Neutron Dosimetry with Ion Chamber-Based DIS System

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INTRODUCTION

A new type of personal dosimeter has been developed by RADOS Technology Oy. This system is based on a novel detector type, an ionisation chamber with so-called Direct Ion Storage (DIS).

Ionisation chambers are sensitive to both neutrons and photons. Therefore, the application of the DIS principle to neutron dosimetry requires a double-chamber system for separating photon from neutron dose components. A chamber with the highest-possible and a chamber with the lowest-possible neutron sensitivity must be used, and their signals have to be differentiated. The energy dependences for photons of the two chamber types have to be almost equal to obtain good photon discrimination.

PRINCIPLE OF DIRECT ION STORAGE

In a nonvolatile solid-state memory cell, information is stored in the form of an electronic charge trapped on the floating gate of a MOSFET transistor. The first memory designs were used to store only digital information, which meant that in each memory cell there was either a low amount or a high amount of charge stored to represent one of the two binary digits 0 or 1.

In 1991, a new type of nonvolatile memory was introduced and made commercially available to be used for storing analog information. This meant that the amount of charge in each memory cell could now be made fully variable at will and therefore the memory cell could be used to store analog information such as non-digitized speech directly. Since then the use of these new low-cost Analog-EEPROM memories has caused a boom in all kinds of speech recording applications, in electronic telephone answering systems, voice-memo pads etc.

The radiation sensitivity of normal solid-state memory cells is inherently too low for use as detectors for ionising radiation in radiation protection applications. The main reason for this is that the memories are deliberately designed to be insensitive to ionising radiation so that they can be used in space and military environments without damage.

Figure 1 shows the structure of a standard Analog-EEPROM memory cell. The charge on the floating gate can be set to a predetermined level by tunneling electrons through the oxide layer. The charge is then permanently stored on the gate because in the normal operating temperature range the electrons have a very low probability of exceeding the energy barriers in the metal-oxide and oxide-silicon interfaces. A high level of purity is essential in the silicon dioxide formation process during the manufacture of these devices, to free the oxide of any mobile charge carriers, of which Na-ions are usually the most dominant. In modern facilities memory cells capable of retaining the stored charge for hundreds of years can be manufactured.

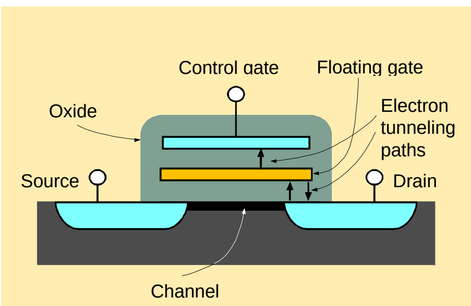

Figure 1. An Analog-EEPROM memory cell.

Reading the information stored is done without disturbing the charge stored, by measuring the channel conductivity of the transistor.

In order for ionising radiation to have an effect on the charge stored, either a new charge would have to be brought to the gate or some existing charge removed. Ionising radiation incident on the oxide layer will produce electron-ion pairs but due to the very low mobility of charge carriers in the oxide, recombination occurs with high efficiency and most of the free charge is neutralised before it has a chance to cross the metal-oxide interface. MOS dosimeters based on this principle therefore have a very low level of sensitivity to ionising radiation and are not sensitive enough for radiation protection applications.

The DIS principle is based on the following discovery:

If the oxide layer surrounding the floating gate is provided with an opening allowing the surface of the floating gate to be in direct contact with the surrounding air (or any other gas), the situation becomes quite different. Any ionising radiation incident in the air or gas space now produces electron-ion pairs with extremely high mobility and, if there is an electric field surrounding the floating gate, these charge carriers can very efficiently be transferred to the gate before recombination occurs. The structure of a DIS memory cell is shown in Figure 2.

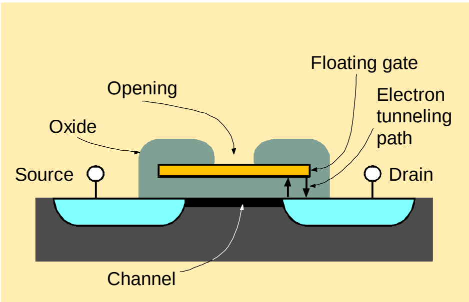

Figure 2. A DIS memory cell.

