Gamma-Insensitive Fast Neutron Detector with Spectral Source Identification Potential

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ABSTRACT

Calculations are presented to support the claim that fast neutron detection systems can achieve higher performance in detecting weak neutron sources than conventional thermal neutron detection systems involving moderators. Minimum Detectable Limits (MDL) are used as a comparative metric, more representative than the metric of absolute sensitivity, which does not take into account the influence of natural backgrounds. Monte Carlo simulations are used to show that heavily shielded neutron sources emit a substantial fraction of fast neutrons. Arguments are presented to support the claim that fast neutron detection systems are superior at defeating heavy neutron shielding than thermal systems.

INTRODUCTION

Neutron detection in passive screening applications has in the past been carried out primarily by means of thermal neutron detectors, mostly using devices involving ^{3}He. This approach was justified by the high detection efficiency over large areas achievable using thermal neutron detectors in conjunction with a moderator. Following the assumption that sources surrounded by shielding emit substantial fractions of slow neutrons, resorting exclusively to thermal neutron detection appeared fully justified.

Since the industry has been confronted with a shortage of ^{3}He in the past few years, the search for adequate replacement technology has ensued. For the purpose of evaluating candidate replacement technologies, a performance metric relating to a system's sensitivity was instated. The metric, referred to as *absolute sensitivity* or *cps/ng* throughout this note, measures the number of counts per second (*cps*) a given neutron detection system registers when a ^{252}Cf source of 1 ng is placed in a defined configuration at a standoff of 2 m from the system.[1] In this paper, the described configuration of 1 ng of ^{252}Cf is assumed to expose a detector at 2 m standoff to 0.006 μSv/h of neutron radiation. This paper presents arguments that suggest the metric of absolute sensitivity be replaced by the more representative metric of *Minimum Detectable Limits (MDL)*.

The performance of fast neutron detector systems is evaluated using *MDL*, demonstrating superior performance potential. The impact of shielding on the fractional fast neutron population is studied, indicating that configurations of heavily shielded sources may elude detection by thermal neutron systems while remaining detectable by fast neutron systems. A technology with the potential to fulfill such a task is briefly reviewed.

TAKING INTO ACCOUNT THE NATURAL NEUTRON BACKGROUND

Dependence of Background

The natural neutron background has a *1/E* energy dependence, as can be seen from the work of R.T. Krouzes et al.[2] Accordingly, the background of lower energy neutrons is substantially more intense than the fast neutron background. Thermal neutron detection systems using moderators are particularly sensitive to this background. Fast neutron detectors can reject the vast majority of background by focusing on the energy of interest from ~500 keV to ~8 MeV in which the fission sources emit most of their neutrons.

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Threshold Computation

The detection of background neutrons is a statistical process subject to fluctuations. In passive screening applications, a threshold is set, defining the value above which an alarm is triggered. The closer the threshold value is to the average background value, the higher the sensitivity of the system, and the higher the expected False Alarm Rate (FAR) from fluctuations. Setting a threshold significantly above the expected neutron background reduces both the sensitivity of the system and its susceptibility to false alarms. It will be shown in this subsection, that fast neutron detectors, being less susceptible to background neutrons, can operate at significantly lower thresholds than thermal neutron systems. Blessinger and York present a method based on Poissonian statistics to set the threshold of a system for a given FAR probability requirement *P* and a background M a system will detect during a measurement, with the prediction of M based on a background rate measurement.[3] According to the method, the correct threshold k is the lowest integer for which y<P, where

$$y = 1 - \sum_{x=0}^{k-1} \frac{\mu^x}{x!} e^{-\mu} \qquad (1)$$

MINIMUM DETECTABLE LIMIT (MDL) COMPUTATION

Once the correct threshold has been ascertained for a given background M and FAR requirement *P*, the Minimum Detectable Limit (MDL), defined as the radiation quantity sufficient to reach the threshold (triggering an alarm with a 50% probability), can be calculated using the systems sensitivity *s* (in units of *cps/*M*Sv/h*), and the measurement time *t*:

$$MDL = \frac{k - \mu}{t * s} \qquad (2)$$

In the calculations presented in this note, measurements are assumed to be of the "wait-in" type, meaning, the source is at rest during the measurement, which is carried out in a defined time window *t*.

