Improvement of construction of recombination chambers for mixed radiation dosimetry at work places

Michał Gryziński[1], Mieczysław Zielczyński[1], Natalia Golnik[2], Edyta Jakubowska[2]

[1]National Centre for Nuclear Research, Otwock-Świerk, Poland

[2]Institute of Metrology and Biomedical Engineering, Warsaw University of Technology, Poland

First recombination chambers were invented about 50 years ago. Up to now there are about 20 methods, about 30 types of chambers and about 15 various recombination dose meters developed for several applications and different dose rates. Among them, there are large recombination chambers, e.g. of REM-2 type, which can be used for determination of H*(10) in mixed radiation fields. New generation of such chambers (denoted as REM-3) is now under development and tests. The main innovations in REM-3 recombination chamber include proper positioning of insulators, which effect in decrease of the time needed for stabilizing the signal after a change of the polarizing voltage; the use of polypropylene as the material for electrodes and of a cylindrical polypropylene insert which results in improvement of sensitivity and energy response characteristics in neutron-gamma radiation fields; and easy switch between summation and differential modes of the chamber operation.

Key words: Radiation protection, radiation dosimetry, recombination chambers

1. Introduction

Recombination chambers are high-pressure ionization chambers, designed in such a way that the initial recombination of ions occurs when the chamber operates at polarizing voltages below saturation and, for a certain range of gas pressure and dose rates, the initial recombination is much greater than volume recombination. Measuring methods based on determination of radiation quality from the amount of initial recombination are called recombination methods.

Conditions of initial recombination can be achieved in specially designed chambers. They are usually parallel-plate and the spacing between electrodes is of the order of millimeters. At larger spacing, the volume recombination limits the maximum dose rate at which the chamber can be properly operated. Sets of electrodes connected in parallel are used to increase the chamber sensitivity.

First recombination chambers and the first recombination methods were elaborated about 50 years ago [1,2] for dosimetry of mixed radiation fields. The idea was based on theories of columnar recombination of ions in gases, developed by Jaffe [3,4] and of initial recombination in ion clusters, by Lea [5]. Both theories, and further works of Zielczynski et al. [6], Sullivan [7], Makrigiorgos [8] and Golnik [9] made it possible to establish a relationship between ion collection efficiency in an ionization chamber operating under conditions of initial recombination of ions and such parameters, as LET, restricted LET or linear ionization density in small volumes (linear dimensions few tens of nm of water) around the point in the track. These parameters could be further correlated with radiation quality factor.

Up to now there are about 20 methods, about 15 various recombination dose meters developed for several applications and different dose rates and about 30 types of chambers [10]. Among them, there is a large recombination chamber of REM-2 type [10,11], which roughly approximates dosimetric parameters of the ICRU sphere and can be used for determination of H*(10) in mixed radiation fields.

This work presents a new design of the chamber (denoted here as REM-3), based on the REM-2 chamber but with several changes improving the energy response characteristic. There is also a new option of fast switch between summation and differential modes of operation. An additional improvement of whole dosimetric system is met by use remote control, by Wi-Fi or Ethernet cable, for data transfer from the detector. This excluded long electrometric cables, which were very inconvenient and could generate considerable noise.

2. Measurements of H*(10) using recombination chamber

The output of the recombination chamber is the ionization current (or collected charge) as a function of polarizing voltage. Most of the recombination methods require the measurement of the ionization current (or charge) at least at two values of the polarizing voltage applied to the chamber. The highest voltage should provide the conditions close to saturation (but below discharge or multiplication). The charge collected at the maximum applied voltage is nearly proportional to the absorbed dose D. Measurements at other voltages are needed for the determination of the radiation quality.

Two main methods were proposed for the determination of the radiation quality factor, both based on the fact that the dependence of initial recombination on LET is different for different polarizing voltages applied to the chamber.

