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Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

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Pacific Northwest National Laboratory
Richland, Washington

Summary

The detection of neutron sources from a considerable distance constitutes a problem that must be treated separately from the bulk of other neutron-detection applications. This report analyzes this problem, describes a number of possible approaches, and describes the design and construction of a square-meter detection system using the approach of moderator-free directional neutron detection. Although experimental results are not the focus of this report, a few preliminary results are offered in the last section. Both theoretical and preliminary experimental results confirm that useful detection of neutron sources for national-security applications is relatively easy at a distance of 50 meters, yet becomes somewhat challenging from a distance of 100 meters.

The square-meter detection system designed for this effort was intended to be, in decreasing order of priority, optimally capable of neutron-source detection at 100 meters, lightweight and easy to use, and low in cost. Thus, the majority of design decisions were driven by the need to maximize sensitivity for remote source detection. Several surprises resulted from this design effort. First, we discovered that ^{10}B, rather than cadmium or gadolinium, must be used as a shielding material. Second, we discovered that a relatively open collimator is best for remote detection. These and other design decisions are described in detail in the third section of this report. The final detector weighs roughly 45 kg and incorporates hardware with a cost of roughly $100K. Of course, lighter or cheaper detection systems could be designed with some reduction in sensitivity. As designed, our 1-square-meter moderator-free detection system is expected to be superior to conventional moderate-and-capture detection for some applications.

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1.0 Introduction

The goal of this report is to explore a number of non-standard options for achieving improved performance for long-range neutron detection. It is widely acknowledged that innovation in the area of long-range radiation detection may be necessary to meet future national-security needs. In some cases, the improvement may come not from more sensitive detection in the strict sense, but rather from other factors, such as detector weight or directional information. A more specific, but no less important, goal of this report is to explore in detail the performance of moderator-free neutron detectors. Both the theoretical and experimental results presented in this report indicate that moderator-free detectors are quite competitive for this application.

It is generally considered to be axiomatic that the amount of moderator present is highly correlated with the performance of neutron-detection systems (Knoll 1989). Exceptions to the liberal use of moderator in the detection system usually resulted from the lack of a practical alternative. We now believe, however, that the case for moderator is not nearly so compelling. Assuming that a standard neutron-capture-based detection medium, such as ^{3}He tubes, ^{6}Li-containing glass fibers, boron-loaded plastic scintillator, etc., is used, a moderator has both advantages and disadvantages.

A moderator allows higher efficiency detectors to be constructed using less capture agent (^{3}He, ^{10}B, Gd, etc.) and allows detection of fast neutrons. The 10 to 30% detection efficiency achieved with moderated detectors is higher than the detection efficiency typically achieved by moderator-free detectors. In addition, the detection efficiency for moderated detection systems is a less sensitive function of the amount of capture agent used. Thus, it is possible to build lower cost detectors with a less severe reduction in detection sensitivity. When using ^{3}He-tubes, this advantage is realized by using fewer tubes with gaps between them. A moderator-free detector is generally forced to place the tubes side-by-side.

Finally, a moderator favors the detection of fast neutrons, which is advantageous in some situations. Fast neutrons undergo less attenuation by air. In addition, a fast-neutron detection system is sometimes less sensitive to the amount and nature of the materials in proximity to the source.

The advantages of moderator-free detection systems are related to physical form, background count rate, and directionality. Moderator-free detectors are, of course, likely to be lighter and more compact than their moderated counterparts. This may be important for some applications. Moderator-free detectors are inherently low background because they are insensitive to the fast component of the background flux. Further, it is possible to achieve further background reduction by shielding the detector with any of the common thermal neutron absorbers (B, Li, Gd, Cd, Sm, or Eu). Although it is possible to shield moderated detectors directionally (Menlove 1976; Byrd 1992), this is far easier to do well with moderator-free detectors. This is simply because of the relative effectiveness of the materials used for thermal and fast neutron shielding, respectively.

The applications for the technologies discussed in this report all involve detection of neutrons from a significant distance. These studies were conducted at Pacific Northwest National Laboratory.[(a)] Foremost among the applications that require the ability to detect neutrons from a distance is aerial- or vehicle-based search and interdiction. Application is, of course, limited to neutron-emitting radionuclides, such as the plutonium isotopes. Moderator-free neutron detection is especially attractive for aerial search because of its relatively low weight.

(a) Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle under Contract DE-AC06-76RLO 1830.

The need to detect neutrons from a remote source is well illustrated by a "request for purchase" issued by the Atomic Weapons Establishment (AWE) of the United Kingdom. The desired detection system must be capable of detecting a neutron source with a strength of 3×10^5 n/s from a distance of 30 meters in one second with 5-sigma statistical confidence. Such a system is to be used for rapid search and localization of neutron-emitting material. The cost and weight for such a system are not specified, although it is reasonable to suppose that a size not much greater than one square meter would allow for vehicle mounting and/or some degree of portability.

A second possible application for moderator-free and/or long-range neutron detection may be detection of human intrusion. It is generally acknowledged that neutron detection offers an attractive option for monitoring storage vaults. A neutron-based monitoring system is sensitive to both the sources being stored and to the environment of the room itself. It is possible that moderator-free neutron detection would be the preferred approach for this application, with its increased sensitivity to those neutrons that have scattered within the room a relatively large number of times.

The final application category of which we are aware is to waste characterization. Because the location of suspected transuranic (TRU) waste is known, it is possible to surround the waste with low-absorption moderating materials such as heavy water or graphite. This moderating "cave" creates a strong flux of thermalized neutrons that can be detected remotely using a moderator-free neutron detector. Conventional neutron-detection equipment cannot measure remotely handled waste because of excessive gamma-ray flux. This approach, however, can perform such measurements. In addition, large or oddly shaped waste may be characterized in this manner. (Such waste may not fit into standard waste-characterization systems.) The need for characterization sufficient to permit segregation of these types of waste is a serious concern at the Hanford site.

2.0 Possible Approaches

The goal of this section is to present and at least partially analyze a number of possible approaches to long-range neutron detection. To this end, six possible approaches are listed and briefly described in Section 2.1. Several of these approaches are relatively novel. In addition, Section 2.2 presents interesting numerical results specific to long-range detection using the unshielded, moderator-free detection approach.

2.1 Approaches

2.1.1 Moderated Neutron Detection

Moderation followed by capture is the conventional approach to neutron detection that has been used in well over 90% of all neutron-detection applications outside of the realm of fundamental physics. Typical detection efficiencies are between 10% and 25% for planar detectors, although somewhat higher efficiencies are possible with especially heavy and expensive detector systems. Roughly speaking, a moderated detector records incident fast neutrons, but is insensitive to incident thermal neutrons. (Note the complete contrast with the moderator-free approaches that follow.)

Many of the advantages and disadvantages of moderated neutron detection can be inferred from the advantages and disadvantages of moderators generally as discussed above. For the specific application of neutron-source detection at 100 meters, moderated neutron detection is significantly aided by the fact that fast neutrons undergo less attenuation in air. However, this advantage may not uniquely apply to moderated detectors. Section 2.3 presents numerical evidence for the importance of fast neutrons in moderator-free neutron detection.

