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A PASSIVE NEUTRON DOSEMETER FOR MEASUREMENTS IN MIXED NEUTRON-PHOTON RADIATION FIELDS

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Abstract**:** The project combines the highly sensitive salt (NaCl) dosemeter for photon radiation with a neutron-photon converter in the form of thin gadolinium foils enclosing the salt. Using an identical salt dosemeter but without gadolinium cover determines the primary photon contribution. With these twin dosemeters placed in a polyethylene sphere, both photon and neutron dose contributions can be estimated. This paper describes the design and optimization of the construction as well as tests and a preliminary calibration of the dosemeter for estimation of neutron dose equivalent in the mixed neutron and photon beam from a ^{252}Cf-source. Currently, the lowest neutron dose equivalent possible to quantify is around 1 mSv. Some suggestions for further improvements are also discussed.

Keywords**:** neutrons, photons, dosemeter, OSL, NaCl, Gd

1. Introduction

Despite great efforts of many research groups to develop environmental and personal passive dosemeters for neutron radiation, there is to date no equipment that can be considered as a solution to the problem. Dosemeters that are available today have shortcomings in their properties, and the combination of different dosemeter types that would be needed often turns 1) so expensive that the cost will be a barrier to use, and 2) their use is so complex that only a few experts in radiation protection can fully use the methodology.

Examples of neutron dosemeters currently used are pairs of thermoluminescent detectors [1], activation foils [2], bubble detectors [3] and track detectors [4]. The most common passive neutron area monitor uses pairs of TLD-6 (^{6}LiF: Ti, Mg) and TLD-700 (^{7}LiF: Ti, Mg) lithiumfluoride chips. The sensitivity is limited by the thermal neutron capture cross section for the ^{6}Li(n,α)^{3}H reaction, which is 925 barn. Some authors have tried to homogeneously incorporate gadolinium oxide as a neutron converter together with Al_2O_3: C pellets [5]. The limited possibility to include a larger number of gadolinium atoms in the dosemeter bulk and the subsequent adverse effects on TL properties are the main shortcomings of that method. Mukherjee et al. [6] proposed a neutron area monitor with higher sensitivity using Al_2O_3:C (TLD-500) chips covered by two gadolinium foils.

The aim of the present project is to develop an effective and inexpensive neutron dosemeter for determination of ambient dose equivalent and personal dose equivalent from neutrons in mixed photon/neutron fields. The proposed dosemeter is based on a pair of detectors that both contain salt (NaCl). Ordinary salt was chosen as it has shown to be able to detect low levels of photon radiation [7]. Of the two salt cavities, one is covered with thin Gd foils and the other one with paper.

2. Materials and methods

A dosemeter with two detectors was constructed; one for measurement of neutron and photon contributions, and one to measure only the photon contribution. The neutron and photon dosemeter was made from a salt containing cuvette (10×10×11 mm^3) with four small salt containers (3×3×1 mm^3 each) totally surrounded by foils of gadolinium and lead layers of different thicknesses (Detector A). The photon dosemeter was made from an identical salt cuvette surrounded by a layer of paper instead of gadolinium (Detector B). The salt used was "Falksalt-Fint bergssalt", (Mine salt, no additives, Hansson and Möhring AB, Halmstad, Sweden). The dosemeter pair (Detector A and B) was placed in the centre of a 25 cm (diam.) polyethylene sphere constructed in the form of two separable hemispheres (Figure 1). The sphere acts as moderator for neutrons of higher energies incident upon the dosemeter.

The thermal neutron capture cross section of natural gadolinium is 49000 barn and for the ^{157}Gd(n,γ)^{158}Gd reaction it is 255000 barn, which is orders of magnitude higher than for the ^{6}Li(n,α)^{3}H reaction mentioned above. The prompt gamma photons from neutron capture in ^{157}Gd have the energies 80keV (11.5%) and 182 keV (13.6%). The difference in the OSL signal between Detectors A and B is supposed to give information about the neutron dose contribution.

