A Novel Dosimetry System for Military Use in Response of Nuclear Emergencies

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Abstract. A novel dosimetry system capable of determining the absorbed dose to tissue (cGy) arising from detonated tactical nuclear weapons was developed with the intention of replacing the system used by the U.S. Army and addressing newer challenges related to modern nuclear events. In addition, the new system eliminates the need for a second dosimeter to be carried out during operation other than war as is the case with the current system.

The system is composed of a portable and self contained new dosimeter (RadWatch®) and dosimeter reader (RadLight®). The ensemble assesses the absorbed dose to tissue (cGy) from neutrons and photons and the personal dose equivalent (mSv) from neutrons and photons at occupational dose in accordance to ANSI N13.11-2009. The RadWatch® dosimeter contains a plurality of Al2O3:C discs as active detection material and a radiofrequency identification chip (RFID) that stores critical information. The dosimeter could be equipped with an additional fluorescent nuclear track detector (FNTD), as a redundant detector for neutron monitoring. The dosimeter is using the Al_2O_3:C detectors to measure photons with energies greater than 70keV in addition to fusion and fission neutrons with energies greater than 0.5 MeV. Neutrons with energies greater than 0.025 eV are assessed using Al_2O_3:C,Mg fluorescent nuclear track detector (FNTD). The portable RadLight® is a small battery operated instrument designed to prevent interference from dust and dirt and withstand severe environmental and operational conditions. The reader uses pulsed stimulation method (POSL) and reflection geometry to analyze the dosimeter. The reader has the ability to interrogate and write information on the chip and also stores pertinent information regarding the reading.

The objective of this work was to examine the photon response due to different non-nuclear events. The dosimetric characteristics as of: energy response, angular dependence, lower limit of detection, linearity and depletion were investigated.

Key words: RadWatch, RadLight, aluminium oxide, Al_2O_3:C, Army

1. Introduction

The development of the RadWatch® dosimeter and RadLight® reader arose from the need of the U.S. Army to have a dosimetry system that could be used to determine the fitness for duty of the troops in an event of nuclear detonation. U.S. Army also showed the intention of replacing their existing dosimetry system with a more miniaturised system while maintaining the properties of the existing device of combining medical record keeping requirements with tactical requirements. The RadWatch® and RadLight® system fulfils these requirements by providing a portable, field ready option with the ability to asses the absorbed dose to tissue and personal dose equivalent due to exposure to neutrons and photons fields. The RadWatch® is intended to be worn on the wrist and still assess the whole body dose. The dose due to exposure to the photon and neutron fields is assessed using the Al_2O_3:C detectors within the RadWatch® slide. Description of the entire system and the photon response properties such as energy response, angular dependence, lower limit of detection, linearity and depletion are presented in this paper.

2. Methods and Materials

2.1. RadWatch® Dosimeter

The RadWatch® dosimeter assesses the absorbed dose to tissue (cGy) from neutrons and photons arising from the exposure to detonated tactical nuclear weapons and other large-scale radiological incidents. The dosimeter can also assess the personal dose equivalent (mSv) from neutrons and photons at occupational dose levels satisfying criteria in ANSI N13.11-2009. The design of the dosimeter includes three main parts: base, slide and cover as depicted in Figure 1.

Figure 1: *RadWatch® Components--Cover, Base, Slide*

The dosimeter identification is engraved on the slide and cover for easy reading and also encoded in the radiofrequency identification chip (RFID) that accompanies every slide to enable electronic data management.

The slide contains three optically stimulated luminescence sensors (OSL) of carbon doped aluminium oxide Al_2O_3:C, manufactured by Stillwater Crystal Growth Division of Landauer. The incident ionizing radiation interacts with the Al_2O_3:C, releasing electrons that are trapped in the crystalline structure of the material. The electrons are released from the traps when stimulated with wavelength centred around 520 nm. Once they return to the ground state, light with wavelength around 420 nm is emitted.

The three OSL sensors are housed under different filtration, each of them serving a specific purpose. Element E3 is intended for detection of photons and neutrons, Element E2 is intended for photons detection and constitutes the reference sensor, and element E1is intended for detection of photons and can be used in conjunction with E2 to provide photon energy information. The sensors and filters are inserted into the slide. Stimulation occurs with the OSL sensors fixed into their filter cups eliminating the need of removing them from their housing for analysis.

