Michał A. Gryziński, Piotr Tulik,
Mieczysław Zielczyński

Ionisation Chambers Containing Boron as Neutron Detectors in Mixed Radiation Fields

Institute of Atomic Energy, PL 05-400 Otwock-Świerk, Poland
e-mail: m.gryzinski@cyf.gov.pl

The paper presents a newly designed ionisation chambers containing boron, operated in the initial recombination regime. The chambers were either filled with BF_3 or the chamber electrodes were covered with B_4C . The chambers can be placed in paraffin moderators. The sensitivity of the chambers was investigated depending on gas pressure, moderator thickness and polarizing voltage. The results showed that it was possible to obtain nearly the same sensitivity of the chamber to $\text{H}^*(10)$ for photons and neutrons in restricted energy range, however further investigations are needed to make an optimum design. The examples of applications for dosimetric measurements in mixed radiation fields near medical linear accelerator and in the vicinity of high-energy proton accelerator are presented.

Key words: recombination chambers, neutron dosimetry, boron.

Introduction

Gas-filled radiation detectors cannot detect neutrons directly but there are several nuclear reactions producing energetic charged particles that ionize atoms. These reactions include:

The reaction rates are significant only for thermal neutrons, so the detectors are usually surrounded by moderators made with hydrogen containing materials, like polyethylene or paraffin.

Proportional counters, filled with either ${}^3\text{He}$ or gas compounds made with ${}^{10}\text{BF}_3$ are the most frequently used neutron detectors. The technology of manufacturing such devices is well established, but there are several disadvantages of the proportional counters. Because the proportional counters use gas multiplication, their detection signals are highly sensitive to gas impurities. Another problem is that the counters cannot be used neither in the radiation fields of high dose rate nor in pulse radiation fields.

It can be expected that in some cases the problems can be override by use of ionisation chambers containing boron ${}^{10}\text{B}$, either in the filling gas or on the electrodes. This paper presents studies on possible applications of such chambers in mixed neutron-gamma radiation fields for two cases – radiation fields around medical linear accelerators and high energy stray radiation fields Applications of the chambers containing boron for dosimetry and microdosimetry of epithermal neutron beams for boron neutron capture therapy (BNCT) were described elsewhere [4, 5].

Materials

Four types of the chambers containing boron have been used in this work. All of them were designed at the Institute of Atomic Energy. Two chambers, denoted as B2 and B3, were filled with BF_3 to the gas pressures between 300 and 500 kPa (gas density above 8 kg/m^3). At such gas density, there is considerable initial recombination of ions in the gas cavity, especially at low polarizing voltages. Since this kind of recombination does not depend on the dose rate, so the chamber sensitivity can be determined as a function of the polarizing voltage and the appropriate operating voltage can be chosen for optimisation of the chamber response. The chambers were designed for the measurements at different dose rates, so they differ considerably in size and gas volume. The main idea of the B2 and B3 chambers design was to combine the common principle of a thermal neutron detector inside a moderator with the features of recombination chambers, in order to design the detector with similar sensitivity to the ambient dose

equivalent, $H^*(10)$ of photons and neutrons at medical accelerators. Then, the signal of the detector would be proportional to $H^*(10)$ with acceptable dependence on composition (neutron to photon dose ratio) of the radiation field.

The chamber B2 is a graphite one of KG2 type [6]. The gas cavity volume is 190 cm^3 . The chamber was filled with $^{10}\text{BF}_3$ (almost 100% enriched) up to 480 kPa. The sensitivity of the chamber was determined for a number of configurations with different moderators:

- Configuration B2-0 – the chamber without moderator.
- Configuration B2-Pp – the chamber surrounded with 2.5 mm of polypropylene.
- Configuration B2-A – the chamber in a paraffin cup (ca. 3 kg).
- Configuration B2-APb – like the configuration A plus 4mm Pb layer outside the paraffin cup.
- Configuration B2-B – like the configuration A plus the paraffin cylinder with thin layer of polypropylene. The outer diameter of the cylinder is 28 cm and the inner diameter is 17 cm.
- Configuration B2-C – a 2 mm thick polypropylene cylinder with diameter of about 17 cm was introduced between the chamber and outer moderating block of configuration B2-B. About one third of the polypropylene cylinder surface was covered with B_4C (10 g), in order to improve the energy dependence of the chamber response to the ambient dose equivalent of low-energy neutrons.
- Configuration B2-D – like configuration B2-B plus a 4 mm thick Pb filter.

