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ENERGY RESPONSE OF TISSUE EQUIVALENT PROPORTIONAL COUNTER FOR NEUTRONS ABOVE 20 MeV

Submitted to *Radiation Protection Dosimetry*

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Abstract

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The calculation of energy response of the tissue equivalent proportional counter with low pressure for neutrons in the energy region from 20 up to 5 GeV is performed. The dependence of TEPC neutron response and errors of the measured neutron dose equivalent on a counter design and measurement methods are discussed. The comparison between calculation and measurements in radiation field at the top shielding of the IHEP accelerator is presented.

Аннотация

Алексеев А.Г., Харлампиев С.А. Чувствительность тканеэквивалентного пропорционального счетчика к нейтронам с энергией выше 20 МэВ: Препринт ИФВЭ 97-18. – Протвино, 1997. – 12 с., 13 рис., 2 табл., библиогр.: 22.

Проведены расчеты энергетической зависимости чувствительности тканеэквивалентного пропорционального счетчика низкого давления к нейтронам в диапазоне энергий от 20 до 5 ГэВ. Рассмотрена зависимость чувствительности и погрешности измерения эквивалентной дозы нейтронов от параметров конструкции счетчика и метода измерения. Представлены результаты сравнения расчета и эксперимента в поле излучения за верхней защитой протонного ускорителя ИФВЭ.

Introduction

A dosimetric method based on a low pressure tissue equivalent proportional counter (TEPC) which had been put forward by Rossi [1] for microdosimetric investigation of radiation, has been widely used in radiation dosimetry lately [2], [3]. The problems of construction, response to some types of radiation, measurement methods and application fields are presented [2], [3], [4], [5], [6].

One application feature of TEPC is that it is a major dosimetric technique for dose equivalent measurement, when we deal with high energy radiation behind the shielding of high energy accelerators and space ships.

High energy neutrons, i.e, those with energy above 20 MeV, are one of important components of radiation in such cases. The calculation and experimental investigation of TEPC response for neutrons above 20 MeV are insufficient ([7], for example). Precise evaluation (calculational as well as experimental) of response dependence of TEPC energy is necessary for errors estimation of dose equivalent, which is needed for practical usage (in cases of radiation safety).

Here the TEPC energy response estimated by the calculation of secondary charged particles spectra by HADRON code [8] was carried out in a neutron energy region from 20 MeV up to 5 GeV. This code based on the cascade-exiton model of nuclear interactions calculations has been developed for light nuclei. Because of the absence of standard neutron sources in the energy region of our interest, the only way for verification of the TEPC calculation was to compare doses measured by TEPC with those of other dosimetric instruments and calculation codes in high energy radiation fields behind the top shielding of the IHEP accelerator (U-70).

1. Calculational method

As it has been shown in our previous publications [7], [10], [11], neutron response depends on the TEPC construction and atomic composition of materials, which are used in a counter design. The counter design, used at IHEP, is schematically presented on Fig.1.

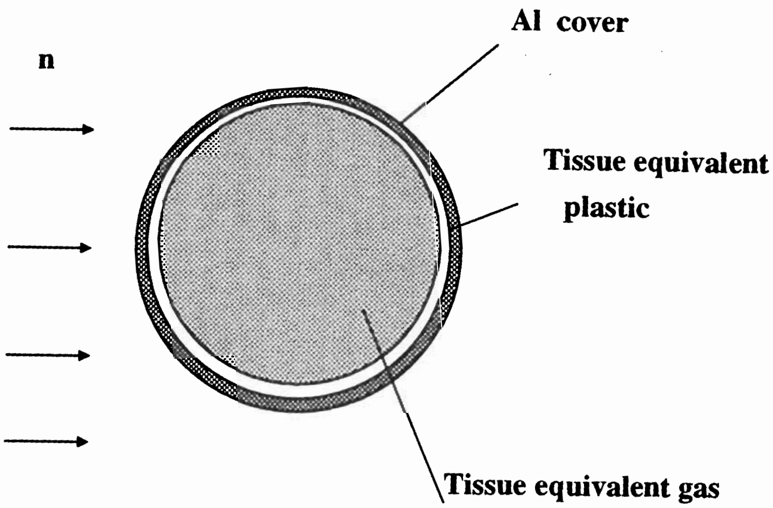

Fig. 1. Geometry of TEPC neutron energy response calculation.