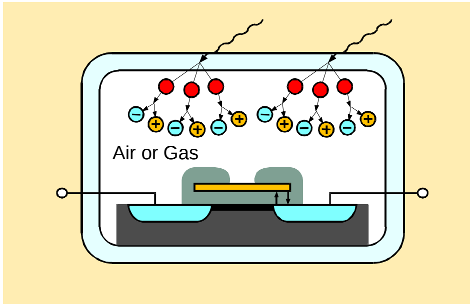

Figure 3. A DIS memory cell surrounded by a conductive wall.

By surrounding the entire structure with a conductive wall, an ion chamber is effectively formed between the wall and the floating gate as shown in Figure 3. For photon radiation, the initial interactions then take place in the wall material and the secondary electrons thus formed ionise the air or gas between the wall and the gate. For charged particle radiation, if the wall is sufficiently thin, the charged particles are allowed to transfer all or part of their energy directly into the air or gas space. The dosimetric characteristics can therefore be adjusted in the usual way by altering the properties of the wall material and the gas used.

Figure 4. Prototype DIS dosimeters and readers.

DESIGN OF THE DIS ION CHAMBER

The ion chambers are positioned inside a hermetically-sealed housing measuring 35x40 x7 mm^3. The weight of a prototype dosemeter without on-line display is about 35 g. For the readout of the dosimeters two types of electronic readers are used, one being a table-top unit and the other a small pocket-size unit (Figure 4).

The first dosemeters used contained only one type of ion chamber in each housing, either a neutron/photon sensitive ion chamber or an ion chamber sensitive to photons only. The detectors were subsequently combined in one housing to enable direct photon discrimination (combined dosemeters).

CALCULATION OF NEUTRON SENSITIVITY

The response to fast neutrons was calculated for a planar detector-wall configuration with 10 mm tissue equivalent wall material. In Figure 5 the calculated response f_R is compared with the fluence to personal-dose-equivalent conversion coefficients $h_{p\Phi}(10)$ given by ICRU. The ratio between f_R and $h_{p\Phi}(10)$ is shown in Figure 6. The calculations show that for neutron energies above about 1 MeV there is an almost constant ratio between the quantity measured and Hp(10). For lower neutron energies, especially for thermal neutrons, additional converters such as lithium (^{6}Li) or boron (^{10}B) are needed to obtain an acceptable response.

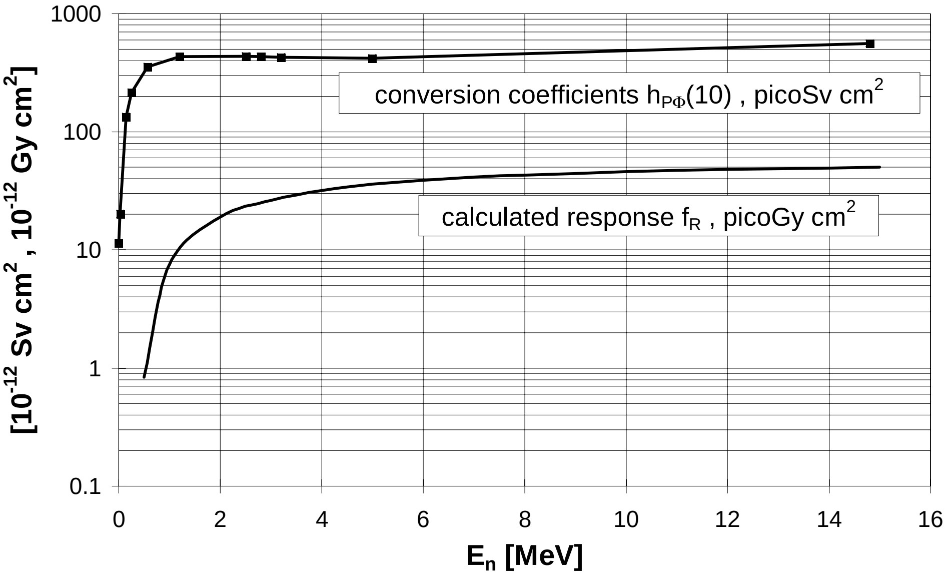

Figure 5. Calculated response f_R of an ionisation chamber with 10 mm tissue equivalent wall material in picoGy cm^2 and fluence to personal-dose-equivalent conversion coefficients $h_{P\Phi}(10)$ in picoSv cm^2.

