CHARACTERISTICS OF SELF-POWERED NEUTRON DETECTORS USED IN POWER REACTORS

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Abstract

Self-Powered Neutron Detectors have been used effectively as in-core flux monitors for over twenty-five years in nuclear power reactors world-wide. This paper describes the basic properties of these radiation sensors including their nuclear, electrical and mechanical characteristics. Recommendations are given for the proper choice of the self-powered detector emitter to provide the proper response time and radiation sensitivity desired for use in an effective in-core radiation monitoring system. Examples are shown of specific self-powered detector designs which are being effectively used in in-core instrumentation systems for pressurised water, heavy water and graphite moderated light water reactors. Examples are also shown of the mechanical configurations of in-core assemblies of self-powered detectors combined with in-core thermocouples presently used in pressurised water and heavy water reactors world-wide.

This paper is a summary of a new IEC standard to be issued in 1996 describing the characteristics and test methods of self-powered detectors used in nuclear power reactors.

Self-powered neutron detectors – General characteristics

In Self-Powered Neutron Detectors (SPNDs), the interactions of neutrons and atomic nuclei are used to produce a current which is proportional to the neutron fluence rate (flux). Compared to other in-core detectors, they feature some advantages:

- Need no power supply.
- Simple and robust structure.
- Relatively small mechanical “size” desired for in-core installation.
- Good stability under temperature and pressure conditions.
- Generate a reproducible linear signal.
- Low burn-up (dependent on emitter material).

In addition, there are also some disadvantages:

- Limited operating range due to relatively low neutron sensitivity.
- Compensation for background noise required (for some emitters).
- Delayed signal response (for some emitters).

Mechanical structure and characteristics

The typical SPND (see Figure 1) is a coaxial cable consisting of an inner electrode (the emitter), surrounded by insulation and an outer electrode (the collector).

Preferably, the lead cable and detector sections are integral, i.e. the signal wire of the lead cable mates directly to the emitter; the insulation of both sections are identical and the collector of the detector section is also the outer sheath of the lead cable section. Detectors constructed in this manner are termed Integral SPNDs. SPND assemblies may also be made from separate detector and lead cable sections and are termed Modular SPNDs (see Figure 2).

Figure 1. Typical integral self-powered neutron detector (rhodium type)

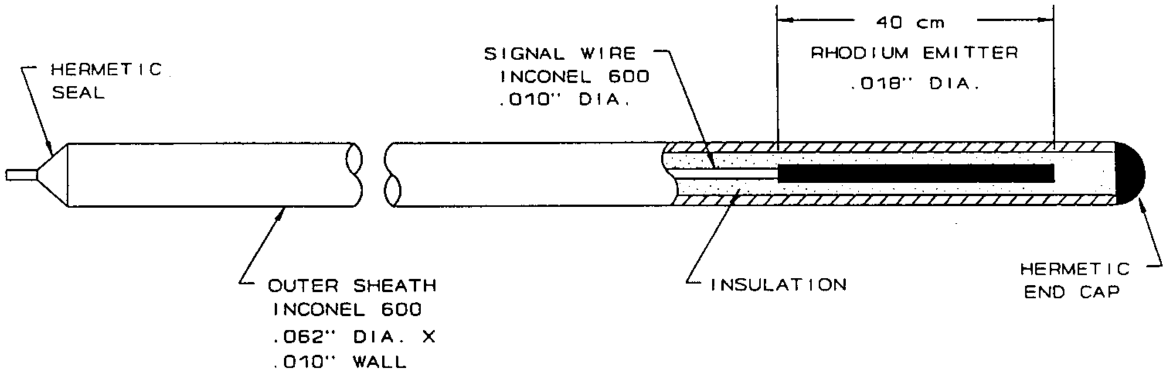
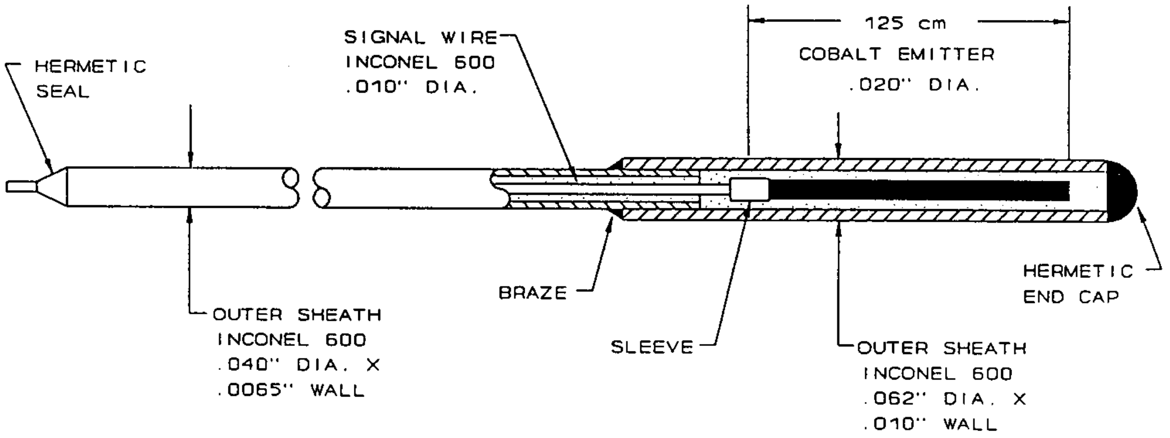


