CONF-9610193--1

LA-UR- 96-3409

Title:

Estimated and Observed Performance of a Neutron SNM Portal Monitor for Vehicles

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OCT 30 1996
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Submitted to:
All Russia Research Institute of Automatics
Obninsk, Russia
October 7-11, 1996

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ESTIMATED AND OBSERVED PERFORMANCE OF A NEUTRON SNM PORTAL MONITOR FOR VEHICLES

P. E. Fehlau, D. A. Close, K. L. Coop, and R. York

I. INTRODUCTION

In July 1987, we completed our development of a neutron-detection-based vehicle SNM portal monitor with a conference paper[1] presented at the annual INMM meeting. The paper described the neutron vehicle portal (NVP), described source-response measurements made with it at Los Alamos, and gave our estimate of the monitor's potential performance. Later, in December 1988, we had a chance to do a performance test with the monitor in a plant environment. This paper discusses how our original performance estimate should vary in different circumstances, and it uses the information to make a comparison between the monitor's estimated and actual performance during the 1988 performance testing.

II. THE 1987 DESIGN AND MCNP RESULTS

The final NVP design discussed in the conference paper uses neutron-chamber detectors that are slabs of polyethylene with a hollow, interior chamber that contains four neutron proportional counters. The slabs are 1.22-m (4-ft) by 2.44-m (8-ft) in area, and, from front to back, they have a 1.27-cm (0.5-in) thick wall for neutrons to enter, a 5.08-cm (2-in)-deep hollow chamber, and a 5.08-cm (2-in) thick back wall and edges for neutron moderation. An additional external layer of boron-loaded polyethylene was added to the back to reduce the detector's background response. The hollow chamber contains four, well spaced, 5.08-cm (2-in)-diameter ^{3}He tubes (fill pressure 2 A_s) that are each 1.83-m (6-ft) long. This design was the one offering the best performance among several variations of wall and chamber thicknesses that were originally calculated. The source location used for the performance calculations (using MCNP) was 2.28 m (7.5 ft) away from the chamber and 61 cm (2 ft) above ground (ie, at the horizontal and vertical center).

The results of the MCNP performance calculations for a single NVP detector are given in Table I. Results are given for both bare and moderated spontaneous-fission neutron sources (such as sources containing the californium isotope ^{252}Cf and the plutonium isotope ^{240}Pu). The solid angle factor column gives the detector solid angle subtended by a source divided by the largest possible solid angle, 4π, which corresponds to a detector

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[1] K. L. Coop, P. E. Fehlau, and H. F. Atwater, "A Neutron Portal Monitor for Vehicles," Nucl. Mater. Manage. XVI (Proc. Issue), pp. 454-460 (1987).

entirely surrounding the source. The final value in the table, intrinsic efficiency, was verified with an actual detector and a californium source in 5.08-cm (2-in)-thick polyethylene. That measurement result gave a detector efficiency of 0.082 counts per incident neutron at a 2.28-m (7.5-ft) distance in good agreement with the expected result, 0.090, from the table.

TABLE I
Monte Carlo Calculation Results for a Single NVP Detector

Type of Source (at 2.29 m (7.5 ft) from detector)	Solid Angle Factor $\Omega/4\pi$	Total Efficiency (detected counts/ emitted neutron)	Intrinsic Efficiency (detected counts/ incident neutron)
bare plutonium	0.039	0.0026	0.067
plutonium in 5.08-cm (2-in)-thick polyethylene	0.039	0.0035	0.090

III. THE PROTOTYPE NVP

Two NVP detectors were used for the prototype monitor, and they were spaced 7.32 m (24 ft) apart for measurements in Los Alamos (Fig. 1). In this geometry, a central source would be at a distance of 3.66 m (12 ft) from either detector, and, as it happens, each detector response is reduced to just about half of the Table I results by the decreased solid angle subtended by a source. Hence, the measurement results in Table II for two detectors and a source at 3.66 m (12 ft) do not look much different than the results in Table I for a single detector with a source at 2.28 m (7.5 ft).