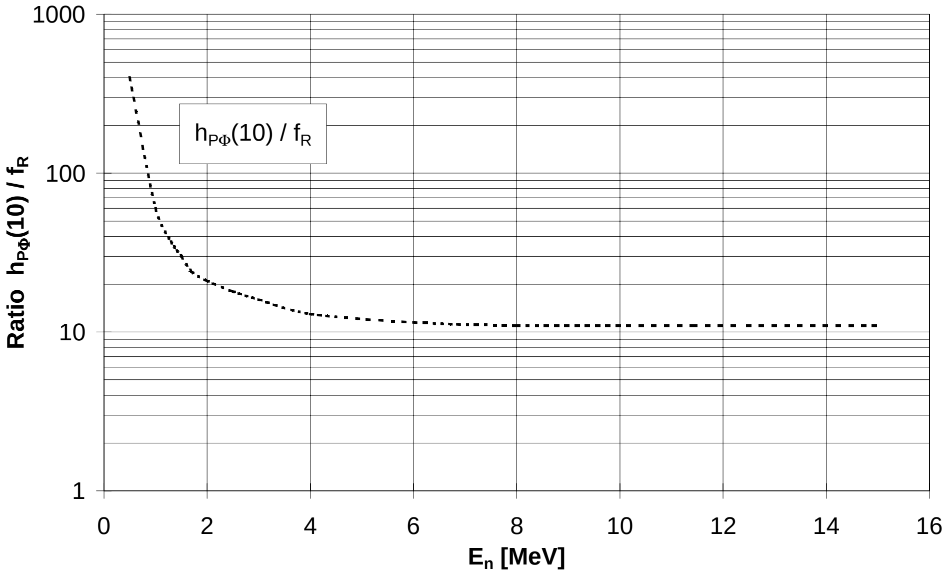

Figure 6. Ratio $h_{P\Phi}(10)$ / f_R in Sv/Gy.

ION CHAMBER WALL MATERIALS FOR NEUTRON DOSIMETRY

Different wall materials for the ion chambers were studied. Prototype dosimeters with a high response for fast neutrons were built with tissue equivalent wall materials A-150 and polyethylene (PE) for detection of recoil protons. For the measurement of thermal neutrons A-150 containing different contents of boron nitride (BN) and PE containing $LiNO_3$ were used. Thermal neutrons can then be detected by the secondary charged particles of the (n, α) reaction with ^{10}B and ^{6}Li respectively (Figure 7). Teflon and graphite, which are materials with low interaction probabilities with neutron radiation, were used for the construction of dosimeters with a low neutron sensitivity (Figure 8).

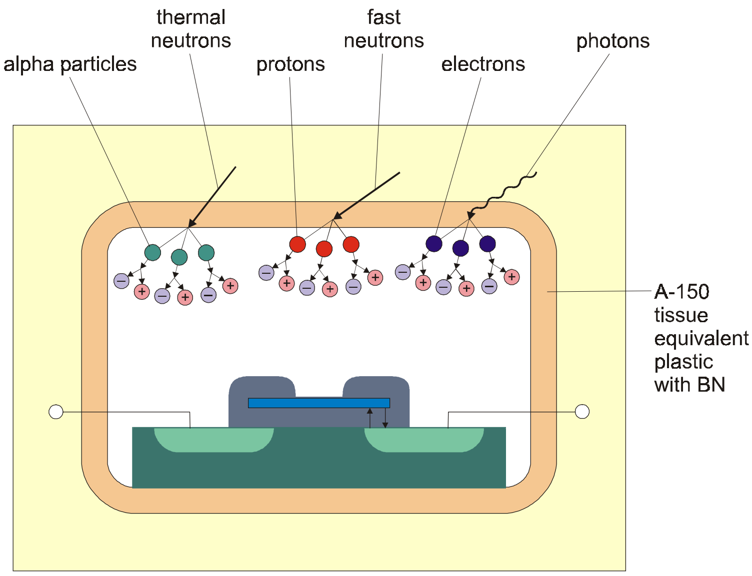

Figure 7. Ion chamber with A-150 containing BN.

