U.S. DEPARTMENT OF ENERGY

PNNL-18938

Boron-Lined Neutron Detector Measurements

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November 6, 2009
March 7, 2010 Revision 1

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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. 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.

Reported here are the results of tests of a newly designed boron-lined proportional counter option. This testing measured the neutron detection efficiency and gamma ray rejection capabilities of two successive prototypes of a system manufactured by GE Reuter Stokes.

Results indicate that the boron-lined neutron detector Prototype I, with an active surface area of 0.305 m by 1.75 m (12” x 69”) or 0.5345 m^{2}, had an efficiency that is 72% of a single ^{3}He tube in the current RPM polyethylene moderator box. The intrinsic gamma efficiency (rejection factor) was found to be on the order of 10^{-6} at an exposure rate of 10 mR/hr from a ^{60}Co source, which meets the requirement for this parameter. The GARRn value at 10 mR/hr is 1.01(1), which is within the required window.

Results from testing Prototype II of the boron-lined tubes showed significant improvement in the absolute efficiency of the boron-lined tubes, while slightly improving the gamma ray insensitivity. With a threshold that gave an absolute neutron efficiency of 3.01(18) cps/ng ^{252}Cf, the GARRn value at 10 mR/hr is 1.01(6), which is within the required window.

The boron-lined system shows significant promise as an alternative to ^{3}He for neutron detection in large homeland security radiation detection systems.

Acronyms and Abbreviations

ANSI	American National Standards Institute
ASP	Advanced Spectroscopic Portal
atm	atmospheres
CBP	Customs and Border Protection
cps	counts per second
DOE	U.S. Department of Energy
GARRn	Gamma Absolute Rejection Ratio in the presence of neutrons
MCNP	Monte Carlo for Neutrons and Photons Transport Code
mR	milli-Roentgen
Pa	Pascal
PNNL	Pacific Northwest National Laboratory
PolyBox	polyethylene moderator/reflector box
POV	personally owned vehicle
PVT	Polyvinyl Toluene (plastic) scintillation gamma detector
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, the 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. These technologies are:

1) Boron trifluoride (BF_3)-filled proportional counters (from LND),
2) Boron-lined proportional counters (from GE Reuter Stokes or LND),
3) Lithium-loaded glass fibers (from NucSafe), and
4) Coated non-scintillating plastic fibers (from IAT).

Reported here are the results of tests of two prototypes of a newly designed boron-lined proportional counter option. This testing measured the neutron detection efficiency and gamma ray rejection capabilities of the system that is being manufactured by GE Reuter Stokes.

The purpose of this testing was to measure the efficiency of the GE Reuter Stokes prototype neutron detection system to determine if this technology can meet the specified neutron detection requirements. The measurements made as part of this testing included:

1) response of the system with the original moderation configuration provided by GE Reuter Stokes to moderated and unmoderated neutrons
2) response of the system to moderated and unmoderated neutrons with added moderation to the front of the detector
3) response of the system to a high gamma-ray exposure rate with and without a neutron source.

2. Alternative Neutron Detector Requirement

Boron-lined proportional counters are a possible neutron detector replacement technology for ^{3}He-filled tubes. These tubes, with moderation, were designed to fit in the space available to the currently deployed SAIC RPM polyethylene box [0.114 m deep x 0.304 m wide x 2.180 m tall (4.5 in. × 12 in. × 85.7in.)] that has an active surface area of 0.663 m^2, which contains the ^{3}He tubes. The GE Reuter Stokes detector tested had an active detector surface area, including moderator, of 0.535 m^2. The difference in active surface areas was due to the space required for the GE Reuter Stokes electronics. Pacific Northwest National Laboratory (PNNL) has tested the GE Reuter Stokes boron-lined prototype neutron detection system.

The SAIC 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 0.5 cm of lead. To moderate the neutron spectrum, 2.5 cm 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) neutron absolute detection efficiency, 2) intrinsic efficiency of gammas detected as neutrons, and 3) Gamma Absolute Rejection Ratio in the presence of neutrons (GARRn) (Kouzes et al., 2009).

The neutron *absolute* detection efficiency ($\epsilon_{abs\ n}$) required was previously specified (2.5 cps/ng from a ^{252}Cf source at 2 m in a specified pig) as listed above. The *intrinsic* efficiency of gamma rays detected as neutrons ($\epsilon_{int\ \gamma n}$) is the number of events that are counted as neutrons in the presence of a gamma ray source divided by the number of photons hitting the active detector area, and shall be less than 10^{-6} at an exposure rate of 10 mR/hr. The GARRn is the number of events that are counted as neutrons ($\epsilon_{abs\ \gamma n}$) in the presence of both gamma and neutron sources divided by the neutron count rate in the presence of the neutron source only; the requirement for this parameter is that $0.9 < \text{GARRn} < 1.1$ 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 2004). 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 value

3. Test Hardware

3.1. GE Reuter Stokes Prototype Neutron Detector

The GE Reuter Stokes boron-lined detector that was tested is a new prototype design that utilizes multiple boron-lined proportional counters in a moderator assembly instead of a single two-inch tube as previously produced. Thermal neutrons react with the ^{10}B resulting in charged particles from the $^{10}B(n,\alpha)^{7}Li$ reaction that subsequently produce a signal in the proportional counter. The goal of the prototype development is to produce an assembly with comparable efficiency to a single ^{3}He tube in the SAIC RPM. The assembly of boron-lined proportional counters from GE Reuter Stokes came enclosed in a polyethylene moderator box as seen in Figure 3.1. Prototype I had a front and back row of tubes consisting of 10 boron-lined tubes each. The front row and back row of tubes were individually connected to the electronics for readout. Prototype II grouped the tubes by dividing into left and right halves. External electronics were used for the testing, as seen in Figure 3.2. A computer accumulated the spectra of proportional counter responses. A single ^{3}He tube in the SAIC moderator box was also measured as a comparison to the GE Reuter Stokes assembly.

Figure 3.1: View Of GE Reuter Stokes Detector (Right Side) In The RPM Radiation Sensor Panel.

Figure 3.2: GE Reuter Stokes External Detector Electronics Used In The Testing.

