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APPLICATION OF LOW-PRESSURE TISSUE-EQUIVALENT PROPORTIONAL COUNTER FOR IHEP RADIATION PROTECTION

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Abstract

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Mixed radiation fields behind the shielding of the 70-GeV proton synchrotron are composed of neutrons with energy from thermal up to several GeV, high energy charge particles (E> 20 MeV) and photons. Now one of the major techniques for direct dose equivalent measurements in such mixed radiation fields is based on low-pressure tissue-equivalent proportional counters (TEPC). The dosimetric method based on TEPC is described, which is used for radiation dosimetry in IHEP. The main technical data of TEPC and experimental results of dose characteristics measurements are presented for the reference fields of IHEP and JINR (Dubna). The results are compared with other dosimetric systems. An application of correction methods for neutron dose equivalent measurement on the base of TEPC microdosimetry spectra and using the detector with different neutron energy response is discussed.

Аннотация

Алексеев А.Г. Использование тканеэквивалентного пропорционального счетчика низкого давления в радиационном контроле ИФВЭ: Препринт ИФВЭ 95–69. – Протвино, 1995. – 13 с., 12 рис., 1 табл., библиогр.: 18.

Смешанное излучение за защитой протонного синхротрона на 70 ГэВ состоит из нейтронов с энергией от тепловой до нескольких ГэВ, высокоэнергетических заряженных частиц (E> 20 МэВ) и фотонов. В настоящее время одним из основных методов измерения эквивалентной дозы в таких смешанных полях является метод на основе тканеэквивалентного пропорционального счетчика низкого давления (ТЭПС). Описан метод измерения эквивалентной дозы на основе ТЭПС, используемый в радиационном контроле ИФВЭ. Представлены основные характеристики ТЭПС. На основе результатов измерений в опорных полях ИФВЭ, ОИЯИ проведено сравнение с другими дозиметрическими системами. Обсуждается возможность использования методов коррекции для измерения эквивалентной дозы нейтронов с помощью ТЭПС, основанных на анализе микродозиметрических спектров или с использованием дозиметра с другой энергетической зависимостью чувствительности к нейтронам.

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INTRODUCTION

Radiation behind shields of high energy charge particles accelerators (for example, the IHEP 70 GeV proton synchrotron (U-70)) is of a mixed composition. The major component of radiation is high energy neutrons with energy above 20 MeV. The dose equivalent measurement of high energy neutrons is a difficult problem for the radiation protection dosimetry, because there are no standard devices for this energy region. Now only a measurument method on the base of low-pressure tissue equivalent proportional counter (TEPC) is used as universal in mixed radiation fields. This dosimetric method has more than 20-year history of application at the IHEP accelerator. The method has been improved in measurements, the counter design and applications. The linear energy transfer (LET) spectrometer (SLET-03) on the base of TEPC [1] is used for metrological measurements in IHEP radiation protection. In this paper the TEPC method is presented as now used in IHEP.

1. EXPERIMENTAL PROCEDURE

The spherical tissue equivalent proportional counter has been developed in collaboration with the Institute of Biophysics (Moscow) [2] . Fig. 1 shows the external view of TEPC. The TEPC has been designed by Benjamin P. The TEPC body was produced from caprolon (tissue equivalent material) 10.8 cm in inside diameter and 0.2 cm thick. The aluminium layer 0.1 μm thick was evaporated on the inner of the counter body. The counter design has been presented in [2]. It has a gas tight aluminium cover 0.2 cm thick and is filled with methan under a pressure corresponding to 2 μm tissue. The counter is provided with the α-monitor with alpha source for calibration. The gas gain is kept constant in $\pm$ 10 % region over 2 years due to the special training of the counter. The standardized commercial multichannal analyser is used for events spectrum measurement. A charge produced in the counter cavity (the counter as an ionization chamber) is behind measured simultaneously with an event spectrum by the standardized commercial

electrometer (DRG2-01). The tissue kerma and dose equivalent are then calculated as follows:

