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A novel design of survey instrument for neutrons

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A survey instrument has been designed and developed for measuring neutrons with energies in the range from thermal to 20 MeV. The device is spherically symmetric, and features a polyethylene moderator and Borotron® attenuating layer to facilitate accurate detection of fast and intermediate energy neutrons, combined with air-filled guides to channel low-energy neutrons to the single, central proportional counter. Response characteristics in monoenergetic neutron fields have been calculated using Monte Carlo techniques, and are supported by preliminary measured data; the likely performance in workplace fields has also been assessed. Overall, the design offers significant advantages over the alternatives currently available, being acceptably sensitive with an *H**(10) response characteristic that is relatively energy- and angle-independent, whilst being comparatively light. A simple 'upgrade' that may reliably extend the scope of the device up to the GeV energy scale has also been explored.

Keywords: ambient dose equivalent; area surveys; dosimetry; instrumentation; Monte Carlo; neutrons; radiation protection; workplace fields

1. Introduction

At sites where individuals may be exposed to neutrons, such as at nuclear facilities or in the vicinity of accelerators, it is essential that adequate radiological protection is provided. Underpinning this process is the need to accurately monitor dose rates from ambient neutrons, so that risk to personnel may be kept within acceptable limits. One method of achieving this is through the use of neutron survey instruments, i.e. portable devices that can be used to measure dose rates at different locations, and hence lead to a dose map of the area of interest; shielding or other provisions can hence be checked and, if necessary, modified. The ideal such instrument is light and easy to use, has a flat energy-dependence of response across the range from thermal to MeV neutrons, is well-characterized, and is appropriately sensitive. Neutron survey instruments are typically calibrated in terms of ambient dose equivalent, *H**(10).

A number of neutron survey instruments are currently available and in use Worldwide [1-6]. The relative performances of these devices differ to greater or lesser extents, but, aside from being heavy, they all exhibit one common problem: typically, the response characteristics of neutron survey meters either over-respond at intermediate energies (~ keV scale) or under-respond at low energies (~ meV scale). The introduction of a novel type of instrument that improves on this weakness would hence be of obvious benefit. This paper summarizes the development of a survey meter that includes air-filled guides that allow thermal neutrons to be channelled to a single, central detector; this innovation helps the low-energy response to be raised without detriment to the keV or MeV scale components, and without requiring multiple sensitive regions [2]. The concept is protected by international patent PCT/EP2008/065612.

2. Design process

The general-purpose Monte Carlo radiation transport code MCNP5 [7] was used to optimize the design. Essentially, the Monte Carlo modelling process followed an iterative approach:

1. A trial design was modelled, and calculations performed to determine its fluence responses to isotropic and plane-parallel monoenergetic neutrons from ~0.01 meV to 20 MeV, as well as to [241]Am-Be and thermal distribution sources;

2. The results were then converted to *H**(10) responses, normalized to the calculated response to the plane-parallel [241]Am-Be source, and plotted as a function of source energy;

3. The overall energy-dependent relative response characteristics were then compared with those from previous trials, and the design changed accordingly in an attempt to improve whichever feature was judged most unsatisfactory. This modified design formed the basis for the next trial.

The sequence was repeated many times, until a good

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overall performance was achieved. Nominally, all of the trial designs followed the same basic template: they were spherically symmetric, were constructed from concentric shells of various materials, and, apart from a few scoping calculations, all had air-filled guides that penetrated some or all of the outer layers. More specifically, the configurations generally incorporated: a central, spherical, 2 atm ^{3}He-filled (plus quench gas) SP9 proportional counter, with a thin steel wall of outer radius 1.65 cm; an inner moderating layer of 0.95 g/cm^3 polyethylene (PE); an attenuating layer of 1.05 g/cm^3 Borotron$^®$ UH050, a polymer loaded with neutron-absorbing ^{10}B; and an outer moderating layer of 0.95 g/cm^3 PE. As experiments, a few trials did also consider materials other than Borotron$^®$, or featured more than one attenuating layer. There were no 'gaps' between these layers: the outer radius of one shell is also the inner radius of the shell that immediately surrounds it. Determining the radii of each of these layers was an obvious goal of the optimization process. However the number, shape, size, depth and extension of the guides are also variables that have a significant impact on the response of the device, and their optimization was hence also an important focus of research. Of course other factors, such as overall size, mass, ease of manufacture and likely cost, were also important considerations.

