THE DEVELOPMENT OF A SCALABLE HE-3 FREE NEUTRON DETECTION TECHNOLOGY AND ITS POTENTIAL USE IN NUCLEAR SECURITY AND PHYSICAL PROTECTION APPLICATIONS

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ABSTRACT

A $^6$LiF:ZnS(Ag) based technology has been developed as a replacement for He-3 detectors in Radiation Portal Monitors (RPMs). An early prototype having an active area of 1000 cm$^2$ has been independently tested at the Pacific Northwest National Laboratory [1]. These tests reported a sensitivity comparable with that of a 1m long, 5cm diameter, 3 atmosphere He-3 proportional counter and an ability to operate with a full-field gamma-ray dose-rate of 100 mR/h (2.58x10$^{-5}$ c/kg/h in air). Subsequent developments have included scaling the detector technology to provide both smaller (200 cm$^2$) and larger-area detectors (1131 and 1740 cm$^2$) and using multiple detectors in combination. For example, the sensitivity and gamma-ray rejection performance of a neutron detection module (NDM) intended for use in an RPM which included 4x1131 cm$^2$ detection elements, has been verified by the UK Health Protection Agency [2] as providing a sensitivity of between 4.05±1.10 counts per second per nano-gram of $^{252}$Cf. This was measured using a calibrated source encapsulated within 1mm steel, 6.4mm lead and surrounded by 25mm of HDPE. This detector also simultaneously demonstrated a gamma-ray sensitivity less than 7.94 x 10$^{-8}$. The Gamma Absolute Rejection Ratio for neutrons (GARRn) [3] of the detector varied by less than 5% as the gamma-ray dose-rate increased from zero to 200 mSv/h (20 mRem/h). This paper will introduce the technology and discuss its application as a He-3 replacement for Nuclear Security and Physical Protection.

INTRODUCTION

The development of this $^6$LiF:ZnS(Ag) based technology for neutron detection was stimulated by a Request For Information (RFI) published by the Department of Homeland Security (DHS), Domestic Nuclear Detection Office (DNDO) [4]. The RFI identified the need for He-3 free Neutron Detection Modules (NDMs) for portals, man-portable applications and handheld instruments.

This RFI was triggered by the shortage of He-3. The US supply of He-3 for neutron detection comes almost entirely from the decay of tritium [$^3$H($t_{1/2}$=12.3y)$\beta$→$^3$H + $\beta$] in the tritium stores used to maintain nuclear weapons [6]. As the US nuclear weapons stockpile has decreased, the production of He-3 has also decreased. The current He-3 availability is such that the forthcoming

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procurement initiatives for RPMs have draft specifications that prescribe He-3 free neutron detection systems [7].

There have been a number of workshops that have discussed the He-3 supply issues, the emerging technologies and outlined the US Government’s approach to the shortage in Medicine, Industry and Security [8]. The emerging technologies include $^{10}$B-lined proportional counters, BF$_3$ filled proportional counters and a number of $^6$Li based scintillation technologies. This paper summarises the development of a promising $^6$Li based neutron detection technology and discusses its application in the Nuclear Security and Physical Protection fields.

**PROTOTYPE DETECTOR CONSTRUCTION (NNS:1000)**

A prototype thermal-neutron detector was developed for characterisation. The prototype detector element consisted of two $^6$LiF:ZnS(Ag) screens viewed by a PVT wavelength shifter and read out by a 51mm Photo-Multiplier Tube (PMT). The detector element was housed within a moderating enclosure in order to maximise the detection of thermal neutrons in the screens.

For security applications, a neutron detector must simultaneously provide a high neutron sensitivity whilst being insensitive to gamma-rays. In order to achieve this it was necessary to develop a robust method of discriminating between the differing scintillation characteristics of the $^6$LiF:ZnS(Ag) screens following gamma ray absorption and neutron capture.

