DEVELOPMENTS IN NEUTRON DOSIMETRY

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Abstract

Chemically etched CR-39 is currently used for neutron dosimetry by Landauer Europe for its clients in France. Recent French regulation requires us to deliver a lower limit of detection of 0.1mSv compared with our existing limit of 0.2mSv. In addition, we currently manually count the etched tracks and would like to increase the efficiency and reliability of our service. In light of these issues, we have reviewed the operation of our neutron dosimetry service and undertaken a number of improvements. These include:

- the installation of an automatic counting system;
- a re-evaluation of the limit of detection; and
- a review of the energy and angular response of the dosemeters with the automatic counting system.

Whilst, the work undertaken has led to significant improvements to our service, it is recognised that chemically etching CR-39 detectors overnight is a slow and potentially messy process. Therefore, Landauer is undertaking a number of projects to develop new systems for neutron dosimetry. These include the development of an albedo type dosemeter, based on our latest optically stimulated dosimeters (InLight) for photon personal radiation monitoring, which is for use by clients with well defined/characterised neutron fields.

This paper will summarise these improvements and reviews. It will also outline the possible future developments to our neutron dosimetry service over the next few years.

1 INTRODUCTION

Landauer provides neutron dosimetry services to over 50,000 participants worldwide and approximately 5000 in France. These participants work in a variety of industries including the nuclear industry and the oil industry.

Since 1985, Landauer have adopted the use of track etch dosemeters, based on CR-39. The CR-39 is chemically etched overnight and, in France, manually counted using human readers and microscopes. In general, our dosemeter conforms to the ISO standard(1). Recent French regulation, introduced 2004 for implementation in January 2008, requires us, in France, to deliver a lower limit of detection of 0.1 mSv compared with our existing limit of 0.2 mSv. In addition, we currently manually count the etched tracks and would like to increase the efficiency and reliability of our service. In light of these issues, we have reviewed the operation of our neutron dosimetry service and are undertaking a number of improvements. These include:

- the installation of an automatic counting system; and
- a review of the limit of detection, energy and angular response of the dosemeters with the automatic counting system.

Whilst, the work undertaken is leading to significant improvements to our service, it is recognised that chemically etching CR-39 detectors overnight is a slow and potentially messy process. Therefore, Landauer is undertaking a number of projects to develop new systems for neutron dosimetry. These include the development of an albedo type dosemeter based on our latest optically stimulated dosimeters (InLight®) for photon/beta personal radiation monitoring.

This paper will summarise these improvements and reviews. It will also give preliminary details about our new albedo neutron dosemeter, for clients with well defined/characterised neutron fields, which is under development.