3.2 Neutron Source

The neutron source used for the static test on Prototype I was ^{252}Cf purchased from Isotope Products Laboratory (IPL) and given a PNNL ID of 60208-40D. The source was measured by IPL to be 20 ± 3 µCi on June 5, 2009. The source composition was activities of 93.193% ^{252}Cf, 0.0395% ^{251}Cf, 6.635% ^{250}Cf, and 0.132% ^{249}Cf according to IPL. From these isotopic contents, the source activity was estimated to be 18.5 µCi for this testing. However, cross-calibration with a NIST traceable ^{252}Cf source (PNNL ID 60208-44) yielded an activity of 20.3 ± 1.2 µCi on June 5, 2009. The activity of 20.3 µCi corresponds to an estimated emanation rate of 8.65×10^4 n/s using the conversion factor stated in Section 2.

The neutron source used for the prototype II tests was the NIST traceable ^{252}Cf source (PNNL ID 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 20.0 µCi on February 5, 2010 and 19.7 µCi on February 23, 2010. This activity corresponds to 37.5 ng and 37.0 ng, respectively, and an emanation rate of 8.5×10^4 n/s and 8.5×10^4 n/s, respectively, using the conversion factor stated in Section 2.

The sources were used in two configurations; 1) moderated (2.5 cm of polyethylene moderator outside of 0.5 cm of lead) and 2) bare (encased only in the stainless steel enclosure of the source). The source was placed on a tripod so that it was at the same height as the center of the detection unit.

3.3 Gamma Source

A ^{60}Co source was used for the gamma sensitivity tests. Due to the uncertainty in the original source strength and the varying degree of scatter contribution to the exposure rate at each position caused by the location of the source inside a room, the source activity on the day of the tests was determined by calculating what source strength would be necessary to deliver the exposure rate measured at each position. The distances for the various exposure rates were determined by PNNL staff and marked on the floor.

3.4 Test Facility

The tests were performed at the 331G Integration Test Facility, and in the 318 Building in the High Energy Calibration Laboratory, both located at PNNL in Richland, WA.

The static tests on Prototype I were performed on Thursday-Friday, October 1-2, 2009, and the gamma insensitivity measurements with the ^{60}Co source were performed on Wednesday, October 7, 2009.

The static tests on Prototype II were performed on Friday, February 5, 2010, and the gamma insensitivity measurements with the ^{60}Co source were performed on Tuesday, February 23, 2010.

4. Test Limitations

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

- Only one test location was used for each test, 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 GE Reuter Stokes detector system was tested. Results may change with different detector designs.

- Uncertainty in the source strength was the main limitation to the test results.

5. Experiment Equipment and Setup

5.1. Electronics

The GE Reuter-Stokes prototypes were designed to be a direct replacement for the currently deployed SAIC ^{3}He neutron detection module. The GE Reuter-Stokes detectors can be physically placed in the available space; however, the current SAIC electronics were unable to process the signals produced. The boron-lined tubes can be operated at a lower voltage than the ^{3}He tubes (800 V vs. 1100 V) but the capacitance of the GE Reuter-Stokes system was apparently too large for the SAIC pre-amps. Thus, external electronics were used to test the systems.

For some of these tests the ^{3}He tubes were also used and operated with the external electronics so that a direct comparison could be made between the two systems. The ^{3}He tubes were operated at 1100 V with the external electronics, a gain of 100 and a shaping time of 3 μseconds; the boron-lined tubes were operated at 800 V, a gain of 10 and a shaping time of 1 μsecond for the static tests and 0.5 μseconds for the gamma insensitivity tests. The shorter shaping time decreased the neutron efficiency by approximately 9% (as can be seen in Figure 6.3), but this decrease was accepted as the shorter shaping time also reduced the system response to gamma rays. The SAIC electronics would need to be slightly modified for this technology to be a replacement for what is currently deployed.

5.2. Static Measurements

Static measurements with Prototype I were made both with the original polyethylene moderator thickness (12.7 mm) as provide by GE Reuter Stokes and with an added 12.7 mm (0.5 inch) of moderation to the front of the detector. The detector system was situated both in the SAIC shroud (Figure 3.1), with and without the door, and outside of the shroud on a table (Figure 5.1). The neutron source was located on a tripod 2 m from the detector housing and at a height that positioned the source in the center of the detector for all of the tests. Measurements were made with neutron source positioned on both sides of the detector when the system was located outside of the SAIC shroud. Data were acquired over five minute intervals with the neutron source in the standard polyethylene pig (6 mm of lead and 25 mm of polyethylene) and bare.

The static measurements performed for Prototype I were used to obtain data that allowed the GE Reuter Stokes detector efficiency to be compared to the efficiency of one ^{3}He tube used in the current RPM systems.

For the Prototype II testing, the data was compared directly with the performance specification.

Figure 5.1: GE Reuter Stokes Detector Assembly Positioned For Static Tests Outside Of The SAIC Shroud.

5.3. Gamma Insensitivity Measurements

The detector sensitivity to gamma rays was tested with an intense ^{60}Co gamma-ray source. Tests were performed in the High Energy Calibration Laboratory in Building 318. Measurements were made with the gamma ray source by itself and with the gamma ray source used simultaneously with a neutron source. Prototype I was tested with a neutron source placed 2 m from the back of the detector and the gamma ray source at the front. Prototype II was tested with the gamma ray source at the front of the detector and the neutron source placed also at the front of the detector 2 m away and slightly off center so as not to block any part of the detector from the gamma rays.

The detector (white polyethylene box in Figure 5.2) was moved different distances from the gamma ray source to obtain the desired exposure rates on the front face of the detector when the ^{60}Co source was shuttled into the end of the source tube (in the foreground of Figure 5.2). Table 5.1 gives the exposure rate versus distance for the gamma ray exposures.

Figure 5.2: GE Reuter Stokes Detector Positioned For Testing With The Gamma Ray And Neutron Sources.

Table 5.1: Exposure Rate Versus Distance For The Gamma Ray Source At Building 318.

Exposure Rate (mR/h)	Prototype I Distance (m)	Prototype II Distance (m)
5	-	5.33
10	3.88	3.77
20	2.74	2.66
30	2.24	2.18
50	1.73	1.69
70	1.47	1.42
100	1.23	1.19

Five-minute measurements were made for four different configurations at each position:

1. ^{60}Co source closed (background)
2. ^{60}Co source open
3. ^{60}Co source open with the neutron source
4. ^{60}Co source closed with the neutron source.

