SAND2020-2664C

SPND Sensitivity Calculations Using MCNP and Experimental Data from ACRR

Joseph King[1,2,*], *Aaron* Miller[1], and *Edward* Parma[3]

[1]Sandia National Laboratories, Albuquerque, NM, USA
[3]Eden Radioisotopes, Albuquerque, NM, USA

Abstract. Self-Powered Neutron Detector (SPND) signals rely on the ejection of electrons from an emitter material through prompt gamma interactions and/or beta decay from an excited nucleus. Electrons travel through an electrically insulated layer to an electrically grounded collector and the resultant net charge generated in the emitter produces a measurable current. The current detector designs used in pulsed research reactors lack the ability to discriminate between a neutron and gamma signals within a mixed radiation environment. Thus, next-generation SPND designs which consider specific materials and geometry could be necessary to provide experimenters with capabilities for advanced mixed field dosimetry. The described method of modeling SPNDs provides the ability to perform preliminary sensitivity calculations on various materials and configurations. Lastly, a parametric study of hypothetical SPND designs was completed to demonstrate that next-generation SPNDs can be accurately modeled with Monte Carlo N-Particle (MCNP) [1]. Experimental data obtained from multiple pulses at the Annular Core Research Reactor (ACRR) was used to validate SPND sensitivity calculations using the MCNP neutronics code. SPNDs are the primary diagnostic tool for pulsed experimentation at ACRR. In high neutron and gamma fluence rate environments, SPNDs generate a current proportional to the fluence rate that captures the temporal shape of the reactor pulse. Integrating the recorded signal, the voltages measured can be adjusted to units of sensitivity (e.g. electrical current, reactor power) through the use of passive dosimetry and characterized spectrum metrics [2-3]. SPNDs were modeled in an MCNP model of the ACRR [4] to calculate signal sensitivities. The sensitivity values from experiments and MCNP calculations agreed within one standard deviation.

---

[2] Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

[*] Corresponding author: josking@sandia.gov

1 Introduction

This report presents the process in which a Monte Carlo N-Particle (MCNP) [1] model of a Self-Powered Neutron Detector (SPND) was validated by experimental data. After validation, parametric studies were performed on materials, dimensions and configurations of different detectors in an attempt to optimize future designs of next generation SPNDs. Experimental data was obtained from multiple pulses at the Annular Core Research Reactor (ACRR). The pulse data was then used in a Matrix Laboratory computing environment (MATLAB) script to calculate time-dependent and integral plots of detector sensitivity.

SPNDs are used in the ACRR as a primary diagnostic tool for pulses performed for experimental purposes. The active dosimetry from the SPNDs is paired with passive dosimetry to provide experimenters valuable information concerning the reactor's operation. Passive dosimetry in the form of nickel foils, sulfur foils, and thermoluminescent dosimeters (TLDs) are placed within the ACRR during experiments to measure the integral spectrum metrics of an operation. The fidelity of the SPNDs is vital because they are a primary tool used in conjunction with passive dosimetry to provide metrics (e.g., ionizing dose rate, non-ionizing dose rate, gamma flux and neutron flux to experiments). Also, current detectors used in the ACRR do not have the ability to discriminate between a neutron and gamma signal; therefore, the design of next-generation SPNDs is necessary to provide experimenters with more detailed data. Thus, the validation of SPND models in MCNP using ACRR is an essential first step to furthering the process of designing these new SPNDs.