Consider the use of conventional "moderate-and-capture" neutron detectors for the benchmark problem of detecting a 3×10^5 n/s source from 30 meters away. The background at sea level at the latitude of the United Kingdom is not likely to be lower than the Hanford (~45 degree latitude) background of 0.014 n/(cm^2-s). A good detection efficiency for a moderated detector using ^{3}He tubes or similar neutron detection medium would be 25% (Reilly 1991). Assuming that background neutrons behave like fission neutrons in the detector, the background count rate for a square meter detector should be roughly 35 cps. The geometric efficiency for a square-meter detector at 30 meters is roughly 9×10^{-5}, leading to an expected signal of roughly 6 cps. Thus, this approach allows roughly 1-sigma detection in 1 second, or 5-sigma detection is roughly 25 seconds, but falls well short of the desired 5-sigma detection in 1 second.

2.1.2 Thermal Neutron Self-Coded Array (SCA)

Coded-array imaging is a general technique in which the incident radiation is made to pass through a specially patterned, absorbing "mask" that casts a shadow onto a radiation detector that is capable of recording the two-dimensional location information. The pattern coded into the mask is specially chosen so that the shadow of a point source striking the radiation detector can be recognized using sophisticated mathematical analysis. This process not only allows the angular position of any radiation sources to be accurately calculated, but also provides a powerful method for reducing the effective radiation background. Simply put, the background can be effectively rejected because it does not share the spatial pattern that the mask imposes upon the "signal" neutron flux.

Coded-array imaging of thermal neutrons is relatively straightforward because of the ease with which an absorbing mask for thermal neutrons can be constructed. An SCA thermal-neutron imager with a 20-cm $\times$ 20-cm active area was constructed at Brookhaven National Laboratory and applied to the problem of long-range neutron detection (Vanier 1995).

The main advantage of SCA thermal-neutron imaging is its ability to form a relatively accurate two-dimensional image of the neutron flux arriving at a given location. This ability would allow not only detection, but also precise location of neutron sources that are sufficiently close for the technique to work. The primary disadvantage of this technique is that it productively records only those thermal neutrons that have not scattered after leaving the vicinity of the source. This limitation combined with the relatively small active areas that are possible in practice limits the applicability of this technique to roughly 25 meters. Further, this technique is known to suffer whenever an image contains multiple-point sources or contains a distributed source (Jupp 1998).

While this technique has its appropriate applications, it is hard to apply to challenging long-range neutron-detection problems on account of low signal. Roughly 10% of source neutrons may be expected to thermalize near the source, 50% of thermal neutrons are lost in the “mask,” and 50% of thermal neutrons scatter in the air. Since a detector with an overall size of 1 m^2 may have an active area of only 0.25 m^2, the expected signal count rate from a 3×10^5 n/s source at 30 meters can be estimated as 0.15 cps. Depending upon the distribution of moderator near the source, this signal may fall within a signal pixel of the image or may be distributed over a number of pixels.

2.1.3 Fast-Neutron SCA

It is also possible to image a fast-neutron flux using a self-coded array. Figure 2.1 shows a possible implementation of such a detection system that uses the time-of-flight between two sheets of plastic scintillator to recognize neutron events. Since the neutrons travel much slower than the speed of light, effective discrimination against gamma rays is possible. Only the first of the two detection planes need be instrumented to record positional information. The mask shown in Figure 2.1 could be constructed from a roughly 10-cm-thick slab of polyethylene. Neutrons passing through an “opaque” part of such a mask would be unlikely to emerge with sufficient energy to be recorded in the two subsequent planes of plastic scintillator. Note that the relatively large thickness of the required mask will limit the spatial resolution that is possible with this method.

It may also be possible to use a moderated detector for this approach using some means to record positional information. Positional information has previously been obtained using resistive wire anodes within otherwise conventional neutron-detecting proportional counters such as ^{3}He tubes.

Monte Carlo N-Particle Transport Code (MCNP) (Briesmeister 1993) calculations have indicated that an efficiency of roughly 10% can be expected for the technique shown in Figure 2.1. Assuming that 50% of neutrons are lost in the mask, that the detector is 10% efficient, and that an active area of 0.25 m^2 is used, the expected signal from a 3×10^5 n/s source at 30 meters is roughly 0.3 cps. It is difficult to estimate the background since no construction along these lines has ever been attempted. It is reasonable to assume that a background count rate of 7 cps is distributed among all of the pixels in the image. Since the number of pixels may exceed 100, the background rate should be greatly exceeded by the signal.

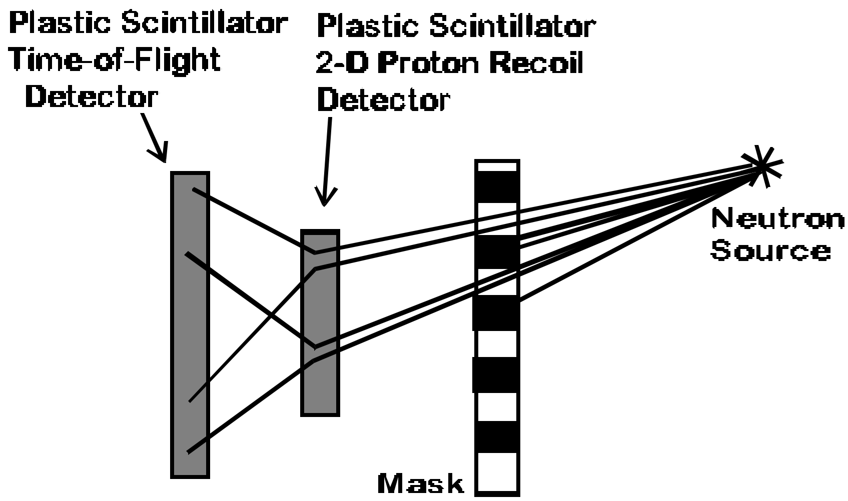

Figure 2.1. Schematic Diagram Showing One Possible Implementation for a Fast Neutron SCA Imager. The three planes, moving right-to-left, are the coded array mask, the start-trigger scintillator able to record proton recoil events with 2-D position resolution, and the stop-trigger scintillator able to record recoil events and reject gamma rays based on time-of-flight.

Although both SCA approaches lack the signal strength necessary for rapid measurements, they both achieve a dramatic improvement in the signal-to-noise level. If sufficient time is available, SCA techniques should work well, and they do provide valuable positional information. Note also that the fast neutron SCA is likely to work well at much larger distances from the source than the thermal neutron SCA because scattering of fast neutrons is relatively unimportant.

2.1.4 Phase-Sensitive Detection

Phase-sensitive detection is essentially an extreme case of the SCA approaches discussed above in the limit where the image consists of only one "pixel." (This means that the system detects sources that lie in one specific direction and learns nothing about sources in other directions.) Figure 2.2 shows a possible implementation for phase-sensitive detection. Either thermal or fast-neutron detection can be used with this approach. Phase-sensitive detection also involves placing a "mask" between the suspected neutron source and the detection medium. However, the mask is much simpler because it is only necessary to recognize the identity of one pattern in the image. For example, something as simple as stripes, a checkerboard pattern, or even a temporal modulation may be used as a mask. The detection equipment can also be correspondingly simplified since accurate two-dimensional position information may not be necessary.