The dosemeter was irradiated in a collimated beam of neutrons and photons [8] from a 47 MBq (2014-08-15) (Malmö Radiation Physics No 7) ^{252}Cf-source. ^{252}Cf is a spontaneous fission source with a half-life of 2.65 years. Neutrons are produced in the fission process at a rate of about 4 per fission. The fission occurs in about 3% of the decays. The neutron energy distribution from spontaneous fission in ^{252}Cf (and ^{250}Cf[1]) goes from thermal energies up to around 10 MeV [11]. It is similar to that of a fission reactor, with most probable energy of 0.7 MeV and an average energy of 2.1 MeV. The distance between the source and detector´s geometrical centre was 87.5 cm, enough to ensure a parallel beam of neutrons incident on the dosemeter. The dose equivalent rate from neutrons was estimated to 75±5 µSv/h using a neutron dose equivalent (acc. to ICRP 60[12]) rate meter based on a BF_3 proportional counter (FHT 752, Thermo Eberline ESM, Erlangen, Germany) as well as an older similar instrument (Neutron dose rate meter AE 2202, AB Atomenergi, Studsvik, Sweden). In addition to neutron (and alpha) emission, ^{252}Cf-sources emit gamma-rays. The photons from ^{252}Cf have a wide range of energies from very low energies to about 10 MeV and even higher with a peak intensity at about 100-200 keV [13] (Bowman et al., 1964). The photon ambient dose equivalent rate at the point of measurements was estimated to 5.5 µSv/h (about 7% of the neutron contribution) and without the moderator sphere to 9.1 µSv/h using a radiation protection instrument (Intensimeter SRV 2000, Rados Technology Oy, Finland). The dosemeter was normally irradiated for 67 hours and occasionally during 48 or 94 hours.

To be able to check and if necessary correct for the photon absorption in the Gd neutron-photon converter foils, comparative exposures of the twin dosemeters were done in the photon radiation field from a ^{60}Co unit (2.5 TBq at 2014-10-01) at a distance of 5.50 m. The dose rate at the point of measurements (centre of sphere) was 0.548 mGy min^{-1} (2013-05-27) as measured using an ionization chamber (PTW Farmer, Germany) calibrated at the secondary standard laboratory of the Swedish Radiation Safety Authority. Using the radiation protection instrument (SRV 2000) the dose rate in the the centre of the sphere was estimated to 0.44 mSv/min, and free in air 0.59 mSv/min. This means a transmission of 75% of the dose through the sphere, a value which is in agreement with the calculations for 12 cm of polyethylene [14]. The exposure time in the ^{60}Co beam for the twin dosemeter was 10 minutes.

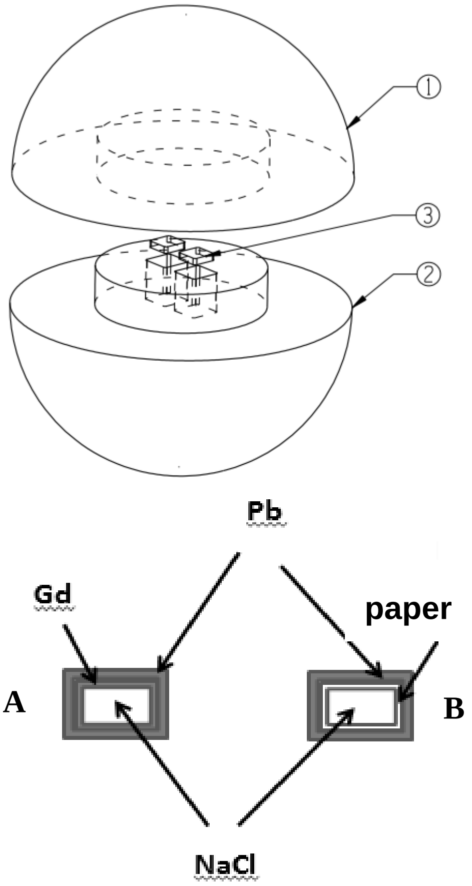

Fig. 1. Schematic representation of the twin dosemeter with one gadolinium covered (A) and one paper covered (B) salt detector. Both the gadolinium covered and the paper-covered detector cubes (3) were surrounded by a layer of lead of the same thickness on all six sides. The twin dosemeter was placed in a moderator sphere of polyethylene (diam. 25 cm) constructed in the form of two separable half-spheres (2) and (1). The thickness of the Gd foil, also covering all six sides of the salt cube, was varied; 0, 0.1, 0.25, and 0.5 mm as was the lead layer; 0, 2.25, and 4.5 mm, covering all six sides of the Gd cube.