The first, simpler approach involves measurements of the ionization current i_S and i_R at two properly chosen polarizing voltages U_S and U_R. A certain combination of these two currents (given by Eq. 1), is called recombination index of radiation quality Q_R [6,12] and may serve as a measurable quantity which depends on LET in a similar way as the radiation quality factor defined by ICRP [13] in different mixed radiation fields including neutrons of energies from thermal to few hundreds MeV [14]. The total dose equivalent in a mixed radiation field is then given by the product $H = D\,Q_R$ of the absorbed dose D and recombination index of radiation quality Q_R, both determined by the recombination chamber.

$$Q_R = \frac{1 - i_R / i_S}{R} \qquad (1)$$

$R = 1 - i_R / i_S$ is determined in gamma radiation reference field (e.g. ^{137}Cs) at specially chosen polarizing voltage U_R, called recombination voltage and U_S which is the maximum voltage which can be applied to the electrodes (near saturation). Most often, the measurements of dose equivalent are performed at such value of U_R that $R = 0.04$. For such conditions Q_R is denoted as Q_4. Ionization currents i_S and i_R in Eq.1 are determined in investigated radiation field.

The second method [9] involves measuring the ionization current of a recombination chamber at several collecting voltages and determining the dose distribution D(L) versus LET. The D(L) distribution is then used for determination of the low-and high-LET dose fractions and for calculation of the radiation quality factor.

The main goal of radiation protection dosimetry at workplaces is the determination of the ambient dose equivalent H*(10). At present, the best recombination chamber investigated for this purpose is the REM-2 chamber [10,11] designed at IAE and manufactured by POLON Bydgoszcz (Poland). This is a cylindrical, parallel-plate ionization chamber with 25 tissue-equivalent electrodes, a volume of 1800 cm^3, a mass of 6 kg and an effective wall thickness of about 2 g/cm^2. For the measurements of H*(10), the chamber was filled with the mixture of methane and nitrogen (5%), up to the pressure of about 1 MPa. The energy dependence of the REM-2 chamber response to H*(10) was investigated in monoenergetic neutron beams with energy ranging from 75 keV to 19 MeV [11] and in radiation fields of isotopic neutron sources [15]. The REM-2 chamber has been also used in a number of experiments and international intercomparisons. Among them, there were measurements in the vicinity of high energy accelerators [16-22] and at medical accelerators [23,24]. The results showed an agreement of better than 10% compared to the reference methods.

The H*(10) response of the REM-2 chamber to photons is about 15% lower than the response to ^{241}Am-Be neutrons.

The main advantages of the REM-2 chamber are: nearly uniform response to H*(10) for all types of penetrating radiation, high reliability during many years [12,14,25] and easy handling with no need of service. With such features the chamber is especially suitable for continuous monitoring of complex mixed radiation fields. The advantages of recombination chambers were recognized also by ICRU [26].

The chamber was initially designed for measurements in mixed radiation fields near nuclear facilities, high-energy accelerators and isotopic neutron sources. Therefore, the parameters of the chamber were adjusted to optimize the measurements at dose rates above 1 μGy h^{-1}. This limit can be extended to lower values using a specially modified chamber and special mode for powering the chamber and reading the signal. Such modified chamber can be used for measurements of low dose equivalent rates, e.g. in cosmic radiation fields [27].

3. Summation and differential modes of measurements

The electrodes of REM-2 chamber form two sets and can be connected either in summation or in differential mode (Fig. 1).