A significant advantage of phase-sensitive detection is that large active area and relatively high detection efficiencies should be readily achievable. Because the field of view is relatively small, however, phase-sensitive detection may be most useful when the location of a suspected source is known. The signal can be calculated by assuming a 50% loss in the mask, a detection efficiency of 20% for fast neutrons, a thermalization efficiency of 10% for thermal neutrons, and a loss of 50% of thermal neutrons by air scattering. Under the further assumption of a square-meter active area, the fast and thermal-neutron signals from a 3×10^5 n/s source at 30 meters become 2.6 and 0.67 cps, respectively. The fast- and thermal-neutron backgrounds of roughly 14 cps and 7 cps will not share the spatial pattern imposed by the mask and thus will ultimately be distinguished from the signal. Under these conditions, roughly 1 minute would be required for definitive identification of the signal and its location. This approach may be the simplest and most rapid technique capable of providing positional information in addition to simple detection of sources. However, this approach does not provide a neutron-flux "image."

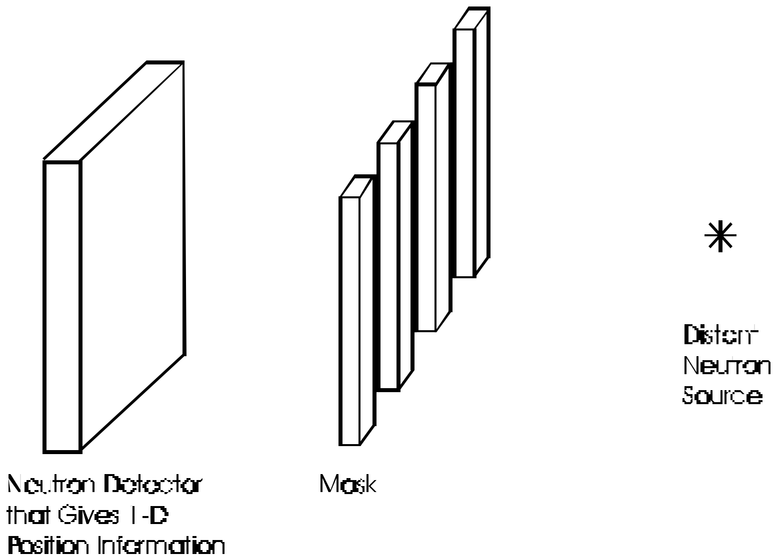

Figure 2.2. Schematic Diagram Showing a Possible Implementation of Phase Sensitive Detection. The neutron detector need only recognize the single pattern imposed upon the signal neutron flux by the mask.

2.1.5 Moderator-Free, Unshielded Thermal-Neutron Detection

For the application of long-range neutron detection, this approach allows construction of an exceptionally simple and high-performance detector. The detector may consist of nothing more than an array of ^{3}He tubes, the hardware necessary to hold them, and the electronics necessary for signal processing. The background for a square-meter detector should be roughly 10 cps. There is reason to believe that the signal strength for a 3×10^5 n/s source at 30 meters may also be as high as 10 cps. Under these conditions, the statistical confidence of a 1-second measurement is roughly 3 sigma. This performance is three times better than achieved with conventional moderated neutron detection. The performance achieved by this approach will be tested in FY99 using the square-meter detector designed and built at PNNL during FY1998. The thermal-neutron shielding designed for this detector can be easily removed.

2.1.6 Moderator-Free, Shielded (Directional) Thermal-Neutron Detection

Figure 2.3 shows a schematic view of the detection process used for this approach. The only difference between this approach and the previous is the addition of an effective thermal neutron. The shield reduces the detector background dramatically while (hopefully) reducing the signal by a lesser amount. The PNNL square-meter neutron detector constructed in 1998 was primarily intended for testing this approach. The expected background is roughly 1 cps. The expected signal at 30 meters distance from a 3×10^5 n/s source should be roughly 2 cps. (This estimate is approximate and is based on the preliminary results discussed in Section III.) Although this represents an improved signal-to-noise ratio relative to the previous approach, 3 seconds are necessary for 3-sigma confidence. While the performance of this technique is somewhat inferior to that of the previous (unshielded approach), it should be noted that this approach does provide limited directional information. In principle, a source could be located accurately via "triangulation." In addition, this approach should be superior to conventional moderated neutron detection at the distance of 30 meters.

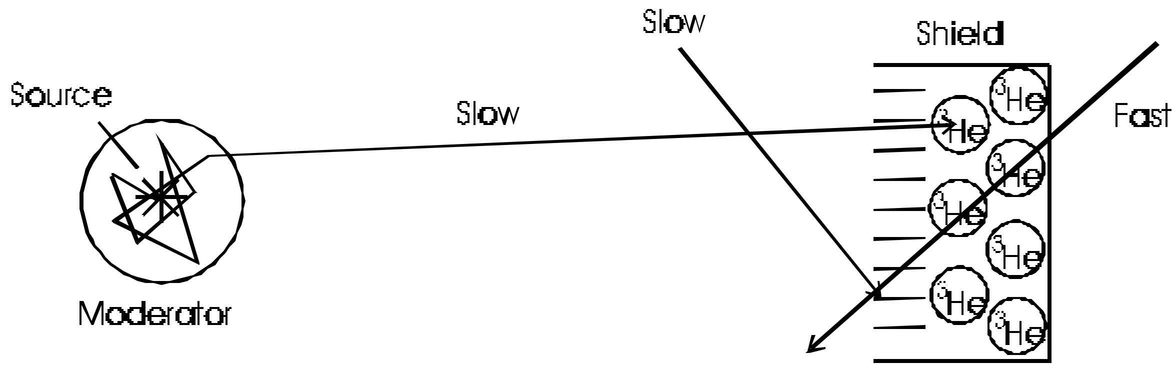

Figure 2.3. Schematic View of the Process Used for Directional, Moderator-Free Thermal Neutron Detection. A shielded set of thermal neutron detectors such as ^{3}He tubes is shielded against thermal neutrons arriving from all but the forward direction. The lack of moderator causes fast neutrons from any direction to pass through the detector.

2.2 Calculations Relating to Moderator-Free Long-Range Neutron Detection

Three major factors motivate the use of numerical calculations in our effort to design, build, and test a technically superior long-range neutron detector. First, these calculations allow prediction of detector performance under conditions not easily created in the laboratory or before the execution of laboratory experiments. Second, these calculations can greatly aid the design of specific detection systems such as the moderator-free detection system constructed at PNNL. Lastly, these calculations can be used to aid the understanding of experimental results that fail to conform to expectations.

Calculations geared to each of these motivating factors were completed during FY1998. A number of design calculations have wide application both for understanding the physics of the constructed detector and for constructing possible future detection systems. These calculations will be described in Section III along with a detailed description of the detector design. A number of additional calculations were also completed to allow prediction of detector performance under long-range neutron-detection scenarios. This subsection presents a selected set of these calculations.

The goals of this study were to understand as much as possible about the processes by which thermal and fast neutrons are detected by a moderator-free detector at long range and to understand the relative importance of thermal and fast neutrons. At the start of this project, it was believed that the dominant process for neutron detection involved moderation of fast neutrons in the immediate vicinity of the source, transport of these neutrons to the detector, and finally, capture of slow neutrons in the detector. These calculations were intended to test this hypothesis.

Figure 2.4 contains the results of a series of MCNP calculations that assume the geometry given in Figure 2.5. A neutron source is placed 2 meters above the ground, which is assumed to have the average composition of the earth's crust. (Wet ground or water surfaces will, of course, lead to different results.) A 2-meter tall, 10-cm-thick, 1-atmosphere-layer of pure ^{3}He is assumed to surround the source at some radius. This cylindrical shell of ^{3}He runs from the level of the ground to the level of the neutron source. There is no moderator or shielding in the vicinity of the ^{3}He.