3. Results

The readings of the signal from the NaCl were done in a Risø TL/OSL-DA-15 reader (Technical University of Denmark, Risø campus, Roskilde, Denmark) using the SAR protocol [15]. Table 1 summarizes the results of measurements after exposures of the twin dosemeter in the ^{252}Cf and the ^{60}Co beams using different thicknesses of lead and gadolinium, respectively. The results are also illustrated in Figures 2-5. Figure 2 shows the readings of detectors A and B after irradiation in the photon beam from the ^{60}Co-source as a function of Gd foil thickness. Various thicknesses of lead (♦ = no Pb, ■ = 2.25 mm Pb, ▲ = 4.5 mm Pb) were used. Figure 3 shows the readings of detectors A and B respectively after irradiation in the neutron/photon beam from a ^{252}Cf-source as a function of Gd foil thickness.

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[1] It should be noted that the ^{250}Cf component in an old ^{252}Cf source can affect the decay correction of the emission rate of a ^{252}Cf source because of its long half-life (13.08 y, also spontaneous fission) compared with that of ^{252}Cf (2.645 y) [9, 10]. The neutron energy distribution is not influenced as both isotopes decay by spontaneous fission.

Table 1. Results of exposures of the twin dosemeters in beams of a ^{252}Cf and a ^{60}Co source, respectively, for various thicknesses of Gd foil and Pb shielding. The salt dosemeters were read using the SAR-protocol and expressed in mGy per 67 hours exposure in the ^{252}Cf-beam and 10 min exposure in the ^{60}Co beam, respectively. The uncertainty indicated is SE of the mean of readings of 3 different aliquots of salt taken from the mixed content of all four small salt containers. (For some combinations two measurements were done).

	^{252}Cf					
Gd / Pb	0 mm	0.1 mm	0 mm	0.25 mm	0 mm	0.5 mm
0 mm	0.646±0.035	0.602±0.012	0.635±0.013	0.556±0.026	0.643±0.035	0.404±0.012
2.25 mm	0.210± 0.003	0.295± 0.021	0.229±0.007 0.285±0.003 x)	0.328±0.007 0.399±0.020 x)	0.198±0.012	0.270±0.011
4.5 mm	0.165±0.017	0.222±0.030	0.198±0.010	0.242±0.010	0.151±0.017 xx)	0.171±0.006 xx)
	^{60}Co					
0 mm	4.45±0.13 4.66±0.08	4.82±0.33 4.61±0.21	4.97±0.14 5.04±=.12	4.48±0.23 4.46±0.13	4.45±0.017	4.82±0.20
2.25 mm	3.00±0.11	2.63±0.04	2.58±0..08	2.74±0.19	3.01±0.50	2.99±0.18
4.5 mm	2.78±0.14	2.36±0.06	2.88±0.10	2.77±0.08	2.92±0.05	2.63±0.05

x) 94 hours exposure; xx) 48 hours exposure

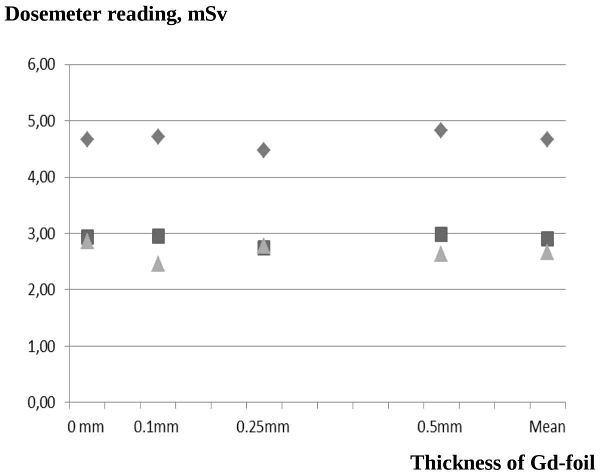

Fig. 2. Readings of detectors A and B respectively after irradiation in the photon beam from a ^{60}Co-source as a function of Gd-foil thickness. Various thicknesses of lead (♦ = no Pb, ■ = 2.25 mm Pb, ▲ = 4.5 mm Pb) were used.

