Research on Rhodium Self-Powered Neutron Detector Signal Processing System and Neutron

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Abstract

Self-Powered Neutron Detector (SPND) serves as an important detection component for in-core neutron fluence rate measurement. Due to its special response mechanism, SPND signal currents are generally small and exhibit delayed response. Currently, research on SPND sensitivity also lacks in-reactor experimental data. This study focuses on Rhodium Self-Powered Neutron Detector (Rh-SPND). By implementing amplification and conditioning of weak currents along with algorithmic processing of delayed signals, a fast response system for Rh-SPND was developed, reducing the detector' s signal response time from hundreds of seconds to approximately 3 seconds. Sensitivity irradiation experiments were conducted on Rh-SPND at the Minjiang Research Reactor (MJTR). Experimental results show that as reactor power continuously increases, the reactor core temperature also gradually rises, reaching 42.4°C in the test section at full power operation. The output current of Rh-SPND increases with rising reactor power, with the current on the anode side being larger and that on the cathode side being smaller. Finally, the thermal neutron sensitivity of Rh-SPND was calculated. The thermal neutron sensitivities of the three SPNDs are: 1.66$ $\times 10-20/A\cdot(n\cdot cm-2\cdot s-1)-1, 1.68\times 10-20/A\cdot(n\cdot cm-\hat{}\{2\}\cdot s-1)-1, and 1.44\times$ $.

Full Text

Research on the Signal Processing System of Rhodium Self-Powered Neutron Detectors and Neutron Sensitivity Reactor Testing

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Abstract

Self-Powered Neutron Detectors (SPNDs) are crucial components for measuring neutron flux inside reactor cores. Due to their unique response mechanism, SPND signal currents are typically small and exhibit delayed response characteristics. Furthermore, research on SPND sensitivity currently lacks experimental data obtained from in-reactor environments. This study focuses on rhodium self-powered neutron detectors (Rh-SPNDs). By developing amplification circuitry for weak currents and implementing algorithmic processing for delayed signals, a fast-response system for Rh-SPNDs was developed, reducing the detector's signal response time from several hundred seconds to approximately 3 seconds. Sensitivity irradiation tests were conducted on Rh-SPNDs in the Minjiang Test Reactor (MJTR). Experimental results demonstrate that as reactor power increased, the temperature in the test section gradually rose, reaching 42.4°C at full power operation. The output current of the Rh-SPNDs increased with rising reactor power, with higher currents observed on the "sunny side" (facing the core) compared to the "shady side" (away from the core). Finally, the thermal neutron sensitivity of the Rh-SPNDs was calculated. The thermal neutron sensitivities for the three SPNDs were: 1.66×10^{-20} $\mathrm{A\cdot(n\cdot cm^{-2}\cdot s^{-1})^{-1}}$, 1.68×10^{-20} $\mathrm{A\cdot(n\cdot cm^{-2}\cdot s^{-1})^{-1}}$, and 1.44×10^{-20} $\mathrm{A\cdot(n\cdot cm^{-2}\cdot s^{-1})^{-1}}$, respectively.

Keywords: SPND; Fast response; In-pile testing; Neutron sensitivity

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On July 16, 2021, the International Atomic Energy Agency (IAEA) released the updated report *International Status and Prospects of Nuclear Power*, which outlined the current status and development prospects of nuclear power generation while emphasizing its role in mitigating climate change and achieving sustainable development. Neutron flux is a critical physical parameter for reactors, holding significant importance for safe and stable reactor operation as well as real-time power monitoring. Self-Powered Neutron Detectors (SPNDs), characterized by their compact size, simple structure, and independence from external power supplies, represent an important means of measuring neutron flux within nuclear reactor cores. They enable real-time mapping of neutron flux distribution and reflect core power profiles. In the late 1950s and early

1960s, the former Soviet Union initiated research on SPND applications in reactor core nuclear measurement systems, followed by competitive development and deployment in the United States, Japan, South Korea, and other nations. In 1972, Brakas M conducted in-reactor tests on various SPND models in the Halden Boiling Water Reactor, obtaining extensive experience regarding the use and performance of sensitive components in nuclear reactor environments. M.N. Baldwin measured detector response characteristics in relation to boron concentration and power density in a typical PWR environment, and determined the relationship between rhodium wire diameter and its beta emission rate by measuring current from bare and cadmium-covered rhodium wires placed in a thermal neutron field. O. Strindehag performed long-term tests on vanadium and cobalt detectors, presented experimental results for fast-response cobalt detectors, and reported on design and installation experience for power reactor flux detection assemblies along with electronic circuits and data processing systems. W. Johnstone employed compensated conductors and differential amplifiers to measure SPND currents, using inverse function amplifiers to predict the final values of slowly varying current amplifier outputs.