The first read position, element 1 (E1) consists of a hollow cylinder and base with a wall thickness of 0.2 mm of aluminium. The cylinder contains a layer of polytetrafluoroethylene (PTFE) (Yoder, 2011) of 0.78 mm thickness against the base of the cylinder followed by the OSL detector, which is secured using a retainer ring. The second read position, element 2 (E2) consists of a hollow cylinder and base with a wall thickness of 0.2 mm of aluminium surrounded by another hollow cylinder and base of copper with a wall thickness of 0.2 mm for a total wall thickness of 0.4 mm. The cylinder includes a layer of PTFE of 0.78 mm thickness against the base of the cylinder followed by the OSL detector. The third disc of Al_2O_3:C, Element 3 (E3) has as construction similar to Element 2 except that a 0.78 mm piece of high density polyethylene (HDPE) is substituted for the PTFE. The OSL detectors are secured with a retainer ring in each of the filters. A detailed layout of the dosimeter is shown in Figure 2.

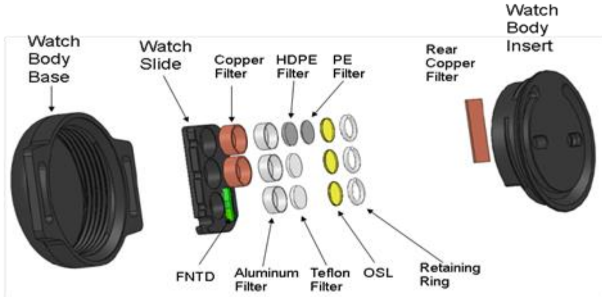

Figure 2: *RadWatch® dosimeter detail layout*

Since the OSL sensors are not sensitive to neutrons, the neutron detection is achieved by adding an additional high density polyethylene (HPDE), a material rich in hydrogen. The HDPE acts as a proton radiator. Collisions of the neutron with the proton radiator creates knock out protons also called recoil protons. Due to different reflective properties of PTFE and HDPE, individual calibration of each sensor is necessary.

Each slide is equipped with a radiofrequency identification chip (RFID). The RFID tag may be read and written to using an RFID antenna and appropriate code. The RFID tag contains identification information for dosimeter and wearer, dose results from the last readout, depletion information, and calibration data for each sensor.

2.2. RadLight® Reader

The dose information from the OSL radiation sensors in the RadWatch® dosimeter is obtained using, the RadLight® reader. The reader weights 2.2 Kg (5 pounds) and can be operated on 4 AA size batteries for approximately 22 hours or about 1000 analyses depending on temperature. The reader is designed to operate in extreme temperature and environmental conditions associated with possible military deployments.

The RadLight® reader, as shown in Figure 3, includes a novel photo-optical engine and pulsed optically stimulation (POSL) in reflection geometry technique for analysing the dosimeters. The pulsed optically stimulated luminescence technique has already been around since 1996 becoming a successful tool in analyzing dosimeters used in personal or medical dosimetry (McKeever et al, 1996). POSL technique could be described as a sequence of pulses of light synchronized with a photomultiplier tube (PMT) counter gate such that the data acquisition during the pulse and a little after the pulse is switched off. The PMT is kept "on" at all times and only the photon counter is gated such that to count during the specified period. The POSL method provides a wide dynamic range, high sensitivity and excellent signal to noise ratio (Akselrod *et al*, 1998).

Figure 3: *RadLight® Reader*

The innovation brought by the RadLight® reader encompasses the reflection geometry which offered the possibility to miniaturize and create a portable reader. The illuminating beam of light stimulates the OSL sensors while they are in the slide and the resultant radiation is routed along the same optical path to a light detector such as photomultiplier tube, which quantifies the amount of luminescencent light.