In order to understand the effects of changing these various parameters, it is useful to separate the response characteristic of the instrument into three broad components: its responses to low (meV scale), intermediate (keV scale) and high (MeV scale) energy neutrons. Each of these components is impacted in different ways by the different parameters that define the design of the device. Schematically:

- The best response to thermal neutrons would be achieved by a bare detector. The addition of surrounding layers thus leads to an under-response at low energies. For detecting low-energy neutrons, the optimum design thus features minimal moderating mass and large air-filled guides.
- Typically, the $H^*(10)$ response of a neutron survey instrument increases with energy, before peaking in the keV energy range because the conversion coefficients rise rapidly above 10 keV. This over-response can be suppressed by the inclusion of a layer of attenuator, such as Borotron$^®$, but increasing the thickness of this layer is made either at the expense of the moderating layers, or else by increasing the overall size of the instrument, which in turn increases its mass. Additionally, significant attenuating layers also further suppress the low-energy response; conversely, the effectiveness of the attenuator is undermined by increasing the radii of the guides that penetrate it.
- Large moderating masses are required to slow high-energy neutrons, thereby facilitating their detection. However, aside from further reducing the low-energy response, the main penalty for increasing the thickness of the moderator is the physical size and usability of the instrument: its

mass increases roughly with the cube of its radius. The optimization process was thus essentially the search for a compromise, with the intention of developing a design in which each component of the response is improved without significant detriment to the others.

A full account of each trial design is beyond the scope of this report: in total, around one hundred different configurations were modelled and compared. Instead, in the next section the salient features of just the final design are presented.

3. Modelled response of final design

The final design from the optimization process is illustrated in **Figure 1**. It features a central SP9 detector surrounded by, in turn: an inner PE moderator; a Borotron$^®$ attenuator layer; and an outer shell of PE of external radius 12 cm. These layers are penetrated by 6 guides, radiating symmetrically from the exterior wall of the SP9 along the cardinal directions to a depth of 0.75 cm from the outside surface of the instrument. The guides constitute air-filled stainless steel tubes of inner radius 0.9 cm and thickness 0.1 cm. The air within these tubes provides channels to the detector for low-energy neutrons; the tubes themselves have no significant dosimetric impact, but provide structural support to the device. Protruding into 5 of these guides are small hemispherical 'plugs' of PE, centred at a depth of 0.75 cm from the exterior surface of the instrument. Inclusion of these plugs was found to reduce the differences in response between isotropic and plane-parallel exposures to low-energy neutrons. The stem of the SP9 proportional counter is positioned inside the remaining tube, and exits the instrument through a built-up region faced with a 0.2 cm thick Al plate of radius 4 cm; the purpose of this plate is to provide a surface upon which to affix the electronics required for operation of the SP9 detector. A small part of the SP9 unit also protrudes into the diametrically opposite guide.