6. Results and Data Analysis

6.1. Modeling Results

In related work, an MCNPX model study of a generic 2-inch diameter boron-lined tube was performed. The result from that study is shown in Figure 6.1(a), where the proportional counter spectrum was simulated by summing the individual alpha and ^{7}Li particle currents leaving the wall of the tube. These results show very nicely a two-shoulder structure that reflects the 4/11 and 7/11 partitioning of the 2.31 MeV total energy available in the alpha-boron center of mass for the ~96%-preferred boron exited state and the 2.79 MeV for the boron ground state. Note that the ability to track both the alpha and lithium products of the neutron-boron reaction has only recently become available with the options in the MCNPX beta versions 2.7b and higher.[2] With this version, the individual currents (tally type F1) can be obtained.[3]

The simulation shown in Figure 6.1(a) is compared to the measured spectrum shown in Figure 6.1(b), where a low-energy threshold was set to count neutron interactions. This threshold was determined by the approximate value required in the experimental measurements to reject gamma ray pileup events when the detector was exposed to a 10 mR/h field. Note that the data show very nicely the shoulder structures that result from the alpha particles emitted to an excited state and the ground state (leading to the shoulder at higher energy). Although the simulation was performed for a large single boron-lined tube, it matches the experimentally observed spectrum from the multi-tube GE Reuter Stokes prototype shown in Figure 6.1(b) quite well. Details on this work will be provided in a separate report.

6.2. Static Test For Prototype I

The data collected for the static measurements were used to determine the net count rate of the system and to estimate the absolute neutron detection efficiency. A lower level threshold was set for the data acquired with the external electronics to minimize the contribution from gamma rays. The channel for the lower threshold was set one channel above the highest channel affected by a ^{60}Co exposure rate of 10 mR/hr (channel 12, note that the selected threshold would be appropriate up to 30 mR/hr).

The front and back layers of detectors in the GE Reuter-Stokes system were read separately. Data from both layers were collected for 5 minutes in each of the static configurations. The data above the lower level threshold were summed for the two layers of detectors across all of the acquisition channels. The configuration-specific background was subtracted to determine the net count rate. The net count rate with the neutron source in both its bare and moderated form was measured with the detector system in the SAIC shroud, with the outer door both open and closed, and with additional front detector moderation, Figure 6.2. The statistical uncertainty in the measurements is based on Poisson statistics and is less than the size of the plot symbols.

When the system was placed in the SAIC shroud the front layer of detectors recorded approximately 1% fewer neutrons per second than the back layer with the moderated source. With the unmoderated source the front layer recorded approximately 28% fewer neutrons per second. The lower neutron count rate recorded by the front layer indicates that the front layer of detectors is under-moderated. However, increasing the front moderation to 25.4 mm (doubling the original moderation thickness) resulted in

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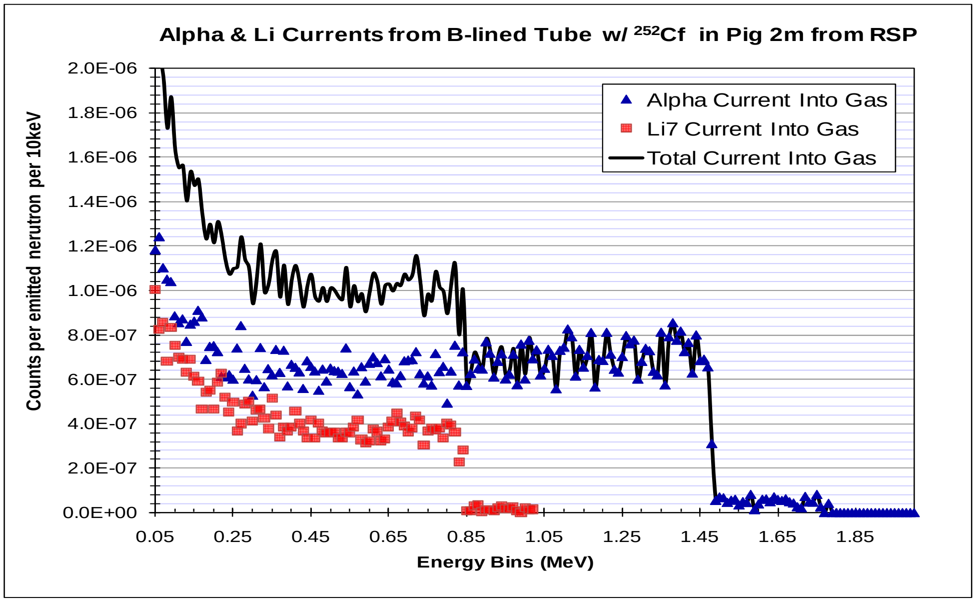
[2] Los Alamos National Laboratory Report, LA-UR-09-04150, "MCNPX 2.7.B Extensions," by D.B. Pelowitz, et al., available at http://mcnpx.lanl.gov.

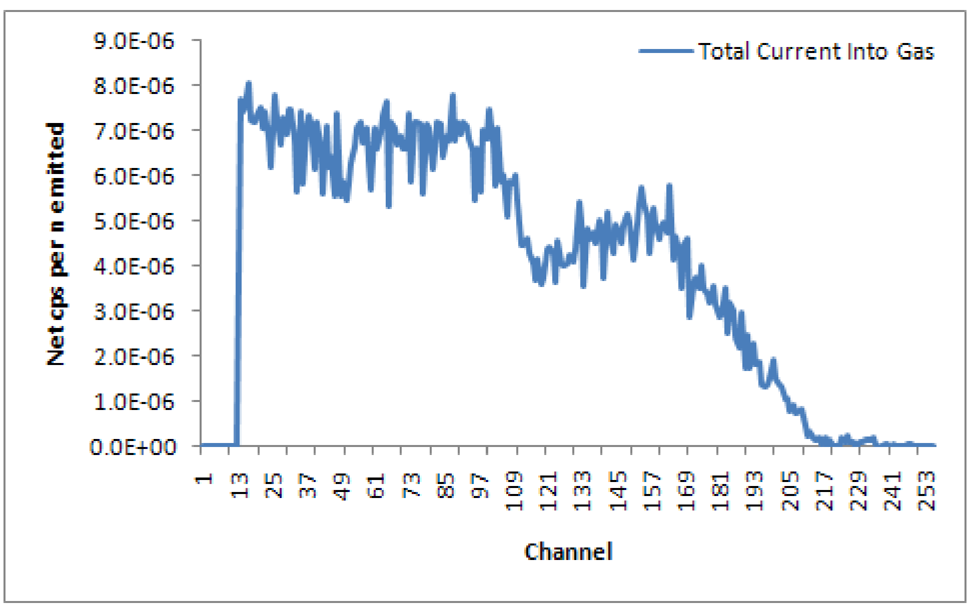
[3] By using a Mode N A # together with the physics and low-energy cut-off settings of: phys:n 20 0 0 -1 -1 0 3 $ Emax = 20 MeV, NCIA is on; phys:# 20 3J 1; and cut:A 1j 0.0001, cut:# 1j 0.0001.

approximately 16% fewer counts per second in the back layer than the front layer of detectors with the moderated source and a slight (less than 1%) overall decrease in the net count rate. Thus, increasing the front moderation of this detector did not result in a net increase in the neutron detection efficiency.

