ISSN 1547-4771, Physics of Particles and Nuclei Letters, 2015, Vol. 12, No. 1, pp. 184–189. © Pleiades Publishing, Ltd., 2015.
Original Russian Text © S.V. Guseva, E.N. Lesovaya, G.N. Timoshenko, 2015, published in Pis'ma v Zhurnal Fizika Elementarnykh Chastits i Atomnogo Yadra, 2015.

Correlation between Effective and Ambient Neutron Doses in Radiation Fields of Nuclear-Physics Facilities at the Joint Institute for Nuclear Research

S. V. Guseva, E. N. Lesovaya, and G. N. Timoshenko
Joint Institute for Nuclear Research, Dubna, 141980 Russia
e-mail: tim@jinr.ru

Abstract—The questions of a correlation between normative and operational quantities in the dosimetry of ionizing radiation still attract the attention of professionals working in the field. Since the neutron fields of nuclear-physics facilities at the Joint Institute for Nuclear Research (JINR) are highly varied, the question of whether the ambient neutron dose always serves as a conservative estimate of the effective dose (in the terms of which the dose limits are set) is of practical importance for radiation monitoring at JINR. We studied the correlation between the calculated values of effective and ambient neutron doses obtained based on a representative set of neutron spectra measured at JINR with the use of a multisphere neutron spectrometer. It is demonstrated that measuring the ambient neutron dose may not serve as a confirmation of compliance with the set dose limits in "hard" neutron fields.

DOI: 10.1134/S1547477115010124

The concept of effective equivalent dose (E) is used for the purposes of rating the irradiation of humans. This quantity helps estimate the received radiation dose, confirm the compliance with the set dose limits, and predict the dose budget of planned works. The concept of effective dose was introduced to evaluate the risk of delayed stochastic effects manifested in personnel and the general population subjected to small-dose irradiation. E is the calculated dose not for an individual, but for a reference person under set irradiation conditions. E (as well as the equivalent dose) may not be measured in practice and may not be applied in dosimetric control with dosimeters. Operational quantities are used to obtain conservative (overstated) estimates of the effective dose E. These operational quantities are defined unambiguously through the physical parameters of the radiation field at the measurement site and are as close to the rated values as possible (though with a certain margin).

The primary operational quantity is the ambient dose equivalent (ambient dose). The ambient dose equivalent $H^*(d)$ is a dose equivalent produced in the spherical International Commission on Radiological Protection (ICRP) phantom made from a tissue-equivalent material with a diameter of 30 cm at distance d (mm) from the surface along a diameter parallel to the radiation propagation direction in a radiation field that is identical to the one under analysis in terms of composition, fluence, and energy distribution, but is monodirectional and uniform. In other words, the ambient dose equivalent $H^*(d)$ is a dose that would be received by someone standing at the site where a measurement with a dosimeter is performed. The ambient dose is, like the effective dose, expressed in sieverts (Sv). The typical d value for penetrating radiation (in particular, for neutrons) is 10 mm. This ambient dose is designated as $H^*(10)$ and is used to monitor the effective dose with the help of the stationary (zone) and operational dosimetric control. The ambient dose is a measurable quantity, and radiation dosimeters are calibrated in units of $H^*(10)$.

In Russia, the energy dependence of the effective neutron dose E per unit fluence (specific dose) is defined in Radiation Safety Standards NRB-99/2009 [1] for two human irradiation geometries (the E value depends strongly on the angular distribution of incident radiation): isotropic (ISO) and anteroposterior (AP). The values of specific E from NRB-99/2009 agree with the values proposed by the ICRP in Publication 74 [2] in 1996 and confirmed in Publication 119 [3] in 2012. The effective dose values in these ICRP Publications are set for energies of up to 180 MeV for AP human irradiation and up to 20 MeV for ISO irradiation. Unfortunately, the upper energy bound of the dependences found in NRB-99/2009 is at 20 MeV for both the AP and ISO irradiation geometries, while the neutron spectra at accelerators may extend to much higher energies. The ambient neutron dose in ICRP Publication 74 is set for energies of up to 201 MeV, and this value is also too low. The values of specific E and $H^*(10)$ for neutrons with energies of up to 1 GeV are given in [4]. All the abovementioned energy dependences of specific doses are shown in Fig. 1.