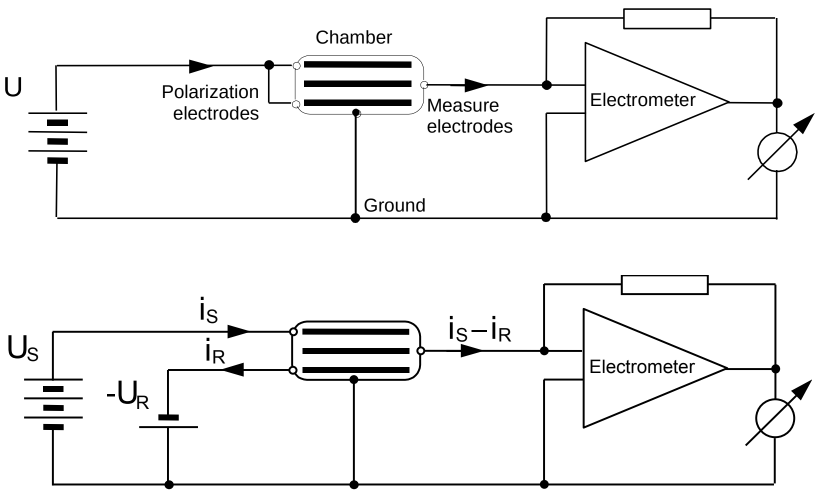

Fig.1. Principal circuits for dose equivalent measurements using summation (upper panel) and differential (lower panel) modes of operation of REM-2 chamber (i_S – i_R in Eq. 2).

In summation mode, both sets of electrodes are connected to the same polarizing voltage and two different voltages (U_S and U_R) are applied to the whole chamber consecutively. Therefore, it is possible to determine both the dose rate and the radiation quality factor separately.

The differential mode makes it possible to measure directly the dose equivalent or dose equivalent rate. In this mode, the near-saturation voltage U_S is applied to one set of polarizing electrodes, while the recombination voltage U_R of opposite polarity is applied to the other set of electrodes. The differential current measured by an electrometer is equal to $i_S - i_R$, so the measuring system might be calibrated directly in units of dose equivalent rate.

[illegible] (2)

The differential mode is especially suitable if dose rate is not stable. However, the sensitivity of the chamber to the absorbed dose is rather low, as the measured current $i_S - i_R$ is much lower than i_S. The measurements in summation mode in unstable conditions require the use of monitoring system, but the chamber sensitivity to the absorbed dose is much higher than for the differential mode.

4. New design of the REM-3 chamber

Long-term experience of measurements using the REM-2 chambers confirmed their advantages but also revealed some disadvantages of these detectors. It is intended to improve the following properties of REM-3 as compared to the REM-2 chamber:

1) More uniform characteristic of energy response to H*(10) for neutrons of energies up to 20 MeV;
2) Almost equal response to D*(10) in standard fields of gamma (^{137}Cs) and neutron (^{241}Am-Be) radiations used for calibration;
3) Lower charge-memory effect [10];
4) Shorter stabilization time after changes of the applied voltage;
5) Higher sensitivity, i.e. larger ratio of ionization current to the ambient absorbed dose rate;
6) Atomic composition, effective wall thickness and radiation scattering properties should be closer to the ICRU sphere (for easier prediction of the response to any type of radiation);
7) Easier manufacturing;
8) Containing monitor in the same housing;
9) Lower influence of voltages applied to one part of the chamber on the current of the other part – in case of differential mode and in case of using one part of the chamber as a monitor;
10) More uniform angular dependence of the response;
11) Lower influence of changes of ambient temperature and of voltage drift;
12) Higher (closer to 1) ion collection efficiency at the highest voltage applied to the chamber. Preferably, this voltage should not exceed 1 kV;
13) Broader possible range of dose rates;
14) Lower mass, especially of hydrogen-free parts;

15) Less number of elements which are not available commercially.

Additionally, there are two more improvements introduced for upgrading the whole measuring system

1) Replacing of the long electrometric cables (inconvenient and sensitive to stress) by the remote control.
2) A possibility of fast switch between summation and differential modes of operation.

Unfortunately, it is not possible to improve all the above mentioned parameters, as the improvement of one parameter may cause a deterioration of the other. Therefore, the solution must be a compromise. Overall dimensions of REM-3 are similar to REM-2. Electrodes for REM-3 are cut from plates of conducting polypropylene (for REM-2 they were formed from a tissue-equivalent material). Ethane is the main component of gas filling the REM-3. Ethane contains less hydrogen than methane and our measurements showed that oversensitivity to neutrons with energy below ca. 8 MeV will be reduced, comparing to REM-2 chamber. Collecting electrodes are kept by a central rod, while the polarizing ones are attached to four, side placed narrow brackets (see Fig.2). Voltage insulators are "invisible" from the active volume.