PERFORMANCE COMPARISON

Assumptions

In the following a performance comparison using the formulae (1) and (2) above will be made. As a basis for the calculation, a hypothetical thermal neutron detection system (System T) will have a sensitivity of s_t=417 cps/MSv/h, corresponding to the minimum requirement of 2.5 cps/ng for a neutron detection panel in a Radiation Portal Monitor (RPM).[4] The system is further assumed to measure an average neutron background of 3 cps.[5]

Table I. Neutron Detection System Specifications Used for Comparison

	Thermal Neutron Detector System	Fast Neutron Detector System
Absolute sensitivity	s=417 cps/µSv/h (2.5 cps/ng)	s=150 cps/ µSv/h (0.9 cps/ng)
Background count rate of system	3 cps	0.06 cps
Background counts during t=10 s measurement window	μ_t=30 neutron background	μ_f=0.6 neutron background
Alarm threshold for t=10 s measurement window [3]	k_t=54 neutrons (compatible with FAR<5× 10^{-5}) k_t=61 neutrons (compatible with FAR<5× 10^{-7})	k_f=6 neutrons (compatible with FAR<4× 10^{-5}) k_f=8 neutrons (compatible with FAR<3× 10^{-7})
Minimum Detectable Limit (MDL)	0.0074 µSv/h (compatible with FAR<5× 10^{-7})	0.0049 µSv/h (compatible with FAR<3× 10^{-7})

The fast neutron detection system (System F) used for comparison is assumed to have a sensitivity of s_f=150 cps/MSv/h (0.9 cps/ng). Although this value is below the 2.5 cps/ng requirement of Kouzes and others,[6] it will be shown that this system is capable of detecting weaker sources than System T, and thus has higher performance. System F is assumed to detect background neutrons at an average rate of 0.06 cps. The sensitivity and background values of 150 cps/MSv/h and 0.06 cps respectively correspond to the expected specifications of a closely stacked array of 30 high-pressure (200 bar) ^{4}He scintillation detector modules of 2" outer diameter and 75 cm fiducial length, with a fiducial volume of approximately one liter. Prototype detectors of this technology manufactured by Arktis Radiation Detectors Ltd have been characterized and tested,[7] including the capability of rejecting 1 mSv/h of gamma radiation from a ^{60}Co source. This exceeds the standard gamma rejection of 0.1 mSv/h required for next generation portal monitors.[8]

For a first comparison, the measurement time window is chosen to be t=10 s. During this time, Systems T and F are expected to measure average backgrounds of M_t=30 and M_f=0.6 neutrons. Using (1), the thresholds k_t and k_f can be computed for given FAR requirements P. Considering that neutron nuisance alarms occur within 10^{-4} of all measurements,[9] it is sensible to require P to be substantially lower.

Table I shows the obtained values for both systems compatible with a FAR requirement of P=5 $\times 10^{-7}$. The MDL values obtained with (2) show that the fast neutron detection system (System F) is significantly more sensitive to weak sources than the thermal neutron detection system (System T), in spite of System T's higher absolute sensitivity.

From these calculations it may be concluded that unless background count rates are taken into account, absolute sensitivity is an inadequate measure for performance comparison. MDL appears to be a more suitable metric for comparison.

Variation of Parameters

In an effort to understand whether the above comparison depends strongly on the assumptions made for measurement time *t* or FAR requirement *P*, these parameters can be varied. Fixing the measurement window to t=10 s and varying the FAR requirement has little impact on the relative performance of the two systems:

MDL for FAR<2 $\times 10^{-9}$	0.0091 µSv/h	0.0063 µSv/h
MDL for FAR<5 $\times 10^{-5}$	0.0058 µSv/h	0.0036 µSv/h

Whereas fixing FAR<5 $\times 10^{-7}$ and varying the measurement time has a more substantial influence on the relative performances.

MDL for t=1 s	0.031 µSv/h	0.026 µSv/h
MDL for t=30 s	0.0041 µSv/h	0.0023 µSv/h

A shorter measurement time shifts the balance more in favor of thermal neutron detection, a longer measurement time makes fast neutron detectors perform better in such a comparison.