The second chamber denoted as B3 is a large, ca 2000 cm^3 , recombination chamber of REM-2 type [6, 7]. It has been filled with natural BF_3 and placed in one of the changeable moderators. Twenty five tissue-equivalent electrodes (ca. 0.8 kg), also can be considered as a moderator. The chamber is foreseen to be a sensitive detector of $H^*(10)$ in mixed ($n + \gamma$) radiation fields. The following moderators were used:

- Configuration B3-A – paraffin (ca. 2.5 kg) was introduced into empty, non-active volumes of the chamber and also replaced the thermal isolation covering the chamber housing.
- Configuration B3-B – the paraffin cylinder with thin layer of polypropylene. The outer diameter of the cylinder is 28 cm and the inner diameter is 17 cm. Total mass of the moderator together with the chamber is about 24 kg.
- Configuration B3-C – a 2 mm thick polypropylene cylinder with diameter of about 17 cm was introduced between the chamber and outer moderating block of

configuration B2-B. About one third of the polypropylene cylinder surface was covered with B_4C (10 g), in order to improve the energy dependence of the chamber response to the ambient dose equivalent of low-energy neutrons. It was expected that the energy dependence of the response is similar to that of common rem-meters with polyethylene moderator and boron insertion [2].

- Configuration B3-D – a 4 mm thick Pb filter was introduced instead of the boron containing cylinder. This configuration was designed for applications in high energy radiation fields. The lead filter should enhance the response of the chamber to high-energy neutrons, due to (n,2n) and other nuclear reactions.

The third chamber denoted as B4, is a free air ionisation chamber, with tissue-equivalent electrodes covered by B_4C . The gas cavity volume was 40 cm³ and the spacing between electrodes was 1 cm. The chamber could be placed in one of three paraffin moderators with weight of 0.7 kg, 3.5 kg or 18 kg. The following moderator configurations were used:

- Configuration B4-K – the chamber in a paraffin cup (ca. 0.7 kg).
- Configuration B4-A – like the configuration B4-K plus the larger paraffin cup (ca. 3.5 kg).
- Configuration B4-B – like the configuration B4-K plus the 18 kg paraffin cylinder.
- Configuration B4-C – like the configuration B4-B plus the polypropylene cylinder covered with B_4C (like in configuration B3-C).
- Configuration B2-D – like configuration B4-B plus a 4 mm thick Pb filter.

The last chamber, denoted as C-1.5, is a special, aluminium walled ionisation chamber operating in pulse mode. The chamber is 85 mm long and 19 mm in diameter. The 0.3 mm thick aluminum housing of the chamber was connected as one of the electrodes (at zero potential). The second, central electrode was made with copper rod, with diameter of 1.5 mm.

Methods

Neutron and gamma sensitivity of the chambers is defined in this work as the ratio of the measured signal to the neutron or gamma ambient dose equivalent (rate), $H^*(10)$, respectively. It was studied for different gas pressures and different moderators as

a function of polarization voltage. These measurements were performed at the calibration facility of IAE with the use of ^{137}Cs , $^{239}\text{Pu-Be}$ and ^{252}Cf radiation sources.

The measurements made it possible to establish the optimum moderators and optimum voltages to be applied to the chambers in other studies, which were performed later in vicinity of accelerators:

- medical electron accelerator (Oncology Centre, Warsaw),
- proton accelerator (INP Kraków),
- heavy ion accelerator (GSI, Darmstadt).

Ionisation current of the chambers was measured using the Keithley 642 electrometer, connected to the chambers with 15-40 meter long cables. The polarizing voltages were applied from a computer controlled, highly stabilized, high-voltage supply unit SZWN-1, designed in IAE.

Sensitivity of the investigated chambers to $\text{H}^*(10)$ of mixed radiation near the accelerators was estimated as a ratio of the ionization current of the investigated chambers containing boron to $\text{H}^*(10)$, determined by the tissue-equivalent recombination chamber type F1 [6] or REM-2 [7].