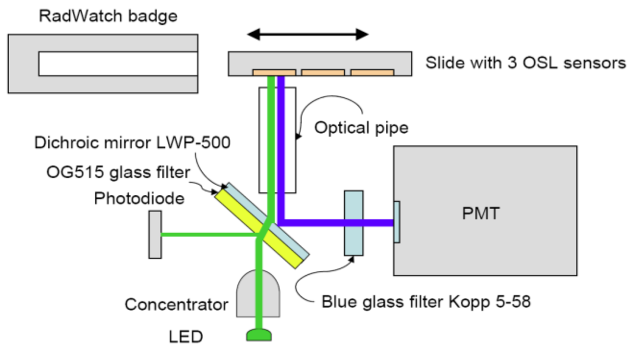

Figure 4*: Optical Engine Components, Reflective Geometry-- RadLight® Reader*

The RadLight® reader uses green light emitting diodes (LED) as the illumination source. A notable feature of the RadLight® reader is the dual range protocol established for reading lower and higher doses. Before the readout process is started, the reader sends a number of test pulses to estimate the magnitude of the dose the dosimeter was exposed to. Based on these test counts the reader decides the duration of the light stimulation. Dosimeters exposed to radiation levels less than 650cGy (Cs-137 equivalent reference response) are read using the "long beam" while the dosimeters exposed to higher levels are read using "short beam". In the low dose regime (long beam), the LEDs are set up to produce 1000 cycles at 1milliseconds per cycle. The LED "time on" in this case is set at 15 to 25 microseconds. For the high dose regime (short beam) the number of cycles is reduced to 400 at 1millisecond per cycle. In this case the LED is on for 5 microseconds.

The reader displays the results of the analysis, stores results of analysis and writes the results to the RFID chip. The data stored could be transferred using an output mechanism such as universal serial bus (USB) plug.

2.3. Methods

Different characteristics of RadWatch® -RadLight® dosimetry system have been investigated and are presented in the continuation of this paper.

2.3.1. Photon Energy Response

The main objective of a dosimeter is to asses the absorbed dose or dose equivalent due to external radiations fields. Ideally the response of the dosimeter to different photon radiation sources would be similar to the response of the human body. Since the OSL material does not have the same chemical composition as water or tissue, its response depends on the photon energy.

The energy dependence was studied by exposing RadWatch® dosimeters to photon sources with average energy ranging from 29 keV to 1250 keV. The irradiations were performed in accordance with ISO 4037-1 (ISO 4037-1:1996).

The dosimeters were read on a RadLight® reader calibrated using dosimeters exposed to Cs-137, which is the reference condition. To account for material sensitivity and reader performance a more independent measure, as converted value, was developed. The converted values for each element were calculated using Equation 1.

$$\text{Converted Values } (E_i) = \text{raw counts } (E_i)/\text{material sensitivity } (E_i)/\text{reader calibration factor} \qquad \text{Equation 1}$$

2.3.2. System Linearity

An ideal dosimeter is expected to display a signal that is proportional to the absorbed dose of radiation for a given radiation field. In addition to the material response, the reading mechanism and the photomultiplier tube response could contribute to deviations from linearity.

Linearity response was studied for delivered doses ranging from 0.05 cGy to 2000 cGy. The dosimeters were read using RadLight® reader. The reader has a wide dynamic range due to its capabilities of automatic switching between long and short beams, adjusting the stimulation time relative to the dose on the dosimeters. With the current settings the reader switches between long and short beam around 600cGy (Cs-137 equivalent reference response). Dose was calculated based on the converted value for element 2. Bias for each dose level was calculated using Equation 2.

$$\text{Bias} = (\text{observed dose-delivered dose})/(\text{delivered dose}) \qquad \text{Equation 2}$$

2.3.3. Dosimeter Re-readability

The OSL material found in RadWatch® dosimeters, stores irradiation signal and releases part of it after stimulation. Since not the entire signal is being released during the stimulation, the OSL material could be reread multiple times. Depletion or loss signal could occur with multiple readings depending on the length and strength of the stimulation method. Depletion for the RadWatch® and RadLight® system has been investigated. For this, one dosimeters irradiated to 4.5 cGy using a Cs-137 source was read 50 times using the long beam. For this beam the light source was on for 15 µs for 1000cycles. Another dosimeter irradiated to a much higher dose, approximately 1000 cGy, using Cs-137 source was read using the short beam, which is set for 5 µs and 400 cycles. Each dosimeter was read 50 times and the depletion rates were calculated for both beams by normalizing the value for each reading to the read value for the initial read. The derived depletion rate was then saved into the reader and multiple readings of another irradiated dosimeter were performed to confirm the equation.