Compared to materials such as cobalt and vanadium, rhodium possesses a larger neutron reaction cross-section, resulting in greater sensitive currents in rhodium self-powered neutron detectors (Rh-SPNDs). Consequently, Rh-SPNDs have become one of the most widely used self-powered detectors. This study investigates signal amplification and delayed response compensation for Rh-SPNDs, proposing a discrete processing method based on step response invariance to mitigate time delay effects. Additionally, irradiation tests were conducted on fabricated detectors in the Minjiang Test Reactor (MJTR) to perform in-pile neutron sensitivity consistency tests for Rh-SPNDs, completing neutron flux measurements and determining the neutron sensitivity for the corresponding channels.

1.1 Basic Structure

A typical Rh-SPND structure is shown in [Figure 1: see original paper], consisting of a probe and a sheathed signal cable at the rear. The probe is the core component of the detector, comprising an emitter, insulator, and collector. The emitter material is rhodium, which is the most critical part of the detector and determines its classification and fundamental performance. The insulator material employs high-temperature-resistant, neutron-insensitive materials, typically aluminum oxide or magnesium oxide, while the collector material uses Inconel.

1.2 Response Principle

The signal current of Rh-SPNDs consists primarily of prompt current and delayed current. As shown in [Figure 2: see original paper], when neutrons enter the detector, they undergo (n,γ) reactions with ^{103}Rh to produce ^{104}Rh and ^{104} Rh. The (n,γ) reaction occurs instantaneously, and the emitted gamma photons generate electrons in the emitter material through the photoelectric effect, Compton scattering, and electron-positron pair production. These electrons traverse the insulator to reach the collector, forming a signal current known as prompt current, which accounts for approximately 5–15% of the total current. The (n,γ) reaction of ^{103}Rh has a 7.6% probability of producing ^{104} Rh and a 92.4% probability of producing ^{104}Rh. ^{104} Rh decays to ^{104}Rh with a half-life of 4.4 minutes, and ^{104}Rh subsequently decays, emitting electrons that form the delayed current, which constitutes approximately 85–95% of the total current. Gamma rays from the reactor also generate current in the detector, contributing about 5–8% of the total SPND current. This component represents an interference signal. Since its generation mechanism is identical to that of the prompt current in Rh-SPNDs, electronic filtering based on response time or waveform characteristics cannot eliminate it. Therefore, Monte Carlo simulation or numerical calculation methods are typically employed to determine the magnitude and proportion of this current component, with algorithmic compensation applied in the backend electronics for correction.

2 Rh-SPND Signal Processing

The sensitivity of Rh-SPNDs is defined as the coefficient for converting output current to neutron flux [16]: $I = S\phi$, where S represents sensitivity, I is the total current, and ϕ denotes the neutron flux near the detector. The output current signals from Rh-SPNDs exhibit weak current intensity, high background noise, significant common-mode interference, and noticeable time delay. Effective signal processing is therefore essential for practical application. This process involves signal amplification, conversion, and filtering to suppress noise and interference, thereby improving signal clarity and accuracy. Processed signals are converted to digital form through a data acquisition system, after which host computer software performs further processing and correction using precise algorithms.

The signal processing system is a multi-channel weak current amplifier featuring differential input and low-pass filtering capabilities, with range selection functionality. It amplifies the detector' s weak current signals and converts them into standard voltage signals suitable for sampling by AD modules while satisfying remote transmission requirements. Weak current amplifier and filter circuit modules along with high-precision analog-to-digital conversion functional modules were designed to implement detector signal processing, data acquisition, and processing. The Rh-SPND output current signals undergo amplification, filtering, and interference suppression, with the weak electrical signals linearly converted to 0–10 V voltage signals. A 16-bit high-precision AD conversion module then transforms the voltage signals into digital values, which are processed, corrected, and converted by the host computer to obtain reactor neutron flux and power data for display, storage, and report generation. The processing flow is illustrated in [Figure 3: see original paper].