Nuclear-physics facilities at JINR (accelerators of various types and a pulsed fast-neutron reactor) generate primary and secondary radiation with a wide energy spectrum and a complex composition. Significant variations of the parameters of radiation fields (their changes in time and space) are typical for accelerators due to the wide variety of accelerator operation modes, the diversity of targets used, and the redistribution of beam losses upon their extraction and transport. The energy range of radiation fields in accelerators is fairly wide and is bounded from the top by the energy of accelerated particles. The composition of radiation fields of a working accelerator also varies depending on the conditions of their generation and includes gamma quanta, neutrons, and various charged particles. Neutrons are the primary dose-forming radiation component of working accelerators. The reactor radiation fields are composed of neutrons with a wide energy spectrum and gamma quanta. Thus, the largest amount of effort in stationary and operational control at nuclear-physics facilities is directed towards the measurement of neutron doses in a wide energy range.

The neutron energy spectra may differ significantly depending on the operation mode of the facility and on whether the radiation field is generated directly behind the shielding or at a distance from the facilities. For example, the neutron spectra behind the side shielding of beam channels of high-energy accelerators may contain large numbers of high-energy neutrons (and even more so behind the frontal shielding). Such spectra are called “hard” ones. At the same time, fields of multiply scattered neutrons with low energies may form at the same accelerators in geometries close to labyrinthian. There are practically no neutrons with energies in excess of 500 MeV behind the side shielding of accelerators (even the ones accelerating to superrelativistic energies) due to the fact that the average transverse momenta of secondary particles pracically stop rising at such energies of primary particles. No strict (formal) boundary between “hard” and “soft” spectra exists, but one may use the average neutron energy in the spectrum or the ratio of the fluence of neutrons with energies higher than 20 MeV to the total neutron fluence ($\Phi_{>20}/\Phi_{\text{tot}}$) as a criterion. Neutron fields with $\Phi_{>20}/\Phi_{\text{tot}}$ lower than 5% are classified as “soft,” and fields with higher ratios are assumed to be “hard.” In actual experiments, the $\Phi_{>20}/\Phi_{\text{tot}}$ ratio behind the frontal shielding (beam trap) does not exceed 40–50% even in the hardest fields.

The spectra of neutrons of a wide energy range were measured at different sites and at different facility operation modes with the use of a multisphere neutron spectrometer (Bonner spectrometer). Carbon activation detectors were used in order to enhance the spectrometer informativity at high neutron energies. Since the energy range is wide, it is convenient to present the neutron spectra in lethargy $\Phi(E) \times E$ units. The neutron spectra measured at JINR over the years were systematized in [5]. The neutron spectra shape is governed by the physics of processes of interaction between neutrons of various energies and matter. The interaction mechanisms differ greatly, and the probability of neutron interaction with matter increases sharply with decreasing energy. Thermal (10^{-8}–10^{-7} MeV), intermediate, and evaporation (0.5–10 MeV) neutrons may be present in the spectra (in various proportions), and the accumulation of cascade (50–200 MeV) neutrons is manifested in hard spectra. There are practically no neutrons with energies in excess of 500 MeV behind the side shielding of actual accelerators (even the ones accelerating to ultrahigh energies) due to the fact that the average transverse momenta of secondary particles practically stop rising at such energies of primary particles.

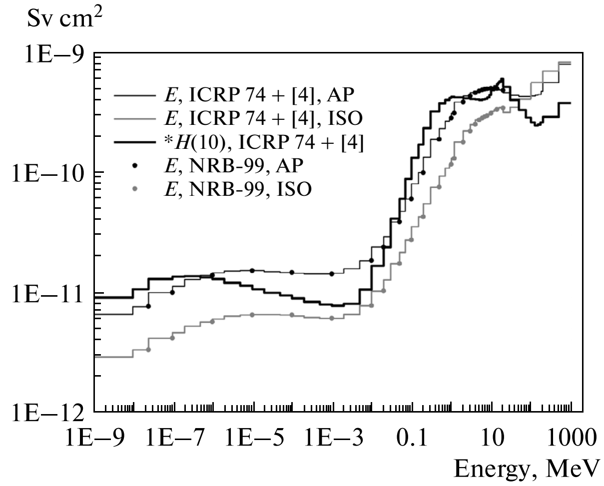

Fig. 1. Energy dependences of the specific effective neutron dose for AP and ISO irradiation in accordance with ICRP Publication 74 and NRB-99/2009 and the energy dependence of the ambient neutron dose in ICRP Publication 74.

Ten spectra representing the entire neutron field variability range (from the softest to the hardest) were selected for the purpose of checking the correlation between the effective and ambient neutron doses in radiation fields of JINR facilities. The dominant type of personnel irradiation (AP or ISO) was determined for each field. Table 1 presents brief descriptions of the generation conditions of every spectrum, the average neutron energies, and the dominant personnel irradiation conditions. The selected spectra presented in lethargy $\Phi(E) \times E$ units are shown in Fig. 2.