$$K_{ph+n} = R_{ph} \cdot q, \tag{1}$$

$$K_n = A_n \sum_{i=i_{min}}^{i_{max}} N_i \cdot i, \tag{2}$$

$$K_{ph} = K_{ph+n} - K_n, \tag{3}$$

$$H_n = A_n \cdot B_n \sum_{i=i_{min}}^{i_{max}} N_i \cdot Q_i, \tag{4}$$

$$H_{ph} = K_{ph} \cdot B_{ph}, \tag{5}$$

$$Q_n = \frac{H_n}{K_n \cdot B_n}, \tag{6}$$

where R_{ph} [Gy·nC^{-1}] and A_n [Gy· MeV^{-1}] are the calibration factors; q is the charge produced in the cavity; N_i is the total number of events in the i-th channel of the pulse-height analyser. The Q_i function has been chosen to simulate the quality factor dependence on linear energy transfer L. K_{ph} and K_n are photon and neutron tissue kerma, respectively. K_{ph+n} is the sum of photon and neutron tissue kerma. H_{ph} and H_n are photon and neutron dose equivalents; B_n and B_{ph} are the phantom conversion factor from tissue kerma to dose equivalent for neutron and photon, respectively. The events with pulse height above 6 keV· μm^{-1} (in the units of linear energy) are included to obtain K_n values. The background for the neutron dose equivalent rate is 2 μSv·h^{-1}. The TEPS background was produced by microparticles captured in the counter cavity from the alpha source layer.

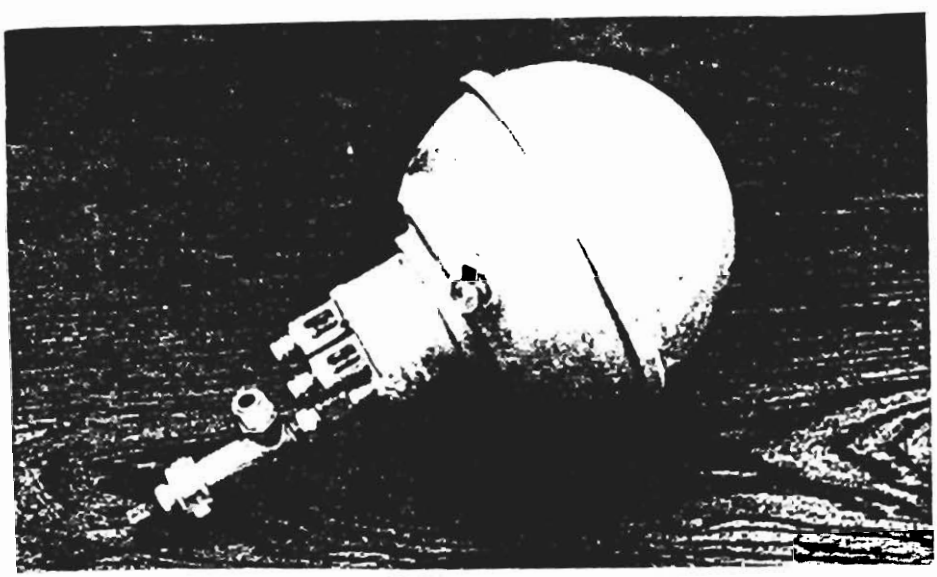


Fig. 1. The external view of tissue equivalent proportional counter.

2. CALIBRATION

The factor R_{ph} (in the units of tissue kerma) is obtained with ^{137}Cs photon source calibration. The calibration error is equal to 4 % . In the course of measurements the factor R_{ph} is determined with the alpha source as follows :

$$R_\alpha = A_\alpha \cdot S \cdot d \cdot \rho \frac{N}{q}, [Gy/nC]. \tag{7}$$

$$A_\alpha = \frac{1.6 \cdot 10^{-16}}{m_g}, [Gy \cdot MeV^{-1}], \tag{8}$$

where d is the counter diameter [cm]; S is a stopping power of alpha particles (S =1140 MeV cm $^2 \cdot$ g $^{-1}$ for 5.2 MeV alpha particle energy); N is the total number of events by alpha particle; ρ is the gas density (g $\cdot$ cm^{-3}); m_g is the mass of gas in the counter [g]. The alpha-to-photon calibration ratio (R_{ph} /R_α) is equal to 1.10±0.05. The use of α-monitor decreases the measurement error. For example, the temperature dependence of the gas gain is equal to 0.5 % per 1 C ^{o}. The factor A_α is derived from the counter sensitive volume size. The event pulse height is calibrated into tissue kerma units with this factor and with the alpha sourse. Primarily the factor A_n can be calculated on the base of geometrical dimensions of the counter and also from the calibration in the neutron reference field. In the common case A_n is equal to A_α. But when the factor A_n was obtained under calibration in the National Primary Standard neutron field of dose equivalent rate on the base of VNIIFTRI [3], the neutron-to-alpha calibration ratio was equal to 1.30∓ 0.12 . The factor B_n was measured using a polyethylene phantom. The phantom size was 70 ×30× 40 cm. The counter was located between the neutron source and the phantom. Two types of neutron sources were used: Pu-Be and ^{252}Cf. The factor B_n was determined by measuring kerma rate and dose equivalent rate with and without phantom. The measured phantom factor was equal to 1.06∓ 0.01. But the factor B_n that has been obtained under calibration with the National Primary Standard of neutron field is equal to 1.17∓ 0.02 [3]. The conversion phantom factor B_{ph} from kerma to H*(10) obtained for a ^{137}Cs photon radionuclide source is equal to 1.094.

