Cadmium-Emitter Self-Powered Thermal Neutron Detector Performance Characterization & Reactor Power Tracking Capability Experiments Performed in ZED-2

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Abstract

Cadmium-emitter self-powered thermal neutron flux detectors (SPDs), are typically used for flux monitoring and control applications in low temperature, test reactors such as the SLOWPOKE-2. A collaborative program between Atomic Energy of Canada, academia (Royal Military College of Canada (RMCC)) and industry (LaFontaine Consulting) was initiated to characterize the incore performance of a typical Cd-emitter SPD; and to obtain a definitive measure of the capability of the detector to track changes in reactor power in real time.

Prior to starting the experiment proper, Chalk River Laboratories' ZED-2 was operated at low power (5 watts nominal) to verify the predicted moderator critical height. Test measurements were then performed with the vertical center of the SPD emitter positioned at the vertical mid-plane of the ZED-2 reactor core. Measurements were taken with the SPD located at lattice position L0 (near center), and repeated at lattice position P0 (in D_2O reflector). An ionization chamber (part of the ZED-2 control instrumentation) monitored reactor power at a position located on the south side of the outside wall of the reactor's calandria.

These experiments facilitated measurement of the absolute thermal neutron sensitivity of the subject Cd-emitter SPD, and validated the power tracking capability of said SPD.

Procedural details of the experiments, data, calculations and associated graphs, are presented and discussed.

1. Introduction

The original self-powered cadmium neutron flux detector was inserted into the instrument socket of RMCC's SLOWPOKE-2 beryllium annulus in 1985 (see Figure 1). This socket is a close-fitting hole in the Be annulus, in which the SPD was continuously immersed in the reactor vessel water. In spring 2011, the original Cd SPD became lodged in and could not be removed from the instrument socket; it was subsequently clipped and terminated inside the deck plate box (which also holds the cable for the core outlet thermocouple), and a replacement detector ordered.

Prior to detector commissioning, a test plan was proposed by LaFontaine Consulting and approved by RMCC, for thermal neutron detector performance characterization and reactor power tracking capability experiments to be performed in AECL's ZED-2 reactor.

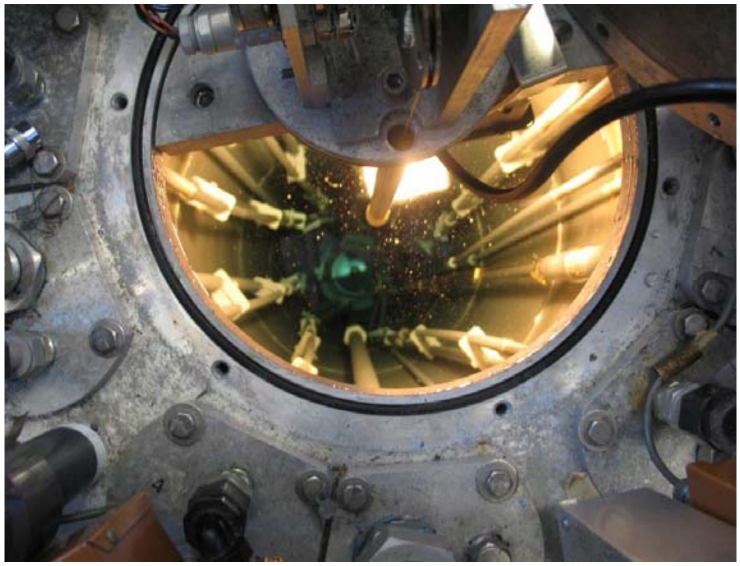

Figure 1 ***Internal View of RMCC's SLOWPOKE-2***

2. SPD Design & Function

The SLOWPOKE-2 cadmium-emitter SPD comprises a 2.11 mm (0.083") diameter x 0.25 mm (0.010") nominal wall Inconel 600 outer sheath/collector, enclosing compacted Al_2O_3 ceramic insulation, around a 0.9 mm (0.036") nominal diameter x 203.2 mm (8") nominal length, 1.1 g natural cadmium emitter. The emitter/collector portion is attached to a leadcable which comprises a 1.57 mm (0.062") diameter x 0.25 mm (0.010") nominal wall Inconel 600 outer sheath, enclosing compacted Al_2O_3 ceramic insulation, around a 0.25 mm (0.010") nominal diameter Inconel 600 core (signal) wire. See Figure 2. Resistance to ground is typically in excess of 10^{11} ohms at 20°C.

