Evaluation of Neutron Detector Performance for Handheld Homeland Security Application

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Abstract

We describe neutron response simulations along with benchmark measurements for various configurations of a moderated Helium-3 filled proportional counter suitable for handheld security applications. The results show an excellent agreement within measurement uncertainties between the measurements and the simulations. This allows us to optimize the detector configuration and predict the detector performance for different packaging and applications.

KEYWORDS: Handheld, Neutron detector, Inspector-1000, IN1K, Monte Carlo simulation, Radiation detection, Spectroscopy

1. Introduction

The Canberra Inspector^{TM} 1000 (IN1K), shown in Figure 1, is a high-performance digital handheld spectrometer for gamma-ray spectroscopy and neutron counting device [1]. It has had great success over the years across a wide variety of applications, including: homeland security; first responder applications; custom and border controls; waste applications; isotope specific health physics applications; *in situ* environment screening; treaty and non-proliferation compliance, and nuclear transportation monitoring.

Figure 1: Canberra handheld Inspector^{TM} 1000 with both neutron (left) and gamma (right) detectors attached to the data acquisition and processing module

The original design criteria was primarily based on the International Atomic Energy Agency (IAEA) recommendation for handheld radioisotope identification device (HHRIID) and the official 1989 version of ANSI standard N42.17A-1989. Both NaI(TI) gamma detectors and Helium-3 neutron detectors can be attached (or detached) to the IN1K unit.

In this paper, we report the performance of the Helium-3 neutron detector. The MCNP^{TM} [2]

based Monte Carlo simulation and experimental benchmark results are presented so that possible future modifications to the neutron detector can be addressed and recommendations made for various scenarios.

2. Monte Carlo Simulations

The neutron detector consists of a 2-atmosphere (atm) Helium-3 cylinder 8 cm in active length and 2.54 cm outer diameter surrounded by a 2.54 cm thick high density polyethylene (HDPE) jacket. Detailed dimensions of the standard IN1K neutron detector are presented in Table 1. The 2-atm Helium-3 fill pressure was originally chosen for the ease of air transit under US DOT and similar regulations. The unit meets the current (i.e. the 2003 version – N42.34-2003) ANSI standard for neutron detection with the alarm threshold set at 3 neutrons for a 2 second time interval. The false positive alarm rate is measured to be less than one per hour under normal environmental background.

Table 1: The standard parameters of the Canberra IN1K Helium-3 neutron detector.

	Dimension	Uncertainty
Active Helium-3 tube length (cm)	8.00	± 0.20
Helium-3 tube radius (cm)	1.22	± 0.02
Helium-3 tube volume (cm^3)	37.41	-
HDPE jacket length (cm)	17.08	-
HDPE jacket side wall thickness (cm)	2.54	± 0.025
HDPE jacket front thickness (cm)	1.95	-
Helium-3 fill pressure (atm)	2.00	± 0.04
Stainless shell thickness (cm)	0.05	-
Aluminum housing wall thickness (cm)	0.15	-