The counter body is a sphere with 10.8 cm internal diameter and 0.2 cm thick. The body material is caprolon. The counter body is mounted in aluminium gas-non-permeable cover of 0.2 cm thick. The counter is filled with methane at 2.33 kPa pressure which simulated 2μm of soft tissue. A thin layer of aluminium ($\sim 0.1\mu$m) was evaporating on the internal surface of the counter, because caprolon is not a conductor. As it was mentioned in [10], such thickness of aluminium is negligible in a calculation of TEPC energy response for neutron above 0.3 MeV. So, the internal aluminium layer was not taken into account, when calculating the TEPC energy response for neutrons above 20 MeV. The atomic composition of caprolon, methane and soft tissue are presented in Table 1. The measurement method, which is used in IHEP [11] allows one to measure absorbed dose (D) and dose equivalent (H) of mixed radiation, neutron absorbed dose D_n and neutron dose equivalent H_n. The TEPC response in units of absorbed dose (R_D, R_{Dn}) and in units of dose equivalent (R_H, R_{Hn}) are then calculated as follows

$$R_D = A \int D(y)dy, \tag{1}$$

$$R_{Dn} = A \int_{y>6} D(y)dy, \tag{2}$$

$$R_H = A \int D(y) \cdot Q(y)dy, \tag{3}$$

$$R_{Hn} = A \int_{y>6} D(y) \cdot Q(y)dy, \tag{4}$$

where A is a conversion factor to Gy; D(y) is a distribution of energy deposition of events in units of linear energy (keV/μm) in a sensitivity volume of the counter. Q(y) is Q-y relationship that is obtained for Q(L) (quality factor dependence on linear energy transfer L relationship specified in the ICRP 21 [12] and ICRU 60 [13] Recommendations).

Table 1. Atomic composition of caprolon, methane and tissue by weight of a percent

	H	C	N	O
caprolon	9.6	45.7	10.2	16.2
methane	25	75	-	-
tissue	10.1	11.1	2.6	76.2

Q(Y) is used in the experimental method for dose equivalent measurement and permits to avoid of unfolding LET spectra from an experimental events spectra D(Y). The relationships Q(y) and Q(L) are presented in Fig.2. The method of D_n and H_n measurement is based on a fact that a contribution of events with y> 6 keV/μm into neutron dose is negligible. On the other hand the contribution of events with y> 6 keV/μm to photon or electron dose is negligible as well. This method has been checked by the experiment involving the IHEP neutron reference fields described in [10].

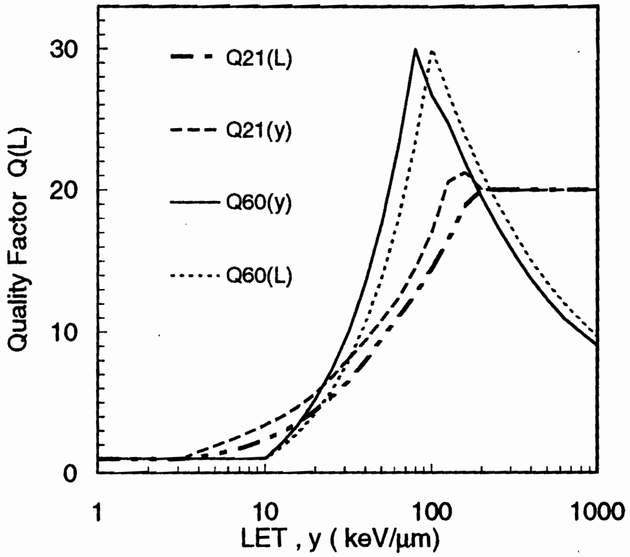

Fig. 2. Q-L and Q-y relationship as specified in ICRP-60 and ICRP-21.

2. Calculational results

Some factors that affected the neutron response of TEPC have been taken into account. The factors are the following: atomic composition of counter materials, heterogeneous of the counter, thickness of the counter body, a separate level y for γ-n discrimination.

As has been shown in [7], [10] the neutron response of TEPC depends on the atomic composition of gas in neutron energy region below 300 keV. And the neutron response depends on the atomic composition of the counter body for neutrons above 300 keV. Table 1 shows that hydrogen concentration in carbon is identical to that for soft tissue.

