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PNNL-19725

Boron-Lined Multichamber and Conventional Neutron Proportional Counter Tests

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September 6, 2010

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Executive Summary

Radiation portal monitors used for interdiction of illicit materials at borders include highly sensitive neutron detection systems. The main reason for having neutron detection capability is to detect fission neutrons from plutonium. The currently deployed radiation portal monitors (RPMs) from Ludlum and Science Applications International Corporation (SAIC) use neutron detectors based upon ^{3}He-filled gas proportional counters, which are the most common large neutron detector. There is a declining supply of ^{3}He in the world, and thus, methods to reduce the use of this gas in RPMs with minimal changes to the current system designs and sensitivity to cargo-borne neutrons are being investigated.

Four technologies have been identified as being currently commercially available, potential alternative neutron detectors to replace the use of ^{3}He in RPMs (Kouzes et al. 2010a). These technologies are:

1) Boron trifluoride (BF_3)-filled proportional counters,
2) Boron-lined proportional counters,
3) Lithium-loaded glass fibers, and
4) Coated non-scintillating plastic fibers.

In addition, a few other companies have detector technologies that might be competitive in the near term as an alternative technology. Reported here are the results of tests of a boron-lined, multichamber proportional counter manufactured by LND, Inc. Also reported are results obtained with an earlier design of conventional, boron-lined, proportional counters from LND (Oceanside, NY). This testing measured the required performance for neutron detection efficiency and gamma-ray rejection capabilities of the detectors.

The LND neutron detectors have been tested and compared to ^{3}He as a possible alternative neutron-detection technology. The multichamber detector differs from standard boron-lined tubes in that it is rectangular and is divided into 25 separate chambers.

The multichamber tests were conducted on a single detector of dimensions 63.5 mm x 63.5 mm x 1.82 m mounted in a standard polyethylene moderator box that normally holds the ^{3}He tubes in a RPM. Results suggest that neutron-detection efficiency comparable to that of existing ^{3}He detectors may be difficult to achieve, even by adding additional, multichamber detectors in the RPM. Tests are necessary with multiple, multichamber detectors to determine if it is possible to achieve the required sensitivity in spite of the interaction among the detectors resulting in neutron-flux suppression.

The conventional, boron-lined detectors (50-mm diameter x 1.82-m length) provided neutron-detection efficiency that was only about 15% of that obtained with the multichamber detector. Thus, these detectors are unsuitable as replacements for ^{3}He detectors because of their poor neutron-detection efficiency. However, the manufacturer has recently changed the design of the conventional tubes to significantly increase the neutron sensitivity. It may be that conventional (cylindrical) tubes of the new design provide sufficient efficiency that additional testing would be appropriate.

Test results indicate that adequate intrinsic gamma-ray efficiency (gamma-ray rejection) is obtained for gamma exposure rates up to 100 mR/hr for both the multichamber and conventional detectors. The gamma rejection factor is estimated to be on the order of 10^{-9} for exposure rates up to 100 mR/hr, which is better than that obtained for ^{3}He ($\sim10^{-8}$).

The GARRn value at a ^{60}Co exposure rate of 10 mR/hr is within the desired range for both the multichamber and conventional detectors. Testing of a multichamber system with a total neutron efficiency designed for use as a replacement for the ^{3}He based system in deployed systems will need to be evaluated to see whether the GARRn value remains in the acceptable range.

Acronyms and Abbreviations

ANSI	American National Standards Institute
cps	Counts per second
GARRn	Gamma Absolute Rejection Ratio in the presence of neutrons
mR/h	Milli-Roentgen per hour
PNNL	Pacific Northwest National Laboratory
RPM	Radiation Portal Monitor
RSP	Radiation Sensor Panel
SAIC	Science Applications International Corporation

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1 Purpose

Radiation portal monitor (RPM) systems used for interdiction of illicit materials at borders include highly sensitive neutron detection systems. The main reason for having neutron detection capability is to detect fission neutrons from plutonium. The currently deployed radiation portal monitors from Ludlum and Science Applications International Corporation (SAIC) use neutron detectors based upon ^{3}He-filled gas proportional counters, which are the most common large neutron detector.