The effective (in AP and ISO irradiation geometries) and the ambient neutron doses were calculated by convoluting the $\Phi(E)$ neutron spectra with the corresponding energy dependences of specific doses (Fig. 1). The results of calculating the ambient and effective neutron doses for all ten selected spectra and the ratios between these doses ($^{*}H(10)/E$) are listed in Table 2. The neutron spectra reconstruction errors

Table 1. Characteristics of the selected neutron spectra at JINR facilities

Spectrum no.	Brief description of the spectrum measurement conditions	Energy range, MeV	Average energy, MeV	Spectrum type	Dominant irradiation conditions
1	LNP phasotron, labyrinth at the ground floor	$10^{-8} - 20$	1.16E-03	“Soft”	ISO
2	LNR MC400, behind door D21	$10^{-8} - 20$	0.208	“Soft”	ISO
3	LNR MC400, behind door D20	$10^{-8} - 20$	0.304	“Soft”	ISO
4	LNP phasotron, behind the shielding with openings	$10^{-8} - 60$	0.431	“Soft”	ISO
5	IBR-2, beam no. 2 behind the shielding	$10^{-8} - 10$	0.394	Intermediate	ISO
6	^{252}Cf source, indoors	$10^{-8} - 10$	0.871	Intermediate	ISO
7	LNP phasotron, in the partition between the accelerator shielding and YaSNAPP	$10^{-8} - 500$	12.1	“Hard”	AP
8	LNP phasotron, at the bund of the northern wall	$10^{-8} - 500$	36.7	“Hard”	AP
9	LNP phasotron, behind the shielding wall of laboratory no. 2	$10^{-8} - 500$	73.8	“Hard”	AP
10	LHEP Nuclotron, the side shielding of the beam channel in building no. 205	$10^{-8} - 500$	55.3	“Hard”	AP

Table 2. Effective and ambient neutron doses calculated for the spectra in Fig. 2

Spectrum no.	Calculated effective dose E (AP), pSv	Calculated effective dose E (ISO), pSv	Calculated ambient dose $^*H(10)$, pSv	$^*H(10)/E$
1		1.85×10^7	2.62×10^7	1.42
2		4.35×10^5	1.13×10^6	2.59
3		1.14×10^2	2.70×10^2	2.37
4		8.00×10^3	1.71×10^4	2.13
5		4.26×10^4	1.21×10^5	2.84
6		2.36×10^4	5.77×10^4	2.44
7	3.16×10^5		3.12×10^5	0.99
8	7.29×10^5		6.78×10^5	0.93
9	2.40×10^5		1.92×10^5	0.80
10	1.20×10^4		1.03×10^4	0.86

were neglected. It can be seen that the abovementioned ratio in the JINR neutron spectra varies from 2.84 to 0.8, and the value of this ratio is clearly correlated with the hardness of the neutron spectra. The fact that the ratio is lower than 1 for hard neutron spectra suggests that the ambient neutron dose no longer serves as a conservative estimate of the effective dose in such fields. Thus, radiation control with dosimeters, the readings of which are presented in terms of the ambient neutron dose, may not guarantee the nonexceedance of dose limits for personnel and the general population that are set in terms of the effective dose.

It should be noted that this problem arises only in scientific centers that are equipped with high-energy particle accelerators. The second part of this problem consists in the fact that the operating energy range of neutron radiation control instruments officially recognized in Russia is limited to 20 MeV, though these instruments are technically sensitive to neutrons of higher energies. Therefore, these dosimeters are not capable of correctly measuring even the ambient neu-