Fig. 1. The prototype NVP at Los Alamos

TABLE II
Measured Results for a Two-Detector, 7.32-m (24-ft)-Wide, NVP

Type of Source (at 3.66 m (12 ft) from detector)	Solid Angle Factor $\Omega/4\pi$ (2 Detectors)	Total Efficiency (detected counts/ emitted neutron)	Intrinsic Efficiency (detected counts/ incident neutron)
bare ^{252}Cf	0.033	0.00215	0.065
^{252}Cf in 5.08-cm (2-in)-thick polyethylene	0.033		0.086[2]

During the measurements at Los Alamos, the prototype NVP had an average background count rate of 60 counts/s. In Ref. 1, the monitor's sensitivity for monitoring a stationary vehicle was (inappropriately) estimated by assuming that only one measurement would be made during monitoring, and then it would be compared with a background plus 4-standard-deviation (4σ) alarm threshold derived from a normally distributed count distribution (the distribution used should have been Poisson). The measurement time was 1 second, and the standard deviation was estimated by the square root of the average background count in 1 second. For the 60 count/s background, the alarm threshold was $60 + 4 * \sqrt{60}$, or 60 + 31 counts. A neutron source that gives 31 detected counts per second on the average would have a 0.5 probability of detection, and that 0.5-detection neutron source was used to represent the monitor's sensitivity. Dividing 31 counts by the total efficiency for a bare source in Table II gives a 0.50-detection source strength of 14,400 neutrons/s. Note that this result applies to a source located at the portal center. Sources positioned elsewhere in the monitor might give results that are larger or smaller depending on the location.

The derived source strength could be used to estimate a corresponding plutonium mass in grams that would be detected with 0.5 probability by dividing 14,400 by the expected number of neutrons per second emitted by one gram of the plutonium. In metallic plutonium, the neutrons are contributed by the isotope ^{240}Pu, which emits about 1000 neutrons/s per gram, so multiplying the percentage of the ^{240}Pu isotope in pure metallic plutonium by 1000 gives the expected number of neutrons emitted per gram of plutonium. For other impure or non-metallic forms of plutonium, there may be other important sources of neutrons, such as (alpha,n) reactions, that have to be considered.

This performance estimate is very elementary, however, because the portal could be much narrower, a better method than the single counting interval test could be used, and a more appropriate method using Poisson statistics for the low neutron count rates could be used for establishing an alarm threshold. Hence, we have to look at a number of possible changes to the monitor's design.

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[2] Only the bare source was measured. The moderated result was obtained from the bare result by using bare to moderated ratios from the MCNP results listed in Ref. 1.

IV. VARYING THE MONITOR DESIGN AND THE PERFORMANCE ANALYSIS

The monitor's performance can be improved by a number of changes in its design, and the analysis of performance can be improved as well. For example, the normal distribution "4σ" alarm threshold from the conference paper using 31 counts above the 60 count background would be expected to have a statistical nuisance alarm rate of 1 in 31,600 passages ($P_{alarm} = 0.0000317$). In fact, the normal approximation does not apply, and an estimate using the actual Poisson count distribution gives a statistical alarm rate of 1 per 8333 passages ($P_{alarm} = 0.00012$) for the 60 + 31 threshold. If the rate of 1 in 31,700 were necessary, the alarm threshold would have to be increased, and sensitivity would be reduced. On the other hand, a more practical nuisance alarm rate could have been used to obtain higher sensitivity. For example, a rate of 1 per 1500 passages ($P_{alarm} = 0.000667$) would require a (Poisson) alarm threshold of 60 + 27 and increase the sensitivity by a factor of 31/27. The following paragraphs discuss other changes and how they affect the monitor's performance.

A. Portal Width. Changing the portal width has the effect of increasing the detector solid angle subtended by the source as the width is reduced. Hence more counts can be registered per emitted neutron, and, most likely, smaller sources can be detected. In Table III, relative increases in detected count rate are scaled from the Table I solid angle factor for several narrower widths. The solid angle factor and total efficiency are also indicated for each width. Note that the relative count rates increase significantly as the width is decreased, but the increase is not as fast as "one-over-distance-squared" because of the large size of the detectors.