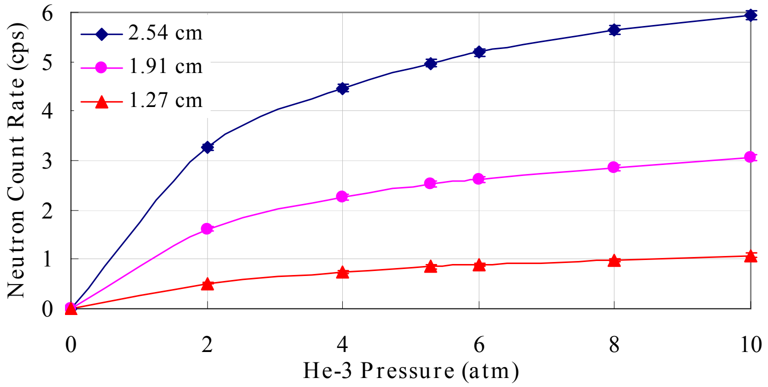
The goal of the Monte Carlo simulations is to evaluate the performance of the neutron detector sensitivity as a function of the Helium-3 fill pressure and HDPE moderator thickness for future modifications which may involve trimming the efficiency and/or weight of the neutron probe. The neutron count rate is calculated in MCNP using an F4 type tally (i.e. path length flux tally) together with FM4 tally multiplier for reaction type n(He, p)T. A Watt representation of the fission neutron spectrum from Cf-252 is used. Instead of using the free atom scattering model, the neutron transport calculation in HDPE employed the ENDF/B thermal neutron incoherent scattering law data, referred to as $S(\alpha, \beta)$ treatment. The model calculates the neutron count rate for various source-to-detector distances, a selection of HDPE moderator thickness and different Helium-3 fill pressures. An isotropic point source is assumed in the simulations. Simulated neutron count rates for various Helium-3 pressures (2, 4, 5.3, 6, 8, and 10 atm), HDPE moderator thicknesses (2.54, 1.91 and 1.27 cm), and source-to-detector distance (20, 25, and 30 cm) when a 0.01 μg of Cf-252 point source (23400 neutron/s) is positioned on the side of the detector (orthogonal to the central axis of the Helium-3 cylinder) are presented in Table 2 and graphed in Figure 2. Source and detector are in free space or air. The uncertainties are quoted at one relative standard deviation and reflect the sampling statistics of the Monte Carlo code.

Simulations are also performed for the case of the source in front of the detector (along the central axis of the Helium-3 cylinder). However, the finite source dimension and larger uncertainty in positioning the source on the central axis of the Helium-3 cylinder resulted in significantly larger measurement uncertainty. As a result, larger disagreement (compared to the case of source on the side of the detector) in count rates between measurements and simulations are expected.

Table 2: Simulated neutron count rates as function of the neutron detector Helium-3 fill pressure and HDPE moderator thickness when the source is placed on the side of the neutron detector with source-to-detector (i.e. the curved face of the HDPE) distance of 25, 20 and 30 cm, respectively.

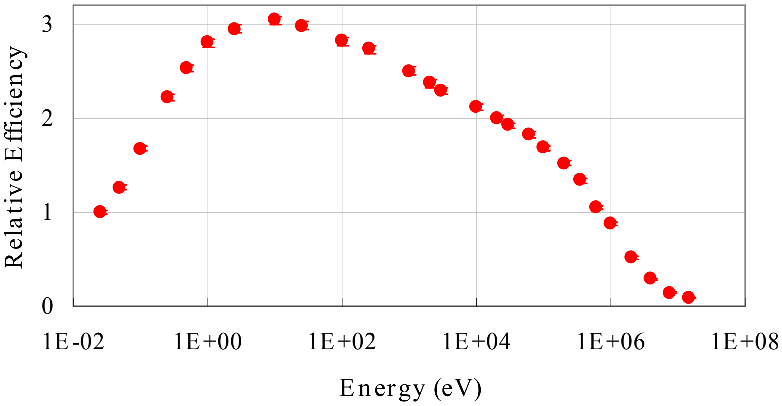
Source-detector distance (cm)	Helium-3 pressure (atm)	HDPE thickness and count rates (cps)		
		2.54 cm	1.91 cm	1.27 cm
25	2	3.27 ± 1.63%	1.61 ± 2.33%	0.52 ± 3.99%
	4	4.46 ± 1.61%	2.26 ± 2.28%	0.75 ± 3.85%
	5.3	4.97 ± 1.60%	2.52 ± 2.22%	0.85 ± 3.77%
	6	5.19 ± 1.61%	2.61 ± 2.23%	0.89 ± 3.73%
	8	5.64 ± 1.60%	2.85 ± 2.18%	0.98 ± 3.54%
	10	5.95 ± 1.59%	3.05 ± 2.17%	1.08 ± 3.51%
20	2	4.71 ± 1.35%	2.32 ± 1.91%	0.72 ± 3.40%
	4	6.50 ± 1.34%	3.22 ± 1.86%	1.03 ± 3.19%
	5.3	7.18 ± 1.33%	3.63 ± 1.84%	1.17 ± 3.11%
	6	7.49 ± 1.33%	3.76 ± 1.84%	1.23 ± 3.08%
	8	8.17 ± 1.32%	4.13 ± 1.82%	1.38 ± 2.98%
	10	8.62 ± 1.31%	4.43 ± 1.81%	1.51 ± 2.92%
30	2	2.38 ± 1.56%	1.18 ± 2.20%	0.38 ± 3.80%
	4	3.26 ± 1.54%	1.64 ± 2.15%	0.55 ± 3.60%
	5.3	3.58 ± 1.53%	1.83 ± 2.11%	0.62 ± 3.54%
	6	3.73 ± 1.52%	1.90 ± 2.12%	0.66 ± 3.50%
	8	4.04 ± 1.51%	2.08 ± 2.09%	0.74 ± 3.38%
	10	4.25 ± 1.49%	2.21 ± 2.06%	0.81 ± 3.31%