3. ENERGY RESPONSE

The TEPC energy response for neutrons and photons is dependent on the counter design (the thickness and the composition of the counter body, the thickness of the aluminium cover). The dependence of TEPC neutron energy response on the counter design has been shown in [2],[4].

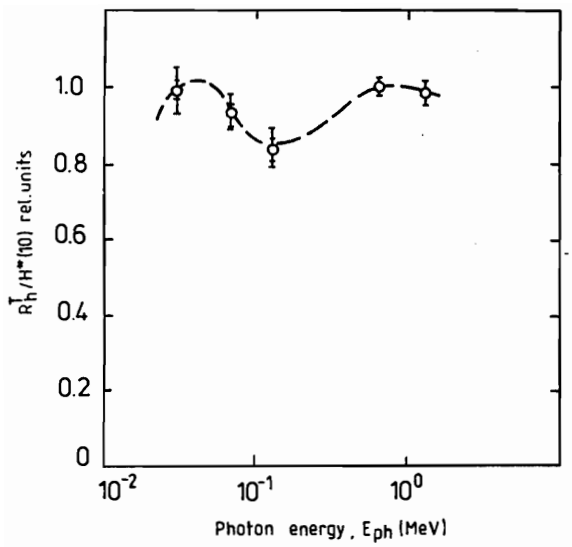


Fig. 2. The photon energy response of TEPC in the units of H*(10): the dotted line is a guide for the eye.

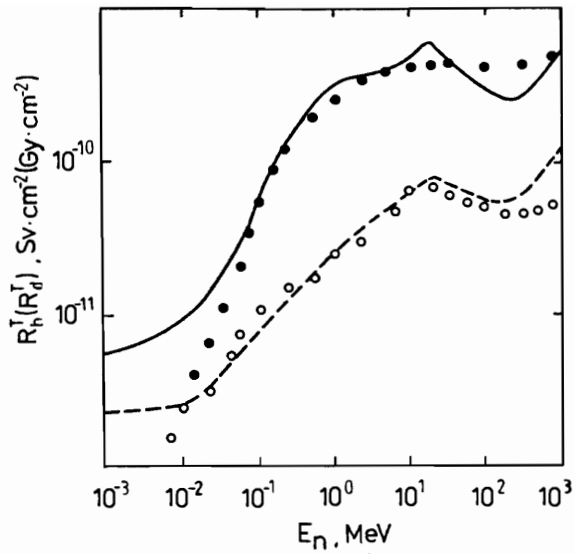


Fig. 3. The neutron energy response of TEPC. Key: (o) (R_h^T) is the energy response in the units of the ambient dose equivalent; (•)(R_d^T) is the energy response in the units of neutron kerma; the solid line is the neutron ambient dose equivalent; the dotted line is the neutron absorbed dose.

Fig. 2 shows the photon energy dependence of the dose equivalent response on TEPC. The photon energy response of TEPC in the energy range from 29 to 114 keV has been investigated by the National Secondary Standard field of absorbed dose (VNIIFTRI) [3]. The measurements were fulfilled in "ionization chamber regime" only. The ratio of H_{ph} (TEPC response unit H*(10) for ^{137}Cs) to the ambient dose equivalent H*(10) is less than $\mp$16% in the photon energy region from 0.03 to 1.2 MeV.

The energy response has been calculated for neutrons from 0.01 to 800 MeV [4], [2]. Fig. 3 shows the TEPC neutron energy response in the units of the ambient dose equivalent (R_h^T) and in the units of the absorbed dose (or tissue kerma) (R_d^T) in energy region from 0.01 MeV up to 1000 MeV. The H*(10) neutron ambient dose equivalent and D*(10) (D* (10)=H*(10)/Q_n) dose absorbed are also presented. The data on H*(10) and D*(10) are taken from [9], [7], [8]. These dose characteristics are presented for quality factors from the Recommendations of ICRP 21 [6].