THE INFLUENCE OF SHIELDING

In realistic scenarios, smuggled nuclear materials are likely to be shielded. Therefore it is necessary to understand the influence of shielding on fission neutron spectra. It will be shown that the intuitive assumption that shielding increases the slow neutron emission of a source relative to the fast neutron emission of the same source is incorrect in many cases.

Simulated Geometry

Using GEANT4,[10] the influence of different shielding configurations on neutron emission was studied. The simulated scenarios consisted of a ^{252}Cf neutron source in the center of a sphere of air of 12.5 cm radius, surrounded by a concentric spherical shell of shielding, having 12.5 cm inner diameter, see Figure 1. Different shielding materials including polyethylene (*PE*), 5% borated polyethylene (*borated PE*), and Iron (*Fe*) were simulated in radial thicknesses ranging from 12.5 cm to 100 cm.

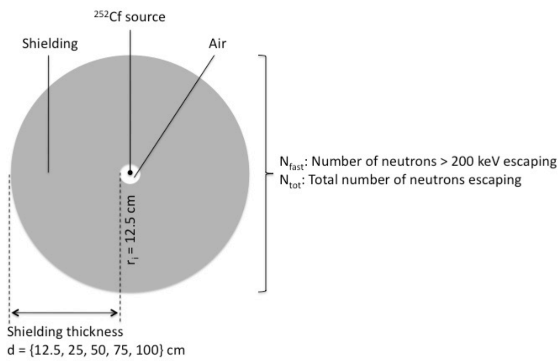

Figure 1. Geometry used for simulation. A 252Cf source is surrounded by air and shielding of thickness d in the shape of a spherical shell.

From the simulation the total number of neutrons escaping the shielding Ntot was obtained. This was compared to the number of escaping fast neutrons Nfast. Fig. 2 uses dashed lines to show the dependence of the fast neutron fraction Nfast/Ntot on shielding thickness for the different shielding materials, where Nfast is defined as the number of escaping neutrons with an energy higher than 200 keV (and 100 keV, shown by solid lines).

Results

The fractional values of neutrons above 200keV are high for *PE* and *borated PE*, materials often commonly selected for neutron shielding purposes. This result may be counter-intuitive, as hydrogenous shielding has the effect of drastically reducing the energy of all neutrons that scatter in the shielding. The results can however be explained by assuming that once scattered to low energy, neutrons have an increased chance of being captured and thus never escaping the shielding. In addition the cross-section for primary interaction of fast neutrons is reduced ("punch-through"). The fast neutron fraction is ~97% for unshielded ^{252}Cf (99% above 100 keV), but quickly drops if shielded by thin (~10 cm) layers of hydrogenous shielding, as would intuitively be expected. For thicker layers of shielding, however, neutron absorption in the shielding becomes substantial, continuously depleting the number of slow neutrons egressing with increasing shielding thickness. This inflection occurs at a smaller radius for borated than for plain polyethylene; and for the polyethylene at a smaller radius than for iron, the latter being a poor neutron shield[11]. This behavior is also observed by Kouzes, et al.,[12] where a similar simulation using MCNP was carried out, studying the relative populations at energies below 1 eV and 1 keV.

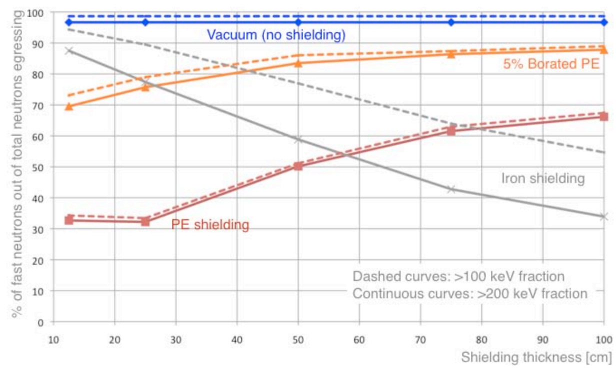

Figure 2. Plot shows what fraction of the total number of neutrons egressing from a shielded 252Cf source (See Fig. 1 for geometry) has an energy above 200 keV. For example, 86% of all neutrons egressing from a 252Cf source shielded by borated polyethylene have an energy > 200 keV.