TABLE III
Impact Of Reducing The Portal Width

Portal Width (center distance)	Solid Angle Factor, $\Omega/4\pi$ (2 Detectors)	Total Efficiency (detected counts/ emitted neutron)	Central Source Relative Count Rate
7.32 (3.66) m, 24 (12) ft	0.033	0.00215	1
5.49 (2.74) m, 18 (9) ft	0.056	0.00365	1.70
4.57 (2.29) m, 15 (7.5) ft	0.077	0.00502	2.33
3.66 (1.83) m, 12 (6) ft	0.112	0.00730	3.39

The improved performance for a narrower portal can be considerable. However, another factor is that as the width decreases, the variation in sensitivity for sources located in different parts of the vehicle becomes greater. Hence, monitoring a vehicle as it moves through the portal, instead of being parked in the portal, becomes attractive.

B. Counting Time. Changing the counting time by making it longer can increase sensitivity in a monitor. The reason is that, as the background count being monitored increases, the amount that must be added to the background to achieve an alarm threshold having a given nuisance alarm rate becomes a smaller fraction of the total. For example, increasing the counting time from 1 second to 16 seconds at 60 counts/s background would increase the Poisson alarm threshold from 60 + 31 to 960 + 116 at a nuisance alarm rate of 1 per 8333 passages (Poisson statistics). The increment above background used for the Poisson alarm threshold changes 51.6% of background to 12.1%, an improvement by a factor of 4.26. Hence, a neutron source strength about one quarter as large should be detected with 0.50 probability.

C. Background. The background counting rate from natural sources in a NVP depends greatly on the altitude at the location where it is being used. Background neutrons are produced by cosmic ray interactions in the atmosphere, and the higher background rates are found at high altitudes closer to where the neutrons are being produced. Hence, the higher the altitude, the higher the monitor count rate. The altitude of Los Alamos, about 2054 M (6738 ft) at the prototype NVP location, is nearly the highest location where monitors are used. At lower altitudes, the NVP count rate decreases, and its sensitivity increases roughly in proportion to the square root of the altitude ratio. Examples of the NVP background observed or expected at various altitudes are shown in Table IV.

TABLE IV
Expected Background Count Rate Vs Altitude

Altitude	Background Count Rate + Alarm Increment (counts/s)	Improvement Factor at 1/8333 Nuisance Alarm Rate
2054 m (6738 ft)	60 + 31	1
1117 m (3664 ft)	29 + 22	1.41
152 m (500 ft)	14 + 16	1.94
0 (sea level)	12 +15	2.06

D. Other Considerations. The improvement in performance obtained by decreasing the portal width, counting for a longer period of time, and moving to a lower altitude location can amount to more than a factor of ten. However, the caveat mentioned earlier, that the sensitivity could be different at positions other than the portal center, still applies. The large dimension of the portal detectors is parallel to a vehicle, but a vehicle longer than 2.44 m (8 ft) overall would extend beyond the detectors. Even a 2.44-m (8-ft)-long vehicle would have reduced sensitivity near its ends for a central source because the solid angle there would be 75% or less of the solid angle at the center.

An inexpensive method for uniformly monitoring vehicles with the NVP is to monitor them in motion as they slowly pass through. This ensures maximum sensitivity for detecting a source located anywhere in the vehicle at some time during its passage through the portal. Another, more expensive, solution for obtaining uniform sensitivity would be to simply use several duplicate detectors to individually monitor small sections of a stationary vehicle, as is done in vehicle monitoring stations.

V. A DRIVE-THROUGH NVP

Drive-through portals have the advantage that, no matter what the vehicle length, any source transported by a vehicle will pass through the portal's most sensitive region between its detectors during passage. Another advantage is that the sensitivity for detecting a source located along a vehicle's centerline will likely be a worst-case sensitivity, and any relocation of the source would likely make it easier to detect.