The concentration of carbon, on the other hand, is higher for caprolon. So, the distinction between the response of tissue equivalent counter (whose atomic composition is the same to that of tissue) , and the response of caprolon counter depends on the variation between oxygen and carbon kerma. Fig.3 shows neutron kerma for carbon and oxygen in the energy region from 20 MeV up to 100 MeV. The comparison between calculation by

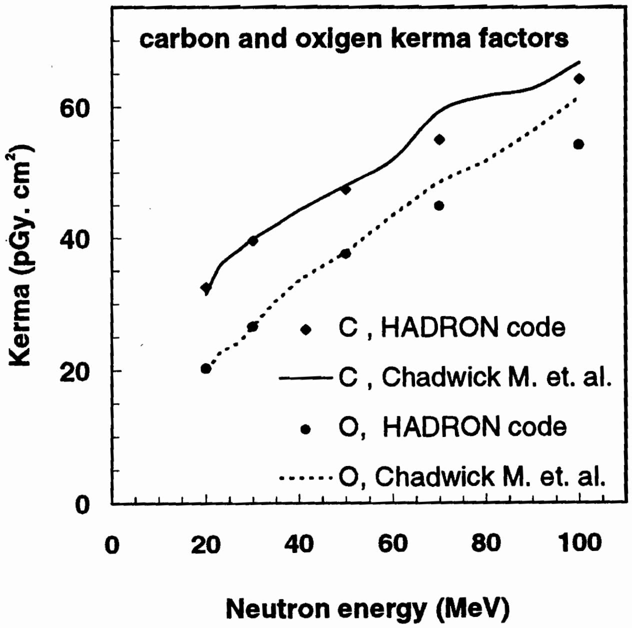

Fig. 3. Neutron carbon and oxygen kerma factor; the circles and the diamonds are HADRON code calculation; the line are the evaluated data.

HADRON code [14] and new evaluation data [15] is presented. Maximum distinction between carbon and oxygen kerma is for 20 MeV and decreases with neutron energy increase. A good agreement between HADRON and evaluation data exists. So, the influence of changing from oxygen to carbon is markedly affected for the neutron response of TEPC in the energy region up to 100 MeV.

Fig.4a,b shows the response contribution into the TEPC response from secondary charged particles emitted in neutron interactions with gas, the counter body and the aluminium cover. The energy response in units of absorbed dose ((R_d) is presented on Fig.4a and the same dependence in units of dose equivalent (R_h) is presented on Fig.4b. The contribution of particles from the neutron interactions with gas is less than 10 %. It is much less for R_D than for R_H. This may be explained by different contributions to these values from a short-range recoil particle produced in neutron interactions. The aluminium cover contribution increases with energy above 1000 MeV, but its contribution to R_h remains negligible. So, for neutrons above 20 MeV the energy response of TEPC is mainly dependent on atomic composition of the counter body.

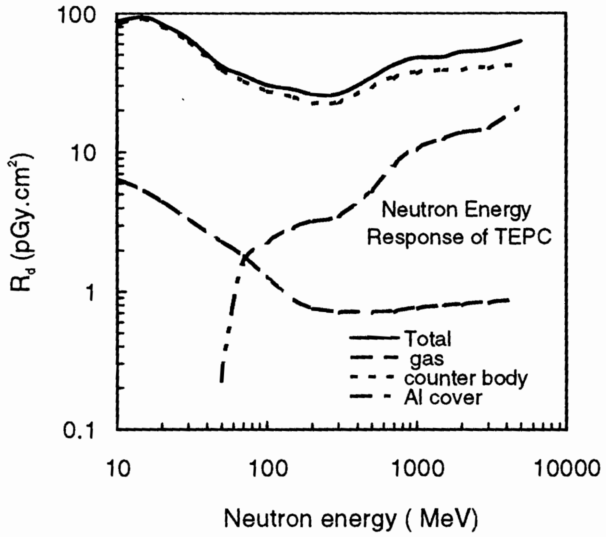

Fig. 4a. Neutron energy response of TEPC in units of absorbed dose: total and the contributions of neutron interaction with a gas, a counter body and Al cover.

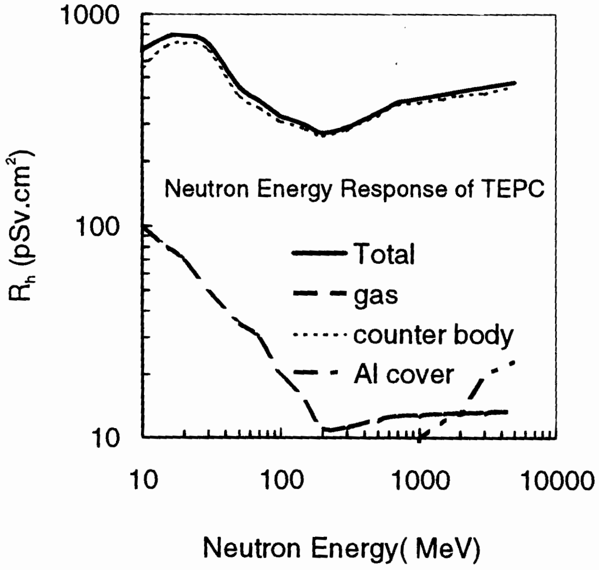

Fig. 4b. The same as in Fig. 4a but in units of dose equivalent.