Figure 2. Typical modular self-powered neutron detector (cobalt type)



Nuclear characteristics

For power reactor applications, typical emitter materials used in SPNDs include Rhodium, Vanadium, Cobalt, Hafnia, Platinum and Silver. These materials should be used because they possess relatively high melting temperatures, relatively high cross sections to thermal neutrons and are compatible with the SPND manufacturing process. Other emitters such as Cadmium, Gadolinium and Erbium may be used in SPNDs, but are not practical for power reactor applications.

Table 1 gives an overview of some of the important characteristics of SPND emitters used in power reactor applications.

Table 1. SPND emitter materials characteristics

Emitter Materials	Thermal Neutron Cross Sections	Delayed n,b	Prompt n,g,e	Prompt g,e	Applications
Co^{59}	$37x10^{-24}$ cm^2	0	X	0	LWR Flux Mapping LWR Control Local Core Protection
Pt^{195}	$24x10^{-24}$ cm^2	0	X	X	LWR Control HWR Control
Rh^{103}	$145x10^{-24}$ cm^2	X	–	–	LWR Flux Mapping
V^{51}	$4.9x10^{-24}$ cm^2	X	X	0	HWR Flux Mapping LWR Flux Mapping
$Hf0_2$	$115x10^{-24}$ cm^2	0	X	0	RBMK* Flux Mapping RBMK* Local Control RBMK Local Core Protection
Ag	$64.8x10^{-24}$ cm^2	X	–	–	RBMK Flux Mapping

X = Primary Interaction   O = Secondary Interaction   *Upgraded RBMK
LWR - Light Water Reactor   HWR - Heavy Water Reactor
RBMK - Graphite Moderated Light Water Reactor   RBMK* - Upgraded SPND for RBMK

Additional design information follows for the most commonly used emitter materials:

Rhodium emitter characteristics

Rh^{103} has a n-beta-interaction with a 145 barn cross-section for thermal neutrons and a resonance at 1.25 e.v.

- The burn-up rate is 0.39% per month in a thermal neutron flux of 10^{13}n/cm^2/second.
- 92% of the signal has a half-life of 42 seconds.
- 8% of the signal has a half-life of 4.4 minutes.
- The beta emission has an energy of 2.44 Mev.
- A SPND with a rhodium emitter has a relatively high sensitivity, high burn-up rate, perturbs the local power density and has a (two-fold) delayed signal.

Vanadium emitter characteristics

V^{51} has a n-beta interaction with a thermal neutron cross-section of 4.9 barns featuring a 1/v characteristic without resonances in the energy range of thermal/epithermal neutrons.