Within the last few years, the amount of ^{3}He available for use in gas proportional counter neutron detectors has become more restricted, while the demand has significantly increased, especially for homeland security applications (Kouzes 2009). In the near future, limited supply is expected to curtail the use of ^{3}He; therefore, alternative neutron detection technologies are being investigated for use in the radiation portal monitor systems being deployed for border security applications (Van Ginhoven 2009).

From a survey of technologies, only four technologies have been identified as currently commercially available, potential alternative neutron detectors to replace the use of ^{3}He in RPMs in the near-term (Kouzes et al. 2010a). These technologies are:

1) Boron trifluoride (BF_3)-filled proportional counters,
2) Boron-lined proportional counters,
3) Lithium-loaded glass fibers, and
4) Coated non-scintillating plastic fibers.

In addition, a few other companies have detector technologies that might be competitive in the near term as an alternative technology. Reported here are the results of tests by Pacific Northwest National Laboratory (PNNL) of a boron-lined multichamber proportional counter (manufactured by LND, Inc., Oceanside, NY). This detector is rectangular and contains 25 chambers. Also reported are test results for conventional, boron-lined detectors from LND. Results from the tests of other manufacturer's designs of boron-lined detectors have been reported previously (Lintereur 2009; Kouzes 2010b). This testing measured the required performance for neutron detection efficiency and gamma ray rejection capabilities. The measurements made as part of this testing included:

1. Response of the system to moderated and un-moderated neutrons
2. Response of the system to a high gamma-ray exposure rate to measure gamma sensitivity and GARRn (Kouzes et al., 2009)

2 Alternative Neutron Detector Requirement

A neutron-detection system for replacement of the current neutron detectors in a standard ^{3}He-based RPM must fit within the space occupied by the present ^{3}He-based neutron detection system [0.114 m deep x 0.304 m wide x 2.18 m tall (4.5 in. × 12 in. × 85.7in.)] in the SAIC RPM system.

The standard ^{3}He-based systems were purchased under a specification (Stromswold et al., 2003) that requires a single radiation sensor panel (RSP) to meet the following requirements:

"A ^{252}Cf neutron source will be used for testing neutron sensor sensitivity:

- To reduce the gamma-ray flux, the source shall be surrounded by at least 5 mm of lead. To moderate the neutron spectrum, 25 mm of polyethylene shall be placed around the source.
- The absolute detection efficiency for such a ^{252}Cf source, located 2 m perpendicular to the geometric midpoint of the neutron sensor, shall be greater than 2.5 cps/ng of ^{252}Cf. The neutron detector center shall be 1.5 m above grade for this test. (Note: 10 nanograms of ^{252}Cf is equivalent to 5.4 micro-Ci or 2.1×10^4 n/s,[1] since ^{252}Cf has a 3.092% spontaneous fission (SF) branch and 3.757 neutrons/SF.)
- The neutron detector shall not generate alarms due to the presence of strong gamma-ray sources. The ratio of neutron sensor gamma-ray detection efficiency to neutron detection shall be less than 0.001."

To evaluate the performance of alternate neutron detectors compared to what is currently deployed three criteria are considered: 1) absolute neutron detection efficiency, 2) intrinsic efficiency of gamma rays detected as neutrons, and 3) Gamma Absolute Rejection Ratio in the presence of neutrons (GARRn) (Kouzes et al., 2009).

The absolute neutron detection efficiency ($\epsilon_{abs\ n}$) required is that previously specified (2.5 cps/ng from a ^{252}Cf source at 2 m in a specified pig). The intrinsic efficiency of gammas detected as neutrons ($\epsilon_{int\ \gamma n}$) is the number of events that are counted as neutrons in the presence of a gamma source divided by the number of photons hitting the detector area, and shall be less than 10^{-6} at an exposure rate of 10 mR/h. GARRn is the number of events that are counted as neutrons ($\epsilon_{abs\ \gamma n}$) in the presence of both a gamma ray and neutron source divided by the number of neutrons recorded without the gamma ray source ($\epsilon_{abs\ n}$). The requirement is that $0.9 \le \text{GARRn} \le 1.1$ at a 10 mR/h gamma exposure rate.