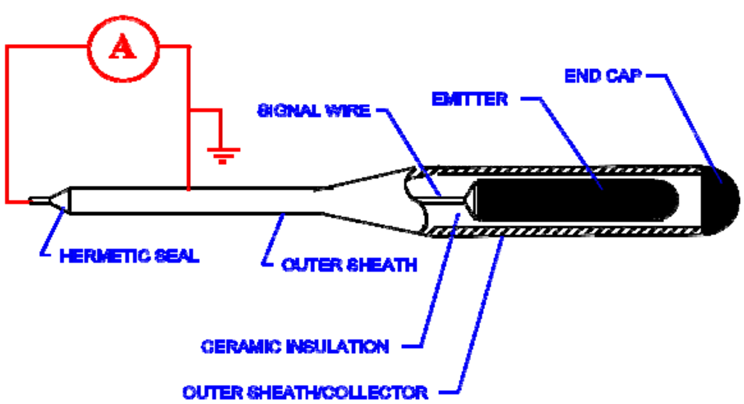

Figure 2 ***SPD Design Elements***

2.1 The Natural Cd-Emitter

The natural Cd-emitter, prompt responding neutron capture SPD, is made up of a number of cadmium isotopes with different abundances: ^{106}Cd (1.25%), ^{108}Cd (0.89%), ^{110}Cd (12.5%), ^{111}Cd (12.8%), ^{112}Cd (24.1%), ^{113}Cd (12.2%), ^{114}Cd (28.7%), and ^{116}Cd (7.5%). The resulting thermal neutron capture cross-section for natural cadmium (based on mass-normalized isotopic abundances) is therefore:

σ_{th} = 0.0125 x 1 + 0.0089 x 1.2 + 0.125 x 11.1 + 0.128 x 24 + 0.241 x 2 + 0.122 x 1.98 x 10^4 + 0.287 x 0.34 + 0.075 x 0.075 = 2,420.67 barns.

Now, visualize the natural Cd emitter as being a finite series of concentric cylinders, each cylinder comprised of the same isotopic mix as previously discussed (Figure 3).

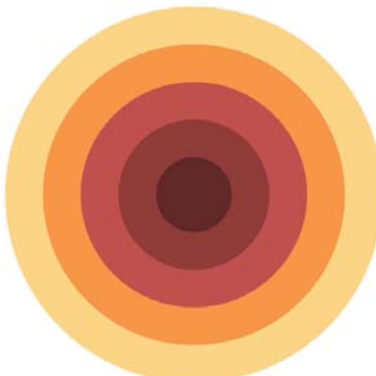

Figure 3 ***Idealized Cross-Section of the Cd Emitter***

The outermost "cylinders" progressively shield the inner "cylinders" from neutron interractions. Concurrent with ^{113}Cd + $n \rightarrow$ ^{114}Cd , each "cylinder" undergoes ^{110}Cd + $n \rightarrow$ ^{111}Cd + $n \rightarrow$ ^{112}Cd + $n \rightarrow$ ^{113}Cd (the major isotopic abundances and thermal neutron capture cross-sections).

The apparent "breeding" capability of natural Cd-emitter SPDs, results in an emitter depletion of about 0.3% per year in 10^{14} nv. This is evidenced by the original RMCC SLOWPOKE-2 Cd-emitter SPD performing with minimal loss of sensitivity until its decommissioning in 2011 (steady-state $\varphi_{th} \approx 3.6 \times 10^{12}$ nv).

2.2 Cd-Emitter SPD Signal Generation

Signal generation in natural Cd-emitter SPDs is instantaneous and almost 100% due to n, γ, e interactions. Thermal neutron capture taking place in the emitter, generates neutron capture gammas which in turn produce high-energy electrons leading to current generation by the SPD.

3. Experimental Set-up & Procedures

3.1 ZED-2 Fuel Description & Lattice Arrangement

The fuel bundles used for the experiment consisted of uniform-enrichment Low Enriched Uranium (LEU) pellets sheathed in zirconium and loaded into 43-element bundles. The LEU enrichment was 0.95 wt% ^{235}U in U.

The fuel bundles were contained in ZED-2 aluminum-channel assemblies. Each assembly comprises five fuel bundles contained within an aluminum pressure tube surrounded by a concentric aluminum calandria tube. The pressure tube is capped at the top using a cylindrical top aluminum end plate and, both the pressure tube and calandria tube are capped at the bottom using a cylindrical aluminum bottom endplate. The bottom endplate has a small opening to allow heavy-water moderator into the pressure tubes to provide "coolant" for the fuel bundles. The purity of the "coolant" and level above the reactor floor is the same as that of the moderator. For these tests the purity and temperature of the moderator was 98.777 weight percent D_2O, at 23.5°C.