- The burn-up rate is 0.012%/month in a thermal neutron flux of 10^{13}n/cm^2/second.
- 99% of the signal has a half-life of 3.76 minutes, 1% of the signal is prompt.
- There is a parallel beta emission of 2.6 Mev.
- A SPND with a vanadium emitter has a relatively low sensitivity, low burn-up rate, minimal perturbation of the local power density, but has a very long delayed signal.

Cobalt emitter characteristics

Co^{59} has a n-gamma interaction with a 37 barn thermal neutron cross-section and a parallel gamma-photon reaction.

- The burn-up rate is 0.094%/month in a thermal neutron flux of 10^{13}n/cm^2/second.
- The signal is prompt, but requires long term compensation due to build-up of radioactive isotopes Co^{60} and Co^{61}.
- A SPND with a cobalt emitter has a relatively low sensitivity, moderate burn-up rate and a prompt signal.

Hafnia emitter characteristics

HfO_2 has a n-gamma interaction with a 115 barn thermal neutron cross-section and parallel gamma-photon reaction.

- The average burn-up rate is 0.3%/month in a thermal neutron flux of 10^{13}n/cm^2/second.
- 96% of the signal is prompt, 4% of signal is delayed as gamma-radiation from fission products.
- A SPND with a hafnia emitter has relatively low sensitivity, high burn-up rate, perturbs the local power density and has a prompt signal.

Silver emitter characteristics

Ag has a n-beta interaction with a 64.8 barn cross-section for thermal neutrons and a few resonances in the range 5-134 ev.

- The burn-up rate is 0.16%/ month in a thermal neutron flux of 10^{13}n/cm^2/second.
- 66% of the initial signal has a half-life of 24.4 seconds.
- 25% of the signal has a half-life of 2.42 minutes.
- 9% of the signal is a prompt signal.
- A SPND with a silver emitter has an average sensitivity, average burn-up rate, average perturbation of local power density and has a (two-fold) delayed signal.

Platinum emitter characteristics

Pt^{195} has a n-gamma interaction with a 24 barn thermal neutron cross-section and a parallel gamma-photon reaction.

- The burn-up rate is 0.03%/month in a thermal neutron flux of 10^{13} n/cm^2/second.
- The signal is prompt and has both neutron and gamma components.
- A SPND with a platinum emitter is sensitive to both gamma and neutron fluxes with 93% of the signal current due to gamma flux response and 7% due to neutron flux response in a typical light water reactor core with the following gamma and neutron fluxes..

  $$(\phi_\gamma \approx 10^8 \text{ R/HR}, \phi_n \approx 10^{13}\text{nv})$$

- A SPND with a platinum emitter has a relatively low sensitivity, low burn-up rate and a prompt signal.

Detector calibration

The calibration of self-powered neutron detectors may be performed at the installation site (in-situ), or in a test reactor prior to final installation.

Absolute calibration

The absolute neutron sensitivity of a SPND may be determined by wire activation analysis. The basic method involves exposing the SPND to a source of neutrons (typically thermal) and measuring the resulting output current. Neutron flux during exposure is determined from activation analysis of high purity, thin foils or wires with a well-defined capture cross-section for the neutron range of interest, e.g. cobalt or gold for thermal neutrons.

Sensitivity is readily calculated as measured output current divided by neutron flux.

Comparison calibration

The absolute neutron sensitivity of a SPND may be determined by comparison to a standard SPND. The basic method involves exposing the SPND undergoing calibration (the test SPND) and a standard SPND (a detector of known absolute neutron sensitivity and physical characteristics identical to those of the test SPND) to a source of neutrons (typically thermal) and measuring the resulting output currents.

Sensitivity is readily calculated as the measured output of the test SPND divided by the measured output current of the standard SPND times the absolute neutron sensitivity of the standard SPND. (it may be necessary to apply corrections to account for flux variance existing between the calibration site of the test SPND and that of the standard SPND)

In-core calibration

There are several well proven in-core calibration systems using fixed or movable detectors as well as activation techniques as follows:

- Fixed in-core detectors characterised by no or low burn-up factors such as vanadium self-powered detectors or gamma thermometers.
- Single or multiple movable in-core fission chambers or self-powered detectors located in calibration tubes within each self-powered detector assembly.
- Columns of steel balls with vanadium content moved by air or other gas which are irradiated in-core and later have their induced activity measured out-of-core.