Relative neutron sensitivity of the chambers

The example of the pressure dependence of the neutron sensitivity for B3 chamber operated at $U = 1000\text{ V}$ is presented in Figure 1. While the sensitivity to gamma radiation was proportional to the gas pressure, the neutron sensitivity had a maximum at about 150 kPa of BF_3 . At higher gas pressures, the ion recombination in the gas causes considerable decrease of the chamber sensitivity. It is worth to note that the maximum of the relative neutron sensitivity (neutron-to-gamma sensitivity ratio) is at about 80 kPa.

Similar dependence of the neutron sensitivity on the gas pressure was determined with C-1.5 chamber, so finally the C-1.5 chamber was filled with $^{10}\text{BF}_3$ up to about 150 kPa.

Figure 2 shows the sensitivity of B3 chamber filled with BF_3 to 450 kPa and placed in the B3-C moderator, as a function of applied voltage. At such gas pressure, the neutron sensitivity of the B3 chamber operated at 1000V is much higher than the sensitivity for gamma radiation, even if natural BF_3 , not enriched with ^{10}B , is used. It is, however,

Figure 1. Dependence of the chamber sensitivity on the gas pressure, measured with B3 chamber for ^{239}Pu -Be source.

Figure 2. Sensitivity of B3 chamber filled with BF_3 to 450 kPa, as a function of applied voltage. Hexagons – ^{252}Cf (neutrons alone, i.e. the photon component was corrected for), stars – ^{239}Pu -Be (neutrons alone), triangles – gamma radiation of ^{137}Cs source.

Table 1. Response to ambient dose equivalent rate ($i(U)/\dot{H}^*(10)$) of B3 chamber with different moderators.

Moderator	U [V]	$\frac{i(U)}{\dot{H}^*(10)}$ [pA mSv ⁻¹ h]		
		γ ¹³⁷ Cs	n ²⁵² Cf	n ²³⁹ Pu-Be
A	700	90	99	32
B	200	64	68	58
C	400	73	80	72
D	30	41	42	37

possible to obtain about the same sensitivity to $\dot{H}^*(10)$ for gamma and for neutron radiations, if an appropriately chosen polarizing voltage is applied.

The optimum voltage value, ensuring about the same sensitivity to $\dot{H}^*(10)$ for neutron and gamma radiations, is not the same for different moderator configurations (see Table 1), because of different attenuation of both types of radiation in the moderators. It depends also on the energy of the accompanying photons.

In principle, the use of a set of different moderators as well as performing measurements at more than one polarizing voltage applied to the chamber with definite moderator carries information about the composition of the investigated radiation field. However no practical procedure for such application of the chamber has been elaborated up to now, using different voltage.

The measurements performed with B4 chamber showed that its sensitivity to the neutrons with energy above ca. 2 MeV was lower than the response to gamma radiation (about two times for the neutron radiation of ²³⁹Pu-Be neutron source). Nevertheless, taking into account the moderators' size it can be expected that the neutron sensitivity will be considerably higher for neutrons of lower energy, so the chamber can be foreseen as suitable for estimation of $\dot{H}^*(10)$ in mixed radiation fields containing such neutrons, e.g. photoneutrons.

More detailed data on neutron and gamma sensitivity of the investigated chambers are displayed in the Table 2. The neutron sensitivity values are given for primary radiation, for radiation at the distances 0.5 m and 1 m from ²³⁹Pu-Be and ²⁵²Cf neutron

sources (primary and room scattered neutrons) and for room-scattered neutrons (behind the shadow cone). Last three columns show the neutron sensitivity values measured in photoneutron radiation field near the medical linear accelerator, the field of secondary neutrons in the vicinity of the therapeutic proton beam and in stray radiation field behind the shields of ^{14}C ion beam with energy 400MeV/u. Conditions of the measurements are described in next sections.

Application in radiation fields at medical accelerator

Medical electron accelerators of energy above 10 MeV usually generate also neutrons. These, so called photoneutrons, arise due to photon-neutron nuclear reactions, mainly in the target and in the beam collimator. They are emitted nearly isotropically and create a neutron radiation field in the treatment room. The whole patient's body is irradiated by the photoneutrons. Neutrons can reach also neighbouring rooms, if neutron-absorbing elements are not introduced to the shielding walls. Therefore, two quantities are of interest for radiation protection – the neutron component of the absorbed dose in the patient's organs, and the ambient dose equivalent of mixed radiation, $H^*(10)$.