The TEPC method of dose equivalent measurement is based on the modelling of tissue volume. The pressure of gas is dependent on a simulated value of sensitivity volume. The thickness of the counter body is chosen in order to ensure the equilibrium of secondary charge particles. The equilibrium commonly exists, when the range of all secondary charged particles is less than the counter body thickness. This condition does not take place for neutrons above 20 MeV, since the range of secondary protons could reach about

10 cm and more. Fig.5 shows the dose equivalent in the center of tissue spheres of 0.2, 0.1 and 1.5 cm in diameters for the neutron energy from 20 MeV up to 5 GeV as well as the neutron energy response of caprolon counter with 0.2 cm thickness of body. The increase 7 times for the diameter accompanies the change of the TEPC response about 20% only. The above-mentioned higher sensitivity of the caprolon counter as compared with the tissue one is explained by higher concentration of carbon in caprolon. So, a choice of the counter thickness for high energy region is a compromise in choosing the thickness to reach the needed response to neutrons with the energy below 20 MeV.

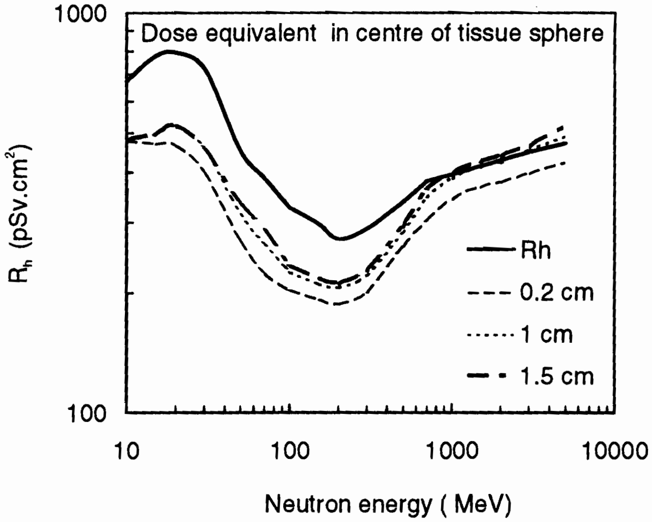

Fig. 5. Neutron dose equivalent in centre of tissue spheres with different diameter. The sphere diameter is present in cm. R_h is TEPC response.

The above-mentioned discrimination level of y=6 keV/μm is suitable for the separation of neutron events from photon events in the neutron energy region below 14 MeV. The contribution from high energy secondary proton events, which overlap photons events, and the region of such overlapping increase with neutron energy. Fig.6 shows a relative dose contribution of events (in units of linear energy) above the given value of y for neutrons with energy 10, 100 and 1000 MeV in 2 μm sensitive volume. In the case of 10 MeV the total absorbed dose (about 100%) is reached by the events with linear energy above 10 keV/μm. On the other hand, in case of 100 MeV a contribution from events with y< 6 keV/μm is equal to about 20%.

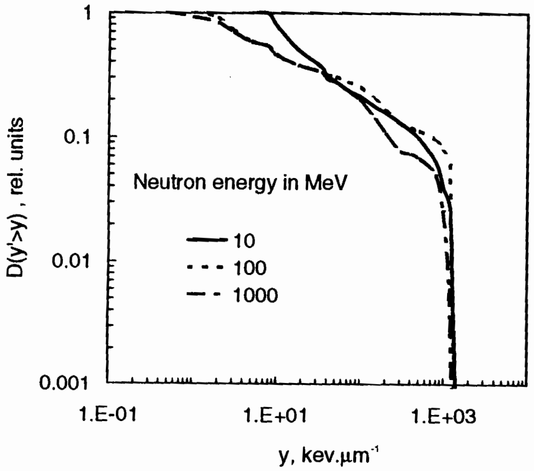

Fig. 6. Fraction of neutron absorbed dose due to events with linear energy above given y.