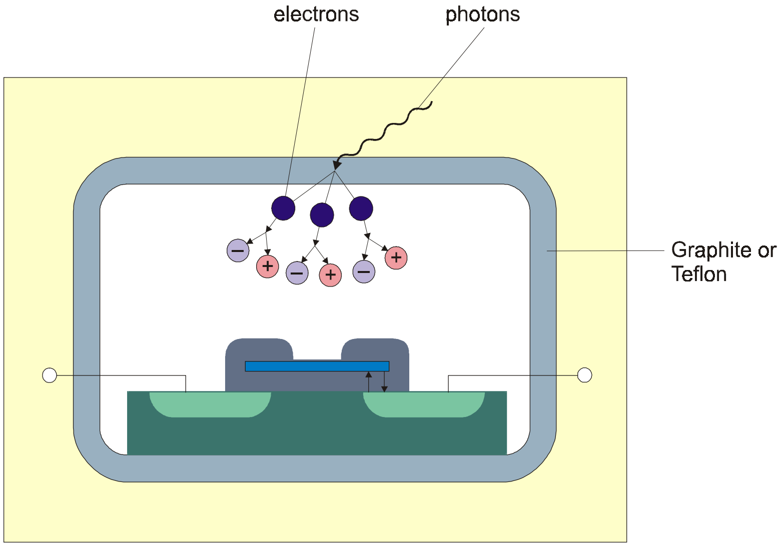

Figure 8. Ion chamber with Teflon or Graphite.

PHOTON ENERGY RESPONSE

To determine the photon energy response, measurements were performed with and without lead shieldings in the energy range from 24 keV to 660 keV photon energy (Figure 9). The detectors were mounted on a water-slab-phantom (30x30x15 cm^3). The results of the detectors are shown relative to their ^{137}Cs response. The uncertainties of the responses are approximately ±3%.

Without lead shieldings, the photon energy dependence of A-150 shows no significant difference from A-150 containing boron (0.1%, 1.25%, 10%). The responses of PE and PE(Li) are for low energies lower than the response of A-150, due to the lower atomic number of PE. Teflon has a higher response in the energy range below 80 keV compared to A-150, which for difference measurements could yield an overestimation of the photon dose contribution in mixed neutron-photon fields. Graphite and PE have very similar photon energy dependences and are therefore suitable for a combination in one housing.

To avoid false photon dose discrimination due to different photon energy dependences, measurements on the detectors were performed with lead shieldings around the whole detector (1 to 3 mm thickness). Photons with energies lower than about 100 keV are then cut off. With increasing thickness of the lead shielding, photons of higher energies are also greatly reduced. Practical considerations, however, show that a lead thickness of 1 mm is sufficient and preferable.

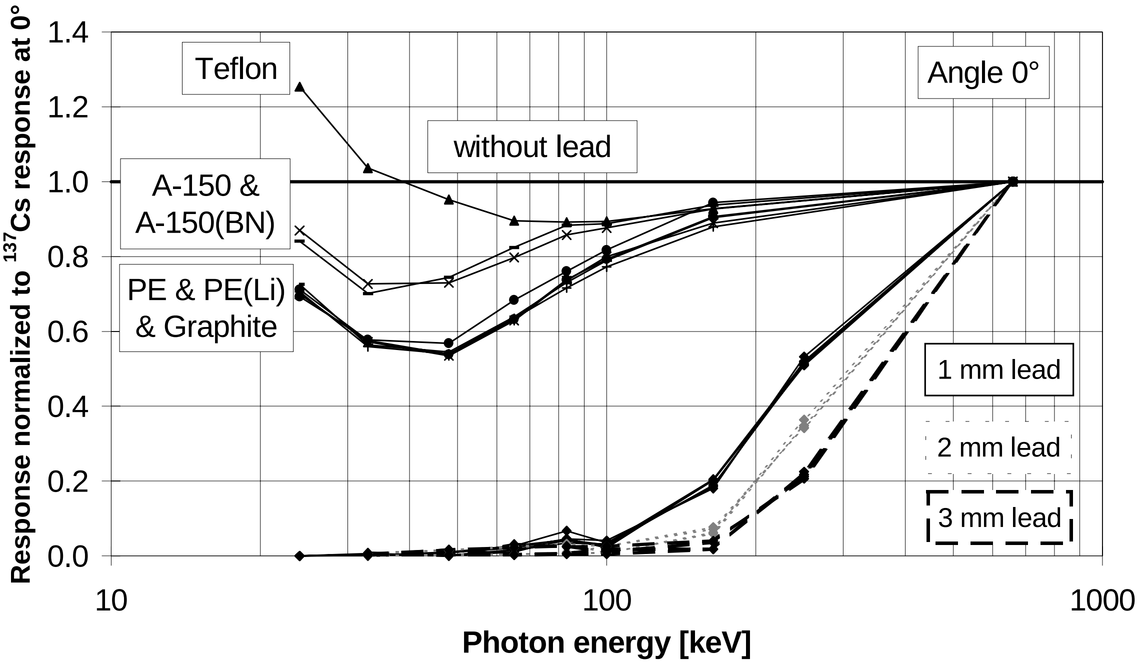

Figure 9. Photon energy dependence of different detectors and the effect of lead shieldings.