There are many papers reporting the results of neutron dose measurements at medical accelerators using several types of detectors [e.g. 3]. Among other instruments, the ionisation chambers are probably the most practical for routine use, because they can work at high dose rate, also in pulsed radiation fields of medical accelerators and because all the equipment needed for the measurements (e.g. electrometers) already exists in medical accelerator departments.

In present studies, the chambers B2 (in a 3 kg paraffin moderator), B3 and B4, have been investigated in the radiation field at a 15 MV medical accelerator Varian Clinac 2300C/D.

The chambers were used in a series of measurement in the treatment room, outside the irradiation field of 15 MV accelerator Varian Clinac 2300C/D photon beam, at the Oncology Centre in Warsaw. The dose rate at the isocentre was 1 Gy/min (100 monitor units) and the irradiation field was 4×4 cm. The beam was directed onto the PMMA phantom. The aim of the measurements was to determine the chambers sensitivity to $H^*(10)$ in the radiation fields of a medical accelerator and to estimate an appropriate size of moderator for a give chambers for such radiation fields.

All the chambers with different moderators were consecutively placed in the reference points – 1 m from the isocentre (on the treatment bed) and 3 m from the isocentre (3.5 m from the accelerator head, 0.9 m above the floor). The ambient dose equivalent at such conditions was mostly due to photoneutrons. The contribution of external photons to $H^*(10)$ was only 16% at the distance of 1 m. The value of $H^*(10)$ and the photon contribution remained about the same when the irradiation field size was reduced practically to zero ($0.2 \times 0.4 \text{ cm}^2$). So, the radiation field at the distances larger than 1 m from the isocentre was created by photoneutrons and accompanying photons, and practically not influenced by the primary beam.

The value of $H^*(10)$ at the reference point (32 mSv h^{-1} at 1 m distance) was determined by a tissue-equivalent recombination chamber using the method based on determination of recombination index of radiation quality [6]. Using this value, the sensitivities(responses) to $H^*(10)$ of all the investigated chambers were determined as

Table 3. Response of chambers containing boron to photoneutrons and ratio of the sensitivity to photoneutrons to the sensitivity to neutrons from the ^{252}Cf radiation source.

Chamber	Paraffin Moderator	$U \text{ [V]}$	$\frac{i_{med \text{ acc.}}}{H^*(10)_{med \text{ acc.}}}$ [pA h / mSv]	$\frac{i_{med \text{ acc.}}}{H^*(10)_{med \text{ acc.}}} \cdot \frac{H^*(10)_{Cr}}{i_{Cr}}$
B2	3 kg	1900	68.3	3.4
B3	A	200	280	7.1
	A	1000	500	7.1
	B	200	155	2.17
	B	1000	280	2.17
	C	200	113	1.8
	C	1000	200	1.8
	D	200	120	1.5
	D	1000	213	1.5
B4	0.7 kg	1900	0.13	2.6
	3.5 kg	1900	0.27	2.4

the ratio $i(U)/\dot{H}^*(10)$, where $i(U)$ is the ionisation current measured at the polarizing voltage U applied to the chamber. The results are shown in the Table 3. The last column of the table presents the ratio of the chamber response to photoneutrons to the response to ^{252}Cf neutrons. All the values are considerably higher than 1, also in the case of the configuration with moderator containing 10 g insertion of B^4C . It seems, that the boron insertion should be considerably larger, in order to obtain a relatively flat energy response up to a neutron energy of several MeV. However, this is not necessary when the chambers are intended for use only in radiation fields of medical accelerators. In such fields, the relatively small, simple moderator can ensure the appropriate response both to photoneutrons and to photons. The B3 chamber with moderator in configuration A (i.e. without boron insertion) was used for the measurements of $\dot{H}^*(10)$ at different distances from the accelerator head, resulting in the values of 68 mSvh^{-1} at 0.5 m, 32 mSvh^{-1} at 1 m, 9.1 mSvh^{-1} at 3 m and 1 mSvh^{-1} in the maze.