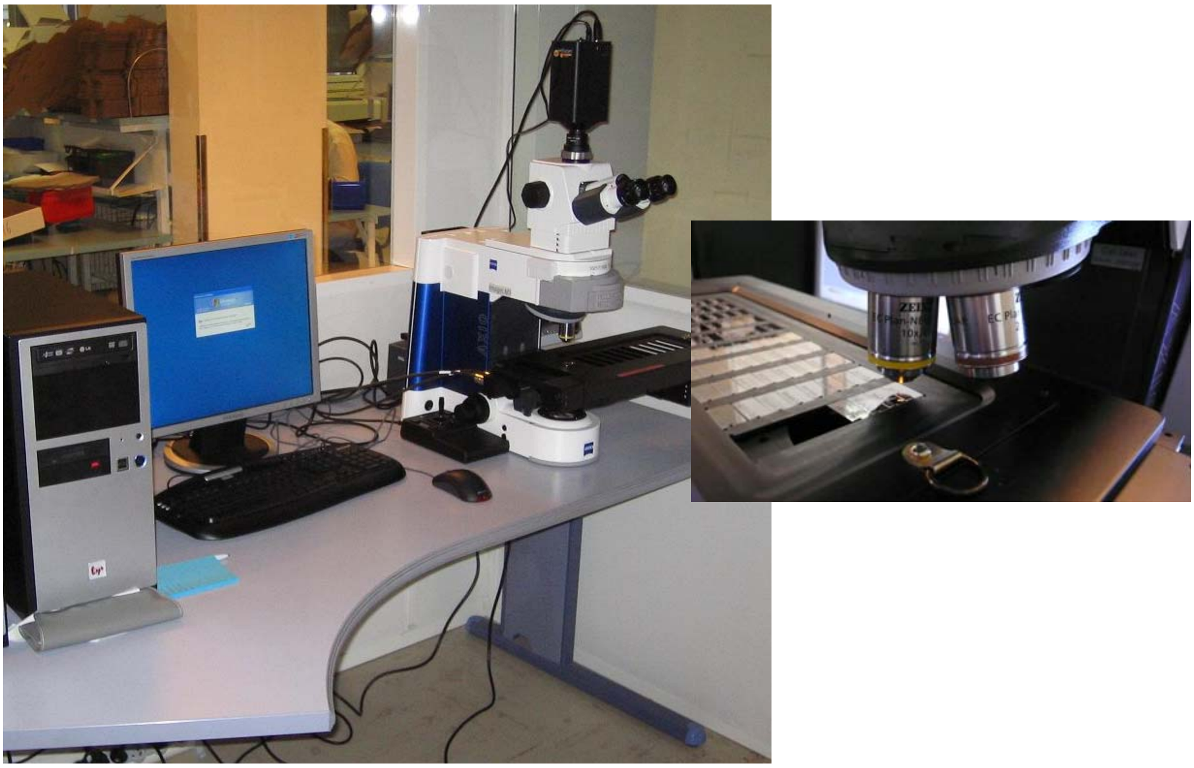
2 AUTOMATIC COUNTING SYSTEM

Resourcing trained operators to perform the manual counting of CR-39 neutron dosemeters reliably is difficult and considerable effort is expended in training, performance testing and review. We want to eliminate, as far as possible, the variability both between readers and for individual readers over time, entailed in human reading, whilst increasing our speed of operation. We have therefore investigated the use of an automatic reader for the assessment of our neutron dosemeters. This will have the added advantage, in the future of being able to undertake further assessment of the etched tracks, for example, characterisation by size.

2.1 The system

The automatic counting system (Figure 1) comprises a motorised optical microscope, an electronic camera (2000 x 2000 resolution), two personal computers (one for collecting the images, one for performing the image analysis) and image analysis software. The automatic reader was purchased from Noesis. The output is linked to Landauer Europe’s information system so that the analysis is integrated into the dose record keeping system. CR-39 neutron dosemeters are set out in trays comprising 80 detectors each. For each CR-39 detector, the system checks the focus and flatness of each CR-39 detector and captures a number of images corresponding to the required scanning area. The second computer performs the image analysis function for each image and transfers the assessed dose data to Landauer’s information system. For manual readers we restrict their counting time to 4 hours per day to ensure there is no strain on their eyes and so that they maintain their optimal reading performance. They can therefore read out up to about 200 detectors per day. The automatic reader has the capability to assess 40 CR-39 detectors per hour at present. Thus, we anticipate processing about 400 detectors per day with the automatic system.

Figure 1: The automatic counting system



2.2 nitial trials and characterisation tests.

In deciding to purchase the equipment and software for the automatic counting of the CR-39 elements in our neutron dosemeters we undertook a number of proof of concept trials. Following purchase and set-up we are undertaking a number of tests, which are ongoing, to characterise the system prior to implementing the system fully into our service. These trials and tests have principally used dosemeters that had been irradiated (principally at the National Physical Laboratory (NPL), UK) for previous type testing and characterisation studies. Example results for the dose and energy and response of the system are reported below.