![Diagram of Symetrica neutron detector](image)

**Figure 1. A schematic diagram of the Symetrica neutron detector.**

The prototype detector element had an active area of 1000cm$^2$ (10cm wide by 100cm long) and a thickness of 2cm. For testing the prototype detector, the detection element was enclosed within a HDPE moderator having outside dimensions of 20cm x 110cm x 10cm. This enclosure was asymmetrical with a moderator thickness of 2.5cm in front and 5cm thickness behind the detector. The moderator was also covered on three sides by a thin copper sheet to block low-energy gamma rays. Following the development of the prototype 1000 cm$^2$ detector (NNS:1000), it was sent to PNNL (Pacific Northwest National Laboratory in Richland, Washington) for independent testing [1].
INDEPENDENT PROTOTYPE DETECTOR TESTS (NNS:1000)
The PNNL tests consisted of two sets of absolute detection-efficiency measurements as well as a set of gamma-ray insensitivity measurements. The absolute detection-efficiency was measured outside using a moderated $^{252}$Cf source [1] at a distance of 2m from the detector. For the first measurement, the detector was positioned, in isolation, on a step ladder whilst for the second measurement, the detector was positioned in an SAIC radiation portal panel, as shown in Figures 2 (a) and 2 (b) respectively.

The gamma-ray insensitivity measurements were carried out inside PNNL building 318 using a high activity $^{60}$Co source. A range of full-field exposures were created by adjusting the source to detector distance so that the gamma-ray rejection could be measured over a range of dose-rates. Similar measurements were also carried out in the presence of a neutron source in order to determine the Gamma Absolute Rejection Radio for neutrons (GARRn).

![Figure 2. Photographs of a) the absolute neutron sensitivity measurement set up, b) the detector fitted into an SAIC portal panel.](image)

PNNL TEST RESULTS (NNS:1000)
The PNNL test report concluded that the gamma-ray rejection capability of the NNS:1000 unit was similar to that obtained using a He-3 counter up to 40mR/h and was adequate up to 100mR/h. The value of GARRn for $^{60}$Co at 10mR/h was also within the desired range for applications in RPMs. The report went on to postulate that, if scalable, the technology had the potential to be comparable to standard He-3 NDMs for portals and that a four element unit of the correct size could provide a sensitivity of $\sim$3.8cps/ng. This latter figure assumed linear scaling and no significant shadowing between elements. The report concluded with the recommendation that a full-scale module should be evaluated to confirm that its performance remained within the target range.

PROTOTYPE PORTAL SCALE NDM (NNS:4000)
In order to demonstrate the scalability of the technology, a four element Portal NDM (NNS:4000) was designed, as shown in the CAD model in Figure 3 (a). The external dimensions of the NNS:4000 moderator was set to (30.5 x 12.7 x 214.6cm or 12 x 5 x 84.5") in order to be compatible with those of the majority of the He-3 based NDM modules that are already deployed within US RPMs.
INDEPENDENT OBSERVATION OF DETECTOR TESTS (NNS:4000)

In order to verify the performance of the NNS:4000 independently, the Radiation Metrology Group at the UK Health Protection Agency observed a series of tests designed to characterise the NNS:4000 [2]. The tests were carried out by Symetrica staff but were observed and witnessed by Radiation Metrology Group personnel.

The absolute sensitivity was measured using a recently calibrated $^{252}$Cf source ($3.18 \times 10^4$ neutrons/s $\pm$ 0.9%) outside the laboratory on step ladders as shown in Figure 3(b). The gamma-ray insensitivity criteria were then investigated in the HPA’s irradiation facility using a range of different $^{137}$Cs sources at distances close to 6m, as shown in Figure 3(c).

The HPA report concluded that the NNS:4000 achieved an absolute sensitivity to neutrons between 4.05 cps/ng for a moderated $^{252}$Cf source at 2m and that the GARRn value varied less than 5% as the gamma dose increased from zero to 200$\mu$Sv/h (20mR/h).