In addition, these systems are required to meet all aspects of the ANSI N42.35 standard (ANSI 2006). A summary of neutron detection systems in RPMs can be found in a PNNL report (Kouzes et al., 2007).

[1] 2.3×10^4 n/s is the currently used best known value

3 Test Hardware

3.1 Neutron Detectors

The LND multichamber detector is a variation on conventional boron-lined proportional counters that are cylindrical and contain a single anode wire. The modified detector as tested is rectangular and contains a 5 x 5 array of anode wires, each in its own hexagonal chamber that runs the length of the detector. All wires are connected to a single output. The dimensions of the detector are 63.5 mm x 63.5 mm x 1.82 m (2.5 in. x 2.5 in. x 72 in.), where the long dimension is the active length. The gas (90% argon and 10% CO_2) in the detector has a pressure of one atmosphere. Figure 3.1 shows the detector.

The other LND detectors tested are conventional, cylindrical, boron-lined tubes of diameter 50 mm and length 1.82 m.

During the tests the detectors were located in the polyethylene moderator box that normally houses a ^{3}He tube in RPMs. This moderator has external dimensions 0.114 m deep x 0.304 m wide x 2.18 m tall (4.5 in. × 12 in. × 85.7in.

The detector has ^{10}B on the inner walls of the detector. Thermal neutrons interact via the ^{10}B(n, α)^{7}Li reaction, and the resultant charged particles produce ionization in the gas that fills the tube.

Electrical pulses from the tube were counted with conventional laboratory electronics (Ortec 142AH preamplifier, Ortec 472 amplifier, and Amptek Pocket multichannel analyzer).

Figure 3-1: LND multichamber proportional counter.

3.2 Neutron Source

The neutron source used for this test was ^{252}Cf, with a half-life of 2.645 years. The source was purchased from Isotope Products Laboratory (IPL) and given a PNNL ID of 60208-44. The source was measured by IPL to be 21.91 ± 1.25 µCi on October 1, 2009. The source used was estimated to be 17.95 µCi during the tests (July 7-9, 2010). This activity corresponds to 33.2 ng and an emanation rate of 7.6×10^4 n/s with the conversion factor stated in Section 2. This same neutron source was used when the gamma sensitivity of the detector was being tested.

The source was used in two configurations; 1) moderated (25 mm of polyethylene moderator outside of 5 mm of lead) and 2) bare (encased only in the source's own stainless steel enclosure).

3.3 Gamma-Ray Source

A ^{60}Co gamma ray source located in the Radiological Calibrations Laboratory in Building 318 at PNNL was used for the gamma ray sensitivity test. The exposure rate as a function of distance from the ^{60}Co source was determined by staff at the facility. The source strength was 106.4 mCi on July 9, 2010.

3.4 Test Facility

The tests were performed at PNNL at the 331G Integration Test Facility and the 318 Radiological Calibrations Laboratory located in Richland, WA. The outside tests were performed at the 331G building at PNNL. The gamma-ray insensitivity measurements with the ^{60}Co source were performed inside building 318.

3.5 Test Limitations

There were several limitations for this test and results may change with different conditions.

- Only one test location for each of the measurements was used, with the corresponding background. Since the testing was focused on net results (background subtracted) this should have little effect on the overall results.

- Only one detector system was tested. Results may change with different detectors.

- Uncertainty in the neutron source's strength (Section 3.2) was the main limitation to the test results.

4 Experiments and Setup

4.1 Outside Measurements

Static measurements were made with the detectors mounted in the polyethylene moderator box located inside a SAIC RSP panel. The neutron source was located on a tripod 2 m from the closed door of the RPM and at a height that positioned the source at the center of the detector.