Figure 2: Simulated neutron count rates as function of neutron detector Helium-3 fill pressure and HDPE moderator thickness when source is placed on the side of the neutron detector with source-to-detector distance of 25 cm.



A typical energy response for the standard Canberra IN1K unit neutron detector with 2-atm Helium-3 fill pressure, normalized to the thermal neutron efficiency is shown in Figure 3.

Figure 3: Simulated neutron energy response for the standard Canberra IN1K 2-atm Helium-3 fill pressure neutron detector. Efficiencies are normalized to the thermal neutron efficiency at 0.0253 eV.



The MCNP^{TM} model has also provided the systematic uncertainty estimate for the benchmark measurements, mainly due to uncertainties on Helium-3 tube effective active length, tube radius, Helium-3 fill pressure, HDPE moderator thickness, source-to-detector distance and source activity uncertainties, etc. In order to evaluate the possible systematic uncertainty due to the uncertainty of these variables, each variable is independently adjusted in MCNP^{TM} by its uncertainty value and the difference in count rates is taken as the systematic uncertainty due to this variable. The uncertainty due to the Helium-3 tube active length and radius is obtained from the count rates difference by offsetting these variables with their uncertainty values listed in Table 1. Note that the effective active length is difficult to estimate accurately; the potential dead space due to electrical field fringing represents several percent for this short tube. An independent fit to the count rate as function of the HDPE side wall thickness, the Helium-3 fill pressure and the source-to-detector distance (0.2 cm uncertainty assumed) is made, and their contributions to the systematic uncertainty is calculated from the fit. The overall systematic uncertainty of the count rate is the quadratic sum of all contributions listed above as well as the source activity uncertainty. The final systematic uncertainty of the count rate for various helium-3 fill pressure, HDPE side wall thickness and source-to-detector distance is presented in Table 3. Note that similar approach was applied to the case of source in front of the detector, but its actual systematic uncertainty maybe much larger for the reasons stated earlier. The results are not presented here.

Table 3: Simulated overall neutron count rate systematic uncertainty (in percent) at various Helium-3 fill pressures, HDPE side wall thicknesses and source-to-detector distances.

	Source-detector distance = 20 cm			Source-detector distance = 25 cm			Source-detector distance = 30 cm		
	2.54	1.91	1.27	2.54	1.91	1.27	2.54	1.91	1.27
2	5.43%	6.10%	7.11%	5.35%	6.03%	7.05%	5.31%	6.00%	7.02%
4	4.65%	5.47%	5.54%	4.56%	5.39%	5.46%	4.52%	5.36%	5.42%
5.3	4.42%	4.78%	5.55%	4.33%	4.69%	5.47%	4.28%	4.64%	5.43%
6	4.27%	5.13%	4.60%	4.17%	5.05%	4.51%	4.12%	5.01%	4.46%
8	4.34%	5.05%	4.93%	4.24%	4.97%	4.84%	4.19%	4.93%	4.80%
10	4.30%	5.04%	5.19%	4.20%	4.95%	5.11%	4.15%	4.91%	5.07%

3. Benchmark Measurements and Results

To minimize the scattering contributions from the floor (typically a few percent), the measurements were performed on a metal structure approximately 140 cm above the ground in the middle of a large open room with a Canberra IN1K unit [3] [4]. The Cf-252 source is a 3 cm long by 0.8 cm cylindrical stainless steel cladding with point-like Cf-252 deposit close to the center. Measurements were carried out at three source-to-detector distances and two source-detector orientations (including source on the side and in front of the neutron detector). The source-to-detector distance is measured from the outer edge of the HDPE moderator to the center of the source. Measurements were performed for both 2 and 5.3 atmosphere Helium-3 neutron detectors from Canberra-Loches.