When the detector system was tested outside of the SAIC shroud the front layer of detectors recorded 4% more counts per second than the back layer. The front and back layer count rates for the system in and out of the SAIC shroud and in the SAIC shroud with added moderation are shown in Figure 6.3. This figure shows the large drop in efficiency outside the shroud compared to inside the shroud. The uncertainty in the measurements is less than the size of the plot symbols.



(a)



(b)

Figure 6.1: Modeling Result (a) For Response Of A Single Two-Inch Diameter Boron-Lined Tube To Neutrons, And The Experimental Result For The Response Of The Multi-Tube Ge Reuter Stokes Prototype Detector System (b).

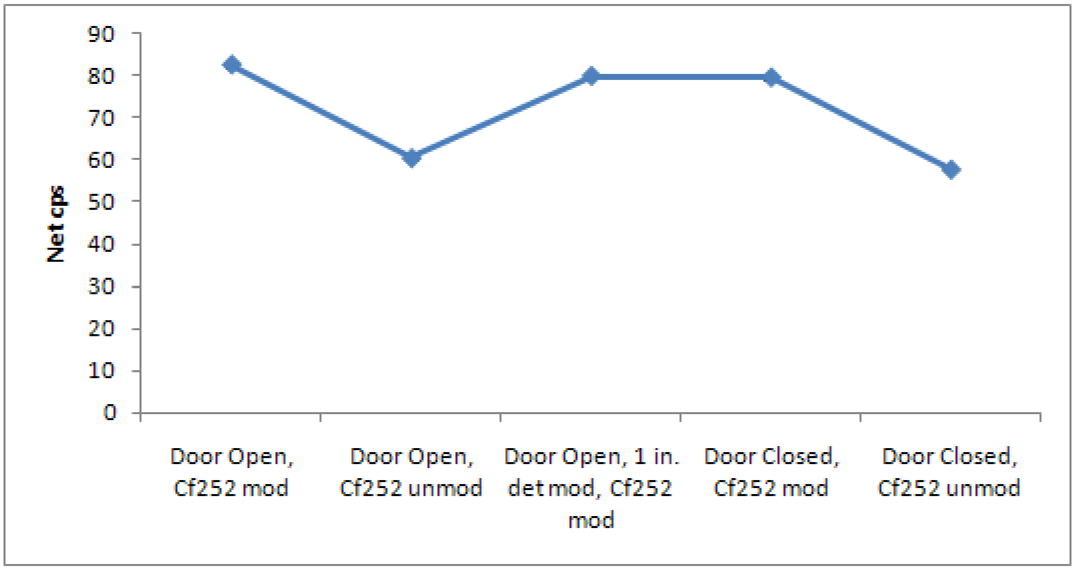


Figure 6.2: Total Count Rate Obtained With The GE Reuter-Stokes Detector Prototype In The SAIC Shroud.

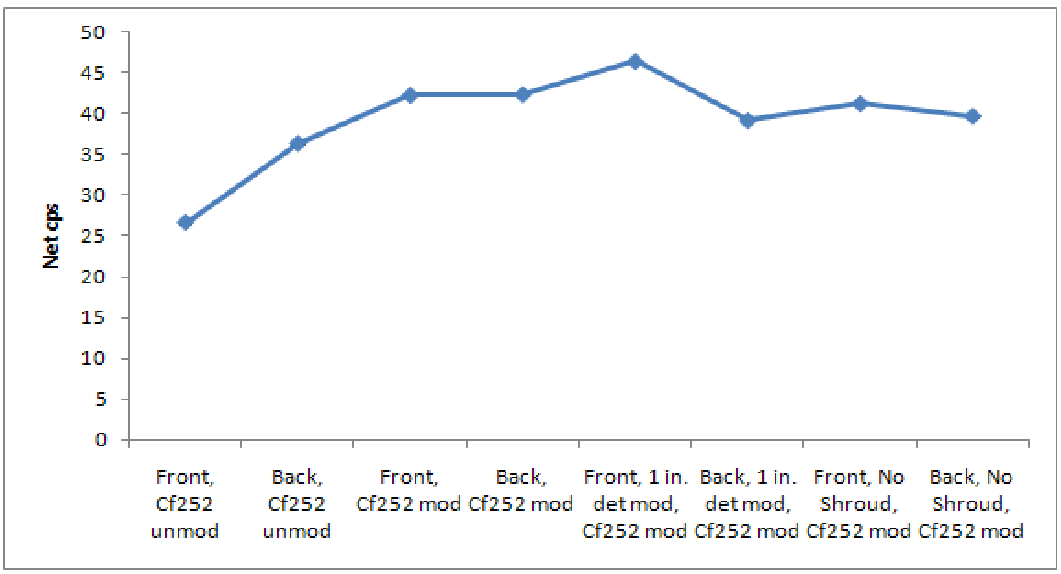


Figure 6.3: Net Count Rate Shown Individually For The Front And Back Layer Of Detectors For Different Test Configurations With The Moderated And Bare Source Inside and Outside The SAIC Shroud.

The absolute neutron efficiency of the boron lined tube detector system for the different configurations (including the different shaping times used) was estimated by dividing the sum of the net count rate from the front and back detector layers obtained with the moderated source by the material mass (in nanograms) of the ^{252}Cf source, Figure 6.4. The absolute neutron efficiency was compared to the efficiency of one ^{3}He tube in the SAIC moderator box and the required absolute neutron efficiency. The efficiency of the boron lined tube detector system is 2.12(12) cps/ng (in the SAIC shroud with the outer door on), which is 85% of the required 2.5 cps/ng. The efficiency of one ^{3}He tube with the external electronics is 2.95 cps/ng. The uncertainty of these calculations is slightly more than the 5.7% that comes from the uncertainty in source strength. The actual uncertainty of the source strength provided by the vendor is 10%, but this was reduced by cross-calibrating the source with a NIST traceable ^{252}Cf source with an uncertainty of 5.7%.