The REM-3 chamber contains 29 parallel plate electrodes, made from a conducting polypropylene. Electrode thickness is 2 mm and the electrode spacing is 6.5 mm. The active volume of chamber is 1850 cm^3. Gas filling the chamber is a mixture of ethane (94%) and nitrogen (6% by weight) at a pressure of 550 kPa. The wall thickness of the chamber is 1 mm Al + 3 mm polypropylene.

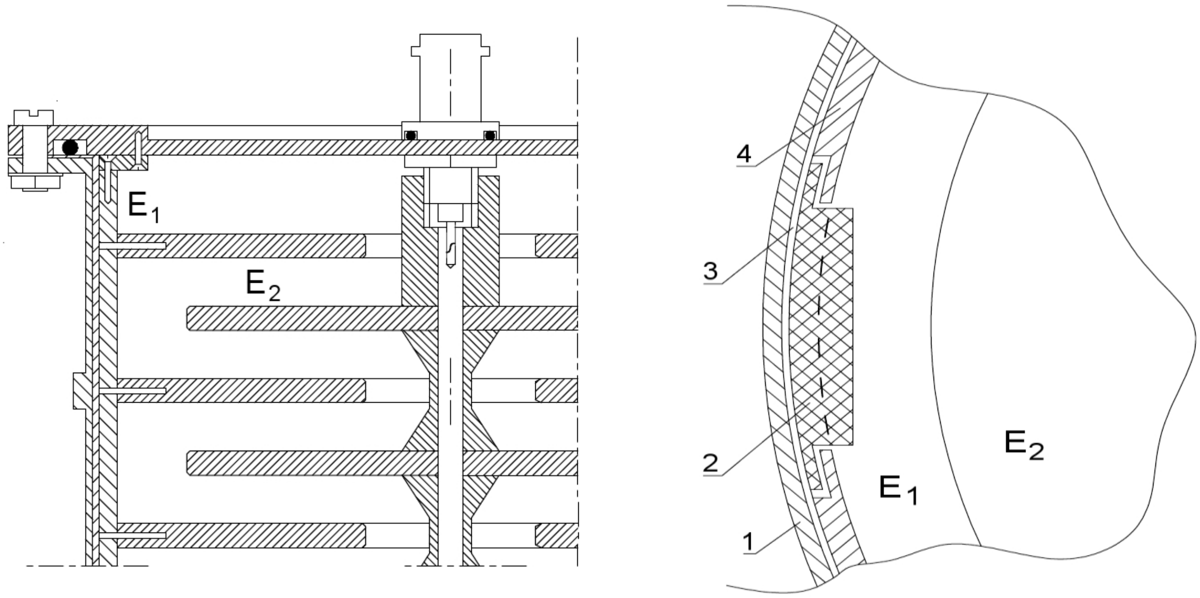

Fig.2. Cross section of REM-3 chamber (on the left) and the planar view of the cross section of the wall (on the right). E1 and E2 refers to electrodes, current and voltage respectively. Materials: aluminum (1), polypropylene vertical mounts for current electrodes (2), small gap (3) for compensation of thermal expansion of polypropylene insert (4).

Effective wall thickness in case of side irradiation only slightly differs from the depth in the ICRU sphere, defining H*(10). This allows to measure the H*(10) in the radiation fields of any composition, performing the chamber calibration in only one standard neutron or gamma radiation field (^{137}Cs or ^{241}Am-Be).

