeter based on the lithium glass (*1*) with the Pb converter with dimensions of ∅10.0 × 10.0 × 0.8 cm in the CH_2 moderator ∅27 cm vs. the mean energy of the neutron spectrum and (*2*) in the CH_2 moderator ∅25.4 cm without the Pb converter. The "ideal" energy dependence is shown with a solid line, and the 15% margins of the errors are shown with dashed lines. UKPN-1M denotes the calibration neutron field.

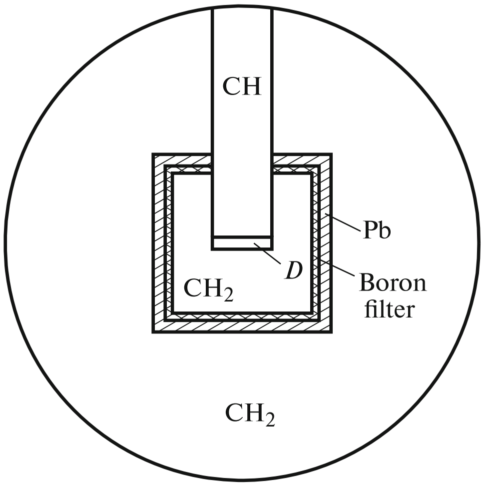

Fig. 6. Diagram of the neutron dosemeter with the spherical polyethylene moderator, lead converter, and perforated boron filter.

It comprises a BF_3 counter with dimensions of ∅3.1 × 11.5 cm in a cylindrical polyethylene moderator with dimensions of ∅23.5 × 26.5 cm and a Pb converter ∅9.7 × 17.3 × 1 cm. A portion of polyethylene (6 mm) under the lead insert has been replaced by a borated synthetic rubber (4.22 wt % ^{10}B) with a density of 1.3 g/cm^3 and a set of holes covering 22% of the area. Borated rubber with the same thickness, composition, and density has been used in the optimization calculations of the neutron dosemeter based on the scintillation detector containing a lithium glass in a spherical polyethylene moderator with a lead converter and a borated filter. The diagram of this dosemeter is shown in Fig. 6. As variable parameters, we used the moderator diameter, the thickness of the Pb converter with outside dimensions of ∅10 × 10 cm, and the area of holes in the borated rubber. As a result, the following optimal variant has been obtained (the PbB_s variant): moderator diameter, 23 cm; dimensions of the Pb converter, ∅10 × 10 × 0.9 cm; and perforation area of the boron filter, 30%.

The RF of this dosemeter is shown in Fig. 7 in comparison with the RF for the optimal variant without the boron filter and the RF of the ABH dosemeter, calculated for the conditions of the side irradiation in [3]. When normalized to $h^*(10)$ at $E = 2$ MeV, the RFs of the dosemeters having boron filters are similar, though their designs and dimensions differ substantially. Their dose sensitivities for different neutron spectra are presented in Fig. 8. It is apparent that the PbB_s variant has a slightly smaller spread in the sensitivity (0.83–1.08) as compared to the ABH dosemeter (0.70–1.00), but its main advantage consists in the considerably smaller size and mass (9.7 kg as compared to 17 kg for the ABH dosemeter).

This gain is attained owing to the detector compactness and, hence, substantially smaller sizes of the lead insert and the polyethylene moderator. The use of the boron filter also provides a 3.4-kg decrease in the

Table 2. Characteristics of the dosemeters with the optimum dimensions of the cylindrical Pb converters in spherical polyethylene moderators in comparison with the dosemeter without the Pb converter

Pb converter dimensions, cm	CH_2 moderator diameter, cm	Relative sensitivity range	Mass, kg	
			Pb converter	entire construction
Without Pb	25.4	0.41–1.09	0	8.2
∅8 × 8 × 1.3	28.0	0.83–1.10	3.1	13.8
∅10 × 10 × 0.8 (Pb_s)	27.0	0.85–1.13	3.6	13.1
∅12 × 12 × 0.7	26.8	0.84–1.12	4.7	13.9

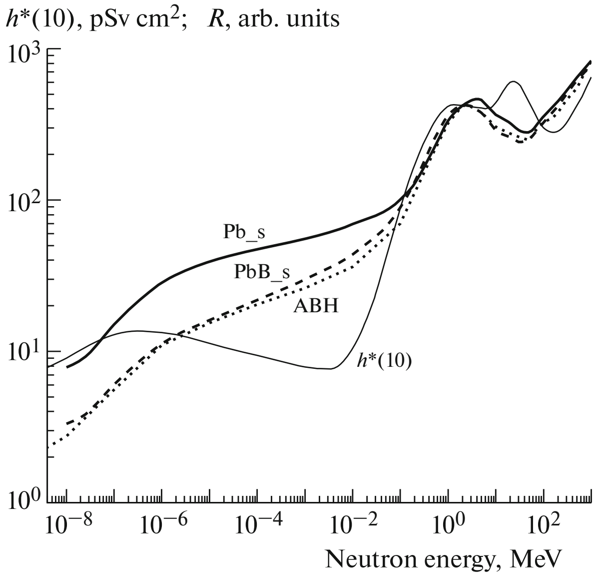

Fig. 7. Response functions of dosimeters Pb_s and PbB_s in comparison with the ABH RF [3]. All RFs were normalized to value $h^*(10)$ at an energy of 2 MeV.