75 cm of borated polyethylene shielding attenuates ^{252}Cf neutron emission substantially, to 2×10^{-4} of the original intensity. In many cases, the egressing neutron intensity from such a heavily shielded source may be lower than the natural neutron background, and thus very difficult to detect even with a large number of thermal neutron detectors. Since the fast neutron background is more than 50 times lower, and the overwhelming majority of neutrons egressing are of high energy, such a signature may still be detectable by fast neutron detectors.

SCALABILITY

Fast neutron detectors are inherently more scalable than thermal neutron detectors and can therefore be bundled into compact arrays. Unlike thermal neutron detectors, they do not suffer substantial sensitivity degradation effects.[13] This geometry-dependent effect is particularly large when several thermal detectors are closely packed. Depending on technology, a single detector panel contains 1-5 thermal neutron detectors within the same moderator. A full portal monitor typically consists of two to four such panels. Figure 3 visualizes this effect, assuming a degradation factor of 1.7.

The fast neutron detection technology used as a basis for the calculations above has the further advantage of being scalable also from a cost perspective, since it does not rely on expensive or rare materials or components. Figure 4 shows a prototype array.

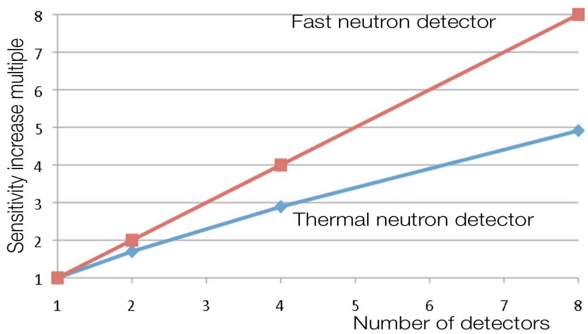

Figure 3. Visualization of the different scaling behavior of fast and thermal neutron detection systems, assuming a degradation factor of 1.7 for thermal neutron detectors.

Figure 4. Array of seven 4He detector modules.

FALSE ALARM SUSCEPTIBILITY

While false alarms arising from statistical background fluctuations have been taken into account above, there are also further potential sources of false alarms worth discussing.

"Ship-Effect" Neutrons

Cosmic spallation can lead to neutron bursts detected by RPMs as spikes. Due to the production mechanism of such neutrons, "ship-effect" neutrons have the tendency to arrive promptly, almost simultaneously. The number of false alarms arising from this effect can be reduced by means of time gating.[14] The time resolution of thermal neutron detectors is limited due to the process of neutron moderation, therefore relatively large time gates of 0.1 s are customary. Fast neutron detectors, having a time resolution of ~2 ns can offer shorter time gating windows, thereby allowing preciser rejection of ship-effect neutrons.

Fast neutron detectors can further afford rejection of ship-effect neutrons on the basis of energy whenever the detected signal indicates a neutron's energy to have been above those energies typical for fission sources.

False Alarms from Misinterpreted Gamma Radiation

For application in portal monitoring, neutron detectors are required to have strong gamma rejection capabilities, as misinterpreted gamma counts can lead to false alarms. A standard requirement is the rejection of 0.1 mSv/h of gamma radiation from ^{60}Co.[15] For most fast neutron detection technologies this is a challenge; even many thermal neutrons can only achieve such rejection at the cost of efficiency.[16] Fast neutron detection technologies based on pressurized ^{4}He have demonstrated rejection of up to 1 mSv/h without compromising efficiency.[17]

Other Potential Sources of False Alarms

Other potential sources of false alarms include microphonics, a phenomenon associated with most wire based ionization detectors. Similar problems also arise from electromagnetic interference with such detectors. The design described here is not subjected to these problems.

CONCLUSIONS

In summary, the following conclusions can be drawn:

1. Absolute sensitivity is an inadequate metric for performance comparison, as it does not take into account the threshold requirements. MDL is a more adequate performance metric.