The TEPC energy response agrees closely with H*(10) in the neutron energy range for 0.3 MeV to 800 MeV. The TEPC response is less than H*(10) function for neutron below 0.3 MeV. Thus the use of methan allows one to increase the TEPC response by a factor of 1.5 for the neutron energy below 0.5 MeV as compared with the use of tissue equivalent gas. The R_d^T is less than D*(10) for neutrons above 100 MeV because the thickness of the counter wall is less than 1 g·cm^{-2}. But R_h^T is higher than H*(10) for that neutron energy

region. It can be explained by more significant contribution of alpha particles to dose in the LET region from 100 up to 200 keV$\cdot\mu$m^{-1} for neutron collision with ^{12}C than with ^{16}O. The ^{12}C content of the counter wall(kaprolon) is higher than for the tissue. Besides, this discrepancy may be explained by the use of different nuclear data for neutron collision in [4] and [9].

4. MEASUREMENT RESULTS

Table 1 reflects the TEPC measurement results over the ones obtained with other dosimeters. The neutron and photon dose equivalents (or photons with charge particles) are presented for IHEP neutron reference fields, JINR neutron reference fields and high energy neutron spectra behind IHEP accelerator shields.

The IHEP neutron reference fields [3], [16] :

- The reference field based on the ^{239}Pu-Be neutron source (the average neutron energy ($\overline{E}$) is 2.7 MeV).
- The reference field based on the ^{252} Cf neutron source (^{252}Cf) ($\overline{E}$ = 1.67 MeV).
- The reference field based on the ^{252}Cf neutron source in the 30 cm diameter spherical iron moderator (^{252}Cf+Fe) ($\overline{E}$ = 0.85 MeV).
- The reference field based on the ^{252}Cf neutron source in the 30 cm diameter spherical polyethylene moderator (^{252}Cf+$\oslash$ 30 cm CH_2(IHEP)) ($\overline{E}$ = 0.67 MeV).

The JINR neutron reference fields [14] ,[15]:

- The reference field based on the ^{252}Cf neutron source in the 12.7 cm diameter spherical polyethylene moderator (^{252}Cf+$\oslash$ 12.7 cm CH_2) ($\overline{E}$ = 0.931 MeV).
- The reference field based on the ^{252} Cf neutron source in the 29.2 cm diameter spherical polyethylene moderator (^{252}Cf+$\oslash$ 29.2 CH_2(JINR)) ($\overline{E}$ = 0.742 MeV).
- The reference field based on stray radiation into a labyrinth concrete shielding of the 600 MeV proton phasotron of the JINR Nuclear Problems Laboratory (concrete labyrinth) ($\overline{E}$ = 0.253 MeV).

High energy fields:

- Radiation field behind the top of the U-70 proton accelerator shielding. Proton energy is equal to 70 GeV. The shield is 220 cm thick concrete. The measurement point was located near an internal target. The measurements were carried out at 1 m height above the shield (top concrete) ($\overline{E}$ = 71 MeV).
- The radiation field behind the calorimeter of XCHARM experiment [17] . The calorimeter consisted of 40 layers. Each layer was from 0.5 cm scintillator and 2 cm Fe. The stray radiation field is created by beams of high-energy neutrons with an average energy of about 40 GeV incident on the absorber. A contribution of charged particles in a beam flux was less 1% (behind iron) ($\overline{E}$ = 51 MeV).

- The radiation field behind the overtop of 10 GeV charged particles beam (the 18-th channel of U-70) (muons torch). The average neutron energy was not determined.

Table 1. The dose equivalent measurements with TEPC, ACR, Bonner spectrometer, REM-2. Normalization with the TEPC data. For the IHEP reference fields normalization with the expert data. Keys for radiation field are presented above.

Irradiation fields	Dosimeter	Dose equivalent, $H^*(10)$, rel. units		$H^*_{ph}(10)/H^*_n(10)$
		neutron	photon and charged particles	Relative units
Top concrete of U-70	TEPC	1.0	1.0	0.2
	ACR	0.60	1.12	
Behind iron	TEPC	1.0	1.0	0.93
	ACR	0.36	0.98	
Muon torch	TEPC	1.0	1.0	9.1
	ACR	0.32	1.01	
Pu-Be source	TEPC	1.00	1.01	0.037
	ACR	1.00	0.83	
	BS	0.99	-	
^{252}Cf	TEPC	0.95	0.90	0.049
	ACR	0.19	0.85	
	BS	1.06	-	
^{252}Cf+⌀30 cm CH_2 (IHEP)	TEPC	0.95	1.07	0.39
	ACR	1.63	0.99	
	BS	1.04	-	
^{252}Cf +Fe	TEPC	1.00	0.80	0.007
	ACR	0.75	0.0	
	BS	0.99	-	
^{252}Cf+⌀12.7 cm CH_2	TEPC	1.0	1.0	0.098
	ACR	0.97	1.03	
	BS	1.19	-	
^{252}Cf+⌀29.2 cm CH_2 (JINR)	TEPC	1.0	1.0	0.34
	ACR	0.51	1.09	
	BS	1.12	-	
Concrete labyrinth	TEPC	1.0	1.0	0.22
	ACR	1.23	1.18	
	REM-2	1.77	1.21	
	BS	1.53	–	

Figs. 4a,b show the energy spectra of high energy fields which have been calculated by D.Gorbatkov with the code ROZ-6M+CADKO [18]. The spectra of neutrons from primary beam energies down to thermal ones, the spectra of charged hadrons (protons and $\pi^{\pm}$ pions) down to 10 MeV and gammas from 0.1 up to 20 MeV were determined by the code.