For comparison, data were also collected using ^{3}He detectors mounted in the RSP.

Data with the multichamber detector were acquired over five-minute time intervals for background and with the source measurements. The acquired data were used to compare the LND detector efficiency with the efficiency of the ^{3}He tubes used in the current systems.

4.2 Gamma Insensitivity Measurements

The LND detector sensitivity to gamma rays was tested with a high-activity ^{60}Co source in Building 318 to flood the entire detector with a high gamma-ray exposure rate. Table 4-1 shows the source-to-detector-face distance for each of the indicated exposure rates.

Measurements were also made with the neutron source and the ^{60}Co source present simultaneously to determine the GARRn value and the gamma ray rejection factor. For these indoor measurements, the neutron source was placed at various distances from the detector since these tests were made in conjunction with testing another detector. This did not impact the GARRn values since the neutron contribution cancels out in the computation.

Table 4-1: Exposure rate versus distance for the ^{60}Co source in Building 318.

mR/h	Distance (m)
5	5.20
10	3.68
20	2.60
50	1.64
100	1.16

The ^{60}Co gamma-sensitivity measurements were made with the detector (inside its polyethylene moderator box) placed horizontally on top of two stands at the height of the gamma ray source. The detector was moved to different distances from the source to obtain the desired exposure rates on the detector's front face when the source was in position. Three-minute measurements were made for different scenarios at each position:

1. Background
2. ^{60}Co source in place
3. ^{60}Co source in place and the neutron source located on a tripod 2 m from the back of the detector.

5 Results and Data Analysis

5.1 Neutron Sensitivity in RPM

Figure 5-1 shows the pulse-height spectrum obtained when the ^{252}Cf source was located 2 m in front of the RPM containing the LND multichamber detector, and the figure also shows a background spectrum. In addition, the figure shows data collected when a ^{3}He tube was in the RPM instead of the LND multichamber detector. For both detectors the large numbers of counts at low channel numbers are from gamma rays and electronic noise, and the upper portions are the neutron signals.

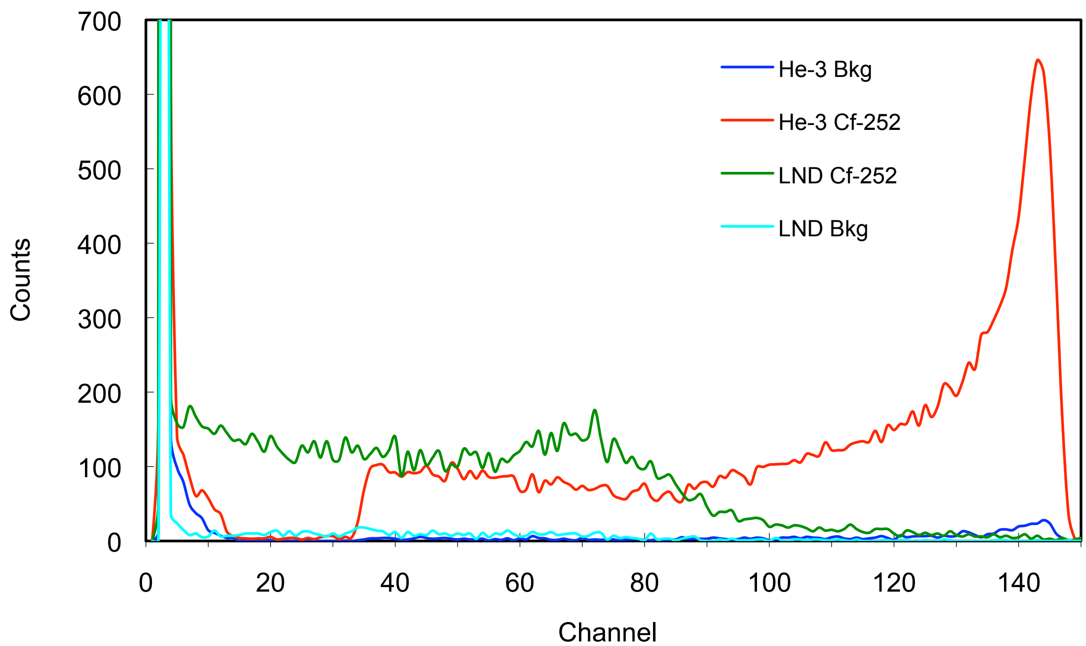

Figure 5-1. Spectra from boron-lined multichamber detector and ^{3}He in RPM (^{3}He counts divided by two).