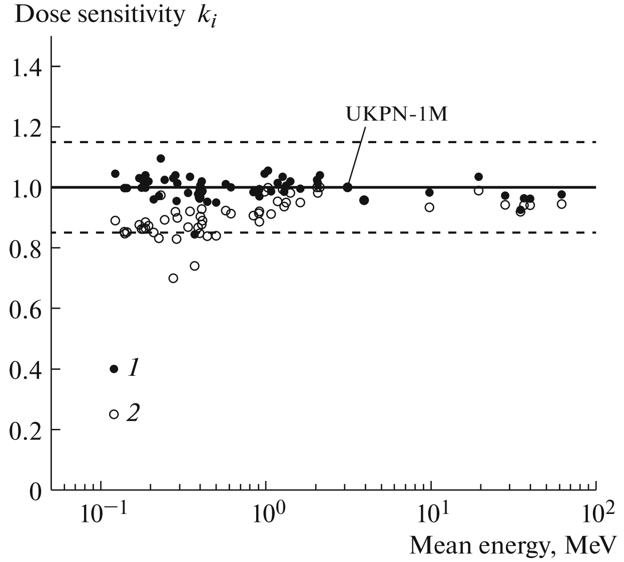

Fig. 8. Dose sensitivity vs. the mean energy of the neutron spectrum (*1*) for dosemeter PbB_s and (*2*) dosemeter ABH [3].

mass of the Pb_s dosemeter with a similar Pb converter, but without the filter. The RFs of the described dosemeter designs are compared in Fig. 9 to the ABH dosemeter RF in absolute units. The mean sensitivity ratio for the dosemeters without and with the boron filter being installed is ~2 for extended spectra. The RFs of the PbB_s and ABH dosemeters are close.

OPTIMIZING THE SIZES OF THE CYLINDRICAL MODERATORS IN VIEW OF THE ENERGY AND ANGULAR DEPENDENCES OF THE RESPONSE

Apart from the spherical polyethylene moderator, easier manufacturable variants of the moderator shaped as a rectangular cylinder or a truncated rectangular cylinder with conical end surfaces cut at an angle of 45° (Fig. 10). A set of calculations of optimal moderator sizes was performed with the aim of lowering the dosimeter anisotropy while retaining a small spread in the dose sensitivity. In this case, the parameters of the Pb converter (∅10 × 10 × 0.9 cm) and the boron filter (thickness, 0.6 cm; perforation area, 30%) remained unchanged.

The following optimum moderator dimensions were obtained: for the rectangular cylinder, ∅21.8 × 19.7 cm (PbB_c); and for the truncated cylinder, ∅22.4 × 22.4 cm (PbB_tc). In the latter case, the distances from the moderator center to the surface at angles of 0°, 45°, and 90° are equal (11.2 cm). The energy dependences of the response of these variants (see Fig. 11) are very close to each other and to the RF of the dosemeter in the spherical moderator ∅23 cm (PbB_s). The dose sensitivities calculated for extended spectra are shown in Fig. 12. They differ from similar results obtained for the spherical moderator (Fig. 8) only slightly.

Figure 13 demonstrates the anisotropy of the dosemeter response for three variants of the polyethylene moderator and five neutron energies. The anisotropy

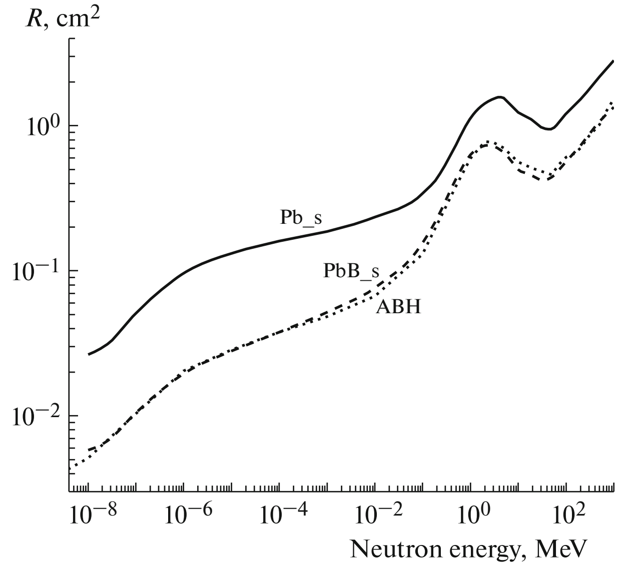

Fig. 9. Response functions of dosemeters Pb_s and PbB_s under isotropic irradiation in comparison with the RF of the ABH (side irradiation) in terms of absolute units.