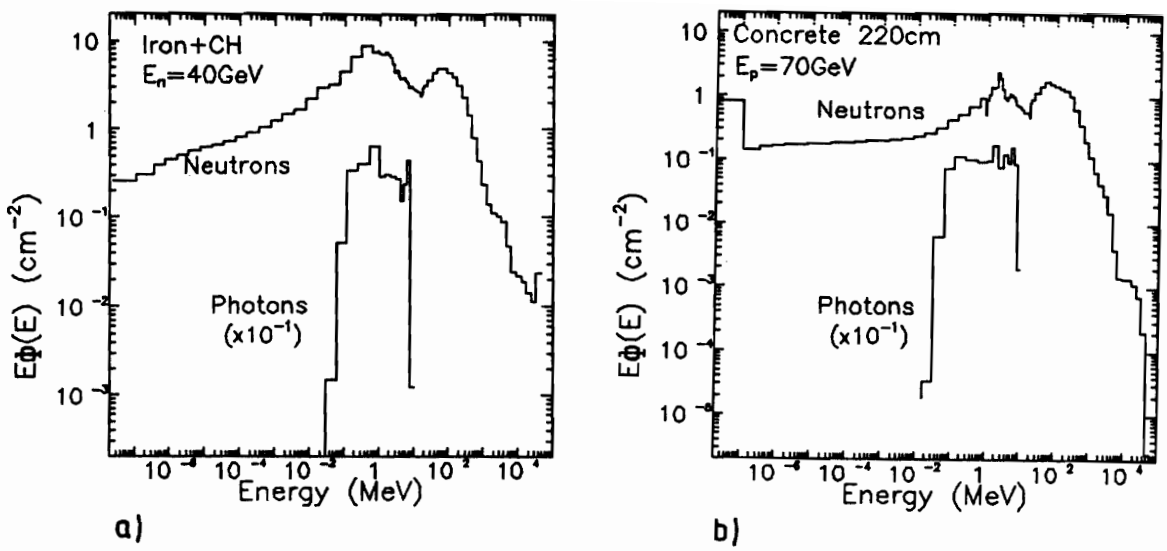


Fig. 4. Neutron and photon energy spectra calculated by D.Garbotkov with ROZ-6M code: a) Behind iron; b) Top concrete.

The comparison was carried out with the following dosimetric systems :

- The analog component remmeter (ACR) [1], that includes an argon-filled ionization chamber, tissue-equivalent chamber, ^{3}He-filled ionization chamber into the 25.4 cm diameter spherical polyethylene moderator. To minimize the neutron dose equivalent measurement systematic error, the correction method based on additional information about a behaviour of the ionization chamber neutron response in different neutron spectra is applied.
- The Bonner multisphere neutron spectrometer (the dose equivalent measurement method by 6-spheres has been certified by VNIIM)[12].
- REM-2 [13], [15].

The dose equivalent data for all dosimeters are normalized with the TEPC values. For the IHEP reference neutron fields the data are normalized by the expert data from [2]. In Table 1 the photon (and charged particles) – to- neutron dose equivalent ratios for radiation fields are presented. Fig. 5, 6, 7 illustrate the dose distribution of linear energy obtained with TEPC in the IHEP reference fields (^{252}Cf into 30 cm diameter spherical iron moderator), in the ^{137}Cs photon source, in high energy radiation field behind the top of the U-70 proton accelerator shielding, in the JINR phasotron reference field (concrete labyrinth).