The Helium-3 detectors are calibrated using standard Canberra IN1K detector calibration software and a neutron source. The calibrations include high voltage and Lower-Level Discriminators (LLD) plateau measurements. The high voltage plateau was measured using a default LLD value of about 1050 in terms of IN1K DAC value. The optimal operating high voltage is typically 40 volts above the 'knee' of the high voltage plateau. A typical operating voltage for a 2-atm Helium-3 detector in the IN1K is about 750 volts, or 3200 in terms of DAC value (in a stable operating region far below gamma breakthrough). The LLD plateau was performed at the optimal operating high voltage. The LLD scan began at some point in the valley between noise and signal of the neutron energy spectrum. For a typical 2-atm Helium-3 tube, as the LLD setting increases, the count rate spectrum shows a plateau followed by a negative slope when the LLD setting begins to cut off the signals. The high voltage and LLD plateaus for the 2-atm Helium-3 detector are shown in Figure 4. For the 5.3-atm Helium-3 detector, the high voltage plateau is less "perfect" than the 2-atm detector due to charge collection in the denser gas mixture, and the operating high voltage is set 150 volts above the knee, 935 volts. Due to the imperfect HV plateau, the choice of the high voltage impacts the efficiency by roughly 0.25% per volt. Measurement also shows a very different LLD plateau spectrum for the 5.3-atm detector – the LLD spectrum shows no obvious plateau as for the 2-atm Helium-3 tube. A manual determination of the LLD for the 5.3-atm detector is then performed by measuring the background and signal count rates as function of LLD values. The optimal LLD value was set to the point where background rate jumps. A typical high voltage and LLD plateaus for the 5.3-atm Helium-3 detector are shown in Figure 5.

Figure 4: High voltage (left) and LLD (right) plateaus for 2-atm Helium-3 tube with 2.54 cm HDPE moderator thickness.

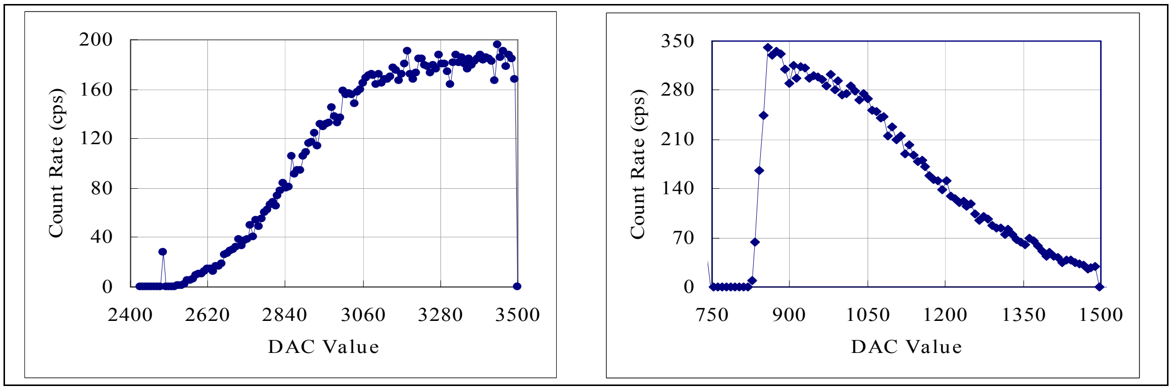
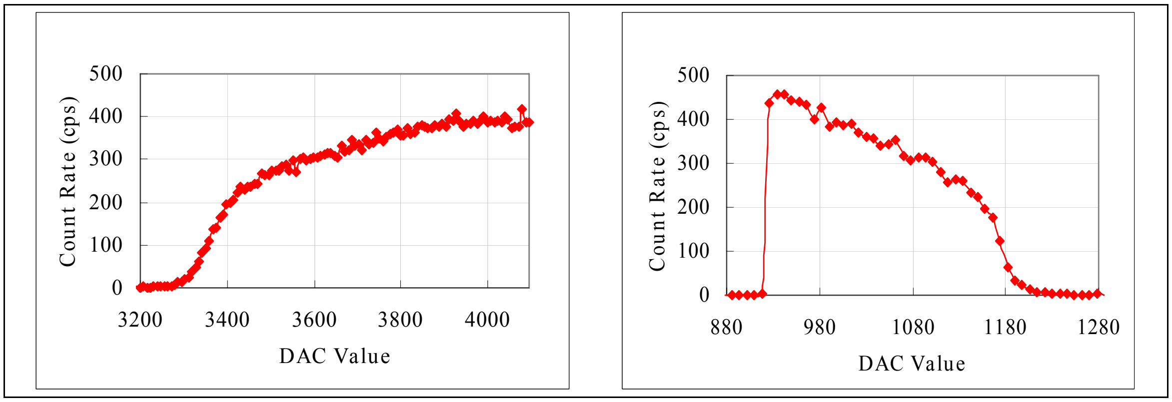