Measurements in mixed radiation field at high energy proton accelerator

The tissue-equivalent recombination chamber B3 chamber embedded in a paraffin moderator with the lead layer (configuration B3-D) was used for the measurements of $\dot{H}^*(10)$ secondary radiation in the vicinity of the therapeutic proton beam of the AIC-144 cyclotron at the Institute of Nuclear Physics in Kraków [1].

The measurements in the fields of radionuclide sources, described above, shown that it was possible to find such polarising voltage, U_m that the sensitivity (response) of the chamber to $\dot{H}^*(10)$ was about the same for ^{239}Pu -Be neutrons and gamma radiation of ^{137}Cs . Obviously, U_m depends on the moderator size. Then:

$$\dot{H}^*(10) \approx \frac{i(U_m)}{R(U_m)}$$

where $R(U_m) = [i(U_m) / \dot{H}^*(10)]_{\text{Cs}}$ is the chamber sensitivity to the reference gamma radiation. Index Cs indicates that the chamber was calibrated in the reference field of a ^{137}Cs gamma radiation source.

It was expected that such voltage can be found also for neutrons in broader energy range, however, the method is not sufficiently well proved yet. In this work, the same voltage was used, as it was determined for the ^{239}Pu -Be source.

The chamber was placed 2.5 m from an eye phantom irradiated by the 40 MeV proton beam in forward direction, 1 m above the floor, 2.5 m from the nearest wall. The beam intensity was 10 times lower than used for eye therapy. The results were related to $H^*(10)_{\text{ref}} = 200 \mu\text{Sv/h}$ derived from the NE NM2B neutron monitor readings. The gamma contribution of 4.7% of total $H^*(10)$ was taken into account.

The resulting value was lower from the value determined by other methods by less than 20%. Such uncertainty is usually acceptable in radiation protection. Therefore, there is an indication that the chamber can be used in most mixed radiation fields.

Conclusions

It is well known that introducing boron to an ionisation chamber increases its sensitivity to neutron radiation. High pressure ionisation chambers are especially advantageous because of the possible use of the initial ion recombination phenomenon to design the chambers with a desirable ratio of neutron to photon response. One of the ideas of this work was to design a chamber whose dose sensitivity to photoneutrons is higher than the sensitivity to photons by a factor close to the radiation quality factor of photoneutrons. It was shown, that there was no need to add a heavy moderator to the chamber – 1 kg of paraffin was sufficient in the case of large chamber B3. The results showed that it was possible to obtain nearly the same sensitivity of the chamber to $H^*(10)$ for photons and neutrons over a restricted energy range, however further investigations are needed to make an optimum design.

It was also shown that a simple free-air ionisation chamber with electrodes covered by boron can be used for monitoring of mixed radiation fields at medical accelerators.

The chambers with additional layer of lead can serve as neutron monitors in pulsed, high-energy radiation fields.

Acknowledgments

The authors would like to thank dr Jan Swakoń and dr Paweł Olko from the Institute of Nuclear Physics in Kraków for their help during the measurements in INP.

The work was partially supported by the Ministry of Science and Higher Education under grant no. 2P05D06530.

References

- [1] Bakewicz E, Budzanowski A, Taraszkiewicz T. AIC-144 cyclotron: present status. *Nukleonika* 2003; 48(Suplement 2): 117-121.
- [2] Bartlett DT, Tanner RJ, Tagziria H, Thomas DJ. Response characteristics of neutron survey instruments. 2002, NRPB-R333.
- [3] Golnik N, Kamiński P, Zielczyński M. A measuring system with a recombination chamber for neutron dosimetry around medical accelerators. *Radiat. Prot. Dosim.* 2004; 110: 271-276.
- [4] Golnik N, Tulik P, Zielczyński M. Recombination methods for boron neutron capture therapy dosimetry. Report IAE 98/A 2003.
- [5] Tulik P, Golnik N, Zielczyński M., Recombination chambers filled with different gases – studies of possible application for BNCT beam dosimetry. *Radiat. Prot. Dosim.* 2004; 110: 827-831.
- [6] Zielczyński M, Golnik N. Recombination Ionisation Chambers (in Polish), 2000, Świerk: Institute of Atomic Energy.
- [7] Zielczyński M, Golnik N, Rusinowski Z. A computer controlled ambient dose equivalent meter based on a recombination chamber. *Nucl Instr Meth, Phys Res A* 1996; 370: 563-567.