LONG TERM STABILITY

The long-term stability of the signal was studied with detectors for photon and beta dosimetry (standard detectors produced by RADOS). The detectors were irradiated with ^{137}Cs to a dose of about 3 mSv Hp(10) immediately after zeroing, stored at room temperature and reread periodically. The results are shown in Figure 10. It can be observed that there is roughly a 0.4 - 1.6 % initial drop in the stored dose information during the first 12-24 hours. This is assumed to be caused by normal dielectric absorption that occurs in the gate-oxide of the MOSFET structure. Following this period, only the normal background dose accumulation was observed for about 100 days. Subsequently there is a slight increase in the signal of about 1%.

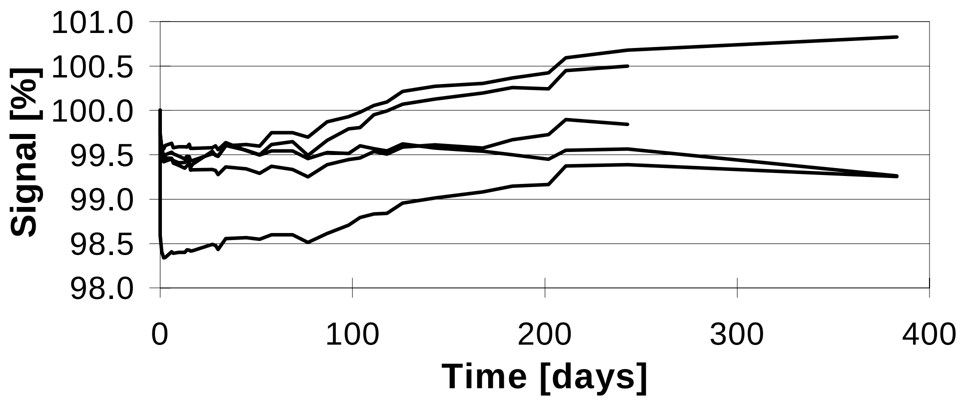

Figure 10. Long-term stability of the dose display of photon standard detectors (80 nSv/h background corrected).

COMBINED PHOTON AND NEUTRON DOSEMETERS

Three types of complete dosemeters containing one detector for both neutron and photon radiation and one detector for photon radiation only, were produced (Table 1). The 0.1% BN - TeGr unit contains a photon detector with a Teflon wall and an electrode made of graphite.

Name	Neutron/photon detector	Photon detector
4% $LiNO_3$ - Gr	PE (4% $LiNO_3$)	Graphite
0.1% BN - TeGr	A-150 (0.1% BN)	Teflon + Graphite
10% BN - Gr	A-150 (10% BN)	Graphite

Table 1. Materials used to produce combined dosemeters.

PHOTON ENERGY AND ANGLE RESPONSE OF COMBINED DOSEMETERS

For each combined dosemeter, the photon energy response was determined from 24 keV to 660 keV at an angle of 0° and 60° (Figures 11, 12 and 13). The measurements were performed without lead shieldings. The detectors were mounted on a water-slab-phantom (30x30x15 cm^3). The results are shown relative to their ^{137}Cs response.

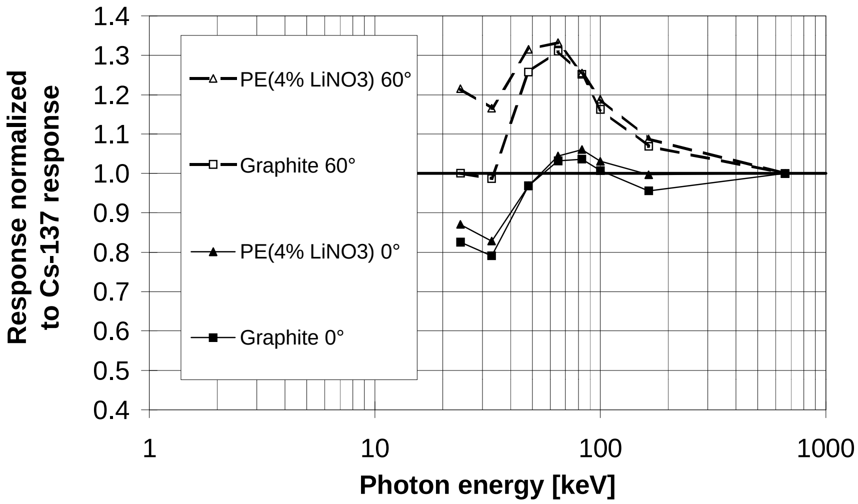

Figure 11. Photon energy response of 4% $LiNO_3$ - Gr at an angle of 0° and 60°.