Figure 5: High voltage (left) and LLD (right) plateaus for 5.3-atm Helium-3 tube with 2.54 cm HDPE moderator thickness.



Data were collected under room temperature for the 2-atm and 5.3-atm Helium-3 detectors, with three HDPE jackets side wall thickness of 2.54, 1.91 and 1.27 cm, respectively. The IN1K is operated in 'locate' mode and the number of neutrons detected is read from the unit through a DLL (Dynamic Link Library) driver to a computer running Tera Term (a software terminal emulator which supports serial port connections). Background data were collected overnight for false positive evaluations. The number of neutrons detected in the unit is updated every one second. Background data were recombined into a two-second time interval for the false positive evaluation. The MCNP derived count rate systematic uncertainty is added to the measurement statistical uncertainty to form the total measurement uncertainty. The measured count rates for the source on the side and in front of the detectors are listed in Table 4 and Table 5 for 2-atm and 5.3-atm Helium-3 detectors, respectively.

Table 4: Measured neutron count rates and measurement uncertainties for three HDPE moderator thickness and source-to-detector distance with source on the side of the detector and source in front of the detector. The Helium-3 fill pressure is 2 atm. Error in the parenthesis is the statistical error only and quoted at one standard deviation.

HDPE (cm)	Distance (cm)	Count rate (cps)	
		Source on the side	Source in front
2.54	20	5.091 ± 0.278 (0.036)	1.436 ± 0.079 (0.015)
	25	3.493 ± 0.189 (0.029)	1.108 ± 0.061 (0.015)
	30	2.635 ± 0.142 (0.025)	0.857 ± 0.049 (0.017)
	Background	0.07234 ± 0.00118	
1.91	20	2.599 ± 0.160 (0.022)	0.754 ± 0.047 (0.011)
	25	1.853 ± 0.114 (0.020)	0.543 ± 0.035 (0.012)
	30	1.367 ± 0.083 (0.015)	0.424 ± 0.027 (0.010)
	Background	0.06729 ± 0.00189	
1.27	20	0.839 ± 0.061 (0.011)	0.257 ± 0.019 (0.006)
	25	0.607 ± 0.044 (0.011)	0.193 ± 0.015 (0.005)
	30	0.448 ± 0.033 (0.009)	0.162 ± 0.012 (0.004)
	Background	0.05294 ± 0.00100	

Table 5: Measured neutron count rates and measurement uncertainties for three HDPE moderator thickness and source-to-detector distance with source on the side of the detector and source in front of the detector. The Helium-3 fill pressure is 5.3 atm. Error in the parenthesis is the statistical error only and quoted at one standard deviation.