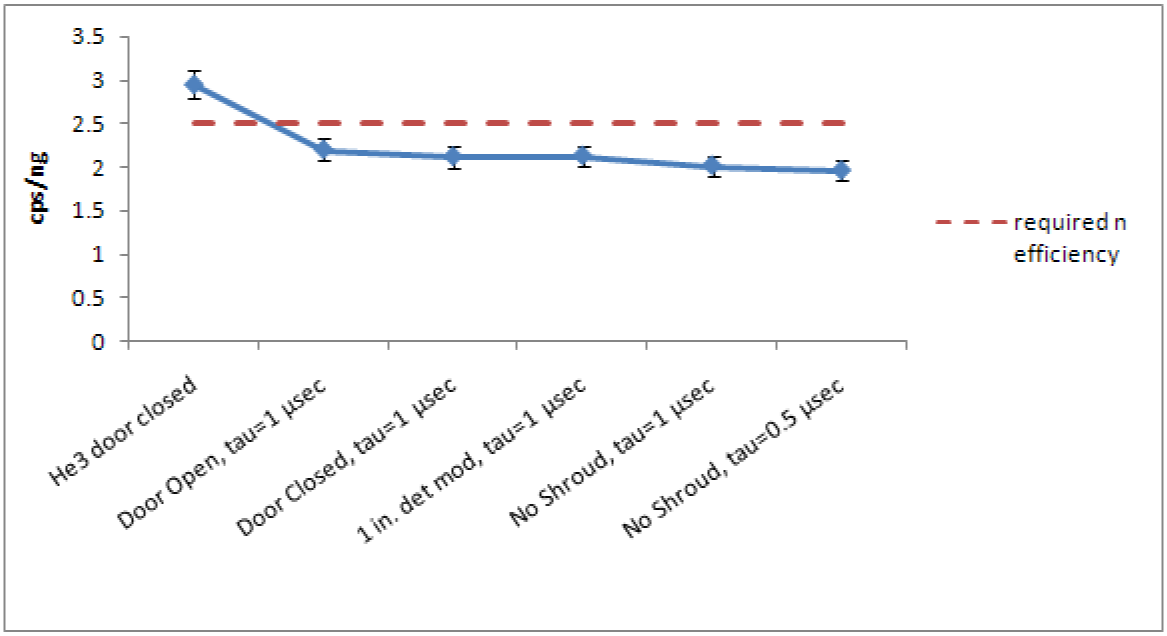


Figure 6.4: Neutron Efficiency Of The GE Reuter-Stokes Detector System Under Different Test Scenarios Compared To One ^{3}He Tube In The SAIC Polyethylene Moderating Box.

6.3. Gamma Insensitivity Test For Prototype I

The response of the boron-lined tubes to a high gamma exposure rate was evaluated with the ^{60}Co source at the High Energy Calibration Laboratory in Building 318. The detector system in its moderating box was positioned at specific distances from the source to achieve the desired exposure rate at the detector surface. Data were collected over 5 minute time intervals for the four test scenarios (background, ^{60}Co, ^{252}Cf, and ^{60}Co with ^{252}Cf). The background was subtracted from all of the test results to provide the net count rate at each position. The data were collected with the external electronics configured to have a shaping time of 0.5 µseconds to minimize the effect of the gamma rays on the signal. With these settings there was minimal detector response to the gamma source above channel 13 (Figure 6.5) at exposure rates up to 100 mR/hr. A ^{3}He tube in the SAIC moderating box was also tested with these external electronics and as seen in Figure 6.6, the boron lined detectors exhibit slightly less response to gamma rays than the ^{3}He detectors over the exposure rates tested. The net count rates obtained with the boron-lined tubes in the presence of different gamma ray field strengths are listed in Table 6.2.

An approximate value for the intrinsic gamma ray efficiency and GARRn can be calculated using the counts recorded in Table 6.2 and the estimated gamma flux at the detector.

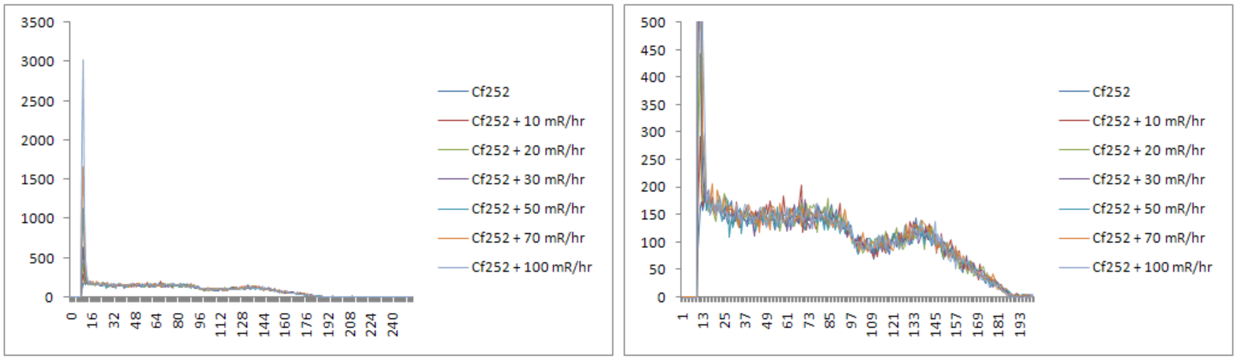


Figure 6.5: Response Of Boron Lined Tubes To ^{60}Co Gamma Rays On The Left And Scaled To Show Neutron Detail On The Right.

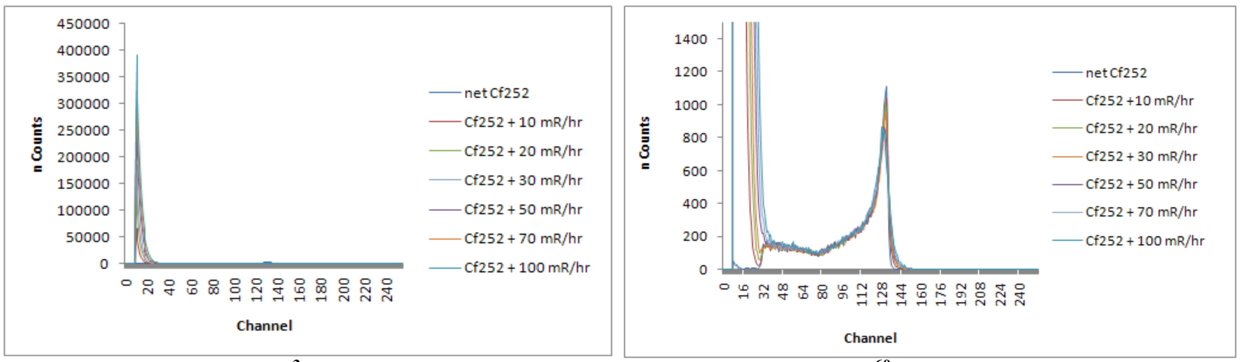


Figure 6.6: Response Of ^{3}He Tubes Operated With External Electronics To ^{60}Co Gamma Rays On The Left And Scaled To Show Detail On The Right.