2.3.4. Angular Response

Angularity response was explored for RadWatch® dosimeter exposed to photons of various energies and angle of incidence. Dosimeters were exposed to photons of energies 73keV, 173keV, 662keV in accordance with ISO 4037-1 (ISO 4037-1:1996). The specific radiation qualities were M150, WS250, and Cs-137. Angles ranged from 0° to 90° for both horizontal and vertical rotations, as follows: 0°, 40°, 60°, and 90°. Dosimeters were read on the RadLight® and dose was calculated based on element 2 converted values (equation 1). Dose for each of the angles was normalized to the delivered Hp(10) for each radiation field and each angle.

2.3.5. Detection Limit

The detection limit or lower limit of detection (LLD) provides a scientifically and statistically defensible method for determining the lowest radiation dose that a dosimeter system can detect. The ability to detect radiation exposure, even at extremely low levels, is important in assessing the occupational exposure. For this test a group of 20 RadWatch® dosimeters were selected. Half of the dosimeters in the set were irradiated using Cs-137. The other half of dosimeters were not irradiated and kept as controls. Both sets of dosimeters were read on RadLight® reader. The mean dose and associated standard deviations for the un-irradiated and irradiated dosimeters were determined. The LLD was calculated using the following formula (DOE/EH—0027, 1986):

$$LLD = \frac{2\,[t_pS_0 + (t_pS_1/H_1)^2\,H'_0]}{[1 - (t_pS_1/H_1)^2]} \qquad \text{Equation 3}$$

Where t_p is the t distribution for n-1 degrees of freedom and a p value of 0.95, S_0 and S_1 are standard deviation for un-irradiated and irradiated dosimeter results, H_1 and H'_0 are the average of the irradiated and un-irradiated dosimeter results without subtracting background.

2.3.6. Performance Results

The RadWatch® dosimeter was submitted for National Voluntary Laboratory Accreditation Program (NVLAP) whole body proficiency testing administered by the National Institute of Science and Technology (NIST) The testing was performed in accordance to American National Standard for Dosimetry-- ANSI N13.11-2009. The testing categories were IA—Accident Photons General and IIC Medium Energy Photons. Dosimeters tested in Category IA are exposed to either Cs-137 or M150 X ray field and doses in the accident range with limits between 0.05 to 5Gy without knowledge of the radiation field. Dosimeters tested in category IIC are exposed to photon of energy greater than 70keV, angles smaller or equal to 60° and dose range from 0.5 to 50mSv without knowledge of the radiation field. For category I, the performance quotient is expected to be less than 0.24 while for category II the performance quotient is expected to be less than 0.3. Performance quotient is calculated as (ANSI/HPS N13.11-2009):

$$B^2+S^2 \leq L^2 \qquad \text{Equation 4}$$

Where B is the bias for all dosimeters tested in a category and S is the standard deviation of the dosimeters tested in a category and L is the category limit.

3. Results and Discussions

3.1. Photon Energy Response

To arrive to the energy response curve, the converted value of each element was normalized to the delivered $H_p(10)$ for each of the radiation fields tested. Average response as a function of photon energy are displayed in Figure 5.

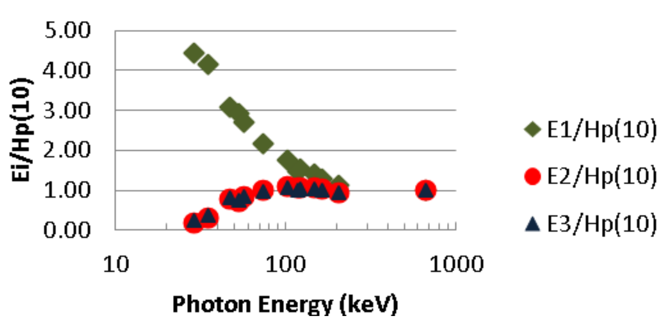

Figure 5: *Element Response Normalized to delivered Hp(10)*

Elements 2 and 3 respond similarly to different energies, which constitutes a very useful tool for photon and neutron discrimination when a neutron field is present. As intended the element 1 (E1) offers a good energy discrimination and ratio of element 1 relative to element 2 could be considered a good indicator for low energy exposures. Element 2 shows a response around 1.00 ± 0.15 for energies above 57 keV which could be a good estimate of Hp(0.07) and Hp(10) without applying any correction.

3.2. System Linearity

The results of the linearity test are detailed in Table 1 were graphed in Figure 6. In addition to the delivered dose, the table also displays the average dose read, standard deviation, bias relative to delivered dose and coefficient of variation at each dose level.