2.2.1 Detection threshold

As mentioned above, a key requirement for our system is to maintain a limit of detection of below 0.1 mSv. The ISO standard(1) (section C.2.3) defines the method for determining the detection threshold for solid state nuclear track detectors (such as CR-39) as:

Etch and read out i = 1 to n unirradiated dosemeters. Use the conversion coefficient for a ^{241}Am-Be or ^{252}Cf neutron source to transform the number of tracks into a measured dose equivalent, H_i, and calculate the experimental standard deviation, s, for the n dos meters. Show that the criterion, expressed in millisieverts, in equation [1] is met:

$$t_n.s \leq 0.3 \qquad [1]$$

where value the values for t_n are listed in Table B.2 [of the standard].

This assumes a detection threshold of 0.3 mSv. For a detection threshold of d_t mSv equation [1] becomes:

$$t_n.s \leq d_t \qquad [2]$$

Historically our minimum reportable dose for Neutrak dosemeters has been 0.2 mSv. French regulation, and clients, are requiring us to determine neutron doses with a limit of detection of

0.1 mSv. We have therefore undertaken trials at Fontenay-aux-Roses, with the new automatic counter to re-evaluate our limit of detection.

30 unirradiated dosemeters were read out and our standard conversion coefficient for based on ^{241}Am-Be irradiations used to determine the measured dose equivalent. For this t_{30} is 1.7 and the standard deviation of the measured dose was 0.03 mSv. This corresponds to a limit of detection of 0.05mSv, well below the required 0.1 mSv.

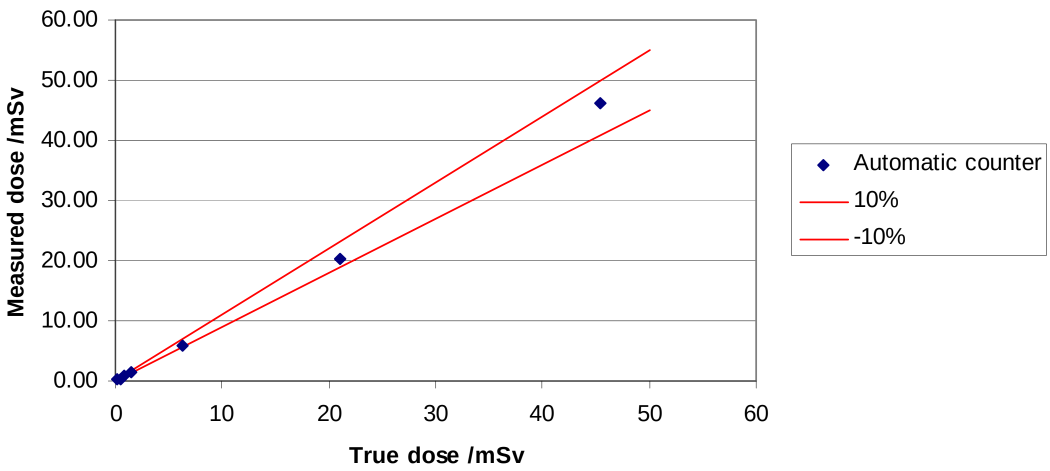
2.2.2 Dose response

Further assessments have been made of the dose response of the system to demonstrate that the linearity falls within the required ± 10% for doses from 1 mSv to 100 mSv. Again detectors used in previous type testing and irradiated at NPL were used for this evaluation the results of which are shown in Table 1 and Figure 2.

Table 1: Dose response using the automatic counting system

True dose /mSv	Measured dose /mSv	Bias %
0.5	0.43	-15
0.79	0.82	4
1.5	1.60	7
6.23	5.84	-6
21.04	20.26	-4
45.35	46.24	2

Figure 2: Dose response using the automatic counting system



The dose response is within ± 10 % for all the dosemeters up to the maximum exposed dose (45 mSv) with the exception of the value at 0.15 mSv. Thus the automatic counting system more than adequately meets the requirements of the International Standard(1) for the dose response (table 5 and paragraph C.2.2 of the standard which requires the response to be linear within ± 10 % for doses from 1 mSv to 100 mSv).