A drive through portal can take advantage of all of the factors mentioned previously except for the extended monitoring time, which needs to be short enough to match the expected time that a source will be near the detectors. As an example of a useful method for monitoring a moving source, we will use a moving average of several 1-s measurements during vehicle passage. The most recent four measurements will be averaged during passage of a vehicle through the monitor, starting with the most recent measurement results stored by the monitor as the vehicle approached. As each additional measurement result is obtained and stored, it is averaged with the most recent three previous results to maintain a timely 4-s moving average that can be compared with an alarm threshold. The four-interval average is used here because it seems adequate to capture the largest number of source counts for the detector size, widest spacing, and an 8-km/h (5 mph) vehicle speed without leading to an excessive number of alarm threshold comparisons and possible nuisance alarms. We are using the four-interval moving average as an example, and, moreover, only four monitoring decisions are used in calculating nuisance alarm probabilities. In other situations, a shorter moving average or larger number of decisions per passage may be necessary.

A. Average Solid-Angle Factor

Another important factor in monitoring moving vehicles is that the portal's subtended solid angle for a moving source changes during measurements as the source passes by. This is something that must be considered when using static measurement results to estimate sensitivity for detecting moving sources.

In the NVP, the variation in detector solid angle subtended by a moving source during a 1-s count, for example, becomes greater as the portal width decreases. When we correct counting data for the portal width, it may also be necessary to correct for the relative change in solid angle during source movement. The data that we have for estimating source counts during passage through the NVP is from Fig. 7 in the conference paper (reproduced below in Fig. 2), which shows stationary counting results at a 7.32-m (24-ft) spacing. The four cross-hatched regions in the figure represent the first opportunity to obtain the largest 4-interval moving average sum during passage of the source.

To estimate the relative variation in solid angle at different widths, we averaged the subtended solid angles at mid-measurement for the four 1-s counts, and then divided the result by the solid angle for the central 1-second interval. The averages and fractions in Table V reflect the variation in solid angle during vehicle passage at each portal width, and the ratios estimate the relative reduction in source count rate during passage that may occur in a narrower portal than the 7.32-m (24-ft) wide one used to obtain Fig. 2.

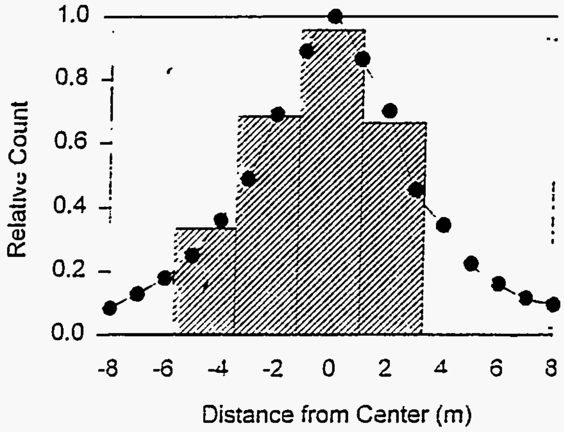

Fig. 2. The counting data from Ref. 1 with superimposed 1-s count areas.

TABLE V
Reduced Solid Angle Factor

Portal Width (center distance)	Average Solid Angle Factor (for 1 detector)	Fraction of the Central Solid Angle Factor	Solid Angle Reduction Ratio
7.32 (3.66) m, 24 (12) ft	0.0129	0.646	1
5.49 (2.74) m, 18 (9) ft	0.0200	0.554	0.858
4.57 (2.29) m, 15 (7.5) ft	0.0259	0.497	0.769
3.66 (1.83) m, 12 (6) ft	0.0348	0.442	0.684

B. Detected Source Counts

To estimate source counts during passage, we used the count rate profile in Fig.2, which represents stationary-source count rates at centerline positions along the vehicle path. The counts rise to a maximum and then fall to background forming a bell-shaped curve. We assumed a vehicle speed of 8 km/h (5 mph) to establish 1-s counting interval distances of 2.24 m through the portal. We positioned the intervals so that one of them, the third, is centered on the peak of the curve, and we used the total counts under the curve in that and the other three crosshatched intervals in Fig. 2 for analysis. For this example, this is the largest 4-s moving-average sum obtained during passage. In Table VI, the relative area under the curve in each interval and the resulting counts in each interval assuming a peak source count rate of 31 net counts/s (from the Ref. 1 example) are shown.