Table 1*: Dose Linearity*

Deliv dose (cGy)	0.01	0.1	0.5	1.0	5.0	10	30	100	300	606	1001	2003
Avg dose read (cGy)	0.01	0.1	0.5	1.0	5.0	10	29	99	313	635	1004	2053
Std dose read	0.001	0.0	0.01	0.02	0.12	0.27	1.17	4.1	6.72	6.75	27	107
Bias Dose Read	-0.02	-0.01	-0.04	-0.04	0.01	-0.04	-0.04	-0.01	0.04	0.05	0	0.03
Coef of Variation	0.15	0.09	0.01	0.02	0.02	0.05	0.04	0.04	0.02	0.03	0.03	0.05

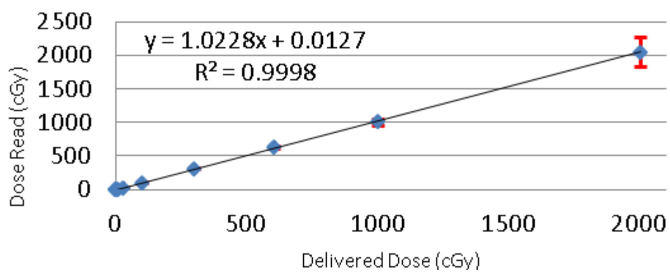

Figure 6: *Dose Linearity*

The system is linear for a wide dose ranges also displaying very good accuracy, dose being within 5% of the delivered dose in all situations.

3.3. Dosimeter Re-readability

Two different dosimeters were read multiple times using long and shorts beam and the depletion rate calculated for each of the beams as of function of number of reads. Data is shown in Figures 7 and 8. The depletion rate for the long beam is 0.7% per read, while the depletion rate for long beam is 0.1%/read.

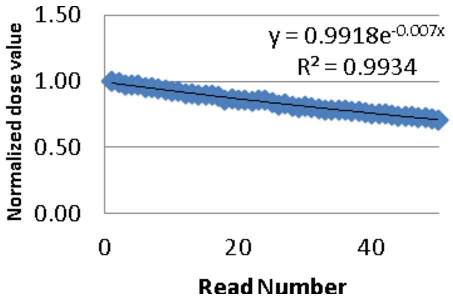

Figure 7: *Depletion curve for long beam*

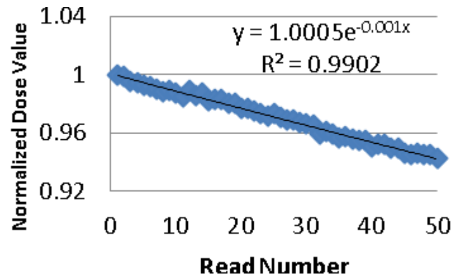

Figure 8: *Depletion curve for short beam*

The reader is capable of correcting for depletion. Once the depletion values were entered into the readers, the dosimeters were read 20 times. These readings are presented in Figure 9. The calculated precision for the system was 1%. Additional testing was also performed having the dosimeters read 130 times. The system maintained an accuracy that is within 5% of the first read.

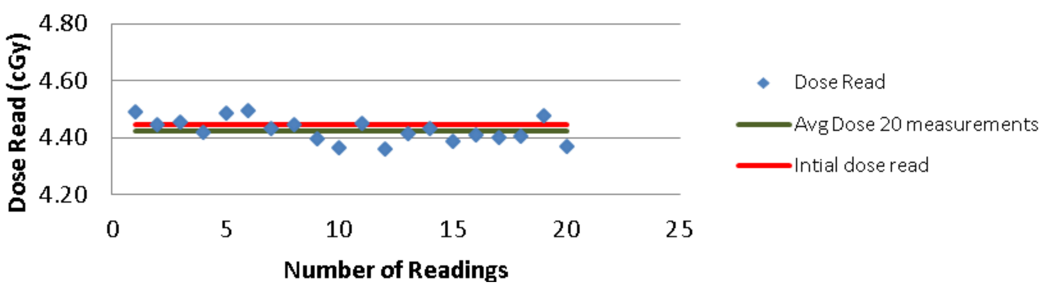

Figure 9*: Multiple readings adjusted for depletion*

3.4. Angular Response

The dosimeter angular response is graphed in Figure 10 for horizontal direction and Figure 11 for vertical direction. The dose response for high energy photons, similar to the irradiation fields encountered in combat or civil operations, is within 90% of the delivered dose for all angles including 90°.
The dose response for the lowest energy is within 60% of the delivered dose for all angles including 90°. Once the dosimeter is exposed to higher energies (173keV), the response at 90° is within 60% of the delivered dose. This great performance at high energies enables the dosimeter to be worn on the wrist and is due to the cylindrical cup shaped filters that house the Al_2O_3:C discs.