2. Fast neutron detectors can achieve better MDL performance because they are less affected by natural backgrounds.
3. Unshielded as well as heavily shielded sources emit mostly fast neutrons.
4. Fast neutron detection technologies are inherently scalable. A specific fast neutron technology is identified that suggests scalability both from a material costs as well as from a technical feasibility point of view.
5. Fast neutron detectors may furthermore be less prone to false alarms arising from phenomena like ship-effect neutrons, microphonics, or electromagnetic interference.

ABOUT THE AUTHORS

Rico Chandra earned a PhD in detector R&D carried out at CERN, then co-founded Arktis Radiation Detectors Ltd, a spin-off company dedicated to commercialising novel detection technologies developed for fundamental science. Rico's past work experience includes consulting work performed for the European Commission in security questions, strategic consulting of several SMEs, and technology consulting as a Council member of the Gerson Lehrman Group. He may be contacted at rico.chandra@arktis-detectors.com.

Giovanna Davatz has broad-based experience in experimental physics, software engineering, and Monte-Carlo simulation programs. Giovanna earned her PhD in particle physics from ETH Zurich while stationed at CERN, Geneva working on the Large Hadron Collider (LHC). She is co-founder of Arktis and member of the board. Her past work experience includes senior research assistantship at ETH Zurich.

Alexander Howard is a former CERN fellow and since 2001 a member of the GEANT4 collaboration, responsible for the implementation of neutron interaction, production, and validation into the most widely used radiation interaction Monte-Carlo. Alex earned a PhD in particle physics in 1997 and went on to develop noble gas scintillation detectors within the UK Dark Matter Collaboration (UKDMC). After a temporary lectureship at Imperial College London and project management of several group projects, he joined Arktis in 2007.

[1] See for example R.T. Kouzes et al., "Alternatives to 3He for Neutron Detection for Homeland Security", PNNL-SA-72445 042210, http://cstsp.aaas.org/Helium3/Alternatives.pdf.

2 R.T. Kouzes et al., "Cosmic-ray-induced Ship-effect Neutron Measurements and Implications for Cargo Scanning at Borders," Nuclear Instruments and Methods A 587, no. 1 (March 2008):89-100.

3 C. Blessinger and R. York, "Neutron Detection Algorithm Development," Oak Ridge National Laboratory, ORNL/TM-2006/157 (2006), http://www.ornl.gov/~webworks/cppr/y2007/rpt/125365.pdf.

4 Kouzes et al., "Alternatives to 3He for Neutron Detection."

5 This value is consistent with realistic values as stated by RPM manufacturers in personal communications.

[6] Kouzes, et al., "Alternatives to ^{3}He for Neutron Detection."

[7] R. Chandra et al., "Gamma-Insensitive Fast Neutron Detector with Spectral Source Identification Potential," *2010 IEEE Homeland Security Technologies Conference Proceedings* (2010).

[8] American National Standards Institute, "American National Standard Performance Criteria for Spectroscopy- Based Portal Monitors Used for Homeland Security," ANSI N42.38 (2006), http://webstore.ansi.org/ansidocstore/product.asp?sku=ANSI+N42.38-2006.

[9] R. Kouzes et al., "Passive Neutron Detection at Borders," *2007 IEEE Nuclear Science Symposium Conference Record* (2007).

[10] S. Agostinelli et al., "Geant4 – A Simulation Toolkit," *Nuclear Instruments and Methods A* 506, no. 3 (July 2003): 250-303: and J. Allison et al., "Geant4 Developments and Applications," *IEEE Transactions on Nuclear Science* 53, no. 1, Part 2 (2006): 270-278.

[11] A solid iron shield of 75 cm radius would weigh more than 15 tons, making it too heavy to be considered a likely configuration in a maritime container.

[12] R.T. Kouzes et al., "Passive Neutron Detection for Interdiction of Nuclear Material at Borders", *Nuclear Instruments and Methods A* 584 (2008): 383-400.

[13] Ibid.

[14] Ibid.

[15] ANSI, "Spectroscopy- Based Portal Monitors."

[16] R.T. Kouzes et al., "Neutron Detection Alternatives to 3He for National Security Applications," *Nuclear Instruments and Methods A* 623, no. 3 (November 2010): 1035-1045.

[17] R. Chandra et al., "Gamma-Insensitive Fast Neutron Detector."