The chamber design is such that the voltage insulator surfaces are practically invisible from the active volume. Thanks to this, the charge accumulated on the insulator surface does not disturb the electric field in the active volume, therefore, the chamber current is stabilized quickly after switching on and after each change of the voltage value. This is a significant advantage because during the measurements by recombination chamber, the high (above 1000 V) and low (30-50 V) voltages of both polarities are usually applied consecutively. Short time of recovery after changing the voltage value is especially important when advanced recombination methods are used [e.g. 9]. Such methods give a possibility to determine the contribution of low-LET particles to the absorbed dose, or the dose distribution versus LET but require determination of extended saturation curves (i.e. measurements of ionization current at several voltages).

The use of polypropylene as the electrode material allowed to improve the energy response characteristics of the chamber to H*(10) for gamma and neutron radiation. It results from the fact that the polypropylene contains more hydrogen than the tissue-equivalent material, which has been used for manufacturing the electrodes of recombination chambers until now. Higher hydrogen content compensates the impact of the lack of saturation and of higher energy expended to create an ion pair by particles of high LET. Moreover, the use of electrodes made from a conducting polypropylene or coated with a thin uniform conductive layer, allows almost completely eliminate the so-called effect of charge memory, which results from the accumulation of electrical charge on non-conductive micro areas of electrode surfaces made from tissue equivalent material. This effect limited the ability to analyze the saturation curves of recombination chamber at voltages below 10 V. In addition, a large reduction in charge memory effect allows for measurements at one polarity, while measuring at both polarities of voltage was recommended in case of REM-2 chamber. This significantly reduces the time of measurements, and for the measurements in the differential mode, allows for continuous, direct registration of the ambient dose equivalent rate in mixed radiation fields.

The chamber is surrounded by thermal insulation (polystyrene foam 12 mm thick) in order to reduce the rapid changes of the interelectrode electrical capacity which would result in generation of parasitic capacitive current, e.g. due to warm hand touching the chamber, or breath of air.

The inner surface of the chamber cover is loosely attached to the 3 mm thick cylindrical polypropylene insert. The insert changes the wall contribution to the ionization of gas in neutron fields and improves the energy response. It also increases sensitivity to H*(10) for neutrons with an energy of several MeV. The sensitivity of REM-2 chamber at such energy was clearly undervalued. In addition, the insert partially reduces the sensitivity of the chamber to rapid changes in ambient temperature.

The parameters of the chamber (gas composition and pressure, distance between electrodes, etc) are optimized by Monte Carlo calculations, so the energy response of the chamber is sufficiently uniform over a wide range of energy of neutrons, photons and other types of radiation. The uniformity within 20% is expected for neutrons in the energy range from 1 meV to 10 TeV. In the standard neutron (^{241}Am-Be) and gamma (^{137}Cs) radiation fields the response differs by less than 6%. These figures relate to H*(10) i.e. to the product of D*(10) and Q*(10) (according to ICRP-60 and ICRP-107). In the case when both quantities are

determined separately, a possibility of more uneven response to D*(10) has to be taken into account.
The REM-3 chamber will be used in the currently developed recombination dose meter of new generation. It can also substitute the REM-2 recombination chambers, or other recombination chambers currently used for determination of H*(10) in some nuclear facilities.

5. Application of triple-mode system in REM-3 chamber

The new REM-3 chamber can work both in the summation mode, when the same voltage is sequentially applied to all electrodes, and in the differential mode, when the high voltage is applied to a part of voltage electrodes, providing conditions close to saturation, and the voltage of opposite polarity and at a much lower value is connected to the second part of the voltage electrodes, providing appropriate conditions for initial recombination of ions.