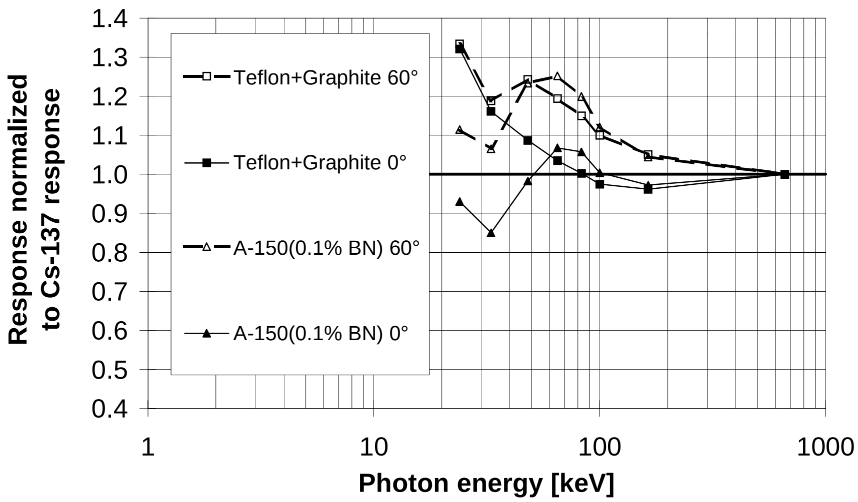

Figure 12. Photon energy response of 0.1% BN - TeGr at an angle of 0° and 60°.

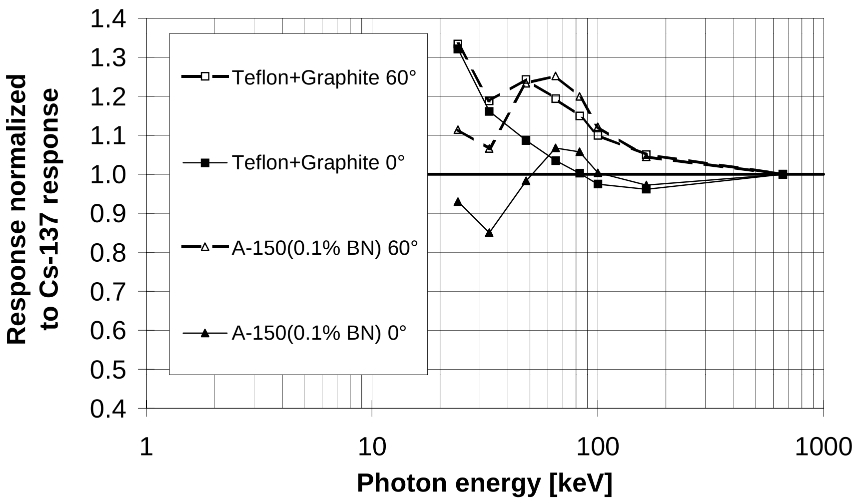

Figure 13. Photon energy response of 10% BN - Gr at an angle of 0° and 60°.

The photon energy response of the 4% $LiNO_3$ - Gr detector is very similar for both angles, and therefore good photon discrimination is expected for this detector. The other two combined dosemeters have a somewhat different photon energy response for lower energies.

NEUTRON RESONSE

The neutron responses have been calculated by taking the signal difference between each photon and neutron chamber (Signal(Photon+Neutron)) and the photon chamber (Signal(Photon)). Every chamber signal is normalized to its ^{137}Cs response to allow intercomparison of different chambers:

$$R = \left[\frac{Signal(Photon + Neutron)}{R_{^{137}Cs}(Photon + Neutron)} - \frac{Signal(Photon)}{R_{^{137}Cs}(Photon)} \right] \cdot \frac{1}{H_n}$$

R: Response of the chamber
R_{137Cs}: Response of the chamber for ^{137}Cs
H_n: Neutron dose equivalent in mSv
Signal: Signal of the chamber in mSv