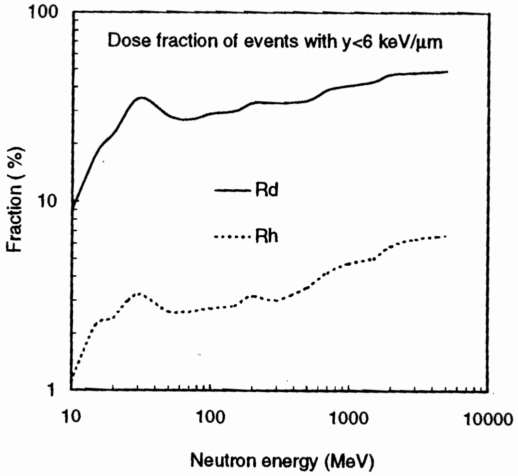

Fig. 7. Fraction of neutron absorbed dose (R_d) and dose equivalent (R_h) in sensitive volume of TEPC due to events with y< 6 keV/μm.

The ratio of TEPC response (in units of absorbed dose and dose equivalent) in the case of y> 6 keV/μm to the same value for zero threshold of y= 0 is presented in Fig.7. The contribution of events with y<6 keV/μm into the absorbed dose increase with neutron energy and is equal to about 30% at 5 GeV. At the same time the contribution of these events into the dose equivalent is less than 5%. So, it is clear that this measurement method of neutron dose equivalent with discrimination of events could be applied to neutrons above 14 MeV.

Fig.8 shows the comparison between calculational data of the energy response of TEPC in units of dose equivalents based on Q(y) relationship from ICRP-21 (Q21) and ICRP-60 (Q60) Recommendations. The calculational data based on Q21 [7] are presented too. Response R_h with Q60 is higher 10...30 % than the one based on Q21. The distinction between the present data and [7] is explained by using different data and codes for the calculation of neutron inelastic interaction with nuclei, and so, a different calculation of heavy nuclear to response exists.

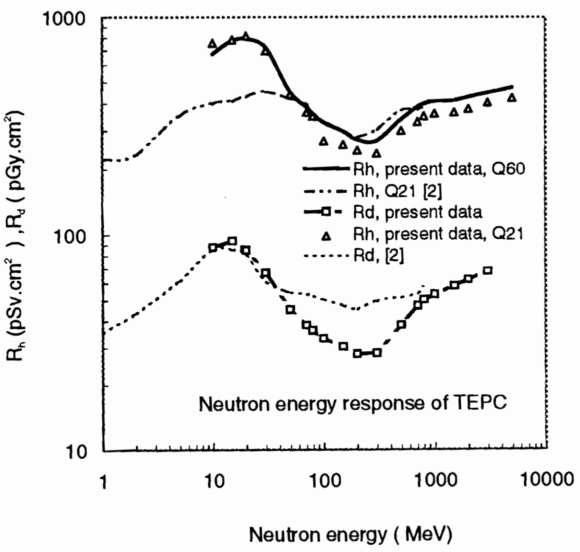

Fig. 8. Neutron energy response in units of absorbed dose and dose equivalent for Q(y) relationships specified in the ICRP-21 and ICRP-60.

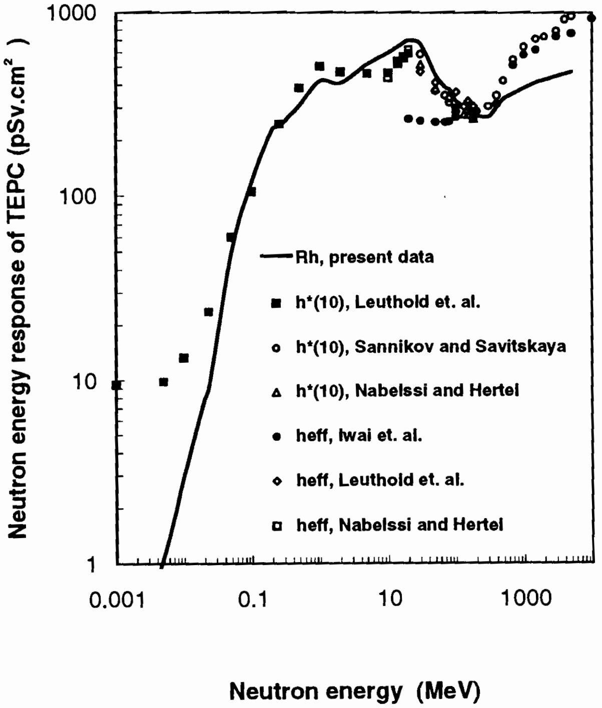

Fig. 9. Comparison of neutron response of TEPC with neutron ambient dose ($h^*(10)$) and effective dose equivalent (h_{eff}).