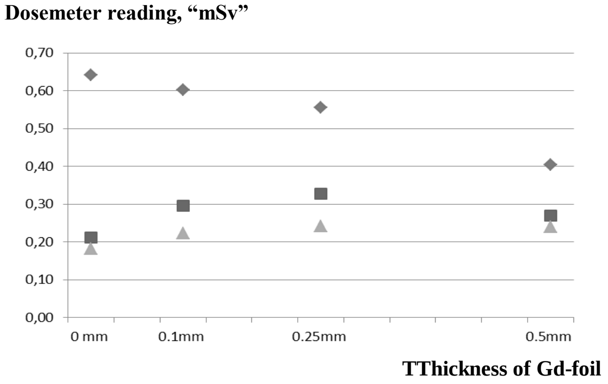

Fig. 3. Readings of detectors A and B respectively after irradiation in the neutron/photon beam from a ^{252}Cf-source as a function of Gd-foil thickness (♦ = no Pb, ■ = 2.25 mm Pb, ▲ = 4.5 mm Pb).

The ratio of the readings of detector A (with Gd) and B (without Gd) is shown in Figures 4 and 5. In Figure 4, the results are arranged according to lead layer thickness and within each thickness group with respect to the thickness of the Gd foil. In Figure 5, the results are presented in groups after Gd thickness and within each group after thickness of Pb layer.

4. Discussion

A dosemeter for measurements of neutron dose equivalent has been constructed. It is in the form of a twin dosemeter capable to measure A) contributions from neutrons and photons and B), the photon contribution, separately. The difference between detector A and B gives information about the neutron dose.

From Table 1 and from Figures 2 -5 the influences of neutron converter thickness as well as of the thickness of the photon shielding layer of lead are illustrated, pointing to advices on the configuration of the dosemeter. Figure 2 shows that the dosemeter reading after irradiation with photons from the ^{60}Co-source is practically independent of the Gd-foil thickness both without lead shields and with 2.25 mm Pb and 4.5 mm Pb. This is what could be expected from calculations of the attenuation of the high energy photons from ^{60}Co in the Gd-foils, which is very limited – less than 5% for energies over 300 keV [14]. After irradiation in the ^{252}Cf-beam (Figure 3) and without lead shielding, however, the detector readings are much dependent on the Gd-foil thickness. This indicates a presence of a large component of low energy photons coming directly from the ^{252}Cf-source and also of photons scattered in the moderator sphere.

From Figure 3 the dependence of Gd-foil thickness when measurements are done without lead shield (upper points) indicates the presence of photons in the energy range 100-150 keV [14]. As earlier mentioned, the photon energy distribution from ^{252}Cf peaks at very low energies and scattering in collimator and the polyethylene sphere may have further reduced the energy. If there is a lead shield (2.25 mm or 4.5 mm), most low energy photons under 150-200 keV are attenuated [14] and an increased reading is observed for increasing thickness of the Gd foil up to a thickness of around 0.2 mm Gd indicating a contribution from prompt gamma photons following neutron capture in Gd. A further increase in Gd-foil thickness will reduce the “neutron contributions” due to absorption of the 80 and 100 keV prompt gamma rays from Gd in Gd material closer to the salt. The same conclusions can be drawn from Figures 4 and 5. When there is no lead to absorb the low energy photons from the ^{252}Cf, 0.1, 0.25 and 0.5 mm Gd (in detector A) more effectively attenuates these low energy photons than the paper spacer in the detector B, thus resulting in a ratio (with Gd/without Gd) which is less than 1. However, as soon as 2.25 mm Pb is used, this effect is marginal even for 0.5 mm Gd. Therefore around 2 mm lead is necessary and also sufficient for absorption of low energy photons. Regarding the necessary thicknesses of the neutron-photon converter Gd, the thickness of gadolinium does not seem to play a critical role, but 0.2 mm seems to be the thickness to prefer (Compare also Figure 3).