The combined dosemeters were irradiated with various monoenergetic neutrons, neutron sources and field spectra. The responses to AmBe are presented in Table 2. In Tables 3, 4 and 5 the responses are normalized to the AmBe response. Irradiation with monoenergetic neutrons from 71 keV up to 14.8 MeV (Table 3 and Figure 14) and quasi-monoenergetic neutrons (UCL 61 MeV) were performed on a PMMA phantom, all other irradiations on a water-slab-phantom. Responses to neutron sources (Table 4) and field spectra at Cadarache and UCL (Table 5) were determined. The field spectra at Cadarache were a highly thermalised spectrum (Sigma, with main dose contributions below 0.5 eV (40%) and between 1 and 5 MeV (30%)), a broad partly thermalised spectrum (Canel with water) and a broad mainly fast spectrum (Canel without water). The spectrum at UCL has a main peak energy at 61 MeV and a low energy tail.

Considering the absolute values, the reading of an A-150 or PE ion chamber for fast neutron irradiation is about 3 times higher than for a Teflon chamber.

	4% $LiNO_3$ - Gr	0.1% BN - TeGr	10% BN - Gr
AmBe response	0.085	0.066	0.114

Table 2. AmBe neutron responses of the combined dosemeter, when calibrated for $H_p(10)$ photon radiation.

Neutron Energy [MeV]	4% $LiNO_3$ - Gr	0.1% BN - TeGr	10% BN - Gr
0.071	0.47	0.20	4.3
0.144	0.31	0.23	1.9
0.57	0.35	0.45	0.70
1.2	0.59	0.67	0.69
5.0	1.2	1.4	0.90
14.8	0.73	0.91	0.63

Table 3. Neutron responses of combined dosemeters to monoenergetic neutrons, normalized to AmBe response.

Neutron Source	4% $LiNO_3$ - Gr	0.1% BN - TeGr	10% BN - Gr
Cf-252(D_2O)	1.1	1.0	5.0
Cf-252(D_2O), Cd	1.0	1.0	3.5
Cf-252	0.79	0.83	0.85
AmBe	1.0	1.0	1.0

Table 4. Neutron responses of combined dosemeters to neutron sources, normalized to AmBe response.

Field Spectra	4% $LiNO_3$ - Gr	0.1% BN - TeGr	10% BN - Gr
Sigma	8.2	2.7	65
Canel with water	2.5	0.91	22
Canel without water	1.0	0.50	6.8
UCL 61 MeV	0.21	0.18	0.24

Table 5. Neutron responses of combined dosemeters to field spectra, normalized to AmBe response.

A PE(4% $LiNO_3$) chamber combined with a graphite chamber turned out to be a suitable combination. The detector has the flattest overall neutron response, except for thermalised spectra like Sigma and Canel with water, where the response increases up to a factor of 8, compared with the AmBe response. The content of $LiNO_3$ must be further optimised to obtain a proper response for highly thermalised spectra, accepting an underresponse for monoenergetic neutrons in the keV energy range (minimum at about 144 keV).

The response of the 10% BN - Gr detector increases substantially with increasing thermalisation of the spectra, even for a moderated Cf-252 neutron source the response is already five times higher than the AmBe response. Therefore, the A-150(10% BN) - Graphite detector is not suitable for single use, but could be used as a flag detector for thermal neutrons accompanying a properly responding detector.

At 71 keV, the 0.1% BN - TeGr detector shows no effect of thermalised albedo neutrons on the phantom but has also a higher response (factor 2.7) for the Sigma spectrum.

For high energy neutrons (61 MeV) the responses of all three combined detectors decrease to about a fifth of the AmBe response.