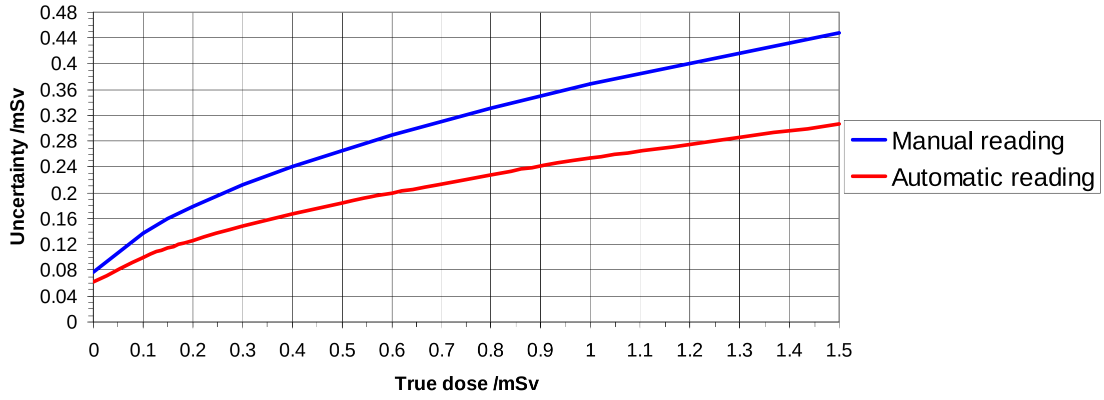
2.2.3 Uncertainty in the dose measured

Further investigations are in progress to determine the uncertainty of the measured dose as a function of dose. At present these are based on measurements of unirradiated dosemeters and dosemeters irradiated with 1.5 mSv ^{241}Am-Be neutrons. The uncertainty was calculated in accordance with section B.4 of the ISO standard(1), ie

$$\sigma = (\sigma_0^2 + \sigma_0^2)^{½} \qquad [3]$$

Figure 3 gives the uncertainty as a function of dose for both human assessments of the dose and the automatic reader. It can be seen that we obtain a significant improvement using the automatic reader, but further experimental work is in hand to verify this.

Figure 3: Uncertainty and a function of dose

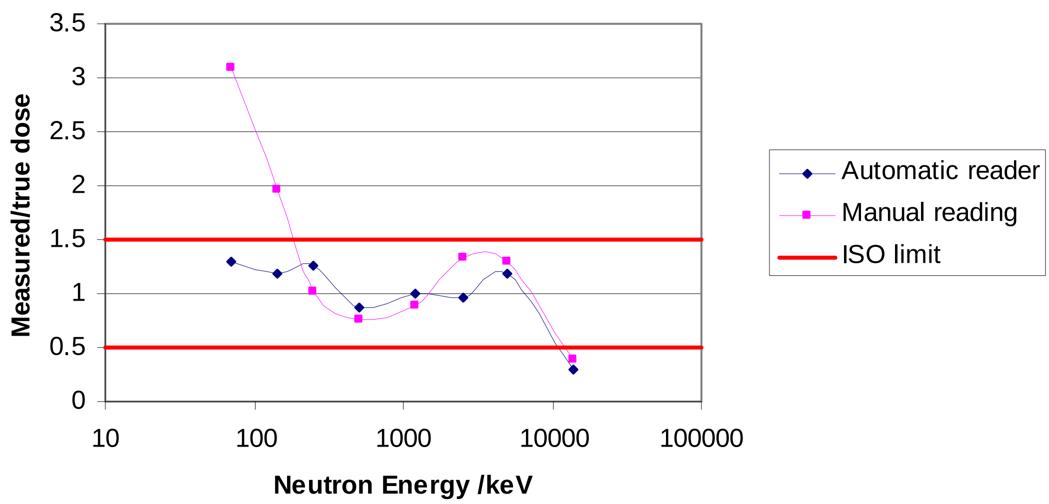


2.2.4 Energy response of the automatic counting system

Detectors irradiated with monoenergetic neutrons in the range from 0.07 – 14 MeV neutrons by the National Physical Laboratory (NPL) in the UK were used for this assessment. These were initially used for type testing and the energy and doses are known with high precision (NPL certificate of calibration reference N618 (E01050144), August 2001). All the samples had been previously etched and read out in accordance with the standard procedures, which have not been changed significantly since then. For each energy, 5 detectors were read out manually, 4 using the automatic reader.