2.1 Weak Current Amplification Module

The delayed signal from rhodium self-powered detectors consists of two main components. As shown in [Figure 2: see original paper], ^{104}Rh has a half-life of 42 seconds, while ^{104} Rh has a half-life of 4.4 minutes. Assuming a saturated maximum total current of 10^{-7} A that decays according to a double exponential function as shown in Equation (2) and [Figure 4: see original paper], after 10 minutes (600 seconds) of decay, the remaining current is 7.5×10^{-10} A, and after 20 minutes, the remaining current is still 8.3×10^{-11} A. Estimation indicates that under normal operation, the detector current varies across three orders of magnitude from 10^{-10} to 10^{-7} A over extended periods. Therefore, an amplifier range covering three orders of magnitude can satisfy practical engineering requirements.

$$I(t) = 10^{-7}\left(0.923e^{-t/42} + 0.077e^{-t/264}\right)$$

To achieve weak current amplification, the high-performance DC operational amplifier LTC2063 chip was selected, featuring an offset voltage as low as 5 V, offset voltage temperature drift of only $\pm 0.03\mu V \cdot °C^{-1}$, bias current of 0.5 pA, and open-loop gain up to 140 dB, meeting the requirements for weak current amplification.

Strong gamma fields inside the reactor core generate gamma currents in both the detector and sheathed transmission cables, while the high-temperature environment introduces thermal noise currents into the detector signals. Various noise and interference currents become particularly pronounced when the detector output neutron current is weak, directly affecting measurement accuracy and reliability. Signal processing is therefore critical for effective detector application, requiring integration of electronic and data systems to adequately suppress background noise and common-mode interference currents for accurate extraction and detection of true neutron-sensitive currents.

The single-channel current amplifier is shown in [Figure 5: see original paper]. The circuit comprises three amplification stages: an input stage using LTC2063, an intermediate gain adjustment stage using OP07, and an output stage also employing OP07. The input stage adopts a differential input circuit structure that can suppress common-mode interference in the signal line through compensation lines, utilizing a resistor amplifier configuration with feedback resistors of 1 MΩ–10 MΩ and low-frequency filtering at the output. The intermediate stage employs high-impedance relays to switch feedback resistors, enabling host computer-controlled gain selection and step adjustment as an inverting voltage amplifier with gains of 46 dB, 66 dB, and 106 dB. The output stage uses a voltage follower configuration for signal driving and filtering. The final current amplifier module achieves a current measurement range of -5.0 A to +5.0 A, measurement accuracy of $\pm$1 nA, and an output voltage range of -5 V to +5 V after current amplification.

2.2 Signal Processing Module

To ensure high precision during analog-to-digital conversion, Siemens S300 series analog input modules were selected for acquiring current and temperature signals, while the ATMEGA128 chip was chosen for the microcontroller unit due to its stable performance and powerful processing capabilities. To meet high-resolution requirements, both ADC (analog-to-digital converter) and DAC (digital-to-analog converter) modules employ 16-bit resolution chips. This configuration ensures high precision throughout the signal conversion process.

The time delay effect of neutron current generated by the rhodium emitter is significant, with signal delays lasting several minutes or more. To enable real-time, rapid measurement of reactor thermal neutron flux variations, compensation processing is required for Rh-SPND output response currents (tens of minutes) to obtain output signals that can quickly follow (within seconds) neutron flux changes. Current methods for eliminating delayed response include inverse function amplifier elimination, Kalman filtering, robust filtering, and $H_2/H\infty$ hybrid filtering. compares the advantages and disadvantages of these methods.

** Analysis and Comparison of Signal Response Delay Elimination Methods**

Delay Elimination Method	Advantages	Disadvantages
Inverse Function Amplifier Filtering [17]	Reduces delay to 2–3 s	May cause signal distortion
Kalman Filtering [18]	Noise reduction	Requires statistical noise information
$H_2/H\infty$ Hybrid Filtering [19]	Reduces delay to 2–10 s	Introduces excessive empirical tuning parameters
Robust Filtering Method [20]	Good noise suppression, fewer tuning parameters	Requires two empirical parameter values

To process these continuous signals, the continuous-time system governing them must be equivalently represented in the discrete domain. Discretization refers to mapping the continuous-time system transfer function to the discrete domain to obtain a discrete-time system transfer function. This study employs four discretization methods: forward difference transformation, backward difference transformation, step response invariance, and bilinear transformation [21]. Using inverse function reconstruction for secondary signal processing enables rapid response (within seconds) and accurate tracking of neutron flux rate changes to output corresponding neutron current signals. The characteristics after processing are shown in . Among these, the step response invariance method yields the optimal result, reducing time delay to 2.8 seconds. Therefore, the step response invariance discrete processing method was adopted for Rh-SPND signal processing to mitigate time delay effects. Laboratory test results for the developed Rh-SPND fast response system are shown in [Figure 6: see original paper], where Waveform 2 (lower) represents the detector' s delayed response output with long delay time, and Waveform 4 (upper) shows the compensated algorithm output with fast response time. For step changes in neutron flux, the detector' s signal response time was improved from hundreds of seconds to approximately 3 seconds.