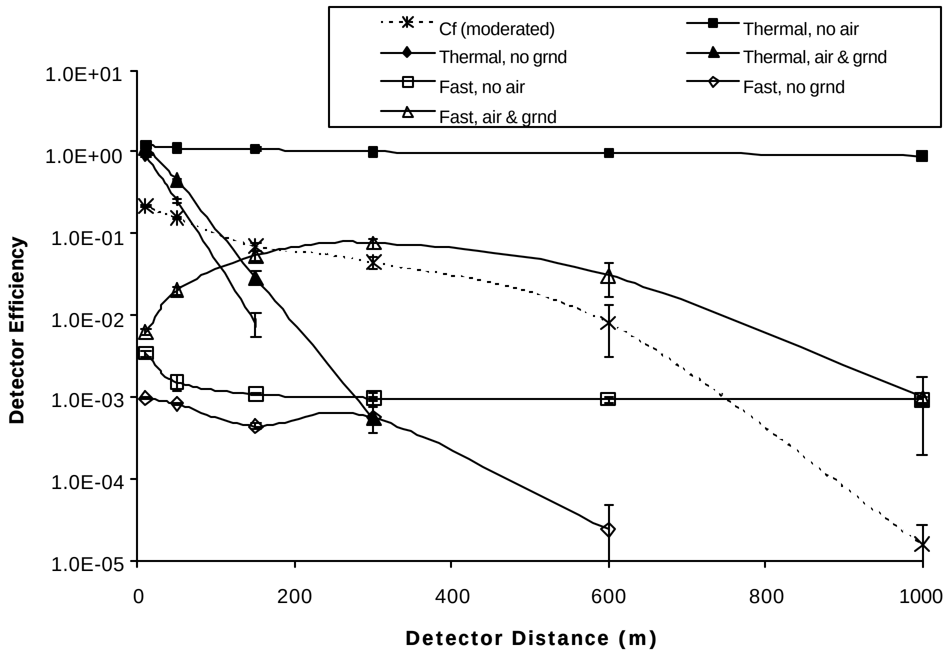

Figure 2.4. Detection Efficiency of a 2-Meter-Tall, 10-cm-Thick Cylindrical Shell of 1-Atmosphere ^{3}He Placed Above a Ground Assumed to Have the Average Composition of the Earth's Crust. These results are the result of MCNP calculations. The detection efficiency plotted here is defined as the fraction of neutrons captured within the cylindrical shell divided by the geometric efficiency.

The cylinder of ^{3}He in these calculations functions as a very large long-range neutron detector. Using only 1 square meter of detector would not have allowed this calculation to proceed on account of poor statistics. This "enlargement" of the detector should have a minimal affect on the physics that we are trying to understand, and is not reflected in Figure 2.4 because of the method used to present the results. Figure 2.4 plots the "detection efficiency" as a function of the radius of the ^{3}He cylinder. The detection efficiency is the ratio of neutrons actually recorded (captured) to the number of neutrons that *would* have passed through the detector were both air and ground replaced by vacuum. This efficiency is obtained by dividing the number of neutrons actually recorded by a calculated geometrical efficiency.

There are seven different curves in Figure 2.4 representing seven different numerical experiments. Three of the experiments assume the existence of a purely thermal (0.025 eV) neutron source with no moderator near the source. Another three experiments assume the existence of a fast (1.0 MeV) neutron source, again with no moderator. Finally, one run uses a "real" neutron source that is modeled as a ^{252}Cf neutron source surrounded by a 10-cm-radius sphere of polyethylene moderator. The list below offers interpretations of the results for each of the seven runs:

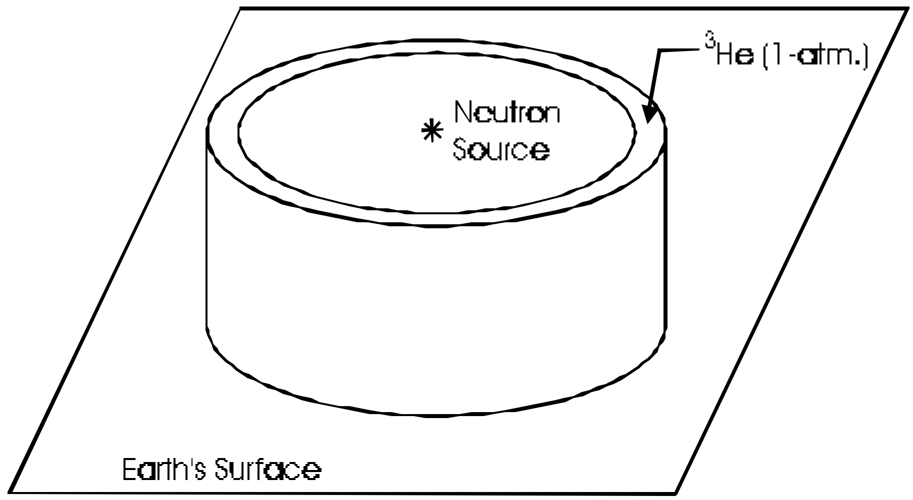

Figure 2.5. Geometry for the MCNP Calculations Used to Generate Figure 2.4. A 2-meter-tall, 10-cm-thick cylindrical shell of 1-atmosphere ^{3}He placed above a ground assumed to have the average composition of the earth's crust. The source is located at the geometrical center of the top of the ^{3}He cylindrical shell.

- **Thermal, No Air (Ground Present):** The nearly straight-line shape of this curve simply reflects the lack of air attenuation. The detection efficiency asymptotes to a value of nearly 100% as would be expected for a thermal neutron flux. We conclude that the >100% efficiency for small detector radii is indicative of the reflection of neutrons from the ground.
- **Fast, No Air (Ground Present):** This curve is very much like the previous except for two key differences. First, the detection efficiency for fast neutrons is only 0.1% as large as for thermal neutrons. Second, the small-radius effect of the ground is much more substantial. This is likely because the ground is able to moderate some fast neutrons, thereby greatly increasing their ability to be detected. The effect of the ground diminishes at large radii simply because the solid angle subtended by the ground approaches zero for large radii.
- **Thermal, No Ground (Air Present):** This curve appears to indicate straightforward exponential attenuation of thermal neutrons by air.
- **Thermal, Ground, and Air Present:** This curve also appears to indicate a nearly exponential attenuation of neutrons with distance, although the air and ground together act to improve detection efficiency through reflection.
- **Fast, No Ground (Air Present):** The low detection efficiency achieved by this experiment indicates the importance of the ground in the detection of fast neutrons. Also, the relatively gradual decrease (statistical uncertainties are relatively large) indicates that air attenuation of fast neutrons, while weaker than for thermal neutrons, is important over distances of several hundred meters.
- **Fast, Ground, and Air Present:** The significant increase in detection efficiency with distance observed for this experiment indicates the importance of ground and air working together to create a flux of significantly moderated neutrons within about 500 meters from a fast-neutron source. For very small radii, the detector records the fast source neutrons with poor efficiency

and is not yet large enough to sample a significant number of the thermalized neutrons created by the action of the air and the ground. As the radius increases, the detector acquired more surface area with which to capture moderated neutrons. Clearly, the scale length for this moderation process is much greater than 100 meters. (Note that a real moderated detector is of fixed area and thus has an overall detection efficiency that includes the factor $1/r^2$, where r is the standoff distance.