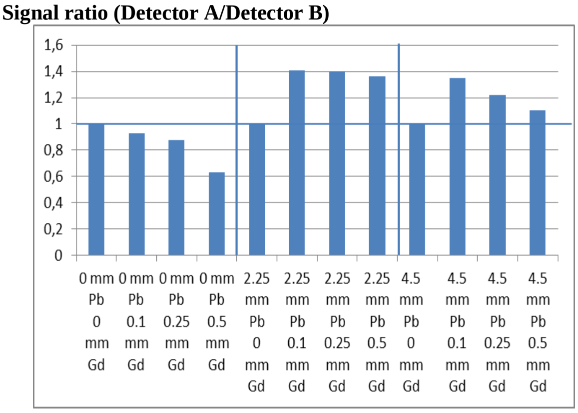

Fig. 4. Ratio of readings of detector A (with Gd) and B (without Gd) arranged in three groups with respect to thickness of lead absorber and within these groups according to thickness of the gadolinium foils.

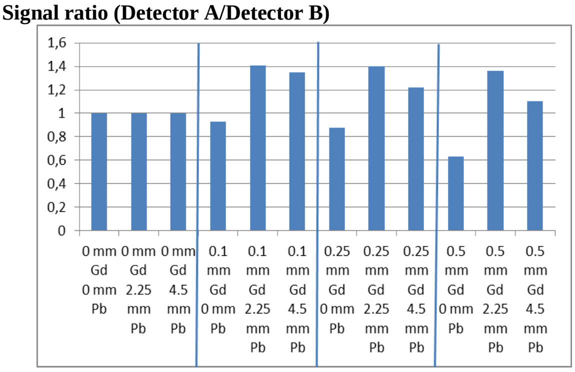

Fig. 5. The same information as given in Figure 4, but sorted in four groups with respect to thickness of gadolinium foils and within each of these groups according to the thickness of the lead absorber.

So with lead absorbers, a net contribution to the readings of the photon sensitive salt dosemeters from photons produced in the neutron-photon conversion in the gadolinium foils surrounding the salt container cube is seen. The salt detector has favorable energy dependence in its sensitivity (which is an order of magnitude higher for the low energy prompt gamma photons from Gd (especially the 80 keV photons) than for disturbing photons of higher energies (Figure 6).

The net contribution from neutrons (Figure 3, 0.25 mm Gd, 2.25 mm Pb) can be estimated to 0.12 “mGy” per 67 hours, which has to be compared with the known neutron dose equivalent at the point of measurements, which is 5.0 mSv per 67 hours. This means a sensitivity of the current dosemeter system of 0.024 ”mGy” per mSv neutron dose equivalent. The smallest measurable neutron dose equivalent is estimated to be close to 1 mSv.

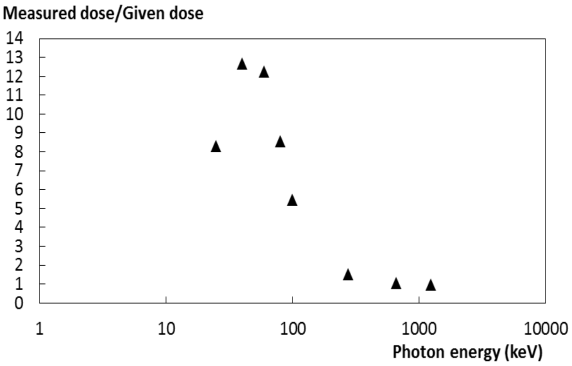

Fig. 6. Sensitivity for dose measurements in salt (NaCl) as a function of photon energy using salt without covering material [16].

5. Suggestions for further work

To use different parts of the CW (continuous wave)-OSL signal to improve the signal to noise ratio.

To use a weaker source (for the calibration doses) in the TL/OSL-reader to lower the minimum detectable dose.

The induced activity has, with the neutron sources used, been very low and has not yet been studied systematically in spite traces of ^{24}Na have been seen.

To also test LiF chips as an alternative to salt.

To investigate the possibility to use the twin dosemeter with reduced diameter of the polyethylene moderator sphere.