** Time Constant Results After Signal Processing with Different Algorithms**

Algorithm	First Processing	Second Processing
Forward Difference Transformation	29.4 s	29.4 s
Backward Difference Transformation	29.4 s	24.0 s
Step Response Invariance	2.8 s	29.4 s
Bilinear Transformation	29.4 s	–

3 Rh-SPND Consistency Test Verification

For self-powered neutron detectors to be maturely applied in nuclear power applications, they must undergo in-pile irradiation testing. Consistency is a critical indicator for SPND deployment in nuclear power, essential for accurate core flux monitoring and reactor safe operation. To test the sensitivity and consistency of SPNDs manufactured in the same batch, in-pile tests were conducted in the MJTR #6 channel, which has a diameter of Φ125$×$3 mm. The #6 channel is a pressure tube channel isolated from the MJTR reactor cooling water, operating at atmospheric pressure with deionized water inside.

3.1 Detector Arrangement

To determine Rh-SPND neutron sensitivity, the Rh-SPND output signal current values were collected during core testing, and the thermal neutron flux at the Rh-SPND probe position was measured using the activation method to calculate the corresponding Rh-SPND sensitivity. The radial arrangement of Rh-SPNDs and activation detectors is shown in Figure 7: see original paper. Activation detectors and Rh-SPNDs were arranged symmetrically along the central radius in the irradiation device. Specifically, activation detectors were placed at the radial center position and at four symmetric outer positions (totaling 5 locations), while Rh-SPND probes were positioned at four symmetric inner radial locations. K11 is oriented toward the reactor core, with 1# and 2# Rh-SPNDs placed on the sunny side and 3# and 4# Rh-SPNDs on the shady side (sunny side refers to the position facing the core, while shady side refers to the position away from the core). Positions T4, T5, T6, and T7 each contain a CoAl detector foil, while position T1 contains five detector foils: CoAl, ScAl, AgAl, AuAl, and Fe.

The relative axial positions of activation detectors and Rh-SPNDs are shown in Figure 7: see original paper. Activation detectors at the radial center position were arranged at upper, middle, and lower axial positions to cover the Rh-SPND length, with multiple different material activation detectors at the center position and one activation detector each at the upper and lower positions. Four activation detectors were placed at the outermost positions (aligned with the mid-plane of the Rh-SPND sensitive element). To ensure that activation detector measurements accurately represent the thermal neutron flux at the Rh-SPND probe location—meaning the ratio of Rh-SPND output current to activation detector thermal neutron flux measurement can characterize Rh-SPND neutron sensitivity—the radial positions of Rh-SPNDs were placed as close as possible to the activation detector positions. K-type thermocouples were used in the irradiation test to measure the temperature of Rh-SPND test specimens, with four thermocouples positioned radially consistent with the Rh-SPND detector head holes to ensure the thermocouple hot junction temperature matches that of the Rh-SPNDs.

3.2.1 Test Temperature Results

Four thermocouples (1#, 2#, 3#, 4#) were installed in the irradiation test section to measure temperatures at the corresponding four Rh-SPND positions. Temperature curves at different test times are shown in Figure 8: see original paper, and temperature curves at reactor power levels of 1 MW, 2 MW, 4 MW, and 5 MW are shown in Figure 8: see original paper. As reactor power increased, the core temperature continuously rose. At full power operation (60–170 min), temperatures remained essentially stable, fluctuating slightly within the 42°C–43°C range.

3.2.2 Thermal Neutron Flux Activation Foil Measurement Results

To obtain the absolute neutron flux at the Rh-SPND locations, the irradiation device was removed from the reactor and disassembled. Radioactivity measurements of activation detector foils were performed using a high-purity germanium gamma spectrometer to determine thermal neutron flux. The dual-detector activation method (Fe and AgAl) determined the thermal neutron flux at the irradiation device center position as $3.55\times10^{12}\ n\cdot(cm^2\cdot s)^{-1}$ (corresponding to the MJTR full power operation value of 5 MW). Average thermal neutron flux values along the central axis are shown in , while average thermal neutron flux values for the axes corresponding to the four outer positions are shown in . The thermal neutron flux values for the four individual Rh-SPNDs are presented in , demonstrating that detectors on the sunny side measured higher neutron flux than those on the shady side, and that neutron flux increases with proximity to the core.