In a high neutron and gamma flux environment, SPNDs generate a current proportional to the flux, allowing them to capture the shape of the pulse on an oscilloscope. Integral neutron and photon spectrum metrics have been characterized for the ACRR by Parma, et. al [2][3]. These integral values can then be related to the SPND signal through the use of passive dosimetry to allow for the pulse shape to be normalized. Once normalized, the pulse shape can then be converted into units of interest (i.e., megawatts [MW]) for this report. This information can then be used in conjunction with knowledge of the electrical configuration of the detector to obtain a sensitivity. A standard unit of detector sensitivity is essential for the comparison between model and measurement; therefore, for this report units of nA/MW will be used exclusively. Using MCNP and an ACRR model [4], the SPNDs can be modeled in the reactor and associated sensitivities can be calculated on a per-megawatt basis. The sensitivities from reactor measurements and the MCNP model results agreed within one standard deviation. With confirmation that MCNP accurately calculates the sensitivity of SPNDs in ACRR, parametric studies were performed with differing dimensions, configurations and materials of SPNDS.

1 SPNDs and the Large Cadmium Detector (LGCAD)

SPNDs rely on a bombardment of neutrons on an emitting material that will cause an ejection of electrons from the material itself. These electrons travel through an electrical insulator layer and deposit into an outside layer referred to as the collector. The collector is electrically grounded; therefore, the net charge of the emitter is the primary source of potential difference in the circuit, inducing a current proportional to the neutron reaction rate. Figure 1 presents a simple diagram of the LGCAD experimental configuration. In a high neutron flux environment, these detectors generate a current proportional to the flux, which is capable of capturing the shape of a reactor pulse on an oscilloscope.

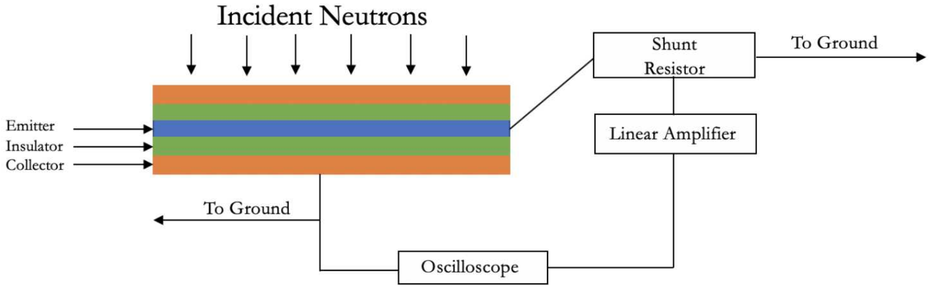

Fig. 1. Experimental Configuration of ACRRs LGCAD Detector

The most common configuration of an SPND is three coaxial cylinders, with the emitter being the innermost layer, followed by an insulator and a collector. Emitter materials are those in which a nuclear reaction of relatively high probability will cause the ejection of an electron; this is primarily accomplished by the excitation of a nucleus followed by a subsequent beta decay or an (n, γ) reaction producing energetic photons that will then produce ionization electrons in the emitter. In the ACRR, cadmium was chosen as an emitting material due to its properties of having intense prompt photon emission following neutron capture, a large neutron absorption cross section and faster response time than its beta-emitting alternatives. The LGCAD is the primary self-powered neutron detector used by the facility's experimenters and is the main diagnostic tool evaluated in this report. The insulating layer of the LGCAD is aluminum oxide (Al2O3), which is a solid dielectric material capable of retaining high electrical resistivity when exposed to intense radiation. The collector is Inconel 600, which was chosen as a conducting material because it produces few electrons in a high neutron flux environment compared to the emitter. Figure 2 shows an illustration of the dimensions and materials of the LGCAD.