HDPE (cm)	HV (DAC)	LLD (DAC)	Distance (cm)	Count rate (cps)	
				Source on the side	Source in front
2.54	3884	1000	20	6.707 ± 0.302 (0.055)	1.885 ± 0.087 (0.023)
			25	4.691 ± 0.207 (0.041)	1.392 ± 0.063 (0.019)
			30	3.511 ± 0.152 (0.024)	1.076 ± 0.048 (0.013)
			Background	0.08316 ± 0.00170	
1.91	3884	1000	20	3.489 ± 0.169 (0.030)	0.990 ± 0.049 (0.014)
			25	2.511 ± 0.120 (0.024)	0.717 ± 0.035 (0.010)
			30	1.85 ± 0.088 (0.020)	0.573 ± 0.029 (0.010)
			Background	0.04708 ± 0.00128	
1.91	3884	980	20	3.657 ± 0.179 (0.039)	1.030 ± 0.052 (0.015)
			25	2.619 ± 0.126 (0.029)	0.739 ± 0.036 (0.011)
			30	1.959 ± 0.094 (0.023)	0.578 ± 0.029 (0.009)
			Background	0.05337 ± 0.00136	
1.27	3884	980	20	1.280 ± 0.072 (0.016)	0.387 ± 0.023 (0.008)
			25	0.921 ± 0.052 (0.014)	0.304 ± 0.018 (0.008)
			30	0.721 ± 0.041 (0.012)	0.250 ± 0.015 (0.006)
			Background	0.05025 ± 0.00132	

4. Comparison between Measurements and Simulations

After background corrections, the net measured count rates are summarized in Table 6 for both 2-atm and 5.3-atm Helium-3 detectors.

Table 6: Background subtracted measured count rates for 2-atm and 5.3-atm neutron detectors at three HDPE moderator thickness and source-to-detector distance.

Pressure (atm)	HDPE (cm)	LLD (DAC)	Distance (cm)	Count rate (cps)	
				Source on the side	Source in front
2	1.54		20	5.019 ± 0.287	1.364 ± 0.079
			25	3.420 ± 0.193	1.036 ± 0.060
			30	2.562 ± 0.144	0.785 ± 0.046
	1.91		20	2.532 ± 0.171	0.687 ± 0.047
			25	1.786 ± 0.120	0.476 ± 0.033
			30	1.300 ± 0.087	0.357 ± 0.025
	1.27		20	0.787 ± 0.059	0.204 ± 0.016
			25	0.554 ± 0.042	0.140 ± 0.011
			30	0.396 ± 0.030	0.109 ± 0.008
5.3	2.54	1000	20	6.624 ± 0.327	1.802 ± 0.090
			25	4.608 ± 0.224	1.309 ± 0.065
			30	3.428 ± 0.164	0.992 ± 0.049
	1.91	1000	20	3.442 ± 0.191	0.943 ± 0.053

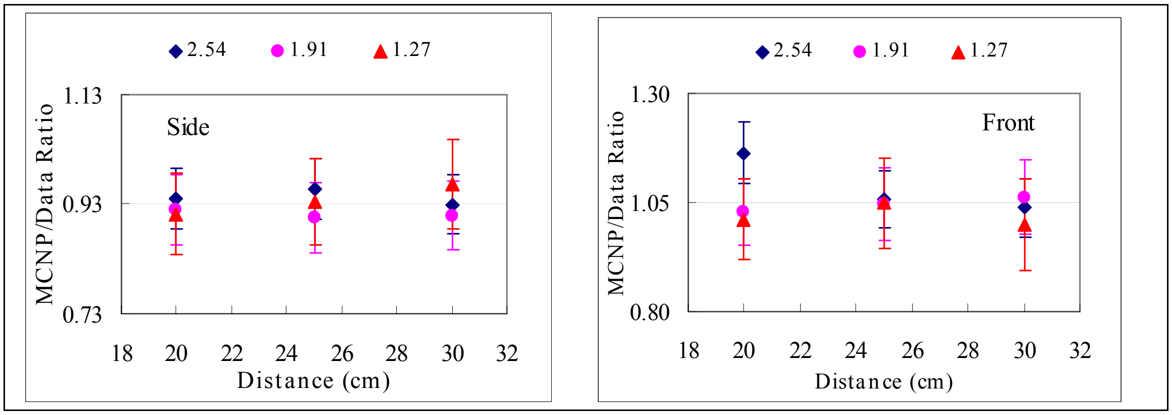
			25	2.463±0.136	0.670±0.038
			30	1.803±0.099	0.526±0.010
	1.91	980	20	3.604±0.199	0.976±0.055
			25	2.565±0.140	0.686±0.038
			30	1.905±0.103	0.524±0.030
	1.27	980	20	1.229±0.077	0.337±0.022
			25	0.871±0.054	0.253±0.017
			30	0.670±0.042	0.200±0.013