TABLE VI
Counting Data

Interval Number	Relative Area	Signal Counts for the Interval (counts)
1	0.33	10.2
2	0.68	21.1
3	0.95	29.5
4	0.66	20.5

The sum of the four signal counts in Table VI is 81.3 counts, and with the 60 counts/s background rate at Los Alamos, the 4 interval moving average would be 240 + 81.3 counts. The Poisson alarm threshold that gives, for four decisions, the same 1/8333 nuisance alarm rate used earlier is 240 + 65 counts. The 81.3 signal counts exceed the 65 count alarm increment, so the detection probability should be a bit greater than 0.5. The 0.50-probability source estimate is 14,400 * (65/81.3) or a 11,513 neutron/s source. At a lower alarm threshold with 1 per 1500 (P_{alarm} = 0.000667) nuisance alarms per four decisions (P_{alarm} = 0.000166 per decision), the alarm threshold would be 240 + 58, and the sensitivity estimate 11513 * (58/65) or 10273 neutron/s.

One further enhancement to the analysis is that there are actually two chances to obtain the largest moving-average sum. One is the one that appears in Fig. 2, and the other would be the next sum during passage, which would look like the mirror image of Fig. 2. So there are two good chances to detect the source. The combined probability for the two identical chances can be calculated by noting that the total miss probability must be 0.50 for the two chances, or 0.707 for each one of them. Hence, the detection probability of each must be 0.293. The count rate that gives a 0.293 probability of detection for the 1/1500 nuisance alarm example with a 240 + 58 alarm threshold is 289 counts, or 240 +

49. Hence, the source needed to alarm the monitor with probability 0.50 with two chances in this example is 10273 * (49/58) or 8679 neutrons/s. In the 1/8333 nuisance alarm example, the estimate would be 11513 * (56/65) = 9918 neutrons/s.

C. Expected Sensitivity for the Tested NVP

The tested monitor used sequential probability-ratio test (SPRT) logic instead of the moving average method. The methods are quite similar for monitoring moving vehicles[3]. To make the nuisance alarm rate close to the 1/1500 example in the previous paragraph, the SPRT was set for one nuisance alarm per 5780 decisions ($P_{alarm} = .000173$ per decision), which amounts to about 1 per 1500 passages if an average of 4 decisions are made per passage. The major differences between the tests and the 1/1500 example are in the portal width, altitude, and counting time. The net effect of the changes are listed in Table VIII.

TABLE VII
Other Differences in the Tested Portal

Difference	Cause and Effect	Net Effect
Width	5.49 m (18 ft) instead of 7.32 m (24 ft), a factor of 1.69 for narrower width (Table III) and 0.858 (Table V) for reduced average solid angle.	1.45
Altitude	1117 m (3664 ft), a factor of 1.41 (Table IV) for lower background count rate	1.41
Count Time	Already included in the analysis	

The overall additional differences reduce the expected 0.50 detection source to 8679/(1.45 * 1.41) or 4245 neutrons/s.

VI. THE IN-PLANT TESTING RESULTS

The in-plant tests were conducted by driving one of two available sources through the portal at 8 km/h (5 mph). One source had a source strength of 15000 neutron/s and the other 3000 neutron/s based on their inventoried plutonium mass and isotopic content. In each case, the source was enclosed inside of lead and polyethylene shielding. The larger source, in particular, was in a 10-cm (4-in)-thick polyethylene shield that is much thicker than the range of polyethylene thicknesses in Table II. To convert to an equivalent bare

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[3] Paul E. Fehlau, "Comparing a Recursive Digital Filter with the Moving-Average and Sequential Probability-Ratio Detection Methods for SNM Portal Monitors," IEEE Trans. Nucl. Sci., vol. 40, No. 2, pp. 143-146, 1993.

source strength, we used Fig. 3 below, which is taken from a recent journal article[4] where it appears as Fig. 6. The article covers similar neutron detectors used for pedestrian monitoring. The correction amounts to about a 48% reduction in the NVP count rate, so the bare-source equivalent to the shielded source would be 7200 neutrons/s. The smaller source was in 2.5-cm (1-in)-thick polyethylene and would be equivalent to a 3600 neutron/s bare source.