Table 5-1 shows integrated counts and calculated count rates and neutron sensitivities from the spectra for the boron-lined multichamber detector and ^{3}He. (The integration starts at channel 9 for the boron-lined detector and at channel 30 for ^{3}He.) Also shown in the table are data collected from a conventional, cylindrical, boron-lined tube (50 mm diameter x1.82 m). Note that the conventional, boron-lined tube has significantly poorer performance than does the multichamber tube (or the ^{3}He tube), with its count rate per nanogram of ^{252}Cf being only 16% of that provided by the multichamber tube.

The requirement for the replacement neutron detector technology to provide at least 2.5 c/s/ng indicates that several of the boron-lined multichamber tubes will be required to meet the sensitivity presently achieved by a single ^{3}He tube. However, it is not clear that adequate space exists in the moderator box to contain a sufficient number of tubes. Tests (described below) performed with conventional, boron-lined tubes indicated that three tubes only enhance the performance by about 70%, relative to a single tube. This diminishing return from the additional tubes arises from interaction among the tubes causing neutron-flux suppression. Experiments with several of the multichamber tubes are required to determine the actual performance and interaction among the tubes.

Table 5-1: Neutron sensitivity of boron-lined and ^{3}He tubes.

	LND Boron-lined Multichamber	^{3}He	LND Boron-lined Conventional
^{252}Cf	10,507	32,305	2854
Background	741	1,153	1899
Net counts	9,766	31,152	955
Net count rate (c/s)	32.6	103.8	5.31
Counts/s/ng	0.98	3.13	0.16

Multiple, conventional tubes (boron-lined or ^{3}He) were placed in the RSP to measure the interaction among the tubes that prevents a simple scaling of efficiency as more tubes are added. These tests were performed previously, and hence the ^{3}He results differ slightly from that given above. Table 5-2 contains the results with multiple tubes. As shown in the table, when one ^{3}He tube was present, its neutron-detection efficiency was 2.90 cps/ng, and this decreased to 2.09 cps/ng when a second ^{3}He tube was added, which itself provided 2.10 cps/ng. Thus the combined efficiency was 4.19 cps/ng for the two ^{3}He tubes, which is only 45% greater than from the single ^{3}He tube.

As also shown in Table 5-2 the addition of a second conventional boron-lined tube increased the count rate from 0.16 cps/ng to 0.25 cps/ng, which is a 56% change. Adding a third conventional boron-lined tube (unpowered and located between the original tubes) reduced the count rates to 0.06 and 0.12 cps/ng for the two tubes. The reason for the larger effect on one of the tubes is unknown. If the third tube would have had the same count rate as the average of the other tubes, had it been powered, then the combined count rate for three boron-lined tubes would be 0.27 cps/ng, which is only 70% greater than what the single tube provided.

Table 5-2: Interference of multiple, conventional tubes.

	Count rate per ng of ^{252}Cf (cps/ng)	
Tubes Present	**First tube**	**Second tube**
One ^{3}He	2.90	--
Two ^{3}He	2.09	2.10
One B-lined	0.16	--
Two B-lined	0.12	0.13
Three B-lined	0.06	0.12

5.2 Gamma Insensitivity Test

Spectra obtained with the multichamber detector in the Building 318 gamma-ray facility were processed to measure the number of “apparent neutrons” actually caused by gamma rays, again starting the integration at channel 9.