Two source orientations were considered: isotropic, and plane-parallel in the vector direction $\underline{x}$, where the SP9 is centred at the origin and the guide containing the SP9 stem radiates in the direction $\underline{x}$. The calculated $H^*(10)$ response characteristics of the final design are shown in **Figure 2**, given relative to the response of 1.96 ± 0.01 nSv^{-1} calculated for plane parallel ^{241}Am-Be exposures; the thermal and ^{241}Am-Be responses are plotted at values representing their peak source energies, i.e. ~30 meV and ~4 MeV respectively. The differences at the eV scale in Figure 2 could be removed by changing the shape and size of the hemispherical plugs, but this would be at the expense of the agreement at thermal energies, which is far more important for workplace field dosimetry [8]. Additional exposures in the $\underline{x}+\underline{y}$, $\underline{x}+\underline{y}+\underline{z}$ and $\underline{y}$ vector directions were also performed to confirm uniformity of response, as well as in the $-\underline{x}$ direction to consider the effect of the presence of the stem and built-up region; at thermal energies, the response from the $\underline{x}$ direction was found to be ~30 %
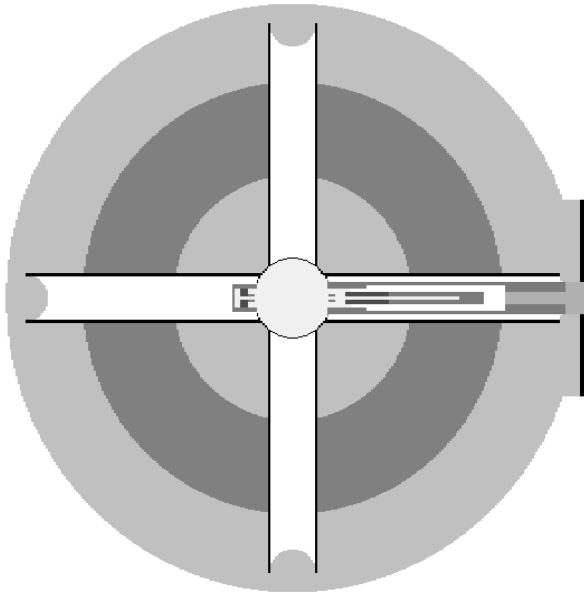
Figure 1. Cross-sectional schematic through the final design of instrument. The locations of the polyethylene (light grey) and Borotron® (dark grey) shells are apparent. The stem of the central SP9 detector is threaded through the guide on the right, opening at the Al-faced built-up region; three of the other five air-filled guides are also seen (white), with the remaining two perpendicular to the page.
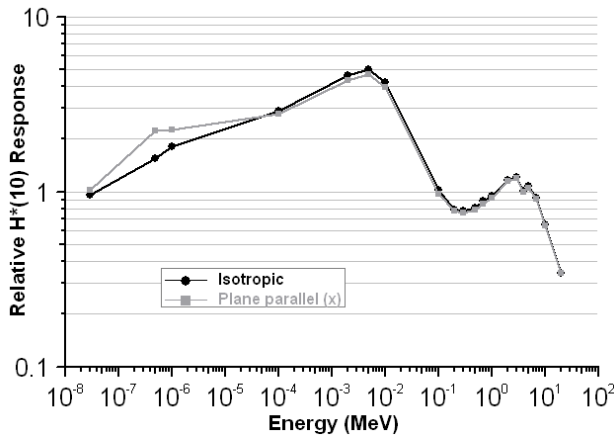

Figure 2. MCNP5-calculated response characteristics of the final design for isotropic and plane-parallel ($\underline{x}$) neutron exposures. All standard uncertainties on the data are < 2 %.

lower than that from -$\underline{x}$, but for [241]Am-Be the responses agreed to >97 %. Of course, a 'plane-parallel thermal neutron' is not realistic, because thermal neutrons have by definition been highly scattered.

It is important also to consider the performance of the device in the types of workplace field in which it is likely to be used: the neutron fields encountered in nuclear facilities have complex and non-uniform distributions spanning energy ranges that cross many orders of magnitude. To this end, the plane-parallel ($\underline{x}$) and isotropic response functions calculated by MCNP5 were convolved with the workplace fields characterized in the EVIDOS project [8], noting that in reality some of

these fields or their components are likely to be much more anisotropic than others. The $H^*(10)$ responses that resulted are presented in **Table 1,** along with the same data given relative to the response to the SIGMA plane-parallel exposure.

Table 1. $H^*(10)$ and relative responses of the final design to the realistic workplace fields, labelled according to [8].

EVIDOS Workplace Field	Isotropic		Plane-parallel ($\underline{x}$)	
	$H^*(10)$ Response (nSv^{-1})	Relative Response	$H^*(10)$ Response (nSv^{-1})	Relative Response
C1	1.74	0.82	1.70	0.80
C2	1.79	0.85	1.74	0.82
SAR	2.52	1.19	2.47	1.17
Top	2.31	1.09	2.27	1.07
VenusF	2.16	1.02	2.14	1.01
VenusC	2.14	1.01	2.13	1.01
BN1	2.05	0.97	2.02	0.96
BN2a	2.01	0.95	1.97	0.93
BN2b	1.98	0.93	1.94	0.92
BN3	2.00	0.95	1.97	0.93
R4-L	2.49	1.18	2.44	1.15
R4-A	2.47	1.16	2.44	1.15
Ring D	2.27	1.07	2.23	1.06
Ring N	2.23	1.05	2.21	1.04
CANEL	2.10	0.99	2.07	0.98
NF1	2.02	0.96	1.99	0.94
NF2	2.16	1.02	2.13	1.01
NF3	1.99	0.94	1.96	0.93
SIGMA	2.08	0.98	**2.11**	**1.00**

From Table 1, it can be shown that the average $H^*(10)$ response of the instrument in the workplace fields is 2.12 nSv^{-1}, and that the standard deviation of the results about this mean is ~10 %, with maximum and minimum relative responses of 1.19 and 0.80 respectively.