The important problem is a correlation of energy response of TEPC with dosimetric values, which are used in radiation safety. These are ambient dose equivalent and effective dose equivalent. The comparison between neutron effective dose equivalent [16], [17], ambient dose [8], [18] and R_h are presented in Fig. 9. The comparison shows that the measurement with TEPC provides a good estimation of ambient dose value for neutron below 300 MeV. The distinction between effective dose data [16], [17] appears in the energy region from 20 MeV up to 100 MeV. It has been explained in [17] by more correct calculation of contribution of heavy nuclear to dose equivalent. On the other hand, the agreement between effective dose [17] and ambient dose [8] exists for neutrons above 100 MeV. So, the TEPC measurement result is a conservative (overestimated) evaluation of dose equivalent for neutron below 300 MeV, if the distinction between data [16] and [17] is taken into account.

3. Experimental verification of response

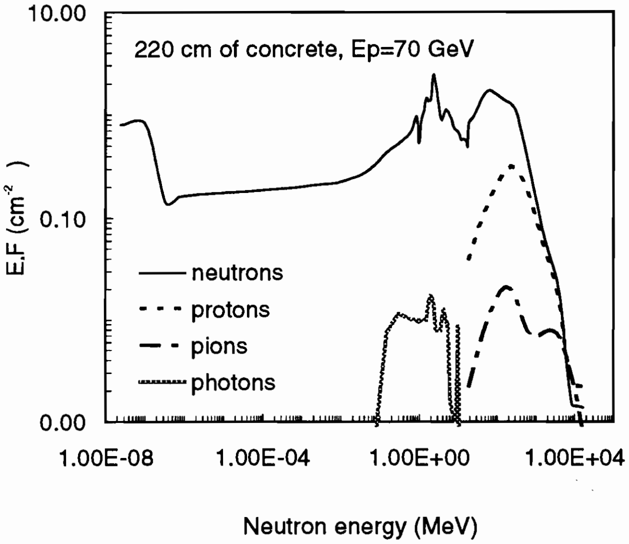

Fig. 10. Neutron, proton, pion and photon spectra behind 220 cm of concrete shielding from 70 GeV proton interacted with thin iron target. Calculation has been carried out with ROZ6H code by D.Gorbatkov.

The experimental adjustment of TEPC response to high energy neutron has been carried out in measurements of dose equivalent behind the top shielding in the U-70 experimental hall, where high energy neutrons give a significant contribution into a total dose. As a typical radiation field behind the top shielding of U-70 we use the IHEP High Energy reference Field (HEF), referring to [19], where its characteristics has been obtained by involving all the available IHEP dosimetric and spectrometric instruments such as the set of measurements with TEPC, analogy component remmeter (ACR) (which includes three ionization chambers: argon fuelled, tissue-equivalent and ^{3}He chamber in polyethylene moderator with 25.4 cm diameter), neutron multispheres spectrometer (Bonner spectrometer) together with carbon activation detector based on $^{12}C(x,xn)^{11}C$ reaction [20]. A good agreement between HEF experimental spectrum measured by the Bonner spectrometer and calculation by ROZ6H code with the SADCO multigroup library of nuclear cross sections [21] had been found in [19]. Fig.10 shows spectra of neutron, protons, photons and pions behind the side concrete shielding with 220 cm thickness arising from interaction of 70 GeV proton beam with thin iron target. As it has been shown elsewhere, for example, in [22], neutron spectrum behind the side concrete shielding has a common shape (it has two peaks: in evaporated neutron energy region and at 100 MeV). The shape is weakly dependent on primary proton energy and a shielding depth. The contribution of neutrons from 20 MeV up to 200 MeV to dose equivalent amounts about 66 % for this spectrum.

In the present paper the measurement has been made at top shielding between geodesycal axes 7 and 8 of U-70 in the place, where the radiation monitors number 53 and 20 are situated. Fig.11 shows the measurement geometry. Measurements with TEPC and ACR were carried out in two points. The first is located above the proton beam line of U-70 (RM 20) and the second one is above the proton beam line of channel 22 (70 GeV proton energy). The measurement has been carried out at 1 m height above the surface of shielding. The thickness of shielding is 220 cm concrete at the point of RM 20 location and 110 cm concrete plus 1 m iron at RM 53 point. An average dose equivalent rate was less than 0.025 mSv/h, so it allowed one to neglect a pick up effect of events for TEPC. The beam loss location and operational regime of internal targets were not fixed during the measurements. During the measurements channel 22 was in operation.