Figure 4 gives the energy response for both the original readout and the readout using the automatic reader. The individual data points are joined for ease of viewing.

Figure 4: Energy response using the automatic counter



The energy response (Figure 4) determined from the automatic reader differed significantly from that of the original readout, particularly for the two lower energies (70 and 144 keV). Indeed the relative response from the automatic analysis are substantially lower than for the manual read and fall within the ISO ranges of ± 50 %, whereas those for the manual analysis are substantially above this range. This effect is not yet understood, it is possible that this effect is due to variations in the size of the tracks. It is possible, using the image analysis software to analyse the diameters of the tracks counted, but further work will be required to assess this in detail and to perform further optimisation of the algorithm used to ensure the energy response extends as low as possible and as flat as possible.

2.2.5 Further work and optimisation

Prior to fully integrating the automatic reader into our system some further work will be undertaken to fully optimise and characterise it. This will include:

- a full dose response including a detailed examination of the limit of detection and uncertainty using dosemeters irradiated at NPL to known doses of ^{241}Am-Be neutrons;
- further evaluation and optimisation of the energy response, in particular extending the range down to 40 keV using dosemeters recently irradiated at NPL.
- Further optimisation of the automatic reader, particularly in terms of speed of throughput.

3 DEVELOPMENT OF OSL ALBEDO DOSEMETER

Themoluminescence dosimetry systems have extensively been used for albedo neutron dosimetry(2), and a number of such systems are in use today, including the Pansonic UD-809 and Thermo-Electron TLD-600/TLD-700 systems.

Optically stimulated Luminescence has been adopted as Landauer's technique of choice for photon dosimetry for many years. The application of optically stimulated luminescence for dosimetry has recently been reviewed(3). The mechanisms for trapping charge during radiation exposure are similar to thermoluminescence. The principal difference compared to thermoluminescence is the release mechanism in which exposure to optical light is used to obtain the signal which is a function of the dose absorbed. This is a quantum process, with no heating, and only a small fraction of the trapped charges are released. Thus, much of the trapped charge is retained following stimulation and may be released in subsequent stimulations. This enables OSL dosemeters to be read out many times without significant loss of signal. As its detectors, Landauer use aluminium oxide powder doped with carbon (Al_2O_3:C), obtained by grinding crystals and sifting the powder to the desired size range. The powder is mixed with a polyester binder and coated onto a roll of polystyrene film. The film roll is subsequently cut to the desired shape and size (for InLight dosemeters this is discs of approximately 5 mm diameter). A number of papers(4 – 9) have described the application of OSL to personal dosimetry. A new material, OSLN has been developed to produce a neutron response which can be assessed using standard OSL readers. The new development of the InLight albedo neutron dosemeter has been summarised by Passmore(10).

3.1 Design

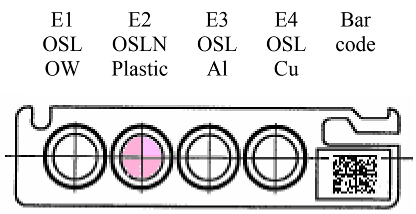
The new albedo dosimeter includes a detector comprising a newly developed material called OSLN. The OSLN material consists of our standard OSL material (Al_2O_3:C) coated with $^6LiCO_3$. Neutron response is induced in the Al_2O_3:C when ^{6}Li absorbs a neutron and produces both tritium (^{3}H)and alpha (^{4}He) particles:

$$^6\text{Li} + {}^1\text{n} = {}^3\text{H (2.75 MeV)} + {}^4\text{He (2.05 MeV)} \qquad [4]$$

The alpha and tritium particles yield their energy through coulomb interactions. The readout process is exactly the same as for OSL material.