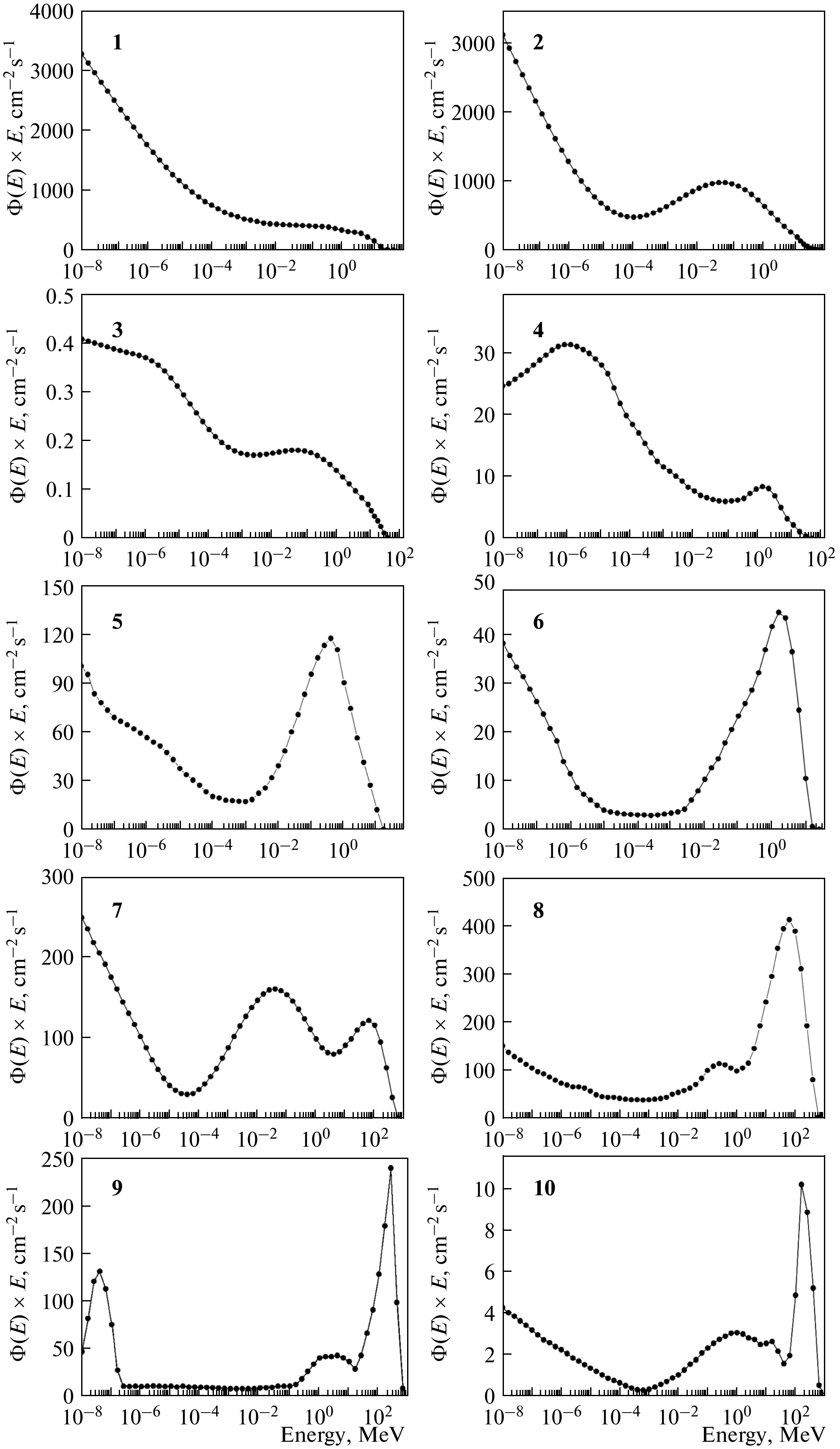

Fig. 2. Neutron spectra from Table 1.

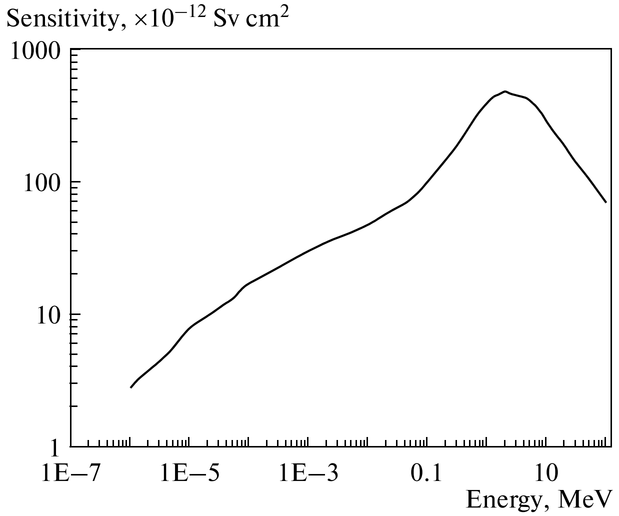

Fig. 3. Sensitivity function of the BDKN-96 neutron detection unit.

tron dose in hard fields with a significant contribution from high-energy neutrons.