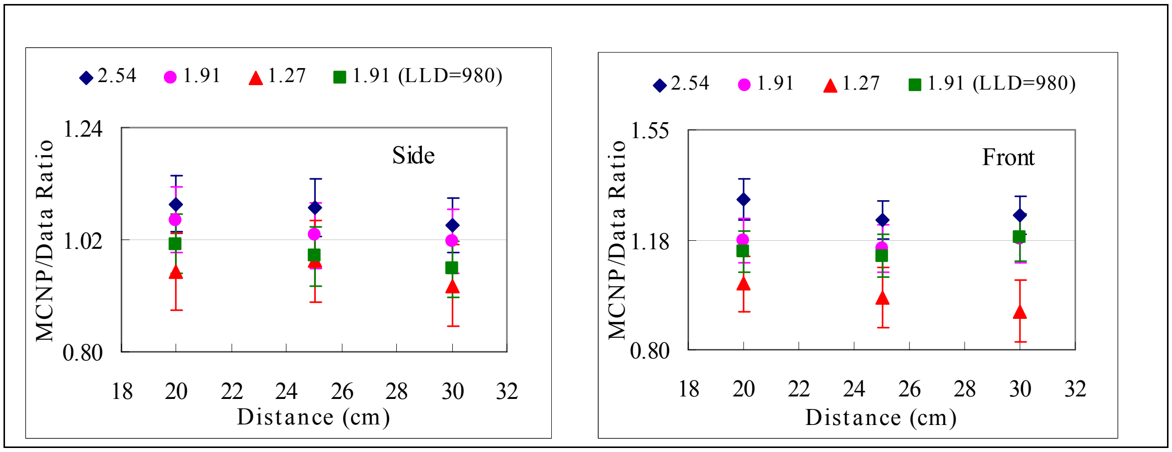
The count rate ratios of the simulations to the measurements for the 2-atm and 5.3-atm Helium-3 detectors with three HDPE moderator thickness and source-to-detector distances are shown in Table 7 and plotted in Figure 6. A good agreement between the simulations and the measurements within measurement uncertainties was found for the case of source on the side of the Helium-3 detectors. This serves to the simulations which may then be used to predict the detector performance for different scenarios. A relatively poor agreement between simulations and measurements for the case of source in front of the detector is due to larger uncertainties during the measurements.

Table 7: The simulations to measurements count rate ratio for various configurations.

P (atm)	d (cm)	Source on the side			Source in front		
		2.54 cm	1.91 cm	1.27 cm	2.54 cm	1.91 cm	1.27 cm
2	20	0.938±0.055	0.918±0.065	0.910±0.075	1.164±0.070	1.029± 0.076	1.011±0.093
	25	0.955±0.056	0.902±0.064	0.932±0.079	1.056±0.065	1.046±0.082	1.049±0.103
	30	0.927±0.054	0.908±0.064	0.965±0.081	1.037±0.067	1.062±0.085	0.999±0.105
5.3 (LLD= 1000)	20	1.085±0.055	1.054±0.062		1.313±0.070	1.173±0.074	
	25	1.078±0.055	1.023±0.061		1.244±0.068	1.146±0.074	
	30	1.044±0.052	1.012±0.059		1.259±0.070	1.179±0.050	
5.3 (LLD= 980)	20		1.006±0.059	0.953±0.067		1.133±0.071	1.025±0.083
	25		0.982±0.058	0.973±0.071		1.120±0.072	0.978±0.086
	30		0.958±0.056	0.925±0.066		1.184±0.080	0.930±0.089

Figure 6: The MCNP/measured count rate ratios for 2-atm (top) and 5.3-atm (bottom) Helium-3 detectors when source is positioned on the side (left) and in front (right) of the detectors for 2.54, 1.91 and 1.27 cm HDPE moderator thickness.