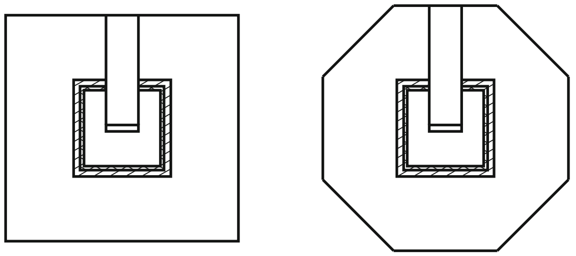

Fig. 10. Schematic diagrams of the neutron dosemeters with the polyethylene moderators shaped as a rectangular cylinder and a truncated rectangular cylinder.

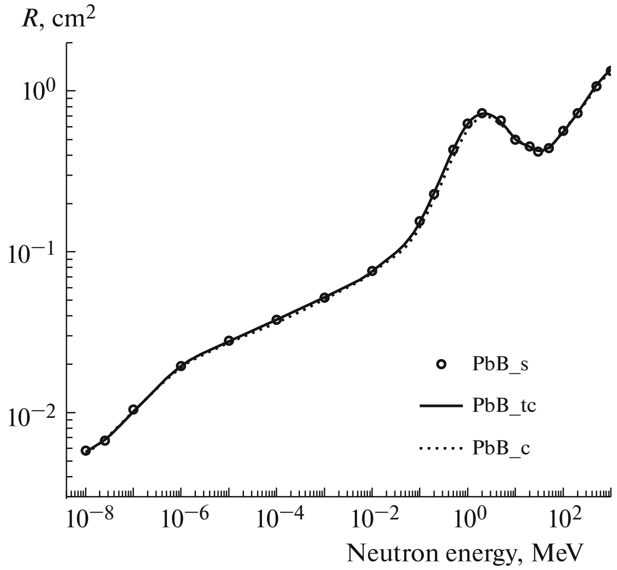

Fig. 11. Response functions of dosemeters PbB_s, PbB_c, and PbB_tc in terms of absolute units. The Pb converters and the boron filters were identical in both cases.

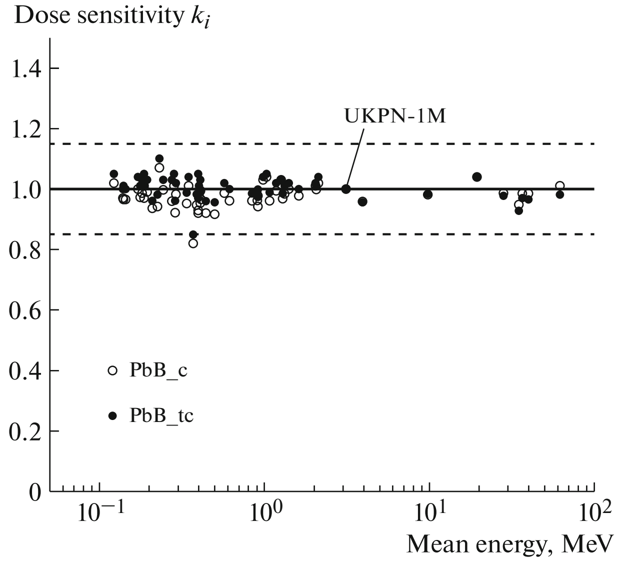

Fig. 12. Dose sensitivity of the PbB_c and PbB_tc dosemeters.

was calculated as the ratio of the response to neutrons incident at angle θ (0° corresponds to irradiation from the bottom) to the response for isotropic irradiation. In this case, the statistical error of calculations was <1% for thermal neutrons and <0.5% at other energies. The highest anisotropy that can be as high as 26%, as is expected, is observed for the CH_2 moderator shaped as a rectangular cylinder. For the truncated cylinder approaching the spherical shape, the anisotropy of the response does not exceed 15%, as is the case with the spherical moderator.