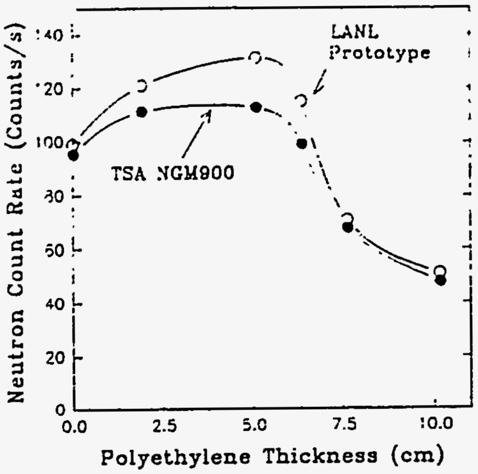

Fig. 3. Variation in neutron count rate with polyethylene thickness for neutron pedestrian monitors.

We were unable to detect the smaller source (3600 neutrons/s), except during one passage when the vehicle was moving slower than 8 km/h (5 mph). We detected the larger source in 9 out of 9 passages at 8 km/h. This result verifies a detection probability for the 7200 neutron/s source of 0.7 with 95% confidence. The results agree with the 4245 neutron/s source strength estimate for 0.50 probability of detection at the end of Sec. V. The 3600 neutron/s source was not detected, and the 7200 neutron/s source was detected with better than 0.5 probability at a 1/1500 nuisance alarm rate.

VII. FURTHER POSSIBLE IMPROVEMENT

Further practical improvement in performance for the NVP may be possible by further reducing its width and operating in the lowest possible background. Going to 3.66-m (12-ft) spacing gives an improvement factor of 3.38 from Table III, but this must be multiplied by the solid angle factor of 0.684 from Table V for a net of 2.31. The altitude

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[4] Paul E. Fehlau, "Integrated Neutron/Gamma-Ray Portal Monitors for Nuclear Safeguards," IEEE Trans. Nucl. Sci., Vol. 4 , No. 4 , pp. 922-926, August 1994.

factor for the lowest background is 2.06 from Table IV. The net result in this case is 8679/(2.31 * 2.06) = 1823 neutrons/s. This is a little less than half of the 0.50 detection test source strength estimated for the in-plant test at the end of Sec. V. So, under the best of circumstances, the sensitivity of the NVP might be bettered by about a factor of two at a sea level location.

VIII. SUMMARY EXAMPLES

SUMMARY EXAMPLES FOR STATIONARY MONITORING			
Monitor Information	**Logic**	**Source Strength for 0.5 Detection**	**Statistical Alarm Rate (per passage)**
7.32 m wide, at 2054 m altitude	Single, 1-s count, "4 σ alarm"	14400 neutrons/s	1/8333
3.66 m wide, at 0 m altitude	Single, 1-s count, "4 σ alarm"	2062 neutrons/s	1/8333
7.32 m wide, at 2054 m altitude	Single, 16-s count, "960 + 116 alarm"	3380 neutrons/s	1/8333
3.66 m wide, at 0 m altitude	Single, 16-s count, "192 + 53 alarm"	484 neutrons/s	1/8333

SUMMARY EXAMPLES FOR DRIVE-THROUGH MONITORING			
Monitor Information	**Logic**	**Source Strength for 0.5 Detection**	**Statistical Alarm Rate (per passage)**
7.32 m wide, at 2054 m altitude	Four 1-s interval moving average, 2 chances	9919	1/8333
7.32 m wide, at 2054 m altitude	Four 1-s interval moving average. 2 chances	8679	1/1500
5.49 m wide, at 1117 m altitude	Four 1-s interval moving average, 2 chances	4245	1/1500
3.66 m wide, at 0 m altitude	Four 1-s interval moving average, 2 chances	1823	1/1500