5. Conclusions and Recommendations for Future Modifications

A constant count rate ratio within measurement uncertainties between the benchmark measurements and the simulations for various source-detector distances gives us confidence in the validity of the model we used to simulate the neutron count rate for IN1K. Based on the measured average count rates, the true and false positive probabilities can be calculated for any alarm threshold settings under the assumption of the Poisson statistics. Table 8 presents the calculated true and false positive probabilities and the measured false positive rate for various HDPE moderator thickness and Helium-3 pressures at alarm threshold of 3 neutrons per 2 second time interval (ANSI requirement). Results for Helium-3 pressure other than 2 atm and 5.3 atm are projected based on the simulation results and the measured count rates for the 5.3-atm Helium-3 detector. Also calculated is the upper limit of the false positive rate in 8-hour measurement time interval at 95% confidence level based on simulated count rates.

Table 8: Measured false positive rate, count rate-based false positive rate and true positive probabilities for various HDPE moderator thickness and Helium-3 fill pressures. Results for pressures other than 2-atm and 5.3-atm Helium-3 detectors are projected based on simulations and 5.3-atm detector measurements. The alarm threshold is set at 3 neutrons per 2 second time interval. Numbers with asterisk are projected based on 5.3-atm measurements.

HT	NF	HP	SR	BR	CT	CF	MF	FU
2.54	0.955	2	6.840	0.145	0.967	0.815	0.839	13.639
	1.078	5.3^1	9.215	0.166	0.995	1.219	0.875	18.045
1.91	0.902	2	3.571	0.135	0.692	0.661	0.766	11.908
	0.982	4	4.603	0.096	0.848	0.245	0.364*	7.089
	1.023	5.3^1	4.927	0.094	0.877	0.233	0.000	6.949
	0.982	5.3^2	5.131	0.107	0.894	0.337	0.500	8.170
	0.982	6	5.317	0.111	0.90707	0.374	0.555*	8.603
	0.982	8	5.794	0.121	0.93411	0.480	0.713*	9.837
	0.982	10	6.216	0.129	0.95180	0.589	0.874*	11.089
1.27	0.932	2	1.107	0.106	0.12334	0.329	0.314	8.077
	0.973	4	1.609	0.093	0.24329	0.224	0.198 *	6.833
	0.973	5.3^2	1.742	0.100	0.28090	0.282	0.250	7.528

	0.973	6	1.900	0.110	0.32603	0.364	0.322 *	8.486
	0.973	8	2.102	0.121	0.38345	0.488	0.432 *	9.928
	0.973	10	2.315	0.134	0.44286	0.646	0.572 *	11.735

HT - HDPE thickness in [cm]
NF - Normalization factor to convert MCNP count rate to measured count rate
HP - Helium-3 fill pressure in [atm]
SR - Count rate with Cf-252 source [counts/2s]
BR - Background count rate [counts/2s)
CT - Calculated true positive
CF - Calculated false positive [per hour]
MF - Measured false positive [per hour]
FU - False positive upper limit at 95% confidence level in 8 hour measurement period
1 - LLD = 1000
2 - LLD = 980

In conclusion, our studies have shown that the Canberra IN1K meets the ANSI standard for handheld neutron detectors with alarm threshold set at 3 neutrons per 2 second time interval, and it is very close to meet a strict statistical requirement recommended by IAEA for HHRIID. The IAEA standard recommended less than 1 false positive per hour at 95% confidence level (or 5 false positive in an 8 hour measurement time period) under normal environmental background. The studies have also suggested that it is possible to reduce the amount of HDPE moderator thickness from 2.54 cm in the existing Canberra IN1K to 1.91 cm by increasing the Helium-3 pressure while still meet the current ANSI standard. A 1.91 cm thick HDPE jacket, together with a 5.3-atm Helium-3 tube will have a predicted average false positive rate of approximately 0.337 per hour while still having high true positive probability of 89.4% (at LLD=980, see Table 8). The reduction in HDPE moderator thickness from 2.54 cm to 1.91 cm will reduce the size of the neutron detector and greatly benefit to the more compact packaging concept in future generation of the handheld radiation detection device as well as reduce the weight for the end user. Further reduction of the HDPE moderator thickness may be possible but it is not recommended to reduce the HDPE moderator thickness to further below 1.27 cm since then the true positive probability will be too low and the weight saving is not justified.

Acknowledgements

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