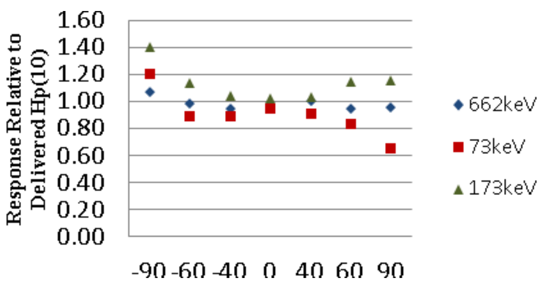

Figure 10*: Angular Response-Horizontal Direction*

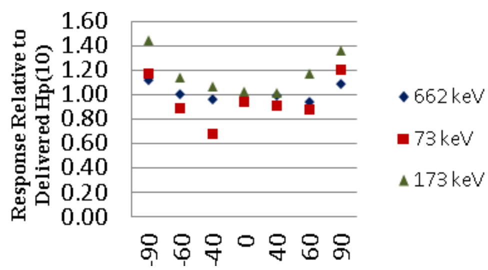

Figure 11*:Angular Response Vertical Direction*

3.5. Detection Limit

Lower limit of detection for RadWatch® and RadLight® system was calculated to be 0.00085cGy (0.85 mrad).

Table 2*: Lower Limit of Detection*

tp	Ho' (mrad)	So	H_1 (mrad)	S_1	LLD (mrad)
1.812	0.499	0.236	5083.5	77.46	0.85

3.6. Performance Results

The bias and standard deviation for each category tested in the NVLAP performance testing are shown in Table 3 and Figure 12. The results were well within the limits for both categories demonstrating a very good performing dosimeter suitable to be used as a tactical dosimeter and as an occupational monitoring dosimeter.

Table 3: *Performance Test Results*

Category	Dose	Bias	Std Dev	Performance Quotient	Category Limit
IA	DDE	0.002	0.052	0.003	0.058
IIC	DDE	-0.015	0.058	0.004	0.090
IIC	SDE	0.004	0.063	0.004	0.090

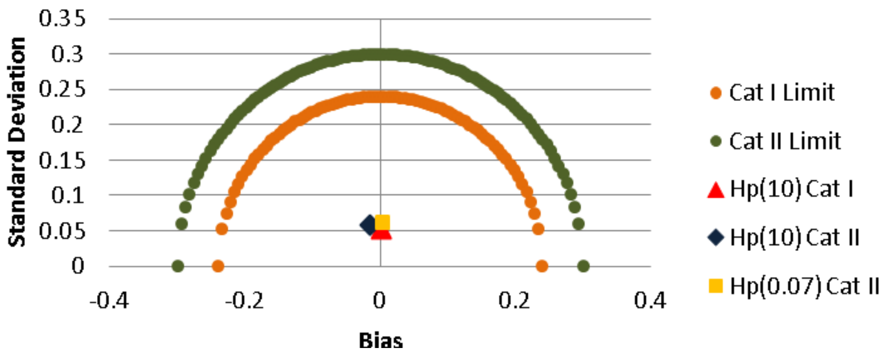

Figure 12*: Performance Test Results Q4 2011*

4. Conclusions

The testing performed using the RadWatch® and RadLight® dosimeter system, demonstrated the capabilities of the dosimeter to be used as a tactical dosimeter due to its capabilities of assessing the probability of acute effects and as a personnel dosimeter due its capabilities of measuring dose equivalent and maintaining a legal record of long term effects. The lightness, reliability, easiness of use and a wide dynamic range make the system a very good tool for assessing dose in the field and in the laboratory. The very simple dose calculation algorithm in conjunction with the unique filter design provides good angular response enabling the possibility of the dosimeter to be worn on the wrist while assessing the whole body dose. The re-readability used in conjunction depletion correction offers the possibility of the dosimeter to be analysed multiple times without dose alteration. The neutron performance of the system will be reported in the future work.

5. References

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