4. Measured response of final design

With the design specifications finalized, a prototype of the instrument was manufactured by Sherwood-Nutec Ltd. In due course, this prototype is to be calibrated at the National Physical Laboratory (NPL), UK, using neutron sources across a wide energy range. In the meantime, preliminary tests comprising background measurements and exposures to [241]Am-Be were performed in the Metrology laboratories of Public Health England. The instrument was also exposed to a gamma source to check photon discrimination. The SP9 unit was connected to a Sensortechnik DLEV26H preamplifier, in turn connected to an SMC 2100DS Serial Micro Channel unit that is peripheral to a PC running AM-SMCA01 software, which both controls the SP9 and handles its output.

The response of the device depends on the choice of parameters used to control and analyze the SP9 signal, such as amplification level and cutoff voltages. These options are still to be finalized, but using a range of likely values, $H^*(10)$ responses between ~2 and ~2.5
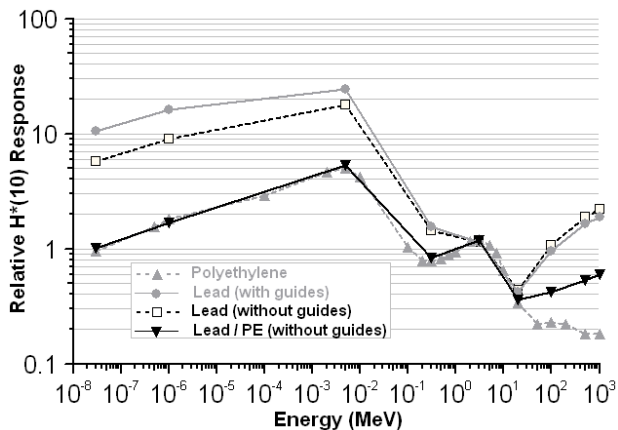
Figure 3. Calculated responses of the device with Pb, PE or Pb+PE inserts, with/without Pb-penetrating guides.

nSv^{-1} were found for ^{241}Am-Be. These preliminary data are broadly commensurate with the isotropic result of 1.98 ± 0.01 nSv^{-1} from the MCNP5 modelling. A background count rate of the order of ~10 h^{-1} was also found, which is consistent with the expected response to the neutron field at ground level due to cosmic rays.

6. Future improvements

The instrument is manufactured in two roughly hemispherical sections, which are then screwed together at the final stage. Aside from easing fabrication, this feature permits future access to the central detector if necessary, such as for maintenance. But in principle, this aspect might also be exploited to allow the SP9 detector to be replaced with an alternative option. One possibility could be a detector with a higher ^{3}He pressure, which could potentially improve the sensitivity of the device. Detectors that do not rely on ^{3}He could also be substituted if necessary. Such possibilities have not yet been fully explored, however.

Another possible modification could be the substitution of the inner PE moderator layer with a neutron multiplying material, such as lead. Such a substitution could be retrofitted easily, and could greatly extend the upper energy range over which the device can accurately measure. Of course, the underestimate of effective dose by ambient dose equivalent above a few 10s of MeV [9], and hence the suitability of using any instrument calibrated in terms of $H^*(10)$ at high energies, could become an issue here, but a discussion of this is beyond the scope of the current paper. The use of a lead insert would come at the cost of a heavier instrument, but its location around the central detector would, at least, effect the smallest increase in mass for a given lead thickness. Exploratory calculations with an 11.16 g cm^{-3} lead insert have used MCNPXv2.7 [10] to determine the response of the device to isotropic neutrons up to 1 GeV, with the impact of extending the guides through the lead layer also investigated. A 'hybrid' insert consisting of a 1 cm thick lead shell surrounded by 2.35 cm PE was additionally considered.

The results are shown in **Figure 3**, compared against the response of the design with the 'usual' PE insert. Although not yet fully investigated, this option is demonstrated to be a promising direction for future evolution of the device.

7. Summary / Conclusions

Monte Carlo modelling has been used to develop a novel design of neutron survey instrument. Concentric with a single SP9 proportional counter, the final design (Figure 1) features moderating PE and attenuating Borotron® shells penetrated by 6 symmetrically-spaced air-filled guides that facilitate detection of low-energy neutrons. The instrument is spherical, with an external radius of 12 cm and a mass of 7.3 kg. The outcome is a sensitive device with fairly flat energy-dependence of response (Figure 2). Discussions with instrument manufacturers are presently underway with the intention of bringing the current prototype to the commercial marketplace.

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