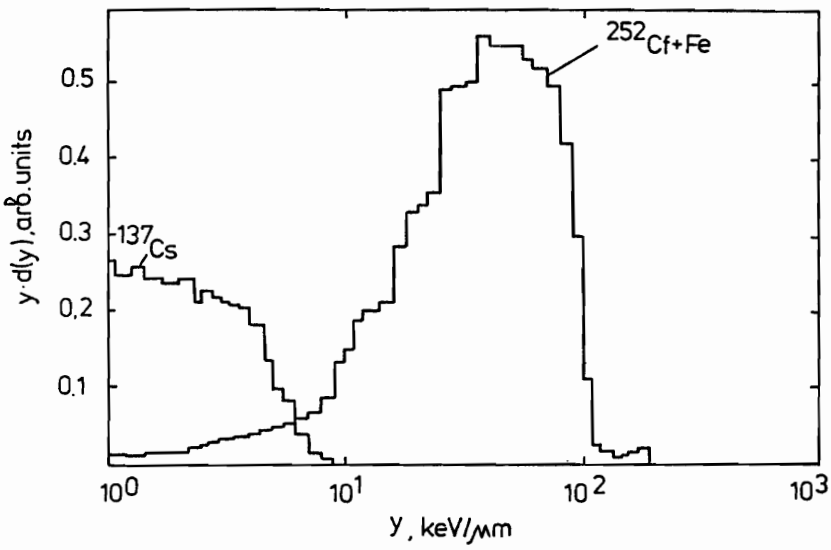


Fig. 5.
Normalized dose distributions measured with TEPC for photon ^{137}Cs source and for the IHEP neutron reference field (^{252}Cf in ⌀30 cm Fe).

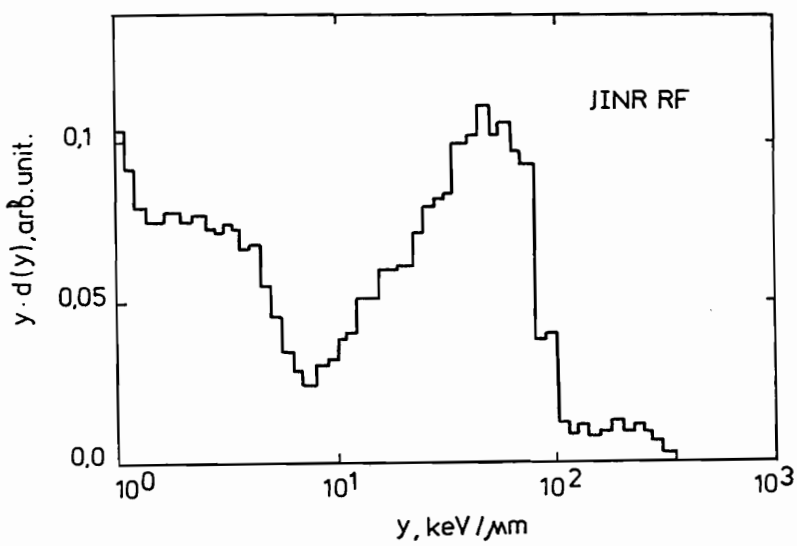
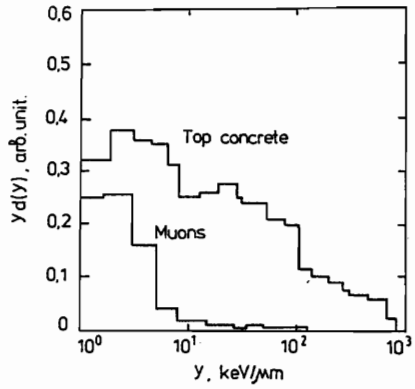


Fig. 6.
Normalized dose distributions measured with TEPC for the JINR neutron reference field (concrete labyrinth).

Fig. 7. Normalized dose distributions measured with TEPC for the ontop concrete shield of the 70 GeV proton accelerator and into " Muons torch" overtop 10 GeV charged particles beam (the 18-th channal of U-70).



5. DISCUSSION

The photon dose equivalent data carried out by TEPC are not significant as compared with those measured with other dosimeters. The comparative results show that the TEPC data are systematically lower than those of the Bonner spectrometer within 20 % except for the JINR concrete labyrinth. The difference between the data of ACR and the ones of TEPC can be explained by the fact that the ACR correction method for neutron dose equivalent measurement cannot be used when the photon-to-neutron ratio of dose equivalent is higher than 0.3 (^{252}Cf+$\oslash$ 30 cm CH_2(IHEP), ^{252}Cf+$\oslash$29.2 cm CH_2(JINR)) or there is a high contribution of muons to the total dose equivalent (behind iron and "Muons torch"). The Bonner spectrometer data are by a factor of 2 higher than for TEPC in the concrete labyrinth. This over-response is explained by a high contribution (about 50%) of neutrons with energy below 0.2 MeV to the neutron dose equivalent. The neutron energy response of TEPC is low for this neutron energy region.