Table 6.1: Neutron Counts Recorded With The Boron-Lined Tubes In The Presence Of A High Exposure Gamma Field.

Exposure Rate (mR/hr)	Neutron Counts With Only ^{60}Co Source (net cps)	^{252}Cf Source Only (net cps)	Neutron Counts with ^{252}Cf and ^{60}Co Sources (net cps)	(^{252}Cf Source) Minus (^{252}Cf & ^{60}Co Sources) (net cps)
10	-0.15(13)	65.7(5)	66.8(5)	-1.1
20	0.16(14)	65.7(5)	66.4(5)	-0.7
30	0.17(14)	65.7(5)	64.8(5)	0.9
50	0.03(13)	65.7(5)	64.8(5)	0.9
70	0.07(14)	65.7(5)	66.8(5)	-1.1
100	0.50(14)	65.7(5)	66.3(5)	-0.6

Gamma Flux Estimate

The exact source strength of the ^{60}Co source used to make the gamma insensitivity measurements was not known so the photon flux at the detector surface was determined by use of the measured exposure rate, shown in Table 6.3. It should be noted that the measurements were made indoors and the contribution of scatter to the measured exposure rate increased with increasing distance from the source. The measured exposure rate was used to develop an estimate of the source strength and to account for the scatter contribution. The gamma factor for ^{60}Co used to determine the number of photons incident on the detector face for a given exposure rate was 13.2 R•cm^2/hr•mCi.

Table 6.2: Number Of Photons Incident On The Active Area Of The Detector.

Exposure Rate (mR/hr)	Detector to Source Distance (m)	'Effective' Source Activity (Ci)	Estimated Photons on Detector From Effective Activity (cps)
10	3.88	0.114	3.00E+07
20	2.74	0.114	6.02E+07
30	2.24	0.114	9.01E+07
50	1.73	0.113	1.51E+08
70	1.47	0.115	2.09E+08
100	1.23	0.115	2.99E+08

The gamma insensitivity estimates were made by using the estimated photon flux on the detector to determine the rate at which gamma rays were miscounted as neutrons. The GARRn was calculated by taking the ratio of the absolute neutron efficiency with no gamma source present (Table 6.3, column two, row one) to the absolute neutron efficiency with the gamma source present (Table 6.3, column two, rows two-seven). The absolute neutron efficiency both with and without the gamma source was measured with the neutron source located on the back of the detector (the same configuration as used in the gamma insensitivity tests). The values shown for Prototype I in Table 6.3 were calculated using a lower level threshold one channel above the highest channel affected by a 10 mR/hr exposure rate (as described for the static tests in Section 6.2). The geometry specific absolute neutron efficiency was used so that the neutron source was in the same position for the neutron efficiency measurements made with and without the gamma ray source present, thus eliminating any geometry effects on GARRn.

Table 6.3: Absolute Efficiency, GARRn And Intrinsic Efficiency Versus Gamma Exposure Rates.

Exposure Rate (mR/hr)	Neutron Efficiency ϵ_n (n/s)	Intrinsic Gamma Ray Efficiency $\epsilon_{int\,\gamma n}$	GARRn $\epsilon_{abs\,\gamma n}/\epsilon_n$
0	7.60E-4	-	-
10	7.72E-4	1.52E-06	1.02(1)
20	7.68E-4	8.06E-07	1.01(1)
30	7.50E-4	5.61E-07	0.99(1)
50	7.50E-4	4.97E-08	0.99(1)
70	7.73E-4	1.03E-07	1.02(1)
100	7.67E-4	5.01E-07	1.01(1)

The measured GARRn values are well within the window specified (0.9 < GARRn < 1.1) for an exposure rate of 10 mR/hr. The intrinsic efficiency meets the required 10^{-6} at 10 mR/hr (there is a possible trade off between neutron detection efficiency and this gamma insensitivity efficiency). It should be noted that both the intrinsic efficiency and GARRn have acceptable values for all of exposure rates tested. Thus, with the lower limit threshold selected, gamma rays do not appear to have a strong effect on the boron lined tubes.

6.4. Static Test For Prototype II

According to the vendor, Prototype II differed from Prototype I in the internal layout of the tubes and moderator. The data collected for the static measurements were used to determine the net count rate of the system and to estimate the absolute neutron detection efficiency. A lower level threshold was set for the data acquired with the external electronics to minimize the contribution from gamma rays. The channel for the lower threshold was set one channel above the highest channel affected by a ^{60}Co exposure rate of 10 mR/hr (channel 13), as discussed below.

The left and right arrays of detectors in the GE Reuter-Stokes system were read out separately. Pulse height spectra from the left and right arrays of tubes are shown in Figure 6.7. Data were collected in 5-minute intervals. The data above the lower level threshold were summed for the two arrays of detectors. The configuration-specific background was subtracted to determine the net count rate. The net count rate with the neutron source in its moderated form was measured with the detector system in the SAIC shroud with no additional moderator.

The resulting absolute efficiency was <u>3.01(18) cps/ng</u> of ^{252}Cf. The statistical uncertainty in the measurements is based on Poisson statistics and is much less than the uncertainty of 5.7% from the source strength. This value is 24% above the specification value (2.5 cps/ng) for the neutron detection system and a 42% improvement over the Prototype I detector.