Production tests

SPNDs and assemblies shall undergo final production tests designed to ensure conformity of manufacture.

The following characteristics shall be measured for all production SPNDs:

- SPND sheath and detector envelope integrity under maximum hydrostatic pressure and temperature conditions (for wet assembly designs).
- Insulation resistance both at 20°C and maximum operating temperature {typical acceptable insulation resistance values are shown in Table 3 for both room temperature (20°C) and maximum operating temperature (300°C)}.
- Continuity of emitter to signal wire.
- Calibration of thermal neutron sensitivity shall be performed on a sampling basis to ensure uniformity of the manufacturing lot.
- Identification of emitter location by radiography for integral type SPNDs.

Self-powered detector operating characteristics

The following tables present the characteristics of self-powered detectors most commonly used in nuclear power plants. They are intended for reference to the user of this publication in selecting the optimum SPND for specific uses for in-core instrumentation systems.

Table 2. Nuclear characteristics of selected emitter materials

Emitter Material	Stable Isotope	% Composition	Activation Cross-section (barns)	Resulting Nuclide	Half-life
Vanadium	$_{23}V^{50}$	0.24	100	$_{23}V^{51}$	Stable
	$_{23}V^{51}$	99.76	4.9	$_{23}V^{52}$	3.76 Minutes
Rhodium	$_{45}Rh^{103}$	100	11(8%)	$_{45}Rh^{104m}$	4.4 Minutes
			135(92%)	$_{45}Rh^{104}$	42 seconds
Cobalt	$_{27}Co^{59}$	100	37	$_{27}Co^{60}$	5.27 years
Hafnia	$_{72}Hf^{174}$	0.18	390	$_{72}Hf^{175}$	70 days
	$_{72}Hf^{176}$	5.20	15	$_{72}Hf^{177m}$	51.4 min
	$_{72}Hf^{177}$	18.50	380	$_{72}Hf^{178m}$	31 years
	$_{72}Hf^{178}$	27.14	75	$_{72}Hf^{179m}$	25.1 days
	$_{72}Hf^{179}$	13.75	65	$_{72}Hf^{180m}$	5.5 hours
	$_{72}Hf^{180}$	35.23	14	$_{72}Hf^{181m}$	42.4 days
Silver	$_{47}Ag^{107}$	51.82	35	$_{47}Ag^{108}$	2.42 min
	$_{47}Ag^{109}$	48.18	93	$_{47}Ag^{110}$	24.4 seconds
Platinum	$_{78}Pt^{192}$	0.78	14	$_{78}Pt^{193m}$	4.3 days
	$_{78}Pt^{194}$	32.90	2	$_{78}Pt^{195m}$	4.1 days
	$_{78}Pt^{195}$	33.80	24	$_{78}Pt^{196}$	Stable
	$_{78}Pt^{196}$	25.30	1	$_{78}Pt^{197m}$	1.3 hours
	$_{78}Pt^{198}$	7.22	4	$_{78}Pt^{199}$	30.8 min.

Reference for Nuclear Data used in Table 2: Lederer, C.M., J.M. Hollander, and I. Perlman: "Table of the Isotopes" 6th Edition John Wiley and Sons, Inc., New York, 1967