The systematic error of neutron dose equivalent measurement may be reduced with a correction factor when the average spectra neutron energy is less than 0.5 MeV. The correction factor may be obtained by one of two procedures. The former is based on the neutron energy dependence of the neutron response ratio of TEPC to neutron response of another detector. The TEPC is conventionally used together with the ^{3}He-filled ionization chamber into the 24.5 cm diameter spherical polyethylene moderator for routine measurements. An alternative method may be based on the neutron energy dependences of average parameters for linear energy spectra [10].

Fig. 8 shows the ratio R_h^T/R_h^C as a function of neutron energy and Fig. 9 shows the ratio R_h^T/R_h^C as a function of average neutron energy, where R_h^T and R_h^C are response of TEPC and ^{3}He chamber in the 25.4 cm polyethylene moderator, correspondingly. The energy response of ^{3}He chamber in the 25.4 cm polyethylene moderator has been calculated by S.Kharlampiev. This method is similar to that for the ACR correction method for neutron dose equvalent measurement [3], where the tissue equivalent chamber is used as TEPC here. Fig. 10 shows the ratio of $R_h{}^T$ / H^* (10) for the neutron spectra as a function of R_h^T/R_h^C. Thus the use of R_h^T/R_h^C ratio allows one to get information about neutron spectra and estimate the neutron dose equivalent. The systematic measurement

error of neutron dose equivalent by TEPC may be reduced from 100% up to 10% for a wide region of neutron spectra.

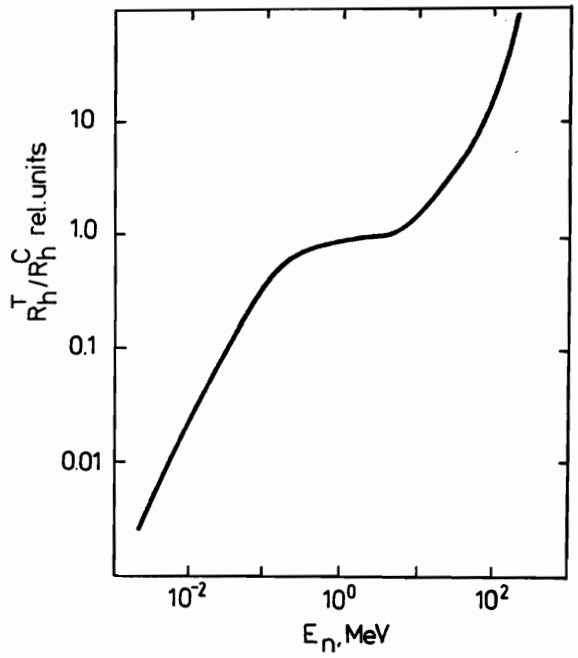


Fig. 8. The ratio of neutron energy response of two dosimeters: TEPC and ^{3}He ionization chamber into 25.4 cm polyethylene sphere.

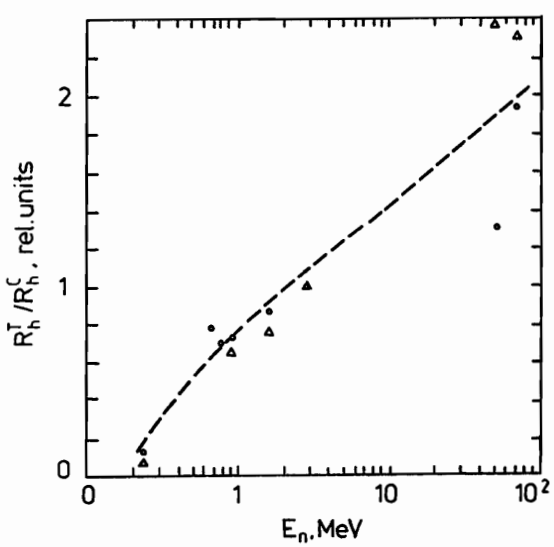


Fig. 9. The ratio of neutron energy response of the dosimeters (TEPC (R_h^T) and ^3He ionization chamber into 25.4 cm polyethylene sphere (R_h^C).

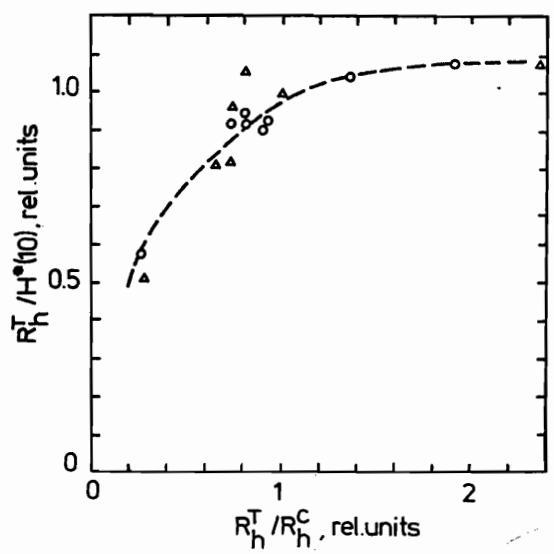


Fig. 10. Conversion factor $R_h^T/H^*(10)$ plotted against ratio R_h^T/R_h^c; (o) calculation for neutron spectra, (Δ) measurements.