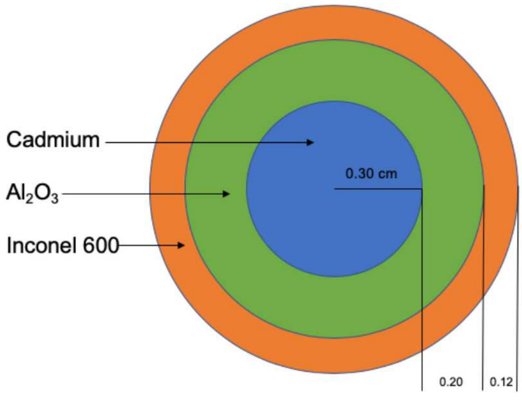

Fig. 2. Cross-sectional Layout of ACRR's LGCAD Detector

3 MCNP Modeling and Tallies

Knowledge of the location for LGCAD had to be determined using the layout of the core elements from ACRR. Using the ACRR model, 3 identical modeled LGCAD detectors were placed in each of three Detector Elements (DE) in the ACRR; DE1, DE2, DE5. Due to limitations on quickly accessing the core, the exact location of the experimenter LGCAD is not known. What is known is that it is located in one of these three DEs, therefore the results of each will be used for comparison later in this report. It is important to note is that all three possible locations for LGCAD to be in are in the 7th row of elements in the hexagonal core. Full scale MCNP calculations were then run and the results analyzed.

3.1 Tally and Sensitivity Calculations

The main advantage of using an SPND is its ability to generate a signal without an external power source simply from the potential difference caused by ejection of electrons driven by nuclear reactions. This presents a challenge on how to properly compute the electric current needed to calculate sensitivities from a KCODE calculation. Initially, two potential tally methods were identified: surface current tally (F1) and charge deposition tally (F8+).

An F1 tally tracks particles crossing a surface and each time it does, the particle's weight is added to the tally. This tally was chosen because of its ability to also track the positrons created in pair production; which was found to be a considerable contribution. Preliminary runs used this tally to track charged particles in both directions through the emitter surface, and summing each component resulted in a net current of positrons and electrons. The resulting net electrical current is equivalent to the resultant positive charge of the cell in which the neutron and photon interactions took place. F1 tally results and intermediate steps that show how this calculation is performed are shown below in the following tables and figures.

1. MCNP is executed and an F1 tally is calculated for incoming and outgoing positrons and electrons across the surface of the emitter,

Table 1. MCNP Tally Values for DE2.

Description	F1 Tally (particles/src-n)	Tally Uncertainty (%)
F1 Electron In	9.44E-06	2.38
F1 Electron Out	2.35E-05	3.01
F1 Positron In	3.13E-06	8.19
F1 Positron Out	7.78E-07	17.5

2. Tally values are converted into sensitivity values on a per-megawatt basis.

$$\frac{9.44\text{E-06 } e^-}{\text{src - n}} \cdot \frac{2.442 \text{ src - n}}{\text{fission}} \cdot \frac{\text{fission}}{192 \text{ MeV}} \cdot \frac{\text{MeV}}{1.602\text{E-19 MJ}} \cdot \frac{1.6022\text{E-19 C}}{e^-} \cdot \frac{1\text{E9 nC}}{1 \text{ C}} = 120 \text{ nC/MJ} = 120 \text{ nA/MW}$$

Fig. 3. Tally-to-Sensitivity Conversion

3. A positive value is assigned to outgoing electron and incoming positron current, and a negative value for incoming electron and outgoing positron current to calculate the resultant net negative charge leaving the emitter.

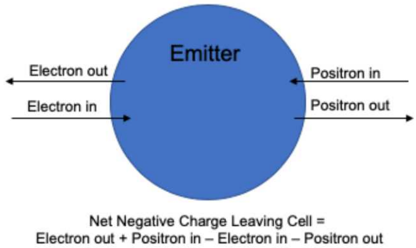

Fig. 4. Net Negative Charge Calculation Diagram

4. Sensitivities are summed, and the resultant value is the estimated sensitivity of the modeled SPND.

Table 2. Computed F1 Sensitivity Values for DE2.