The design of the proposed OSL albedo dosemeter(10) is based on Landauer's Standard InLight dosimeter adopted and approved for use in France(11) and a number of other countries including USA, Canada, S Korea, Australia, Japan, China, Brazil etc.. The badge consists of a slide comprising four detector elements contained within a case in which there is an open window, plastic aluminium and copper filters, respectively in front of detector elements defined as E1, E2, E3 and E4. This badge is modified by the replacement of a standard OSL detector by one of OSLN material as the second element of the slide (covered by a plastic filter) as shown in Figure 5.

Figure 5: The albedo OSL dosemeter



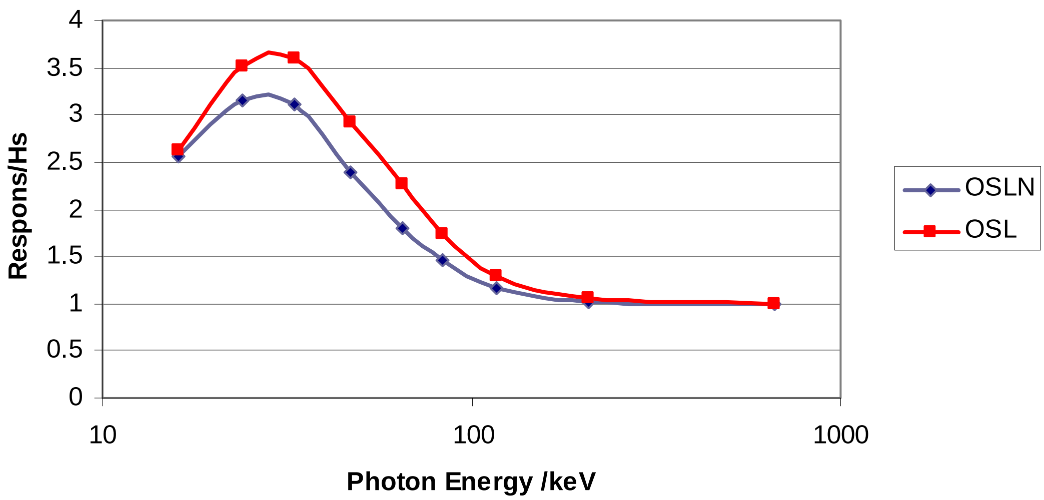
It is proposed that the algorithm used to determine the dose-equivalent quantities (Hp(10) and Hp(0.07)) will perform an initial check to determine if beta particle or neutrons were present during exposure. Element 1 higher than Element 2 would indicate the presence of beta, while Element 1 lower than Element 2 would indicate the possible presence of neutrons.

We have begun testing this new type of dosemeter. Studies undertaken so far include the photon and neutron response of the OSLN material, which are reported below. Other tests include the fading, linearity, depletion and annealing properties all of which show favourable results.

3.2 Photon energy response

The photon response for the OSL and OSLN material was performed to determine if the two materials behaved comparably. The result (Figure 6) demonstrate that the typical energy dependence of the OSL material was also exhibited in the OSLN material. However, the over-response in the energy region 24 – 65 keV is less pronounced in the OSLN material by about 10 – 20 %. This is attributed to the addition of the with $^{6}LiCO_3$ coating covering the OSL material.