- **Californium-252 Source with 10-cm-Radius Polyethylene Sphere:** This curve is complex, but one very important conclusion can be firmly drawn. Neutrons that do *not* thermalize in the vicinity of the source are important in determining the signal count rate. There are three reasons to believe this. First, the overall detection efficiency at small radii is roughly 20%. This is a greater fraction than the fraction of thermalized neutrons expected to emerge from the polyethylene sphere. Thus, fast or at least epithermal neutrons must play some role. Second, the rate at which the detection efficiency decreases with radius is clearly less that the rate that would be expected were source-thermalized neutrons important. Finally, this curve appears to roughly follow the dependence of the curve for fast neutrons with air and ground present. This would be expected if only fast neutrons were important for the moderated Californium source experiment.

In conclusion, these calculations indicate that fast neutrons play an important role in determining the performance of moderator-free neutron detectors. In a sense, this is not a surprising conclusion. Of course, a truly moderator-free neutron detector that uses ^{3}He tubes does not exist. By omitting the moderator from the detector's design and construction, we have simply led to the use of the surrounding air, ground, or other environmental materials as the moderator for the detector. The surprise in these results could be stated as the degree to which this environmental moderation is an effective process.

3.0 Design of a Moderator-Free Detector

The ideal moderator-free detection system is, of course, not constructable with the materials currently available. The perfect system would have a shield that stops none of the thermal neutrons incident from the desired direction and all of those neutrons incident from other directions. In addition, the neutron detectors used would record thermal neutrons with 100% efficiency, but completely fail to record neutrons energetic enough to penetrate the shield. This section describes the design of detection systems that most closely approach this ideal. The shield, collimator, and detection media form the three major components of an overall detection system. The issues associated with each of these three components are discussed separately below.

The overall importance of size, cost, and weight must be decided before any design effort. The technical performance (sensitivity) of a moderator-free detection system always increases with size, weight, and cost. Of course, a particular application may impose limitations and/or may require a given level of sensitivity. The tradeoffs associated with these parameters must be carefully considered as part of each design effort. The detection system constructed at PNNL was designed to have the maximum sensitivity that could be achieved with a square-meter detector. While cost and weight were certainly considered in design decisions, sensitivity was considered to be paramount.

Figure 3.1 shows a photo of the completed detection system. The ^{3}He tubes, each with their signal processing electronics, can be seen running vertically in this photo. The collimating side of the detector faces the camera in this photograph, allowing visibility for the ^{3}He tubes. Shielding material covers the remaining 5 sides of the detector, but is covered by aluminum sheets used for mechanical support and protection of the shielding.

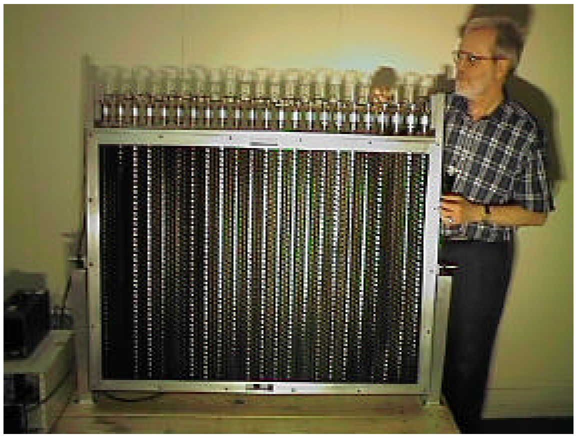

Figure 3.1. Photo of the Completed Square-Meter Moderator-Free Neutron Detection System with ^{3}He Tubes, Collimator, Signal Processing Electronics, and Shield. The detector is roughly 10-cm thick.

3.1 Neutron-Detection Media

It is desired that the detection media used in the moderator-free neutron detector have minimum cost and weight, the ability to clearly discriminate against gamma-ray interactions, and the maximum efficiency for thermal-neutron detection. Helium-3 proportional counters provide an attractive detection medium because of their excellent neutron/gamma ray discrimination, potential for high detection efficiency, and transportability. Boron-10 trifluoride proportional counters are physically similar to ^{3}He tubes, but lack the transportability as a result of real or perceived hazards. Other neutron-detector types generally lack the combination of excellent gamma-ray rejection and high detection efficiency provided by ^{3}He tubes.

Achieving high efficiency is significantly more difficult for a moderator-free detector than for a conventional moderated detector. The reason lies in the fact that neutrons typically get only one chance to be captured and detected as they pass through the active region of the detector. The shield behind the detector absorbs most of the thermal neutrons that transit the detection media without interaction. Even in an unshielded or imperfectly shielded detector, the neutron is unlikely to return. This situation is in complete contrast to the situation within moderated detectors where repeated neutron recoil allows repeated chances for neutrons to be detected. A high detection efficiency for a moderator-free detection system requires that each transiting neutron has a high probability of detection during a single transit of the detection media. The probability that a thermal neutron will not be detected during transit of a region containing ^{3}He is given by exp(-8PL), where P is the pressure in atmospheres, L is the transit length in cm, and 8=0.14/(Atm-cm) is the absorption coefficient. For example, the probability that a neutron with the average thermal energy will not be absorbed when crossing 5 cm of 4-atmosphere ^{3}He is 6%.

Table 1 shows the MCNP-calculated relative detection efficiency of various arrangements of ^{3}He tubes, each of which achieves 1-square meter of area. The geometries described in the table correspond to a single row, double row, and intermediate “zigzag” arrangements. Relative efficiency is given for clarity since the exact detection efficiency for any given application will depend on a number of parameters such as neutron energy spectrum, collimator construction, and general geometry. For these calculations, a thermal neutron flux was assumed. The efficiencies are normalized to the arrangement and pressure actually used in the PNNL detection system. Note that using a smaller number of higher-pressure tubes generally leads to only a modest loss in detection efficiency. However, using a larger number of lower-pressure tubes increases size, weight, and cost.

Table 3.1. Efficiency of Various Arrangements of 5.08-cm-Diameter ^{3}He Proportional Counters Used to Construct Large-Area Thermal-Neutron Detectors. Note that only for a center-to-center spacing of 5.08 cm can the detector be constructed as a single row.

Pressure (Atmospheres)	Center-to-Center Spacing (cm)	Number of Tubes per Meter	Tube Geometry	Relative Efficiency
2	2.54	39	Single Row	1.05
2	3.81	26	“Zigzag”	0.88
2	5.08	20	Double Row	0.69
4	2.54	39	Single Row	1.35
4	3.81	26	“Zigzag”	1.20
4	5.08	20	Double Row	1.00
8	5.08	20	Double Row	1.28

The PNNL detection system was constructed using 23 counters (5.08-cm diameter, 86-cm length) to achieve 1 square meter of detection area. The neutron detecting tubes are placed side-by-side and filled with 4 atmospheres of Helium-3 to maximize the detection efficiency for a fixed cost and weight. Signal processing electronics (Precision Data Technology, Everett, Washington, manufactured the signal processing electronics) placed at the ends of each tube maximize the system's tolerance of gamma-ray exposure.