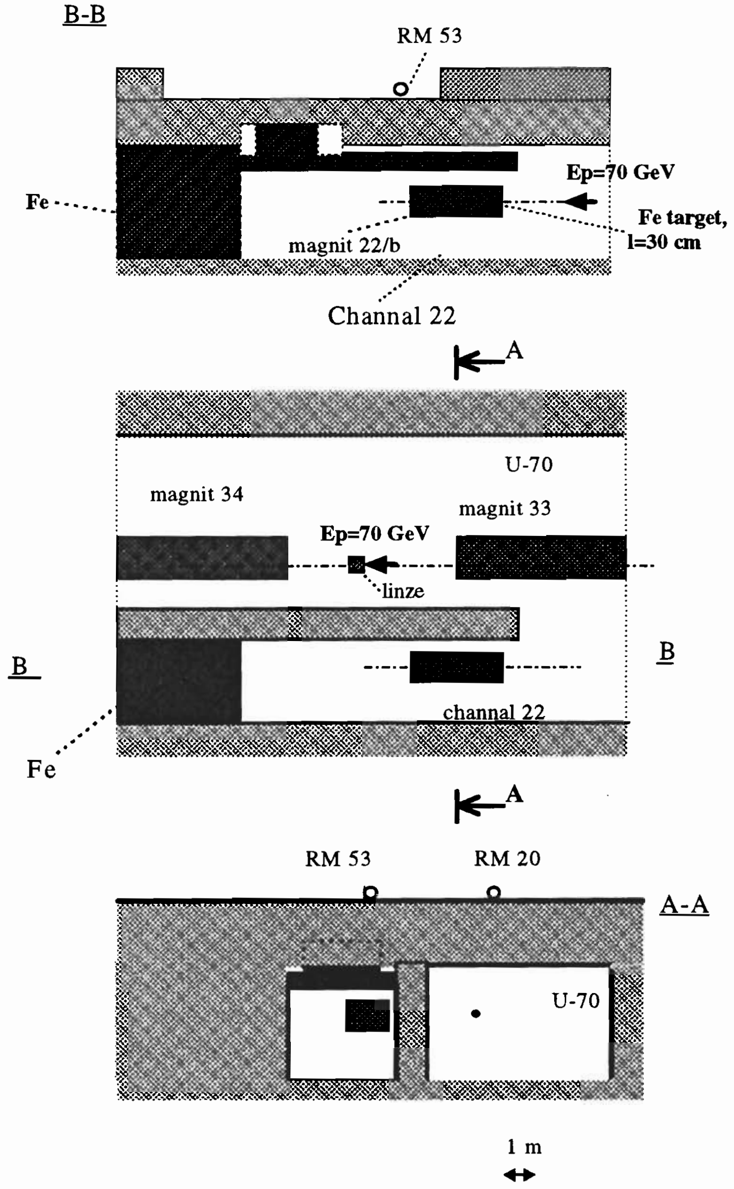

Fig. 11. Experimental geometry.

The Bonner spectrometer measurements were carried out independently from the present one (at the other regime of channel 22 and internal targets). Therefore, the ratio of neutron dose equivalent for energy below 20 MeV to total neutron dose equivalent ($H(E_n < 20\ \mathrm{MeV})/H_n$) was chosen to compare different experimental methods and calculation. Dose equivalents for neutron below 20 MeV were estimated by ACR measurement results. The total neutron dose is the result of measurements with TEPC and ACR. In case of ACR the total neutron dose equivalent and neutron dose below 20 MeV were obtained as multiplication of ^{3}He chamber measurement results and the two factors, which are dependent on the combination of readings from three chambers (Ar, tissue-equivalent and ^{3}He). The ambient dose equivalent conversion factor was used to calculate $H(E_n < 20\ \mathrm{MэB})/H_n$ factor from neutron spectra.

Fig.12 shows the ratio of $H(^3He)/H_n$ measured with ACR in two directions (along and across the proton beam line of U-70). The points of beam line above U-70 and channel 22 are 0 and -4 m coordinates, correspondingly. The ratio remains constant along the line between measurement points of RM 20 and RM 53 in the limits of 12%. This ratio increases with the increase of the distance from the beam line, because the shielding thickness and, consequently, the contribution of scattering component raises, too.

Fig.13 shows the distribution of average neutron dose equivalent for the same geometry as for Fig.12. The maximum of dose rate is located above channel 22, where thickness of concrete is 1 m and additionally there are holes in shielding.