Another way of getting information about neutron spectra and estimating systematical measurement errors may be the analysis of microdosimetric spectrum, for example d(y), where d(y) is the dose distribution in the units of linear energy y measured by TEPC. The ratio of dose fraction (δ) for events with y > 100 keV/μm to dose fraction for events with y> 2 keV/μm is related to average neutron energy of spectra. Fig. 11 displays this ratio δ for the average neutron energy of spectra from 0.1 up to 100 MeV, δ is calculated as follows:

$$\delta = \frac{\int_{y_1}^{y_{max}} d(y)dy}{\int_{y_2}^{y_{max}} d(y)dy}, \tag{9}$$

where y_1= 100 keV/μm, y_{max}= 1000 keV/μm, y_2= 2 KeV/μm. The value y=100 KeV/μm is chosen as maximum of proton events, 2 KeV/μm is chosen as maximum of photon events. Fig. 12 shows the correction factor($R_h^T/H^*(10)$) as a function of δ. If photon contribution to total dose equvalent is higher than 70%, the integration threshold must be equal to 6 or 10 KeV/μm, because the value of events in the units of linear energy from photon and muons is less than 10 KeV/μm. But the increase of integration threshold results in the decrease of neutron spectra, where this correction factor may be used. Besides the correction with δ cannot be used when a large contribution of neutron with the energy is below 10 keV. For example, the concrete labyrinth, because neutron events in this energy region are less than 2 and 6 KeV/μm. The latter procedure is rare, because it may be used when photon and charged particle contributions to dose are negligible. For example, this procedure may be used in measurements behind iron shields.

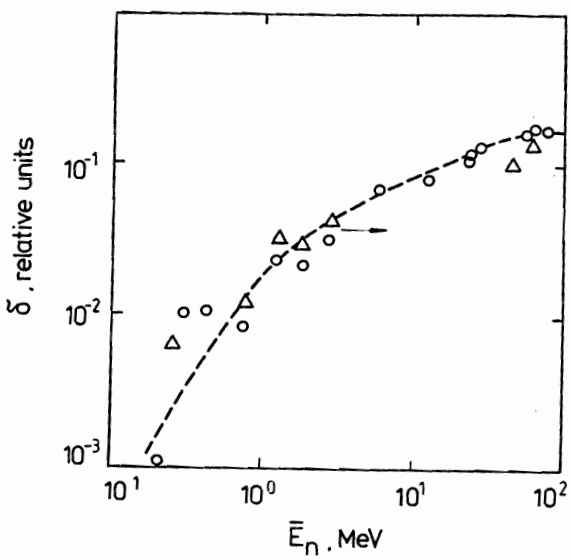


Fig. 11. Fraction of dose δ for events with y> 100 keV/μm plotted against average neutron energy of spectra: (o) calculations, (Δ) measurements.

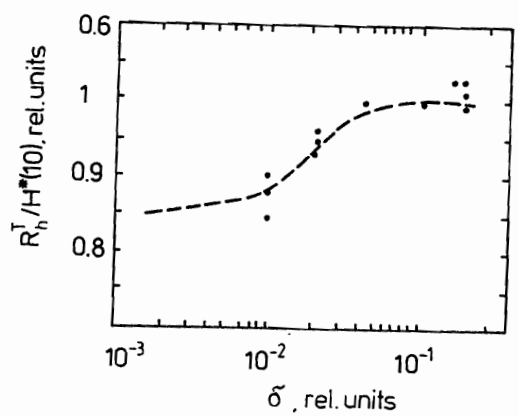


Fig. 12. Conversion factor $R_h^T/H^*(10)$ plotted against δ.

CONCLUSION

The use of neutron dose equivalent meter based on TEPC may be successful in a variety of radiation fields of a high energy accelerator . The TEPC may be used as a reference meter in various neutron fields for routine dosimeters. Alhough neutron response of TEPC is low for neutron energy below 0.3 Mev, the use of TEPC together with another simple dosimeter may be helpful to reduce systematic measurement errors of dose equivalent.

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