3.2 The Shield

The shield can in principle be constructed from any of the class of materials such as cadmium, gadolinium, boron, lithium, or europium that has an exceptionally high thermal-neutron-capture cross section. In fact, it takes remarkably little of each of these materials to closely approach the desired 100% efficiency for stopping thermal (0.025 eV) neutrons. There are, however, several additional considerations. Boron and lithium provide the best stopping power per unit of weight. Practicality tends to favor the use of boron or gadolinium since they can easily be obtained in a safe but relatively pure form. An examination of the capture cross sections as a function of energy strongly favors boron as shown in Figure 3.2. The "detection probability" shown in Figure 3.2 is the product of two separate probabilities: the probability that a neutron will penetrate a shield formed from 1 kg/m^2, and the probability that such a neutron will be captured (detected) while traversing 5 cm of 4-atmosphere helium-3 gas. This figure indicates that the background neutrons most likely to be recorded by a ^{10}B-shielded moderator-free detection system are epithermal neutrons with energies of roughly 10.0 eV. The detection system recently constructed at PNNL uses boron carbide powder (B_4C) that is enriched in the isotope ^{10}B for constructing the shield and collimator.

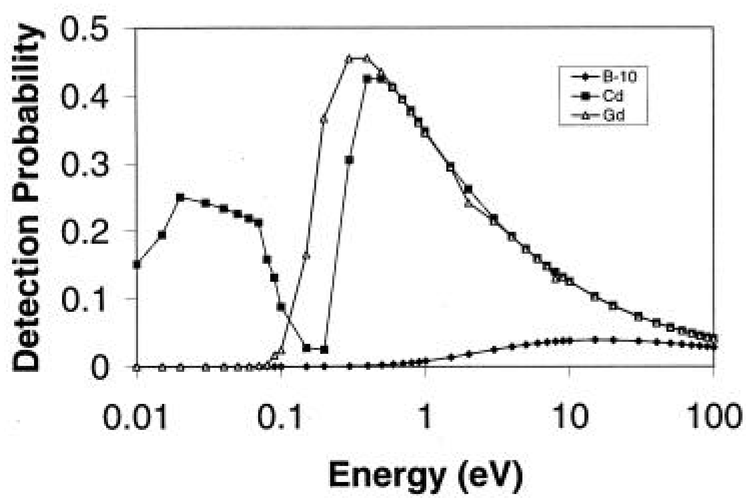

Figure 3.2. Plot of the Probability that a Neutron Will Pass Through 1 kg/m^2 of Shielding Material and Subsequently Be Captured Within a Bank of ^3He Tubes as a Function of the Shielding Material and the Neutron Energy. Clearly, ^{10}B is a superior shielding material.

A further issue in constructing the shield is the necessary amount of shielding material. While more shielding material is clearly better, the situation is one of strongly decreasing benefit to additional increases in the amount of shield material. MCNP transport calculations indicate that in many applications, the response of completely shielded ^3He tubes will depend roughly inversely on the amount of ^{10}B used. That is, each doubling of the shield mass density results in roughly a halving of the response of a ^{3}He neutron detector that is completely covered by that shield. However, since the shield does not completely surround the ^{3}He tubes in a directional detector, there is little point to improving the shield's effectiveness beyond roughly 95%. It is for this reason that the PNNL detector was constructed with roughly 1.0 kg/m^2 of ^{10}B in the shield and collimator.

Unlike other shield materials, such as cadmium or gadolinium, the pure form of boron is not mechanically suitable for shield construction. For this reason, it is necessary to understand the effect of an admixture of hydrogenous material to the shield. The shield and collimator designed and constructed for the PNNL detection system used B_4C powder that was mixed with a hydrogenous "binder" to allow the formation of a robust, 1-mm-thick coating.[a] While any moderator in this detector is clearly undesirable, a small amount is found to be acceptable. MCNP calculations indicate that the admixture of 1 kg/m^2 of CH_2 to an equal mass density of ^{10}B increases the detector's background count rate by roughly 25%. Less hydrogenous material than this was used in the construction of the PNNL detection system.

3.3 The Collimator

The function of the collimator is to act as a shield for those neutrons that are not incident from a particular direction. For this reason, all of the design principles discussed in the previous subsection apply in addition to collimator design. The PNNL collimator was constructed from the same $^{10}B_4C$-binder mixture as was used for the remainder of the shield.

There are, however, additional design considerations for the collimator itself. There is no "perfect" geometry for the collimator, where a perfect geometry is defined as one whose response depends only on the angle between an incident neutron's actual trajectory and the direction in which the detector is "aimed." A hexagonal lattice is a fairly good approximation to the ideal collimator, and a square lattice is also probably satisfactory. The collimator can range in thickness tremendously from less than 3 cm to even greater than the lateral size of the entire detector. The collimator thickness does not matter provided that the ratio of unit cell size to thickness remains constant. The ability to make relatively thin collimators is important in that it allows the construction of low-profile detection systems. The PNNL collimator is formed from a 2.5-cm thick section of lightweight aluminum honeycomb. The face-to-face separation distance for the hexagonal cells used in the collimator is 1.91 cm. Figure 3.3 contains a close-up photograph of the PNNL collimator.

Determining the appropriate degree of collimation requires a detailed understanding of the process by which neutrons reach the detector. The collimator used to construct the PNNL detection system has a collimation angle of roughly 45 degrees, corresponding to an open solid angle of roughly 5%. The choice of this relatively poor collimator resulted from our knowledge of the diffusive process by which many neutrons are transported from the source to the detector. Additionally, any neutrons that have been moderated by either the air or the ground are not likely to strike the detector from precisely the direction of the neutron source. Figure 3.4 shows four calculated images that would be taken by an idealized thermal neutron "camera" from distances of 10, 40, 70, and 100 meters from a thermal-neutron source surrounded only by air. The "images" shown in this figure consist of two-dimensional plots of the neutron flux arriving at a distant detector as a function of the two angles that describe direction with respect to the actual direction of the source. The full range on both of the angular axes corresponds to 45 degrees. The third axis describing the intensity of the neutron flux is normalized for each of the plots. (The image is much brighter at 10 meters than at 100 meters.) These calculations indicate that

(a) Euro Collimators Limited, Lansdown Industrial Estate, Cheltenham, England, GL581PS, manufactured the collimator and shield.

unscattered neutrons constitute less and less of the flux striking the detector as the source-to-detector distance is increased. Clearly, a very narrow collimator would be unsuited for long-range neutron detection.

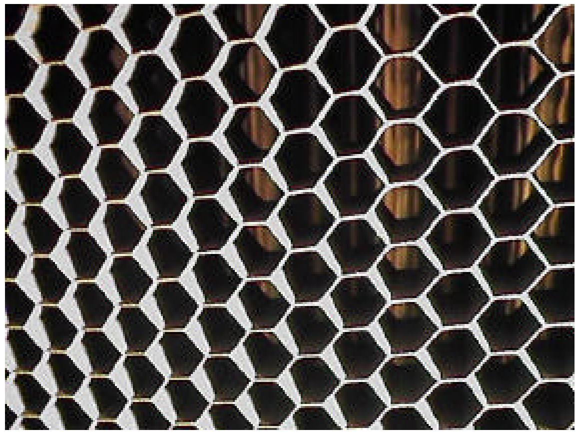

Figure 3.3. Close-Up Photo of the PNNL Collimator Showing the Hexagonal Structure and Roughly 45-Degree Opening Angle