The arrangement of the assemblies in the ZED-2 lattice is shown in Figure 4 and a cross-section of a fuel assembly, showing the bundle geometry, is shown in Figure 5.

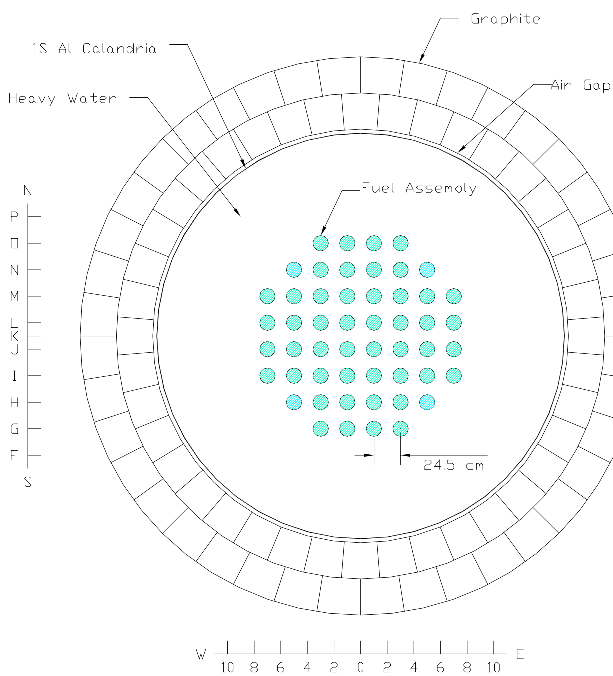

Figure 4 ***Plan View of the ZED-2 Lattice***

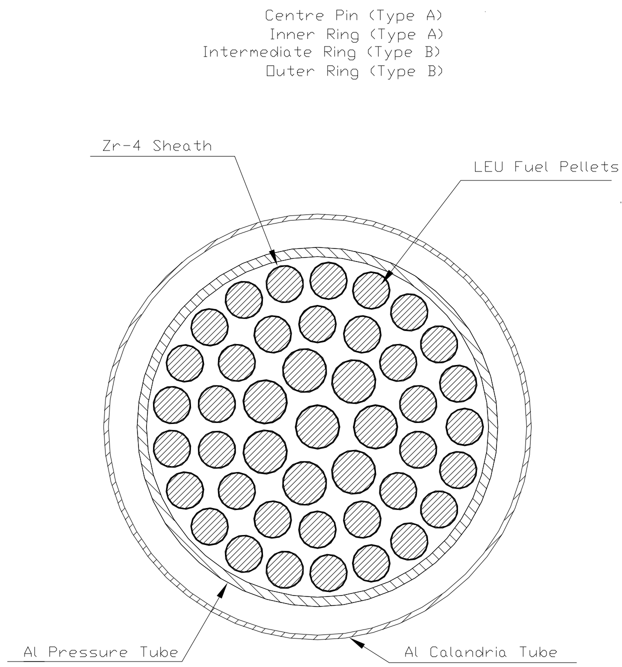

Figure 5 ***Cross-section of a ZED-2 Assembly***

3.2 Experimental Set-up - Data Acquisition

A Reuter-Stokes Model RS-C2-2511-137 Ion Chamber was used to monitor the neutron flux/reactor power at a position located on the south side of the outside wall of the reactor's calandria. The bias voltage for the ion chamber was provided by a high voltage DC power supply (part of the ZED-2 core monitoring system).

The prompt-responding, Cd-emitter SPD was also used to measure the neutron flux in the core.

The output current from both the ion chamber and Cd-emitter SPD were measured using calibrated Keithley Model 6514 System Electrometers. Stability of the electrometers was ensured by powering the devices through an Isolation Transformer.

The CRL ZED-2 data acquisition hardware and software acquired and archived the output of the electrometers (through an IEEE bus), the time of day (from the PC's clock), and the irradiation period (from the data acquisition card) in an ASCII data file which was written to an Excel® spreadsheet and later exported to Sigmaplot 10® for analysis. ***Note:*** *ZED-2 operational experience has shown that there is quite good linear response between the output from the back-off amplifier (that reads indicated power in watts on the strip chart recorder in the ZED-2 Control Room) and the output current from the ion chamber in the radial graphite when the reactor is critical.*

3.3 Abridged Test Procedure - Critical Height & Power Tracking Experiment

Prior to performing the Power Tracking Experiment, ZED-2 was operated at low power (5 watts nominal) to verify the predicted moderator critical height.