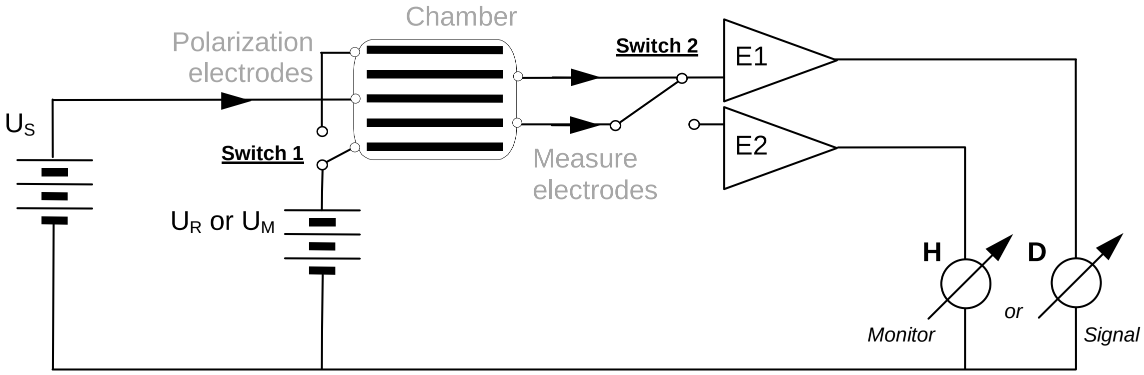

Fig.3. The idea of the triple-mode detector (summation mode raises sensitivity, differential mode gives possibility of direct measurements of the ambient dose equivalent rate, self-monitoring chamber in case of fluctuations of dose rate). Two switches are needed for proper configuration of polarizing electrodes and measuring the ionization currents.

The triple-mode chamber can operate e.g. in summation mode at low dose rate and automatically switch to the differential mode in case of raised dose rate. The device can be used for monitoring of workplaces if essential changes of the dose rate can be expected while the usual background is low. It is also possible to use one part of the active volume for the measurements of H*(10) and the second part as a monitoring chamber, in case of unstable conditions (fluctuations of the dose rate).

6. Conclusions

New recombination chamber of REM-3 type has been designed in order to improve dosimetric properties of the REM-2 chamber. The considered improvements were defined, checked and applied to the recombination detector and to the recombination dosimetric system. Final construction of the chamber, measuring system and complete dose meter are under model preparation and will be validated soon.

Acknowledgment

The work was partially supported by the National Science Centre under grant no. N N404 135039.

Reference

[1] Zielczyński, M. Use of columnar recombination for determination of relative biological efficiency of radiation (in Russian). Nukleonika 7, 175-182 (1962).

[2] Sullivan, A.H. and Baarli, J. An ionization chamber for the estimation of the biological effectiveness of radiation. CERN Report 63-17 (1963).

[3] Jaffé, G. Zur Theorie der Ionisation in Kolonnen. Ann. der Physik, Folge 4, Band 42 (12), 303-344 (1913).

[4] Jaffé, G. Zur Theorie der Ionisation in Kolonnen II. Ann. der Physik, Folge 5, Band 1 (7), 977-1008 (1929).

[5] Lea, D.E. The theory of ionization measurements in gases at high pressures. Proc. Camb. Phil. Soc. 30, 80-101 (1933).

[6] Zielczyński, M., Golnik, N., Makarewicz, M. and Sullivan, A.H. Definition of radiation quality by initial recombination of ions. In: 7th Symp. on Microdosimetry, EUR 7147, Eds J. Booz, H. G. Ebert and H. D. Hartfiel (Luxembourg: CEC), 853-862 (1981).

[7] Sullivan, A. H. The Estimation of the distribution of energy loss of ionizing radiations from observations of the initial recombination of the ions in a gas. Ph.D. Thesis, University of London, (1968); Report CERN 69-1 (Geneva: CERN) (1969).

[8] Makrigiorgos, G. and Waker, A.J. On a Modification of Lea's model for initial recombination of electrons. Int. J. Appl. Radiat. Isot. 36(6), 509-510 (1985).

[9] Golnik, N. Microdosimetry using a recombination chamber: method and applications. Radiat. Prot. Dosim. 61, 125-128 (1995).

[10] Zielczyński, M. and Golnik, N. Rekombinacyjne komory jonizacyjne. Monografie IEA, vol.3, Świerk (2000).