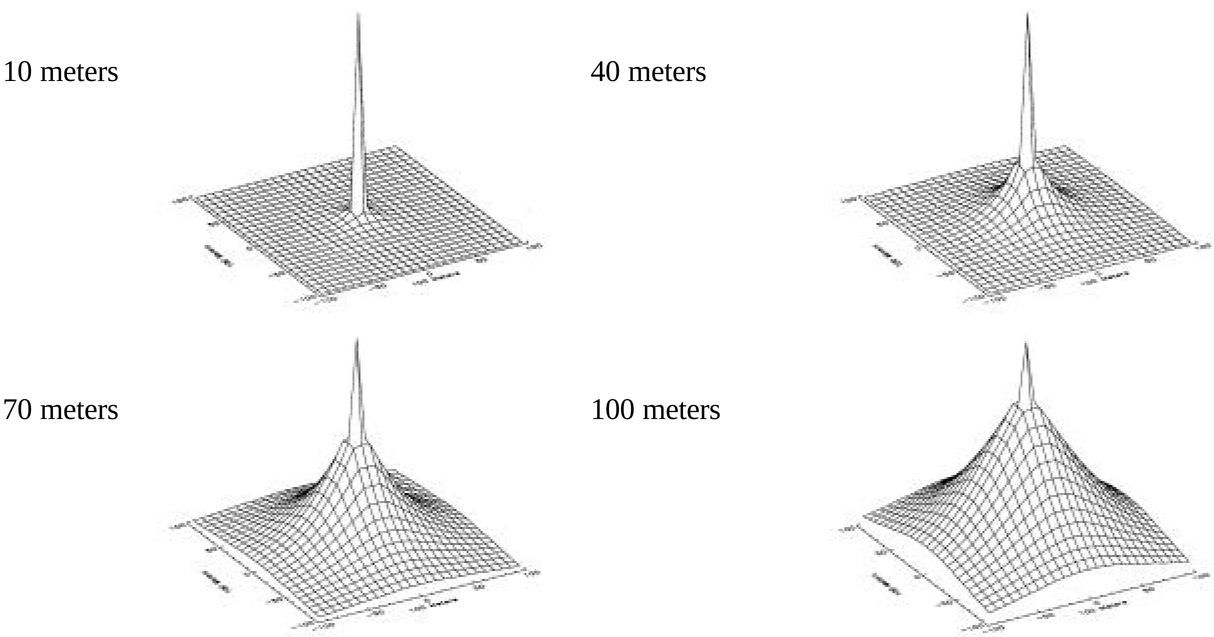

Figure 3.4. Four Plots Showing Calculated Thermal Neutron "Images" that Would Be Recorded at 10, 40, 70, and 100 Meters from a Thermal Neutron Source in Air. The increasing effect of neutron scattering and "diffusion" is apparent in these plots. The full range on both of the angular axes corresponds to 45 degrees. The third axis describing the intensity of the neutron flux is normalized for each of the plots.

The above data indicate that the optimal collimator open angle depends on the details of a particular application. Our choice of 45 degrees was intended to maximize the sensitivity of the detector for neutron sources at a significant distance. Whether this choice was correct will become clear upon experimental testing of the detector during FY99.

4.0 Preliminary Results

The completed detector system was tested to obtain an initial assessment of its performance and capabilities. A complete evaluation of the detection system and its potential for long-range neutron detection will be completed in FY99. This section describes the results of this preliminary series of tests.

4.1 Background

The background observed in the detector is roughly 1.3 cps. Because the testing at this point is incomplete and preliminary, it is not known if this is the lowest background that can be achieved with the detector's current design. It is possible that electronic problems continue to add background counts. (There is a demonstrable temperature sensitivity that should not exist.) However, this count rate is close to the desired goal of 1.0 cps or less for the square-meter detector. In contrast, a moderated detector with the same area could be expected to have a background of roughly 20 cps. Note that the total Hanford flux of cosmic-ray-induced neutrons is roughly 140 n/(m^2-s) and that fewer than 10% of these neutrons should be thermalized. Since the detector's unshielded solid angle is only 5% of the total solid angle availible, one might expect a background count rate below 0.7 n/s. Understanding the origin of background counts will be one of the first goals of the testing to be performed in FY99.

4.2 Directionality

Figure 4.1 shows the response of the detector to a partially moderated plutonium-beryllium (",n) source with strength 1.6×10^5 n/s. The data shown in Figure 4.1 were acquired with a source-detector separation of 14 meters. The solid points correspond to a "lateral" rotation of the detector along the surface of the earth. Two open points are also shown that correspond to "vertical" rotations of the detector so that it points toward the sky. The reduction in signal as a function of degree of misalignment between the detector and the source is consistent with the 45-degree open angle used in the construction of the hexagonal collimator. However, as expected, a thermal neutron signal is observed at all angles relative to the source, including a complete misalignment of 180 degrees. Note that the reduction in signal is roughly equal for the different ways in which the detector can be misaligned.

It should be carefully noted that the directionality of the detector is expected to be a strong function of parameters such as the source energy spectrum, source environment (especially the amount of moderator very near the source), and the source-to-detector separation. For example, the directionality of a directional thermal neutron detector in space (vacuum) would be nearly complete because of the lack of air or ground to moderate and scatter neutrons. The directionality of any indoor detector is necessarily decreased by the tendency of walls to moderate and diffusely reflect neutrons. The detector's directionality should decrease as the source-detector separation distance increases simply because of the decreasing importance of unscattered neutrons. This expectation was confirmed during our initial experiments. At a distance of 14 meters, the ratio of 0-degree to 180-degree signal ratio is roughly 7. However, when used to detect a ^{252}Cf source from 100 meters distance, the ratio of the signal at 0 degrees to the signal at 180 degrees was only 1.3 (see below). Another reason for this dramatically decreased directionality at long distances may be the increasing importance of fast neutrons able to penetrate the shield. These questions should be answered by the series of characterization experiments planned for FY99 (see Section 5.)

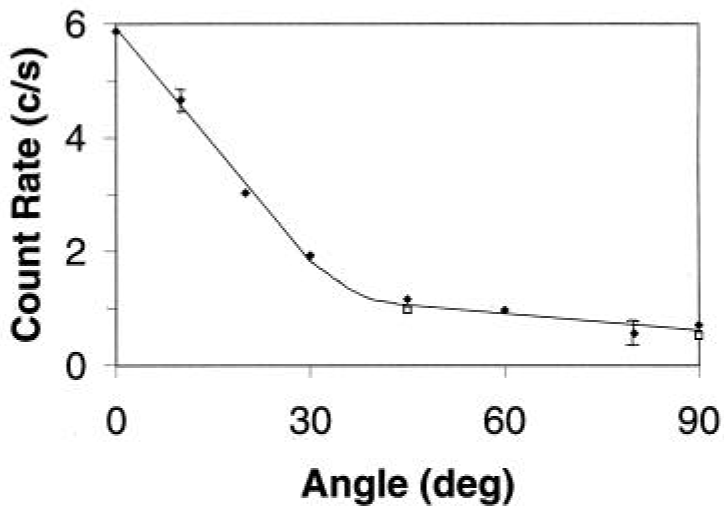

Figure 4.1. Plot of the Count Rate Observed in the Detector as a Function of the Angle Between the Direction in Which the Detector Is "Aimed" and the Direction Toward the Source. These measurements were taken outdoors over level earth using a moderated plutonium-beryllium (",n) source with strength 1.6×10^5 n/s. The source-to-detector distance was 14 meters. The solid points correspond to a "lateral" rotation of the detector along the surface of the earth. Two open points are also shown that correspond to "vertical" rotations of the detector so that it points toward the sky.