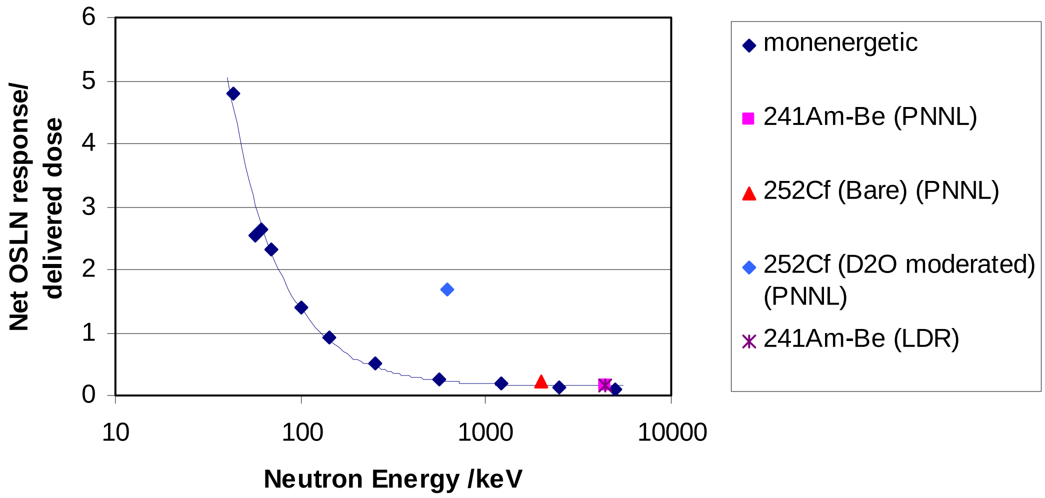
Figure 6: Photon energy response of the OSLN and OSL material



3.3 Neutron energy response

The response of albedo neutron dosemeters fluctuates with neutron energy. This variation has been characterised for the new dosemeter being developed by Landauer. Two elements of OSLN and two of OSL material were placed in the slide of an InLight badge and placed under approximately 160mgcm^{-2} plastic in all four read positions. This was then loaded into a standard Landauer cover. The dosemeters we irradiated at NPL on a water-filled ICRU phantom, at normal incidence to neutrons with energy in the range from 40 keV to 5 MeV. Further dosemeters were irradiated with ^{252}Cf bare and moderated at PNNL and to bare ^{241}Am-Be sources at Pacific Northwest National Laboratory (PNNL) and at Landauer. The results of these irradiations are shown in Figure 7.

Figure 7: Neutron energy response of the OSL albedo dosemeter



Neutron correction factors (NCF) must be determined for each field in which the albedo dosemeter is used. The response to D_2O moderated ^{252}Cf was significantly high, but not unusual compared to other albedo dosemeters. As with other techniques a separate NCF should be used when conducting measurements or performance testing in this type of field.

Further field testing was conducted at Callaway Nuclear Power Plant (a Pressurised Water Reactor in the United States of America). Dosemeters were placed on a phantom at various locations in the reactor containment and the delivered neutron dose determined using a Hawk tissue-equivalent proportional counter (TEPC). This data gave neutron conversion factors in the range of 1.61 top 1.48, relative to the response for ^{241}Am-Be, for a variety of locations. Further field testing is being undertaken by the US army, Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory (PNNL) and Georgia Power.

3.4 Further developments

The albedo dosemeter will be a very useful supplementary dosemeter to the CR-39 dosemeter already in widespread use. Unfortunately, it requires knowledge of the field in which it is being used to determine the neutron correction factor and will, therefore, not be suitable for all applications. Further, long term, work is in hand to develop a novel fluorescent nuclear track detectors for passive neutron dosimetry[(12)].

4 CONCLUDING REMARKS

Considerable improvements are being made to the neutron dosimetry services provided by Landauer Europe at its Fontenay-aux-Roses facility. These are currently being achieved by the incorporation of a new automatic counting system. This will have several advantages over our existing human assessment system:

- reduced dependence on human readers, the variability between them, individual's variability from time-to-time and the need for extensive programme of training, performance testing and review
- improved limit of detection
- improved energy response
- the possibility to add a second reader with limited time and effort.

Further improvements to our service are in the process of being developed, the first of which is an abledo dosemeter designed around our standard InLight badge. This incorporates a detector element comprising our standard detector material (Al_2O_3:C) coated with $^6LiCO_3$. The characteristics of this new dosemeter have been evaluated and, in terms of its neutron response is comparable with other albedo neutron dosemeters available. The Landauer dosemeter will include the advantages of Optically stimulated readout, principally that it can be re-assessed many times. It is anticipated that this new dosemeter will be fully tested and approved within 2 years.

ACKNOWLEDGEMENTS
We are grateful to Mr C Graham, CHP, for undertaking the field testing at Callaway Nuclear Power Plant.

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