Description	**Value (nA/MW)**
F1 Electron In	-120 ± 5.74
F1 Electron Out	299 ± 9.01
F1 Positron In	39.8 ± 3.26
F1 Positron Out	-9.90 ± 1.73
Electron Total	179 ± 14.8
Positron Total	-29.9 ± 4.99
Total Sensitivity	209 ± 19.8

F8+ tally tracks the charge deposited into a cell and is expected to yield equivalent results to the process described for F1 tallies. It is more straight-forward in that only one value for the tally is calculated and can simply be converted into sensitivity using the same scaling as the previous example. Using the same dimensions as the F1 tally example, the sensitivity was calculated to be 209 ± 4.98 nA/MW. These two values are in agreement, and for the sake of simplicity and more accurate statistics, the latter (F8+) tally was chosen for the remainder of calculations in this report.

4 ACRR Experiments and MATLAB Calculation

Data from 4 different ACRR pulses were compared to MCNP calculations. All of the pulses were maximum pulses performed with a Free-Field (FF) environment. The ACRR data was comprised of two sources for each pulse; the oscilloscope data from the LGCAD, as well as the passive dosimetry results processed by the Radiation Metrology Laboratory (RML). First, the oscilloscope data is collected and converted into a .csv file to be read into MATLAB. Figure 5 is an example output from the oscilloscope during ACRR pulse #12505 using the LGCAD.

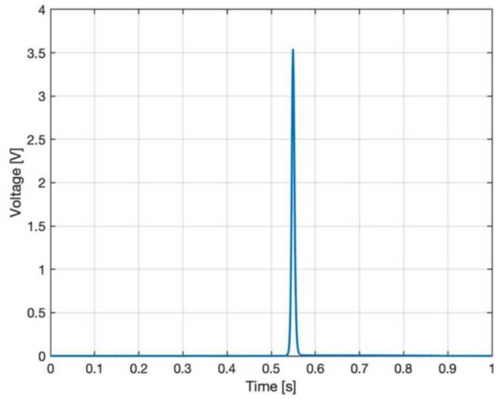

Fig. 5. Raw Data for Shot #12505

To calculate sensitivity using the measured signal, the oscilloscope data is be converted from volts into two sets of units, nA and MW. Conversion to nA is achieved using Ohm's law, knowing that the LGCAD uses a 500-ohm shunt resistor in parallel. Figure 6 shows the plot of shot #12505 converted to units of nA.

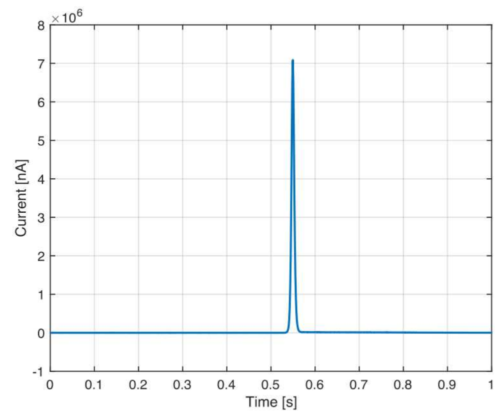

Fig. 6. Data in nA for Shot #12505

Converting the raw data into units of MW is a multistep process involving the previously mentioned integral metrics reported by Parma, et. al. and use of the passive dosimetry fielded during the irradiation. This process is as follows:

1. Smooth the raw data using a Savitzky-Golay filter.
2. Zero the data using the peak power and setup delayed-critical power values.
3. Integrate the pulse shape.
4. Use passive dosimetry measurements, specific to environment, to calculate total MJ value for pulse.
5. Divide total MJs by the integral of the pulse shape to find conversion factor in units of MJ/V-sec or, in other words, MW/V.
6. Multiply raw, smoothed and zeroed data by conversion factor to obtain reactor power in units of MW.
7. Divide the pulse shape in units of nA, by the pulse shape in units of MW to obtain a sensitivity of LGCAD for the specific pulse.

4 Model Verification

Using the full ACRR MCNP model, tallies were calculated for the LGCAD in each of the three DEs locations. Table 3 lists the tally values, statistical uncertainties, and calculated sensitivities for each of the DEs.