For the GARRn measurements, the neutron source was not always at the same distance from the detector because the source was maintained at a fixed distance from another detector that was being tested simultaneously. Although this resulted in different neutron count rates, depending on the source distance, it did not affect the calculation of GARRn, which is a ratio.

The gamma-ray flux at the detector was estimated from the effective activity, which was calculated from the measured exposure rate at the detector, two gamma rays per decay, and the gamma factor for ^{60}Co (13.2 R·cm^2/hr·mCi). The effective activity is defined as the source activity that would be required to produce the measured exposure rate at the detector distance from the source. The effective activity was used to calculate the flux of gamma rays on the effective surface area of the detector.

Values for the intrinsic gamma ray efficiency and GARRn can be estimated from the calculated photon flux and the un-scaled neutron efficiency. The neutron efficiency used to calculate GARRn for each gamma exposure was the efficiency associated with each particular measurement, where the neutron source position was fixed for both neutron and gamma-ray-neutron measurements. Thus, any geometric effects are divided out of the results. The results of the measurements are given in Table 5-3.**Error! Reference source not found.** For each exposure rate from 5 to 100 mR/h, the table shows the background count rate, the net (background-subtracted) count rates for the gamma-ray source, the neutron source, and the combined neutron and gamma ray sources, and the ^{252}Cf count rate per nanogram. The GARRn (also shown in Table 5-3**Error! Reference source not found.**) is seen to be within the acceptable range (0.9 ≤ GARRn ≤ 1.1) for exposure rates up to 100 mR/h, except at 5 mR/h. The marginally low value obtained for GARRn (0.89) at 5 mR/h is inconsistent with the values at larger exposure rates and is unexplained. The intrinsic gamma-ray efficiency (Gamma Rejection (Table 5-3) is better than the required value of 10^{-6} for exposure rates up to100 mR/hr. The negative gamma-ray rejection values calculated for 10 mR/h and 20 mR/h arise from statistical fluctuations.

Table 5-3: Gamma-ray sensitivities for multichamber detector.

mR/h Position	Background cps	Net Gamma cps	Net ^{252}Cf cps	Net Gamma+Cf cps	GARRn	Gamma Rejection
5	1.17	0.21	5.63	5.03	0.89	4 x10^{-9}
10	1.41	-0.22	26.20	26.48	1.01	-2 x10^{-9}
20	1.16	-0.04	12.15	11.70	0.96	-2 x10^{-10}
50	1.30	0.01	32.48	32.55	0.97	2 x10^{-11}
100	1.20	0.65	24.81	24.72	1.00	6 x10^{-10}

Gamma-ray data have not been collected for the cylindrical, boron-lined detectors. Based on the results for the multichamber detector, it is expected that the conventional detectors would have adequate insensitivity to gamma rays.

6 Conclusions

The LND multichamber neutron detector has been tested and compared to ^{3}He as a possible alternative neutron detection technology.

Results show that the neutron detection efficiency (approximately 1 cps/ng) is one third that of a standard ^{3}He tube in a RPM. Several of the multichamber tubes are required, especially because of interference among multiple tubes resulting in reduced efficiency per tube. However, sufficient space for enough tubes might not be available in the RPM. Additional tests with several, multichamber tubes are needed to measure the combined efficiency.

Test results for conventional (cylindrical), boron-lined detectors show that they do not have adequate sensitivity to neutrons to serve as replacements for ^{3}He detectors in RPMs. However, the manufacturer has changed the design of the cylindrical, boron-lined tube to provide more neutron sensitivity and additional testing is needed on the new design to measure the change. Prior testing suggests that it is unlikely a single tube would be an adequate replacement for a ^{3}He tube.

Test results indicate that adequate intrinsic gamma ray efficiency (gamma-ray rejection) is obtained with the multichamber detector for gamma exposure rates up to 100 mR/hr. The gamma rejection factor is on the order of 10^{-9} for dose rates up to 100 mR/hr, which is better than that obtained for ^{3}He ($\sim 10^{-8}$).

The GARRn value at a ^{60}Co exposure rate of 10 mR/hr is within the desired range.

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