For the Power Tracking Experiment, the Cd-emitter SPD was installed in either L0 (near centre of lattice) or P0 (near reflector). ***Note:*** *The Power Tracking Experiment required two reactor runs, one with the SPD at lattice position L0, and one with the SPD at lattice position P0.* The SPD emitter centre line was aligned with the vertical mid-plane of the core. The reactor was brought to 30 watts power and allowed to stabilize for 30 minutes before recording SPD current measurements. Reactor power was then increased in 10 watt increments until 120 watts nominal was reached; at that time, reactor power was decreased in 10 watt decrements until 30 watts was reached. The SPD current was measured specifically at each power step and continuously recorded for increasing and decreasing power transitions. The reactor was shut down immediately following the final 30 watt current measurement. The irradiation period was be timed from the point at which reactor power first reached 30 watts until the time the reactor was shut down.

3.4 Abridged Test Procedure – Cobalt Wire Activation

Cobalt wire activation was performed to determine the absolute thermal neutron sensitivity of the RMCC SLOWPOKE-2 Cd-emitter SPD. ***Note:*** *Cobalt wire activations were performed on multiple in-core irradiations at lattice position L0.* For each Co wire activation, a 0.127 mm (0.005”) diameter cobalt wire was taped directly on top and along the length of the SPD’s emitter using halogen-free, waterproof tape. The mass of each cobalt wire was recorded on an AECL “Count Order Form.”

The SPD emitter centre line was aligned with the vertical mid-plane of the core. The reactor was brought up to 120 watts power. Reactor operation period was timed from the point at which reactor power indicated 50 watts power, then allowed to stabilize for 30 minutes, until taking SPD current measurements and reactor shut-down.

4. Results

The thermal neutron sensitivity, S_{th}, of the RMCC SLOWPOKE-2 cadmium-emitter SPD was calculated to be:

$$S_{th} = I_{SPD} / \varphi_{abs} \quad (1)$$

where I_{SPD} was the detector output current (amperes) produced by the SPD on which the cobalt wire was mounted, and φ_{abs} was the absolute Westcott flux as determined by Co wire activation as per the methodology detailed in [1]. Based on multiple Co wire activations performed with the Cd-emitter SPD installed in L0, $S_{th} = 1.0514 \times 10^{-20}$ amperes/nv.

The graph of Power Tracking Capability (Figure 6) was prepared by normalizing the current readings from the data acquisition (both from the ion chamber and the cadmium-emitter SPD) to the indicated power in the ZED-2 Control Room.