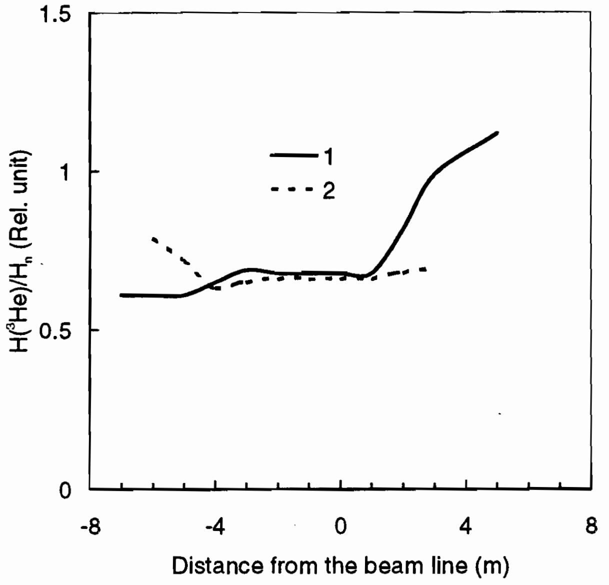

Fig. 12. Ratio of $H(^3He)/H_n$ along (1) and across (2) of beam line of U-70.

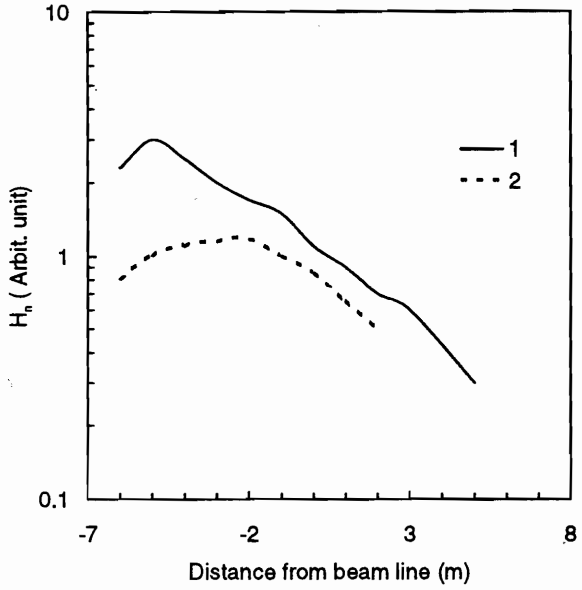

Fig. 13. Neutron dose equivalent rate along (1) and across (2) of beam line of U-70.

The results of comparison are presented in Table 2.The estimation of $H(E_n < 20\ \mathrm{MeV})/H_n$ ratio based on experimental and calculation data varies from 0.40 to 0.54. The estimation of the same factor [22] (H_{AB}/H_n) for the Anderson-Braun remmeter (which has approximately the same neutron energy response as ^{3}He chamber in polyethylene moderator) based on experimental data for neutron spectra behind the concrete shielding is equal to 0.5 ±0.1. So, the TEPC result agrees with experimental and calculational estimations. The ACR method gives much higher estimation of H(E_n <20 MэB)/H_n ratio. It could be explained by the fact that the ACR correction factors for the evaluation of high energy neutron dose equivalent are fitted from the measurements with the ACR, TEPC and Bonner spectrometer at different points at the top of concrete shielding of U-70.

Table 2. Comparison of experimental and calculation data

measurement point	TEPC	ACR	ROZ6H	Bonner spectrometer	[22]
RM20	0.42	0.57	-	-	-
RM53	0.40	0.52	-	-	-
estimation	-	-	0.54	0.49	0.44

Conclusion

The calculation of TEPC neutron energy response has been carried out for neutron energy range from 20 MeV up to 5 GeV. The present data agree with the measurement results obtained at the top of concrete shielding of high energy proton accelerator. The measurements with TEPC allow one to obtain a correct estimation of ambient dose (errors are less than 15 %) for neutrons below 200 MeV.

The change of calibration methods for dosimeters, which are used in routine radiation dosimetry is need, because the substitution of quantities in the radiation safety field (NRB-96, ICRP-60), for example, dose equivalent is substituted by effective dose, exist. The routine neutron radiation dosimetry (for example, at IHEP) is based on the detectors that don't allow one to correctly measure an ambient dose, effective dose for neutrons above 20 MeV. At the same time the ambient dose is a conservative estimation of effective dose in a wide neutron energy region (up to 10 GeV). So, TEPC can be used as a reference dosimeter for the calibration of routine dosimeters in units of ambient dose for applications in high energy neutron fields.

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