** Average Thermal Neutron Flux Along Irradiation Device Central Axis**

Activation Detector ID	Activation Position	Specific Activity at End of Irradiation ($Bq\cdot mg^{-1}$)	Average Thermal Neutron Flux Along Central Axis ($\times10^{12}\ n\cdot cm^{-2}\cdot s^{-1}$)
CoAl-1	Upper	664.20±42.50	3.53±0.23
CoAl-2	Middle	645.10±41.30	
CoAl-3	Lower	672.20±43.00	

Note: Position indicates upper, middle, and lower locations along the central axis; the absolute thermal neutron flux at the middle position (with multiple detectors) is 3.550$\times10^{12}$ n$\cdot$(cm$^2\cdot$s)$^{-1}$ (corresponding to MJTR full power operation at 5 MW).

** Average Thermal Neutron Flux for Outer Detector Corresponding Axes**

Activation Detector ID	Activation Position	Specific Activity at End of Irradiation (Bq $\cdot$ mg^{-1})	Average Thermal Neutron Flux for Corresponding Axis ($\times10^{12}$ n $\cdot$ cm$^{-2}\cdot$ s^{-1})
CoAl-1	Outer-1	3.89±0.25	3.71±0.24
CoAl-4	Outer-2	3.92±0.25	3.72±0.24
CoAl-5	Outer-3	3.31±0.21	3.42±0.22
CoAl-6	Outer-4	3.36±0.22	3.45±0.22

Note: Calculated using the central axis average thermal neutron flux of 3.530$\times10^{12}$ n $\cdot$ cm$^{-2}\cdot$ s^{-1} multiplied by the activity ratio at the corresponding position.

** Thermal Neutron Flux Values at SPND Positions**

SPND ID	Activation Detector Position	Average Thermal Neutron Flux for Corresponding Axis ($\times10^{12}$ n $\cdot$ cm$^{-2}\cdot$ s^{-1})	Thermal Neutron Flux Value at SPND Position ($\times10^{12}$ n $\cdot$ cm$^{-2}\cdot$ s^{-1})
1#	Outer-1 axis	3.53±0.23	3.71±0.24
2#	Outer-2 axis	3.89±0.25	3.72±0.24
4#	Outer-3 axis	3.92±0.25	3.42±0.22
	Outer-4 axis	3.31±0.21	3.45±0.22
	Average for 4 SPND positions	3.36±0.22	3.57±0.23

3.2.3 Rh-SPND Sensitive Current Measurement Results

The sensitive currents output by 1#, 2#, and 4# Rh-SPNDs (3# was damaged) were measured and recorded online during irradiation. The measured sensitive current curves at power levels of 1-5 MW are shown in [Figure 9: see original paper]. The output currents of 1# and 2# SPNDs were higher than that of 4# SPND because 1# and 2# were placed on the sunny side where neutron flux is higher, while 3# and 4# were placed on the shady side with lower neutron flux.

3.2.4 Neutron Sensitivity Test Results

Based on the neutron sensitivity definition in Equation (1) and combining the measured Rh-SPND signal currents with the thermal neutron flux around the detectors at full power, the Rh-SPND neutron sensitivity was calculated. The results are presented in . The 1# and 2# Rh-SPNDs exhibit good consistency with a deviation of only 0.63%. However, when comparing all three SPNDs, the consistency deviation increases to 6.5%, primarily because the sensitivity of 4# Rh-SPND is significantly lower than that of 1# and 2#. Preliminary analysis suggests this discrepancy is due to emitter deficiency caused by welding issues during SPND manufacturing, resulting in smaller signal currents.

** SPND Thermal Neutron Sensitivity Test Results**

Detector ID	Sensitivity Average Value ($\times10^{-20}$ $A \cdot (n \cdot cm^{-2} \cdot s^{-1})^{-1}$)
1#	1.66±0.06
2#	1.68±0.06
4#	1.44±0.06
Average	1.59±0.06

4 Conclusion

(1) By developing amplification circuitry for weak currents and implementing algorithmic processing for delayed signals, a fast-response system for Rh-SPNDs was successfully developed, reducing the detector's signal response time from several hundred seconds to approximately 3 seconds.

(2) During high-power operation (5 MW) of the MJTR, the test section temperature reached 42.4°C. The Rh-SPNDs output sensitive currents that varied with reactor power across 1–5 MW power levels, demonstrating good consistency. The average neutron sensitivity of the Rh-SPNDs reached 1.59$\times10^{-20}$ $A \cdot (n \cdot cm^{-2} \cdot s^{-1})^{-1}$, with good consistency observed among SPNDs from the same production batch.

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Note: Figure translations are in progress. See original paper for figures.