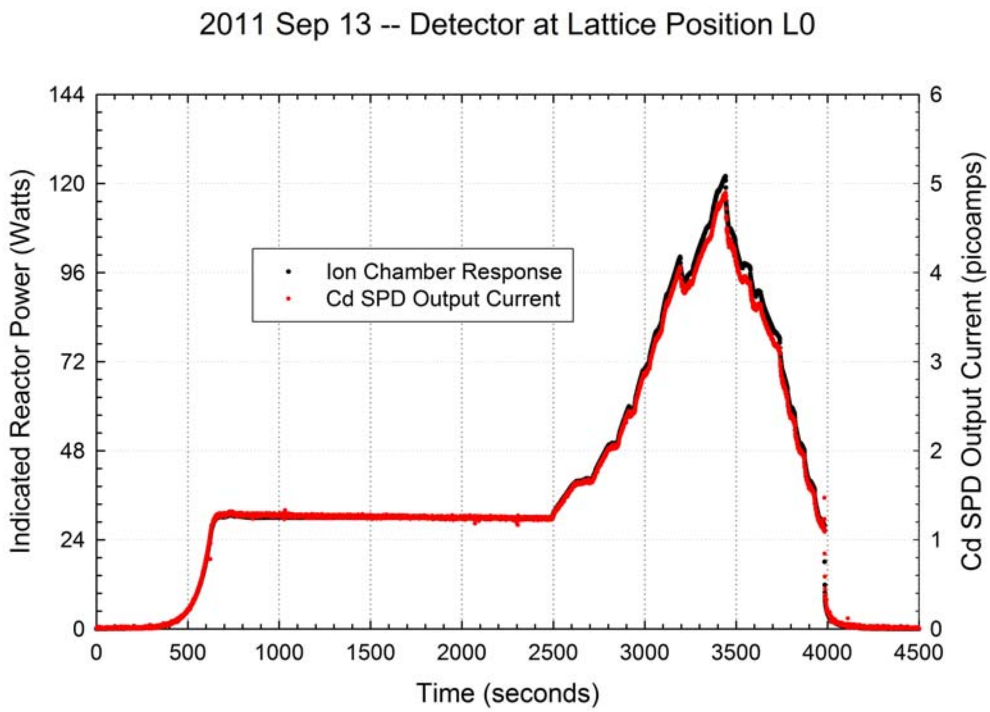

Figure 6 ***Cd-Emitter SPD Power Tracking Capability***

5. Conclusions

(1) The thermal neutron sensitivity, S_{th}, of the RMCC SLOWPOKE-2 cadmium-emitter SPD was calculated to be, $S_{th} = 1.0514 \times 10^{-20}$ amperes/nv. This was validated during commissioning at RMCC (Figure 7): [*Paraphrasing RMCC commissioning notes*] "Current from the Keithley picoammeter connected to the new flux detector at inner site 3 was 3.22×10^{-9} Amps. *Due to Inner Site 3 geometry restrictions*, if one divides the "sensitivity" factor as determined in ZED-2 for the new flux detector, the flux turns out to be (3.22×10^{-9} amperes/0.894amps per unit flux) = 3.60×10^{12} n/cm^2/s. On Friday, 18 Nov 2011, we put a straight 8-inch length of 0.005" diameter Co flux wire into inner site 2, and from its activity in a flat geometry calculated a flux of 3.60 x 10^{12} n/cm^2/s. Therefore the AVERAGE activity over the 8 active inches of the Cd emitter gives one the flux of 3.60×10^{12} n/cm^2/s. RMCC's activation of 8"of Co flux wire and the calibration of the new neutron flux detector in ZED-2 match perfectly."

(2) The real-time reactor power tracking capability of the Cd-emitter SPD was evidenced by the virtually 1:1 correspondence between the normalized current readings from the ion chamber and the cadmium-emitter SPD, to the indicated power in the ZED-2 Control Room. This feature of *n*,γ,*e* responding SPDs was hinted at in experiments to measure the prompt period of Sandia National Laboratories' ACR Reactor [2].

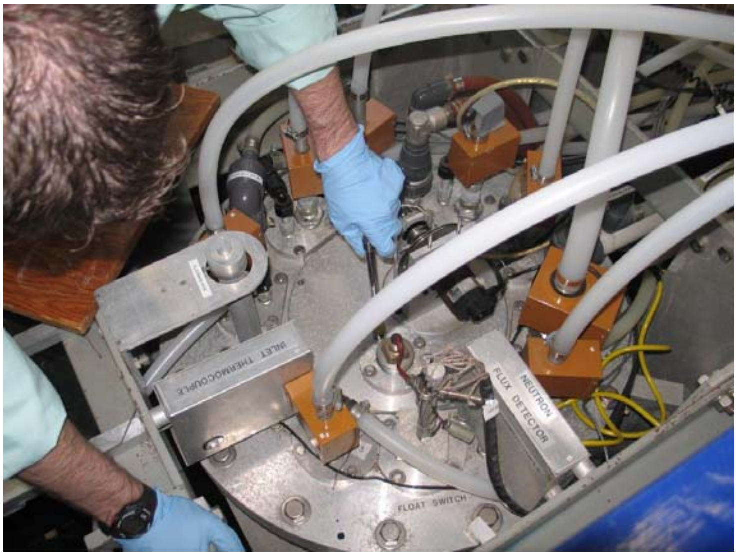

Figure 7 ***Commissioning of the Replacement Cd-Emitter SPD***

6. Acknowledgements

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7. References

[1] M.W. LaFontaine, "Use of Research & Test Reactors for SPD Development & Calibration," <u>Canadian Nuclear Society Technical Meeting on Low Power Critical Facilities & Small Reactors</u>, Ottawa, Ontario, Canada, 2010.

[2] R.L. Coats, D.G. Talley, F.R. Trowbridge, "Prompt-Period Measurement of the Annular Core Research Reactor Prompt Neutron Generation Time," Sandia National Laboratories Report SAND91-0501, July 1994.