4.3 Long Range Detection

True long-range detection generally requires outdoor operation because most buildings containing neutron sources do not have sufficient indoor space. (A notable exception might be the Pantex facility with its long hallways.) To this end, several outdoor tests were carried out with the PNNL square-meter directional detector. The experimental conditions and results of each of these tests are described below.

Ladder Test: A 1.6×10^5 n/s plutonium-beryllium source was placed on top of a 1.5-meter-high ladder above an earthen surface on relatively level ground. The source was centrally placed between two 5-cm-thick slabs of polyethylene to provide moderation. The directionality of the detector at 14-meters distance was measured, and the results are shown in Figure 4.1. The signal was 6 and 1.4 cps at 14 and 24 meters, respectively.

Vault Test: The detector was used over level earth to record neutrons coming from a storage vault in the corner of the 3745 Building at PNNL. The vault contains a number of strong curium sources that are well shielded (well-moderated.). The detected signal for one particular configuration of sources was found to be 6 cps and roughly 1 cps at 24 and 46 meters, respectively. The signal was found to be highly sensitive to the arrangement of sources within the vault. It was also possible to rapidly tell when one of the sources was removed from its protective shield.

Neutron Multiplier Test: As part of the decommissioning of a neutron-multiplier facility at PNNL, it was necessary to measure the dose rates from a 1.2×10^8 n/s ^{252}Cf source. This source was pulled from beneath 6 meters of water shielding for roughly 10 minutes before being replaced. The PNNL detector was positioned on asphalt at 100-meters distance from the multiplier facility. Although neutrons were detected through the facility wall, this wall is not believed to contain a great deal of hydrogenous material such as concrete. No moderator was in the immediate vicinity of the source during the time that it was out of the water. The signal strength at 100 meters was measured to be 31 cps. The data recorded during this test are shown in Figure 4.2. The loss of signal in the middle of the test occurred during a brief period when the source was placed back in the water. The 0-degree to 180-degree signal ratio at this distance and with this configuration was measured to be roughly 1.3.

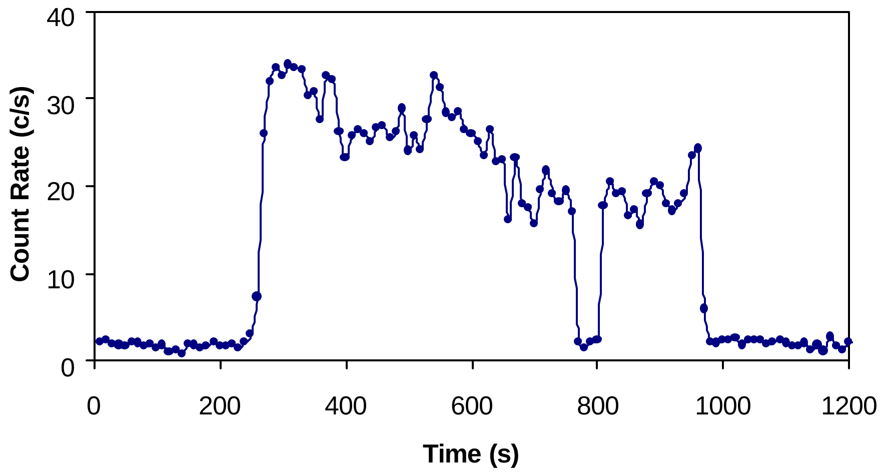

Figure 4.2. Count Rate that Was Observed by the PNNL Detection System when Placed at 100 Meters Distance from a 1.2×10^8 n/s ^{252}Cf Source that was Briefly Taken out of its Shield. The variations in the count rate result from variation of the detector's orientation and movement of the source itself. At roughly 800 seconds after start of the measurement, the source was briefly placed back within the shield.

5.0 Future Plans

This report describes a number of theoretical, numerical, and experimental results germane to the problem of long-range neutron detection. A square-meter detection system designed to have maximum sensitivity for this application has been designed and constructed. This section describes the experimental measurements using this detection system that are being planned for FY99. These measurements should characterize the detection system and determine its capability for the application of long-range neutron detection. Further, these tests should allow validation of the principles discussed in Section 3 for the design of moderator-free neutron detectors.

A brief description of tests planned for FY99 is listed below:

- **Background**: A variety of tests will be used to understand the origin of the detector's background count rate. How many of these counts are environmentally thermalized neutrons that enter through the collimator? How many of these counts are epithermal or even fast neutrons that have entered through the shield and been recorded by the ^{3}He tubes? These questions will be answered through a variety of brief tests.

- **Signal**: Tests will also be carried out to understand the process by which neutrons are recorded as signal. The relative importance of neutrons thermalized near the source, neutrons thermalized near the detector, epithermal neutrons, and fast neutrons will be determined.

- **Directionality**: The directionality of the detector was shown in Figure 4.1 at a distance of 14 meters with a moderated plutonium-beryllium source. It will be necessary to characterize the directionality of the detector at a variety of distances and for moderated vs. unmoderated sources. These data will help in understanding the processes by which the detector records neutrons.

- **Human Intrusion**: The detector can easily be tested for use in the application of human intrusion. This application may benefit from the detector's tremendous sensitivity for only those neutrons that are fully moderated. (These are the neutrons that should be most sensitive to changes in the quantity and/or arrangement of moderator in a storage vault.)

- **Long Range**: The detector will be tested for the application of long-range neutron detection. It is hoped that sources of moderate strength will be rapidly detectable at 50 meters and detectable in 1000 seconds at 75 to 100 meters. Data that allow the prediction of detection sensitivity as a function of detector area, source strength, and measurement time will be acquired.

- **Unshielded Detector**: The performance of the detection system without the collimator and without any of its shield will be evaluated. It is currently believed that such a configuration will be advantageous for those applications where fast neutrons dominate the detection process. Long-range neutron detection beyond 50 meters may be one of these applications.

- **Source Drive-By**: The ability of the detector to record the rapid transit of sources will be evaluated as a function of source velocity and distance of closest approach. Such a test would, for example, assess the ability of unmoderated detection systems to monitor roads or waterways.

- **Gamma-Ray Response**: The response of the detection system to gamma-ray fluxes will be measured. It is expected that the response will be completely insignificant except above 0.1 to 1.0 R/h. Such gamma-ray doses are not likely to be encountered for most applications.

- **Imaging Capability**: The detection system can, in principle "triangulate" to determine the location of a single neutron source. The accuracy with which this can be done will be evaluated as a function of source strength, degree of source moderation, and standoff distance.

- **Source Environment**: The detailed effect of the environment of the source on the performance of the detection system at medium and long range will be evaluated. For example, does the height of the source above the ground matter? Does the type of ground matter (asphalt, earth, water)? What is the optimum amount of moderation?

- **Epithermal Sensitivity**: The detection system can, in principle, be used for the directional detection of epithermal neutrons by placing a thin sheet of cadmium or gadolinium over the front of the detector. This material will completely block thermal neutrons, but largely pass epithermal neutrons above 0.5 eV (see Figure 3.2). The ^{10}B-based shielding in the collimator and on the other five sides of the detector will effectively block both thermal *and* epithermal neutrons. Since epithermal neutrons have a longer range in air, the capability for low-background, directional detection may be advantageous. The performance of the detection system under these conditions will be evaluated.

- **Neutron Spectrometry:** It should be possible to demonstrate the use of this system for neutron spectrometry (Takahashi et al.1994). Tests will be carried out to determine the sensitivity and accuracy of this system when used as a neutron spectrometer.

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