This confirmed that the technology was scalable and that no significant shadowing occurred between the four detector elements,

PRODUCTION READY NDM (NNS:2500)

A production ready NDM (NNS:2500) having a sensitivity of $>2.5$cps/ng $^{252}$Cf at 2m was designed to address the main requirements for portal monitors [9,10]. The NNS:2500 shown in Figure 4 consists of two detector elements, a re-configurable interface module and a moderating enclosure designed to meet the environmental requirements for radiation portal monitors [9].

In order to confirm the performance of the NNS:2500 unit, the system was taken to the PERLA laboratory, of the Joint Research Centre (JRC), Institute for Transuranium Elements (ITU), Nuclear Security Unit in Ispra, Italy. This laboratory specialises in the assessment and evaluation of non-destructive assay (NDA) techniques that are applied in safeguarding nuclear materials. This is an ideal test location for an NDM designed for portals because the site also houses the European Nuclear Security Training Centre (SeTraC) that uses an installed Second Line of defence (SLD) RPM in the provision of training courses to frontline European security personnel.
The NNS:2500 was tested with a range of radiation sources in order to investigate the performance of the detector technology. The tests included measurements inside PERLA and outside, next to an SLD RPM.

![Figure 4. The exploded CAD diagram of the NNS:2500](image)

**TESTING AT JRC**

The detector was positioned horizontally on top of a stack of borated bricks placed on the top of a pair of step-ladders in the laboratory, as shown in Figure 5 (a). In this position, the first measurements investigated the relative sensitivity of the detector to a $^{252}$Cf source positioned in front of the centre of the detector compared to that measured 20cm from each end of the detector. A small decrease in neutron count rate was observed with respect to the central measurement position, shown in Figure 5 (b).

![Figure 5 a) A photograph of the NNS:2500 inside PERLA laboratory and b) the relative sensitivity.](image)

In the same location, the resilience of the detector in the presence of gamma ray sources was also investigated by positioning a source such that a range of exposures were provided at the detector surface. The strength of these sources was such that the detector was exposed non-uniformly. Therefore, rather than the quantitative observation of the gamma rejection factor and GARRn parameters that was possible for the NNS:1000 and the NNS:4000 detectors, a more qualitative
observation was performed on the NNS:2500 unit. Following these experiments, the NNS:2500 was set up outside on a tarmac surface in an open space next to the SeTraC centre, before being installed vertically next to the SLD RPM for sensitivity and drive through measurements. These set-ups were as shown in Figure 6.

![Figure 6. Photographs of a) the detector set up for absolute sensitivity measurements and b) installed next to the SeTraC SLD RPM.](image)

The gamma-ray rejection tests found that a $^{137}$Cs point-source producing a localised dose-rate of 600$\mu$Sv/h on the front face on the detector did not significantly increase the observed neutron count-rate for a range of detector parameters, as shown in Figure 7 (a). It should be noted that the ‘detector parameter’ is a setting that enables us to trade-off between neutron-sensitivity and gamma-ray rejection efficiency.

![Figure 7. a) The net count-rate induced in the NNS:2500 as a function of the localised dose-rate and detector parameter and b) the absolute sensitivity measured in the centre and at either end of the detector assembly.](image)

The absolute sensitivity to an un-moderated $^{252}$Cf source was 2.78 +/- 0.04 cps/ng at 2m with a detector parameter of -8. This provided a good gamma-ray rejection efficiency up to 600 and 800$\mu$Sv/hr exposures from $^{137}$Cs. The absolute sensitivity was also measured 20cm from each end of the detector with a source loosely moderated with approximately 25mm HDPE positioned in the vicinity of the source.
The relative sensitivity of the NNS:2500 to different neutron energy spectra was also investigated, as shown in Table 1. These measurements demonstrated the broad-band response of the NNS:2500 system.