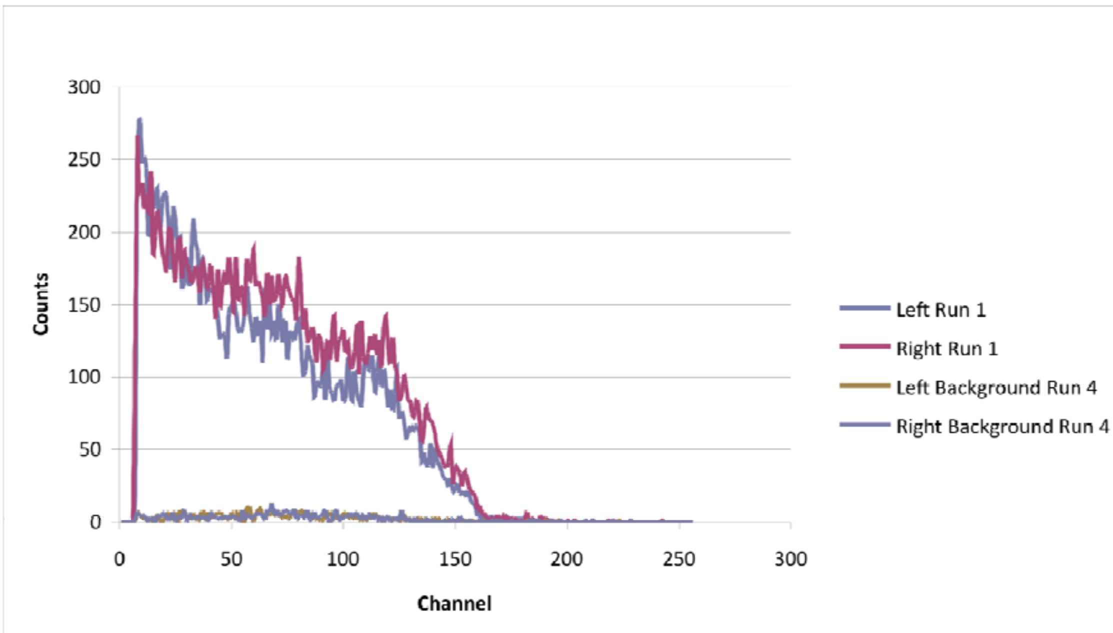


Figure 6.7. Pulse Height Spectra For GE Reuter-Stokes Prototype II With (Run 1) And Without (Run 4) Neutron Source.

6.5. Gamma Insensitivity Test For Prototype II

The response of the boron-lined tubes to a high gamma exposure rate was evaluated with the ^{60}Co source at the High Energy Calibration Laboratory in Building 318. The detector system in its moderating box was positioned on ladders laying horizontally at specific distances from the source to achieve the desired exposure rate at the detector surface (Figure 6.8). Data were collected over 5 minute time intervals for the four test scenarios (background, ^{60}Co, ^{252}Cf, and ^{60}Co with ^{252}Cf). The background was subtracted from all of the test results to provide the net count rate at each position. The data were collected with the external electronics configured to have a shaping time of 0.5 μseconds to minimize the effect of the gamma rays on the signal. With these settings there was minimal detector response to the gamma ray source above channel 10 (Figure 6.8) at exposure rates up to 100 mR/hr. This performance is slightly better than that of Prototype I. Because of gain differences between the static and gamma-insensitivity measurements, channel 10 for the gamma insensitivity measurements corresponds to channel 13 for the static measurements for Prototype II discussed above.

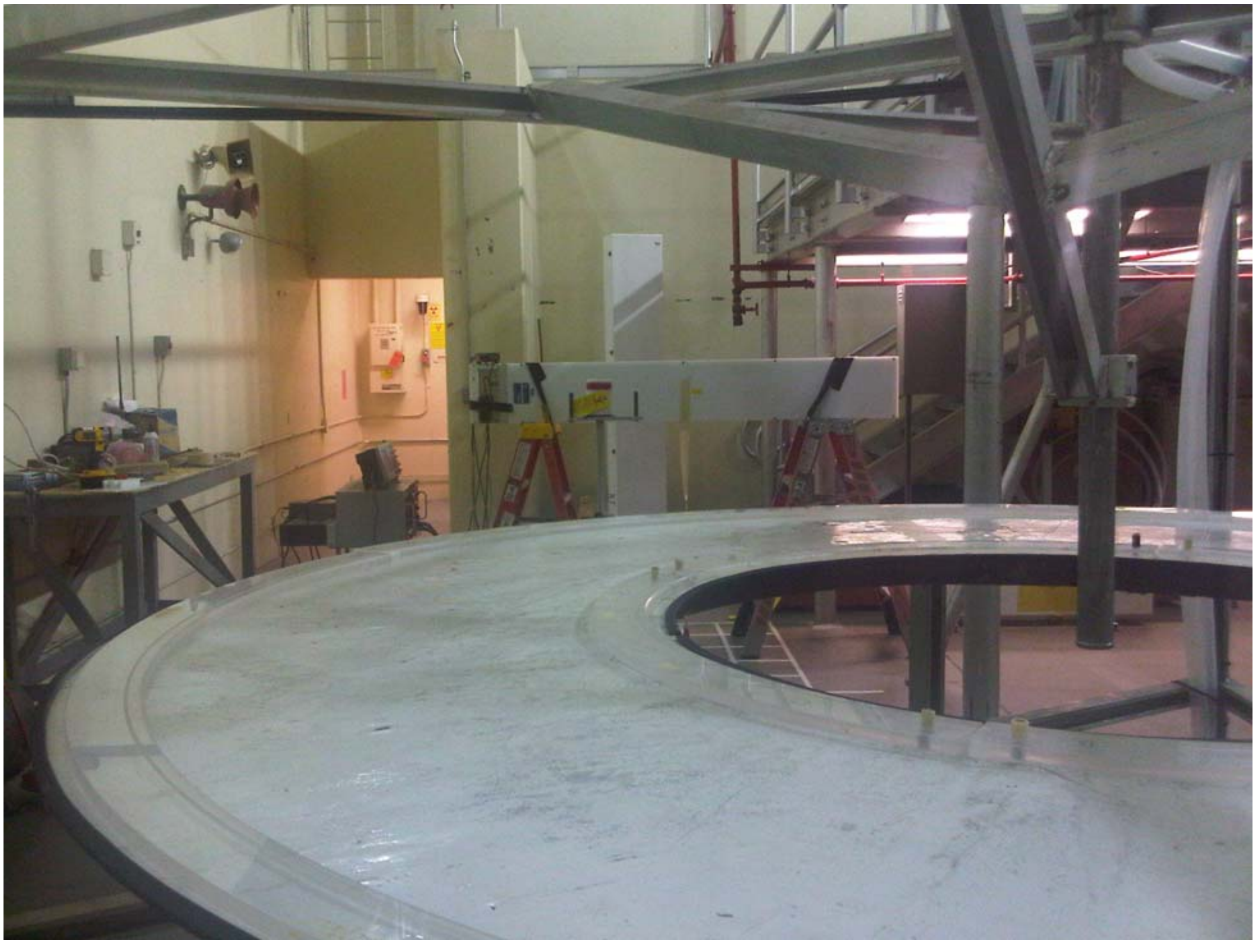


Figure 6.8. GE Reuter-Stokes Prototype II Set On Ladders At A Distance From The Gamma Ray Source In The Foreground.