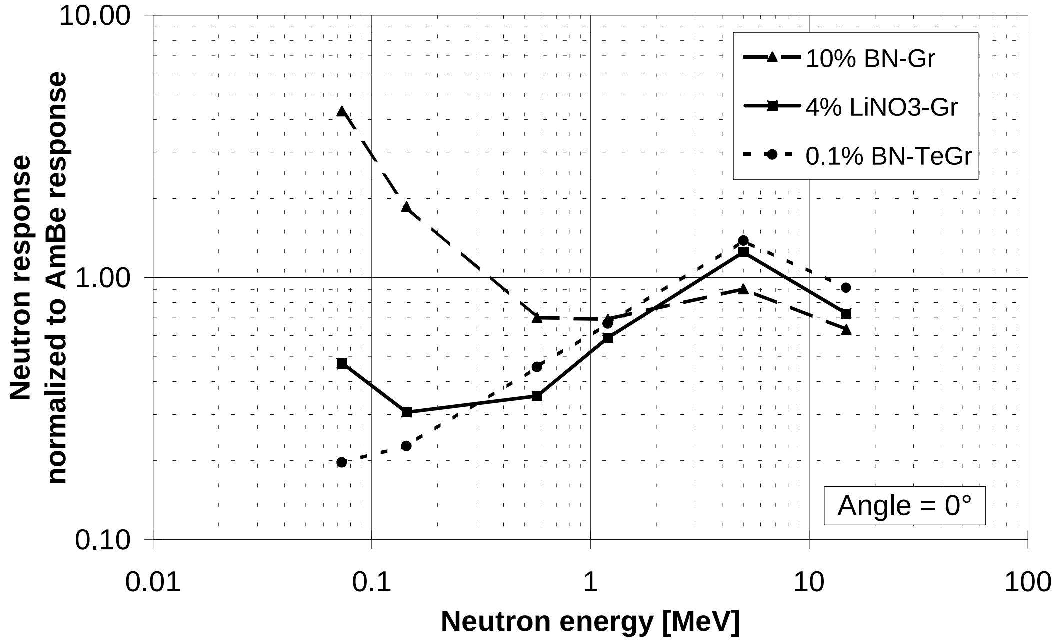

Figure 14. Neutron responses of combined detectors to monoenergetic neutrons, normalized to AmBe response.

ANGLE DEPENDENCE OF THE NEUTRON RESPONSE

The angle dependence of the neutron response was measured at 0°, 30° and 60° for the following neutron sources, field spectra and monoenergetic neutrons. The results (Table 6) show that the neutron responses vary between ±30% for angles up to 60°, except for the field spectrum Canel with water, where for one detector an increase of 87% was obtained at 60°.

Spectrum / Neutron energy	4% $LiNO_3$ - Gr			0.1% BN - TeGr			10% BN - Gr		
	0°	30°	60°	0°	30°	60°	0°	30°	60°
570 keV	1.00	1.09	1.29	1.00	0.87	0.91	1.00	1.04	0.99
5.0 MeV	1.00	0.99	1.02	1.00	0.98	1.07	1.00	0.99	1.06
Canel with water	1.00	0.89	1.03	1.00	1.29	1.87	1.00	0.99	0.74
Cf-252(D_2O), Cd	1.00	-	1.15	1.00	-	1.27	1.00	-	1.01
Cf-252	1.00	-	1.18	1.00	-	1.13	1.00	-	1.02
AmBe	1.00	-	1.05	1.00	-	1.14	1.00	-	1.07
UCL 61 MeV	1.00	-	1.19	-	-	-	-	-	-

Table 6. Angle dependence of the neutron response of the combined dosemeters, normalized to the response at 0°.

DETECTION LIMIT IN MIXED PHOTON-NEUTRON FIELDS

The detection limit of the neutron dose in mixed neutron-photon fields was determined for the three combined dosemeters types. The detectors were irradiated with an AmBe source and then, without resetting the dose, with a ^{137}Cs source. Photon-to-neutron dose ratios from 2 to 10 were tested. It turned out that with these prototypes it is possible to measure neutron doses down to 100 µSv with uncertainties of about 20%, as long as the photon dose is not higher than twice the neutron dose. The uncertainty of the neutron dose component increases rapidly with higher photon-to-neutron dose ratios.

DIS detectors can be built with extremely high thermal neutron sensitivity (e.g. 10% BN in A-150). Such detectors can be used in albedo dosemeter systems. The energy dependence of such systems is much more pronounced, but for known spectra with reasonable thermal neutron components, the detection limit can be lowered significantly.

UNCERTAINTIES OF NEUTRON RESPONSE

Successive irradiations with 100 μSv of fast neutron dose yield a standard deviation of 12-14%. For a neutron dose of about 3 mSv, the reproducibility is within 5-10%.

DISCUSSION

The feasibility of dosimetry with ion chambers and DIS electronics has been proved in the 4th EU research framework programme. The results obtained with prototype detectors indicate the system's promising potential for future legal dosimetry. Apart from dosimetric properties, the advantages of the system are its small size and weight, easy readout and relatively low production cost.

For neutron dosimetry the system has basic limitations, however, and further development is needed to produce industrial prototypes for future routine use. A new EU research proposal has been prepared for the 5th research framework programme.

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