Table 3. MCNP Detector Sensitivity Results

Detector Element	F8+ Tally (q/src-n)	Tally Uncertainty (%)	MCNP Sensitivity (nA/MW)
DE1	1.79E-05	2.30	211 ± 4.85
DE2	1.78E-05	2.38	209 ± 4.98
DE5	1.75E-05	2.42	206 ± 4.99

Next, Table 4 lists the values and calculations for each of the 4 pulses investigated in this report. The uncertainty for the experimental sensitivity is based on the reported uncertainty from metrics used from Parma, et. al. [2][3] and the uncertainty from dosimetry results. For the sake of simplicity, measurement uncertainty from the experimental setup was not taken into consideration due to the agreement already seen based off metric and dosimetry uncertainties. It can be seen that all of the experimental and MCNP sensitivities are within one standard deviation of each other. The agreement between the sensitivity values validates MCNP as an accurate modeling tool. MCNP was then used to perform a parametric analysis and investigate the different effects of materials and dimensions on different SPNDs in the central cavity of the ACRR.

Table 4. MCNP Detector Sensitivity Results

Shot #	Peak Power (MW)	Integrated Power (MJ)	Ni Foil ($Bq/g_{Ni\text{-}58}$)	Ni Foil Uncertainty (%)	Experimental Sensitivity (nA/MW)
12505	27526	261	1.67E+05	2.96	205.1 ± 10.4
12506	28697	266	1.64E+05	3.02	207.9 ± 10.6
12481	28005	273	1.62E+05	3.10	209.6 ± 10.8
12482	27876	274	1.66E+05	3.05	205.1 ± 10.5

5 Conclusions and Future Work

When modeling SPNDs in MCNP, the calculated sensitivities closely resembled the results from measured pulse data in the ACRR; this validates the use of MCNP for future studies concerning SPND research and development. In search of a high-fidelity neutron signal, MCNP can be used as an optimization tool for designing a next-generation SPND for ACRR. Materials and dimensions can be parameterized in an attempt to optimize for sensitivity, signal-to-noise ratio, and detector size. Lastly, an experiment was performed with SPNDs of unknown emitter thicknesses and materials. With the use of oscilloscope data and MCNP modeling, the dimensions of the detector, as well as its composition will be investigated using the tools and methods validated in this report.

References

[1] C.J. Werner, J.S. Bull, C.J. Solomon, et al. MCNP6.2 Release Notes. Technical Report LA-UR-18-20808, Los Alamos National Laboratory, Los Alamos, NM (2018)

[2] Edward. J. Parma (2015), Gerald E. Naranjo, Richard M. Vega, Lance L. Lippert, David W. Vehar, and Patrick J. Griffin, "Radiation Characterization Summary: ACRR Central Cavity Free-Field Environment with the 32-Inch Pedestal at the Core Centerline (ACRR-FF-CC-32-cl)", SAND2015-6483, (2015)

[3] Edward. J. Parma (2016), Gerald E. Naranjo, Krista I. Kaiser, James F. Arnold, Lance L. Lippert, Ralph D. Clovis, Lonnie E. Martin, Thomas J. Quirk and David W. Vehar, "Radiation Characterization Summary: ACRR Cadmium-Polyethylene (CdPoly) Bucket Located in the Central Cavity on the 32-Inch Pedestal at the Core Centerline (ACRR-CdPoly-CC-32-cl)", SAND2016-10114, (2016)

[4] K. R. DePriest, P. J. Cooper, and E. J. Parma. MCNP/MCNPX Model of the Annular Core Research Reactor. Sandia Report, SAND2006-3067, Sandia National Laboratories, Albuquerque, NM, (2006).

[5] G.R. Imel, P.R. Hart, "The Performance of Hafnium and Gadolinium Self-powered Neutron Detectors in the TREAT Reactor", *Nuclear Instruments and Methods in Physics Research*, **vol. 111**, pp 325-336.