The source strength of the ^{60}Co source used to make the gamma insensitivity measurements and the resulting photon fluxes were found in the same manner as described for the Prototype I tests. The results are also consistent with Prototype I for gamma rejection.

The GARRn values were calculated by taking the ratio of the absolute neutron efficiency with no gamma source present to the absolute neutron efficiency with the gamma source present. The absolute neutron efficiency both with and without the gamma ray source for these gamma-insensitivity measurements was measured with the neutron source located on the front side of the detector (same side as the gamma ray source) and slightly off center to avoid blocking the gamma ray source. The geometry specific absolute neutron efficiency was used so that the neutron source was in the same position for the neutron efficiency measurements made with and without the gamma ray source present, thus eliminating any geometry effects on GARRn.

All results are summarized in Table 6.4 for a threshold at channel 10.The measured GARRn values are well within the window specified ($0.9 < GARRn < 1.1$) for an exposure rate of 10 mR/hr. The intrinsic efficiency for gamma rays detected as neutrons easily meets the required 10^{-6} at 10 mR/hr. Both the intrinsic efficiency and GARRn have acceptable values for all exposure rates tested (5 mR/h to 100 mR/h). Thus, with the lower limit threshold selected, gamma rays do not appear to have a significant effect on the boron-lined tubes, and their insensitivity to gamma rays is as good as, or better than, a ^{3}He tube.

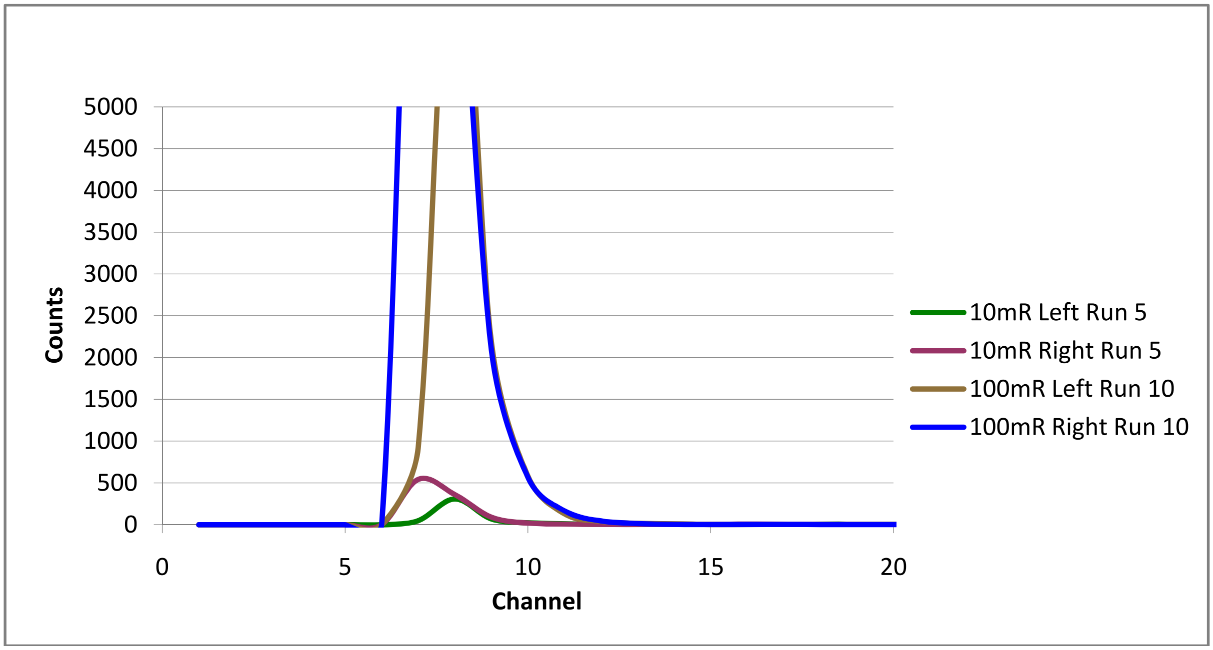


Figure 6.9. Pulse Height Spectra For GE Reuter-Stokes Prototype II From The Gamma Ray Source.

Table 6.4: Absolute Efficiency, GARRn and Intrinsic Efficiency Versus Gamma Ray Exposure Rate.

Exposure Rate (mR/hr)	Neutron Efficiency ϵ_n (n/s)	Intrinsic Gamma Ray Efficiency $\epsilon_{int\ \gamma n \gamma n}$	GARRn $\epsilon_{abs\ \gamma n}/\epsilon_n$
0	1.4E-03	-	-
5	1.4E-03	2.0E-08	1.03(2)
10	1.4E-03	5.5E-09	1.01(2)
20	1.5E-03	3.4E-09	0.96(2)
30	1.5E-03	6.0E-09	0.95(2)
50	1.4E-03	3.3E-09	0.98(2)
70	1.3E-03	3.9E-09	1.04(2)
100	1.3E-03	4.8E-09	1.06(2)

7. Conclusions

Two GE Reuter-Stokes prototype boron-lined tube neutron detector systems were tested and compared to the currently deployed ^{3}He neutron detection system as a possible alternative neutron detection technology. The boron-tubes detect neutrons when the charged particles from the $^{10}B(n,\alpha)^{7}Li$ reaction react with the fill gas in the proportional counter. The GE Reuter-Stokes prototypes were designed to fit into the currently deployed SAIC system but external electronics had to be used to read out the signal because the SAIC pre-amps were not designed to function with the high capacitance of the GE Reuter-Stokes system.

The results suggest that improving the neutron efficiency of the Prototype I system by ~40% would result in a system that would have the same neutron efficiency as one ^{3}He tube in the SAIC moderating box. This was realized by the Prototype II system. The gamma rejection capability of the GE Reuter-Stokes system is better than 10^{-6} at an exposure rate of 10 mR/hr from a ^{60}Co source, as required. This system was tested up to exposure rates of 100 mR/hr and its gamma rejection capability met the requirement at all the exposure rates. The GARRn value met the requirement of $0.9 < \text{GARRn} < 1.1$ at an exposure rate of 10 mR/hr. The GARRn value for this system was within the desired window for all of the gamma exposure rates tested, which indicates that the system neither miscounts gamma rays as neutrons at high gamma ray exposure rates nor experiences a large dead time due to the presence of the gamma rays.

The boron-lined tubes can be operated at a lower voltage than the ^{3}He tubes, so if the SAIC electronics are optimized to accommodate the higher system capacitance the GE Reuter-Stokes system would have the potential to be a drop-in replacement technology. The firmware may require some modification to account for the difference in pulse shape.

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