To investigate the possibility to use the twin dosemeter without moderator sphere, but placed as an albedo-neutron dosemeter on an anthropomorphic phantom to measure the thermal neutron backscatter from the body of the wearer and the thermal neutrons from the radiation field.

6. Conclusions

To measure the neutron dose equivalent in a mixed neutron/photon radiation field, salt (NaCl) enclosed in a neutron/photon converter cube of gadolinium can be used as a neutron dosemeter in mixed neutron/photon radiation fields if used in a pair dosemeter configuration where the other dosemeter measures the contribution from the photon radiation. The current determination level is around 1 mSv for neutrons and 0.1 mSv for the photon component. The current study shows the potential of the developed neutron dosemeter and encourages to continued studies within the area.

7. Acknowledgements

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8 References

1. Buchillier T, Aroua A, Bochud F, Schuler C, Stritt N, Valley J-F, Wernli C. Calibration and testing of a TLD dosemeter for area monitoring. Radiat Prot Dosim 110(1-4), 705-710, 2004
2. Bedogni R., Gómez-Ros J.M., Esposito A., Gentile, A. Chiti M., Palacios-Pérez L., Angelone M., Tana L.Workplace testing of the new single sphere neutron spectrometer based on dysprosium activation foils (Dy-SSS) Nucl Instrum Meth A 684, 105-108, 2012
3. Guiying Z, Bangfa N, Li L, Peng L, Weizhi T, Zhiqiang W, Chunbao Z, Hailong L, Shunli J, Pingsheng W, Donghui H, Cunxiong L, Caijin X. Study on bubble detectors used as personal neutron dosimeters. Appl Radiat Isot 69, 1453–1458, 2011.
4. Kralik M, Turek K, Vondracek V. Spectra of photoneutrons produced by high energy x-ray radiotherapy linacs. Radiat Prot Dosim 132(1), 13-17, 2008
5. Mittani J C R, da Silva A A R, Vanhavere F, Akselrod M S, Yukihara EG. Investigation of neutron converters for production of optically stimulated luminescence (OSL) neutron dosimeters using Al_2O_3:C. Nucl Instrum Meth B 260, 663–671, 2007
6. Mukherjee B, Lambert J, Hentschel R, Negodin E, Farr J. An ultrasensitive fast neutron area monitor using gadolinium covered aluminiumoxide dosimeter (TLD-500) chips. Radiat Meas 46, 1698-1700, 2011.
7. Bernhardsson C, Christiansson M, Mattsson S, Rääf C L. Household salt as a retrospective dosemeter using optically stimulated luminescence. Radiat Environ Biophys 48, 21–28, 2009
8. Ahlgren L, Albertsson M, Areberg J, Kadar L, Lindén M, Mattsson S, McNeill F. A ^{252}Cf-based instrument for in vivo body protein monitoring in cancer patients. Acta Oncol 38(4), 431-437, 1999
9. Roberts N J, Jones L N. The content of ^{250}Cf and ^{248}Cm in ^{252}Cf sources and the effect on the neutron emission rate. Radiat Prot Dosim 126(1-4), 83-88, 2007
10. Kim J, Park H, Choi K-O. Measurement of the ^{250}Cf component in a ^{252}Cf neutron source at KRISS. Radiat Prot Dosim 161(1-4), 171-175, 2014
11. Hjalmar E, Slätis H, Thompson S G. Energy spectrum of neutrons from spontaneous fission of Californium-252. Phys Rev, 1955, 100(5), 1542-1543
12. ICRP. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Ann. ICRP 21 (1-3), 1991
13. Bowman H R, Thompson S G, Rasmussen J O. Gamma-ray spectra from spontaneous fission of ^{252}Cf. Phys Rev Letters 12(8), 195-198, 1964
14. NIST (National Institute of Standards and Technology, USA). http://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html, 2014
15. Christiansson M, Bernhardsson C, Mattsson S, Rääf C. Optimizing a read out protocol for low dose retrospective OSL-dosimetry using household salt. Health Phys 102(6), 631-636, 2012
16. Christiansson M, Bernhardsson C, Mattsson S, Rääf C. Photon energy dependence of household salt for dose assessment using OSL. Manuscript 2015