[11] Golnik, N., Brede H.J. and Guldbakke, S. Response of REM-2 recombination chamber to H*(10) of monoenergetic neutrons. Radiat. Prot. Dosim. 88(2), 135-142 (2000).

[12] Zielczyński, M. and Golnik, N. Recombination index of radiation quality – measuring and applications. Radiat. Prot. Dosim. 52, 419-422 (1994).

[13] Golnik, N. and Zielczynski, M. Determination of quality factor in mixed radiation fields using recombination chamber. Radiat. Prot. Dosim. 44, 57-60 (1992).

[14] Golnik, N. Recombination Methods in the Dosimetry of Mixed Radiation. Report of the Institute of Atomic Energy, Swierk, Poland, IAE -20/A, ISSN 1232-5317 (1996).

[15] Golnik, N. Józefowicz, K. and Králik, M. Measurements of H*(10) in reference neutron fields using Bonner sphere spectrometry and LET spectrometry. Nucl. Instr. and Meth. in Phys. Res. A476, 365-368 (2002).

[16] Höfert, M. and Raffnsoe, C. Measurement of absolute dose and dose equivalent response for instruments used around high-energy proton accelerators. Nucl. Instr. and Meth. 176, 443-447 (1980).

[17] Rusinowski, Z. and Golnik N. Performance tests of the IAE dose equivalent meter in radiation field of high energy calibration facility at SPS-CERN. Nucl. Instr. and Meth. in Phys. Res. A408, 600-602 (1998).

[18] Golnik, N., Silari, M. and Otto, T. On the use of a recombination chamber for radiation measurements in CERN-EU high-energy reference radiation fields. Radiat. Prot. Dosim. 86(3), 173-179 (1999).

[19] Mayer, S., Golnik, N., Kyllönen, J.E., Menzel, H.G. and Otto, T. Dose equivalent measurements in a strongly pulsed high-energy radiation field. Radiat. Prot. Dosim. 110 (1-4), 759-762 (2004).

[20] Silari, M., Agosteo, S., Beck, P. et al. Intercomparison of radiation protection devices in a high-energy stray neutron field. Part III: Instrument response, Radiat. Meas. 44(7-8), 673-691 (2009)

[21] Abrosimov, A.I. et al. Measurement of the characteristics of JINR neutron fields (in Russian). Publications of Joint Institute for Nuclear Research, Dubna, Russia, JINR R16-93-37 Dubna (1993).

[22] Zielczyński, M., Golnik, N., Gryziński, M.A., Tulik, P. Studies of responses of recombination chambers in high energy radiation fields – intercomparison experiments. Raport IAE-140/A, Otwock-Świerk, ISSN 2080-6671 (2009).

[23] Zielczyński, M., Golnik, N., Gajevskij, V.N., Zorin, V.P., Molokanov, A.G., Shvidkij, S.V. and Cherevatenko, E.P. Ambient dose equivalent in a therapeutic cabin for irradiation with 200 MeV protons. Publications of Joint Institute for Nuclear Research, Dubna, Russia, JINR 16-98-345 Dubna (1998).

[24] Golnik, N. Zielczyński, M., Bulski, W., Tulik, P. and Pałko, T. Measurements of the neutron dose near a 15 MV medical linear accelerator. Radiat. Prot. Dosim. 126 (1-4), 619-622 (2007).

[25] Golnik, N., Cherevatenko, E.P., Serov, A.Y., Shvidkij, S.V., Sychev, B.S. and Zielczynski, M. Recombination index of radiation quality of medical high energy neutron beams. Radiat. Prot. Dosim. 70, 215-218 (1997).

[26] ICRU (International Commission on Radiation Units and Measurements). Determination of Operational Dose Equivalent Quantities for Neutrons. ICRU Report 66, (2001).

[27] Zielczyński, M., Golnik. N., Rusinowski, Z. and Tulik, P. Dosimetry with a recombination chamber in outdoor conditions and at low dose rates. Nucl. Instr. Meth. A500, 421-430 (2003).