The comparative characteristics of the dosemeters with different polyethylene moderators are presented in Table 3. The easiest-to-manufacture variant with the moderator shaped as a rectangular cylinder has a higher anisotropy of the response relative to the other moderators. The maximum anisotropy (+26%) is observed, however, for low-energy neutrons that usually contribute to the dose only slightly. In addition, it takes place when irradiation is from the side of the

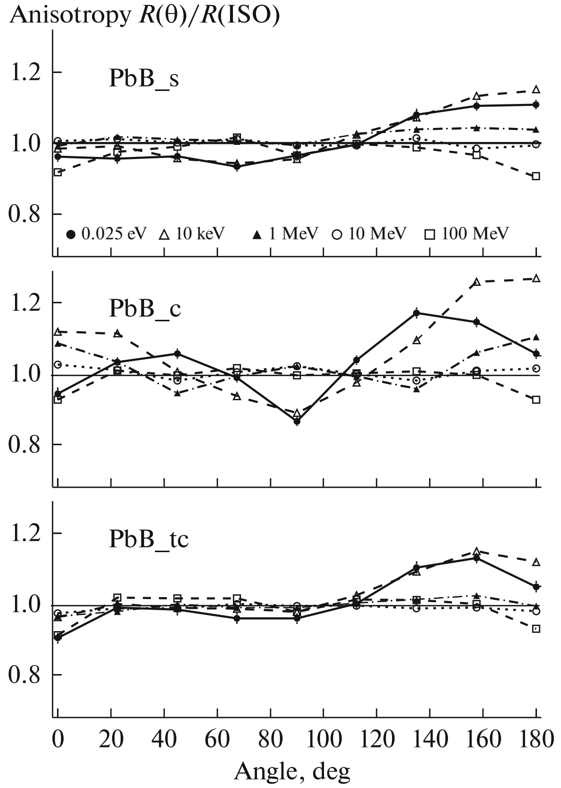

Fig. 13. Anisotropy of the PbB_s, PbB_c, and PbB_tc dosemeter response.

Table 3. Characteristics of the optimum dosemeter variants with Pb converters with dimensions of ∅10 × 10 × 0.9 cm and boron filters 0.6 cm thick with a perforation area of 30% in polyethylene moderators with different shapes and dimensions

Designation	CH_2 moderator shape	CH_2 moderator diameter, cm	Relative sensitivity range	Anisotropy, %	Mass, kg
PbB_s	Sphere	∅23	0.85–1.10	<15	9.7
PbB_c	Rectangular cylinder	∅21.8 × 19.7	0.82–1.07	<26	10.6
PbB_tc	Truncated cylinder	∅22.4 × 22.4	0.85–1.10	<15	9.7

light guide (160°–180°), where the photomultiplier tube housing, the voltage divider, and other devices, all ignored in the calculations, are located in an actual dosemeter. It should also be noted that the design with the moderator shaped as a rectangular cylinder features a higher mass.

CONCLUSIONS

The fast small-sized scintillation neutron detector based on a GS-20 lithium glass with dimensions of ∅25 × 1 mm, a high sensitivity, and a good n/γ-discrimination has been used as a basis in the calculational analysis of optimal designs of a neutron dosemeter for high-energy accelerators with an extended energy range of up to hundreds megaelectronvolts. The neutron detector is located at the center of a spherical polyethylene moderator. An increase in the sensitivity to high-energy neutrons with $E > 20$ MeV is attained by using a lead converter. Placing an additional boron filter under the lead converter has made it possible to reduce substantially the size and mass of the polyethylene moderator while retaining the small spread in the dose sensitivity (within the limits of ±15%) in a wide range of neutron spectra with a mean energy of 0.1–60 MeV. As a result, the dosemeter is applicable both at accelerators and at reactors and other low-energy facilities.

Apart from the spherical moderator, easier-to-manufacture variants of polyethylene moderators shaped as rectangular and truncated cylinders have been considered, and calculations of their sizes have been performed with the aim of optimizing the energy and angular dependences of the response. The dosemeter with the moderator shaped as a truncated cylinder appears to be most promising, since it combines advantages of the accuracy characteristics provided by a spherical moderator and the ease in manufacturing a cylindrical moderator.

Results of this study will find application not only to the problem of designing a neutron dosemeter based on a lithium-glass scintillation detector. Scintillation detectors based on a mixture of LiF and ZnS powders in polystyrene have been widely used in Russian dosemeters, such as MKS-01R, DKS-96, RSU-01, etc. They have similar sizes; therefore, the conclusions on the optimum CH_2 moderators, Pb converters, and boron filters are also valid for these dosemeters, the field of application of which can be extended to include high-energy accelerators. It is expected that detectors enclosed in moderators with Pb converters will be used in high-energy neutron spectrometry in addition to the sole widely used high-energy activation carbon detector based on reaction $^{12}C(n, x)\,^{11}C$.

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