The basic instrument of operational monitoring (the DKS-96 dosimeter–radiometer with the BDKN-96 neutron detection unit) was used to estimate the correctness of readings of the radiation control instruments (in terms of the ambient dose) in neutron fields of nuclear-physics facilities at JINR. A proportional ^{3}He counter serves as a detector of slow neutrons in BDKN-96. The sensitivity function of the BDKN-96 unit calculated using the software model of radiation transport in matter in accordance with the MCNP4A Monte Carlo method is presented in [6] (see Fig. 3).

The dosimeter–radiometer readings in the selected neutron fields (nos. 1–10) were obtained by convoluting the energy dependence of the instrument sensitivity within a range from 1 eV to 100 MeV with the neutron spectra. It was assumed that the instrument had zero sensitivity outside this range. Since neutrons with energies lower than 1 eV produce practically no contribution to the dose and neutrons with energies in excess of 100 MeV are scarce even in hard spectra, this does not introduce any substantial distortion into the comparison results. The calculation results are listed in Table 3.

It can be seen that the ambient neutron dose measurements performed with this dosimeter–radiometer yield understated results in practically all the selected neutron fields. The instrument readings in hard fields are 1.5–2 times lower than the calculated ambient dose value. Thus, the neutron doses measured with an operational monitoring instrument are, for a number of reasons, significantly understated relative to the rated quantities (effective doses) in hard neutron fields, and this dosimeter may not be used in hard neutron fields without a correction applied to its readings.

Several neutron dosimeters–radiometers produced outside of Russia have operating neutron-energy ranges extending to 1 GeV and above. All these instruments use heterogeneous neutron moderators: polyethylene with an ultrafast neutron converter made from heavy metals (steel, copper, lead, or wolfram). The WENDI-2 detector (Los Alamos National Laboratory, United States) [7] with a wolfram piece inside a polyethylene moderator is a fine detector of neutrons with ultrahigh energies. Its sensitivity function rises in the region of energies in excess of 20–30 MeV, which corresponds to the behavior of the energy dependence of the specific effective neutron dose. If such an instrument for measurements in very hard neutron fields is officially recognized and calibrated correctly, its introduction into the practice of radiation monitoring will

Table 3. Comparison between the readings of the DKS-96 dosimeter–radiometer with the BDKN-96 neutron detection unit in neutron fields nos. 1–10 and the ambient neutron dose

Spectrum no.	Dose according to DKS-96 with the BDKN-96 unit, pSv	Ambient dose $^*H(10)$ calculated based on the spectrum, pSv	Ratio of the DKS-96 readings to the ambient dose
1	6.08×10^7	2.62×10^7	2.32
2	1.05×10^6	1.13×10^6	0.93
3	2.49×10^2	2.70×10^2	0.92
4	1.50×10^4	1.71×10^4	0.88
5	1.15×10^5	1.21×10^5	0.95
6	5.56×10^4	5.77×10^4	0.96
7	2.30×10^5	3.12×10^5	0.74
8	3.65×10^5	6.78×10^5	0.54
9	1.05×10^5	1.92×10^5	0.55
10	6.55×10^3	1.03×10^4	0.63

help solve the problem of ultra-high-energy neutron dosimetry at JINR accelerators.

REFERENCES

1. *Radiation Safety Standards NRB-99/2009* (Federal'nyi Tsentr Gigieny i Epidemiologii Rospotrebnadzora, Moscow, 2009) [in Russian].
2. "ICRP Publication 74. Conversion coefficients for use in radiological protection against external radiation," Ann. ICRP **26** (3–4), 1–205 (1996).
3. K. Eckerman, J. Harrison, H.-G. Menzel, and C. H. Clement, "ICRP Publication 119. Compendium of dose coefficients based on ICRP Publication 60," Ann. ICRP **41** (s1), 1–130 (2012).
4. M. Pelliccioni, "Overview of fluence-to-effective dose and fluence-to-ambient dose equivalent conversion coefficients for high energy radiation calculated using the FLUKA code," Radiat. Prot. Dosim. **88**, 279–297 (2000).
5. L. G. Beskrovnaya, E. A. Goroshkova, and Yu. V. Mokrov, "An investigation into the accuracy of the albedo dosimeter DVGN-01 in measuring personnel irradiation doses in the fields of neutron radiation at nuclear power installations of the joint institute for nuclear research," Phys. Part. Nucl. Lett. **7**, 212–221 (2010).
6. A. G. Alekseev and V. N. Lebedev, "A study into methodological problems related to the use of individual albedo-type neutron dosimeters," Preprint IHEP 2003-8 (Institute for High Energy Physics, Protvino, 2003).
7. http://www.thermoscientific.com/content/tfs/en/home.html

Translated by D. Safin