The sensitivity of the detector was also measured after the NNS:2500 was fixed vertically close to the SLD Portal. This showed an increase in sensitivity of 15% due to scattering from the ground.

DYNAMIC TESTS AT JRC

With the NNS:2500 unit close to the SLD portal, it was possible to collect data dynamically as a neutron source was driven through the portal in a car at approximately 8km/h (Figure 8a). To determine a possible alarm threshold for the system assuming 0.1 s measurement resolution and the use of a 1 second rolling integration time, the detector response during a transit was estimated. During the transit the detector can be estimated to have a peak sensitivity equal to 2.78 cps/ng for an un-moderated $^{252}$Cf source at 2m which adjusted for a 1 second interval and sensitivity at +/- 1m (reduced according to an inverse square law) and then scaled to a source activity of 20,000 n/s, the system is estimated to detect 25.2 n/s during the peak 1 second integration time.

The False Alarm Probability (FAP) was calculated, assuming Poisson statistics, for a background rate of 2 n/s. It was found that an alarm criterion of 13 n/s or greater during the integration time will result in a FAP of 0.00002%. This is less than 0.1%, as specified in [9], and the 0.01% specified in the latest US Government NDM specifications. The probability of detection of a neutron source with an emission rate of 20,000 n/s was determined to be 99.9% which exceeds the requirement [9].

An alarm threshold of 13 was applied to the data for each transit measured and the source was reliably detected. The neutron count-rate profile and the alarm state are shown in Figure 8 (b). The data acquired will ultimately enable the JRC staff to compare the sensitivity of the two systems. However, data from only the NNS:2500 tests are presented here.

### Table 1. The relative sensitivity to a range of neutron sources.

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative Sensitivity</th>
<th>Error [+/- 2 σ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{252}$Cf : $^{252}$Cf</td>
<td>1</td>
<td>0.02</td>
</tr>
<tr>
<td>$^{252}$Cf / AmBe</td>
<td>1.27</td>
<td>0.03</td>
</tr>
<tr>
<td>$^{252}$Cf / PuO</td>
<td>0.88</td>
<td>0.02</td>
</tr>
<tr>
<td>AmBe / PuO</td>
<td>0.70</td>
<td>0.02</td>
</tr>
<tr>
<td>$^{252}$Cf / $^{252}$Cf vertical</td>
<td>1.15</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Figure 8. a) A photograph taken during the dynamic testing and b) the count rates recorded during repeat transits with a neutron source in the centre of the luggage space.
CONCLUSIONS

This development program has confirmed the detector modelling predictions and demonstrated the capability and scalability of the technology. The capabilities include:

- Demonstration of a sensitivity comparable to He-3 modules of similar size and the ability to operate over an extended range of gamma-ray exposure rates (up to 100mR/h).
- The lack of shadowing between multiple detector elements.
- A sensitivity of >4.0 cps/ng $^{252}\text{Cf}$ at 2m while simultaneously achieving a gamma ray sensitivity of $7.94 \times 10^{-8}$ and a value for the Gamma Absolute Rejection Ratio for neutrons (GARRn) that varied by less than 5% as the gamma-ray dose-rate increased from zero to 200 mSv/h (20mRem/h) – for an NNS:4000.
- A sensitivity to an un-moderated $^{252}\text{Cf}$ source at 2m of 2.78 cps/ng – for an NNS:2500.
- The ability to detect a $^{252}\text{Cf}$ source with an activity of 20,000 n/s transiting within 2m at 8km/h with a probability of detection and a false alarm probability per occupancy suitable for deployment in Radiation Portal Monitors.

Having developed a sophisticated detector model and verified its validity through this program, the technology is ideally placed to be extended to a wide variety of Safeguards applications. It is expected that the scaleability of the technology and the intrinsic speed will enable sensors to operate in much higher neutron and gamma-ray fluxes. The technology has already been scaled to produce backpack and pager sensors.

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REFERENCES