Table 3. Specifications for typical SPNDs used in power reactors

Emitter Material	Rhodium	Vanadium	Cobalt	Hafnia ($Hf0_2$)	Silver	Platinum
Emitter Diameter mm	0.46	2.0	2.0	1.24	0.65	0.51
Emitter Length mm	400	100	210	7000	7000	3050
Insulator Type	Al_2O_3	Al_2O_3	Al_2O_3	M_g0	M_g0	Al_20_3
Collector Material	Inconel	Inconel	Inconel	Stainless Steel	Stainless Steel	Inconel
Collector Diameter mm	1.57	3.5	3.5	3.0	3.0	1.6
Thermal Neutron Sensitivity A/nv	$3.6x10^{-20}$	$4.8x10^{-21}$	$5.4x10^{-21}$	$7.9x10^{-20}$	$42x10^{-20}$	$2.5x10^{-22}$
Co^{60} Gamma Sensitivity A/R/HR	$7.0x10^{-17}$	$4.0x10^{-17}$	$5.6x10^{-17}$	$2.8x10^{-16}$	$13.5x10^{-16}$	$3.4x10^{-16}$
Insulation Resistance ohms 20°C 300°C	$>10^{12}$ $>10^{8}$	$>10^{12}$ $>10^{8}$	$>10^{12}$ $>10^{8}$	$>10^{10}$ $>10^{8}$	$>10^{9}$ $>10^{7}$	$>10^{12}$ $>10^{8}$
Response Time (0-63%)	1.1 Minutes	5.5 Minutes	Prompt	Prompt	0.5 Minutes	Prompt
Burn-up Rate %/month at 10^{13}nv	0.39	0.01	0.09	0.30	0.16	0.03

Self-powered detector assemblies

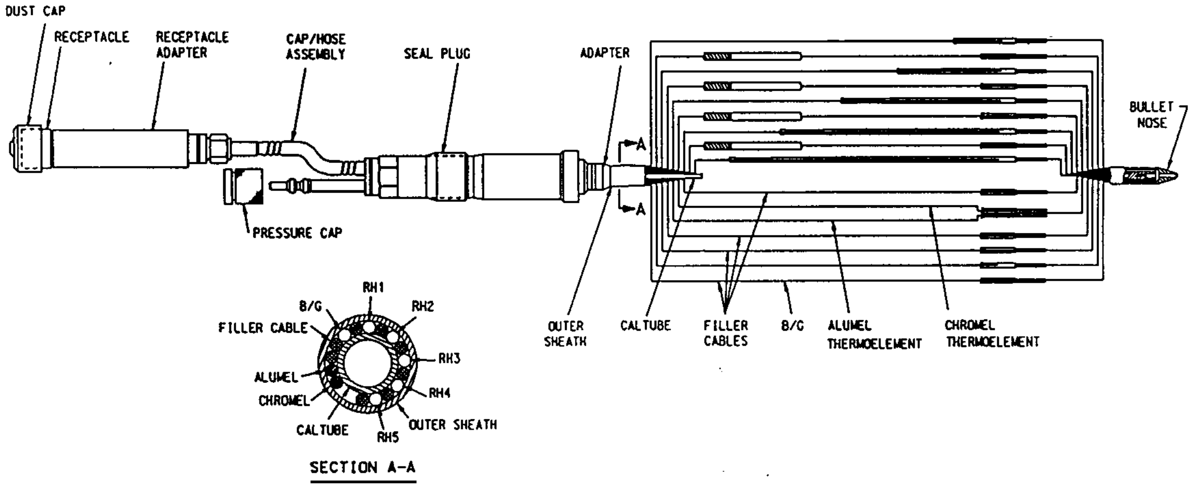
The following description and figures show typical self-powered detector assembly configurations used in light water and heavy water nuclear power plants world-wide. These configurations are only a few of the many combinations of self-powered detector elements and mechanical geometries being used to provide in-core signals for flux mapping, control and core protection applications.

Light water reactor self-powered detector assemblies

Typical bottom mounted rhodium self-powered detector assembly for pressurised water reactors

A typical bottom mounted in-core self-powered detector assembly for pressurised water reactors is shown in Figure 3. The assembly consists of five rhodium self-powered detectors (with emitters equally spaced over the total core height), one background detector (covering the total core height), and one core exit thermocouple. All sensing elements are housed within an Inconel 600 outer sheath tube. A calibration tube, seal plug and multipin electrical receptacle complete the assembly. The total length of the assembly is approximately thirty-five (35) meters.

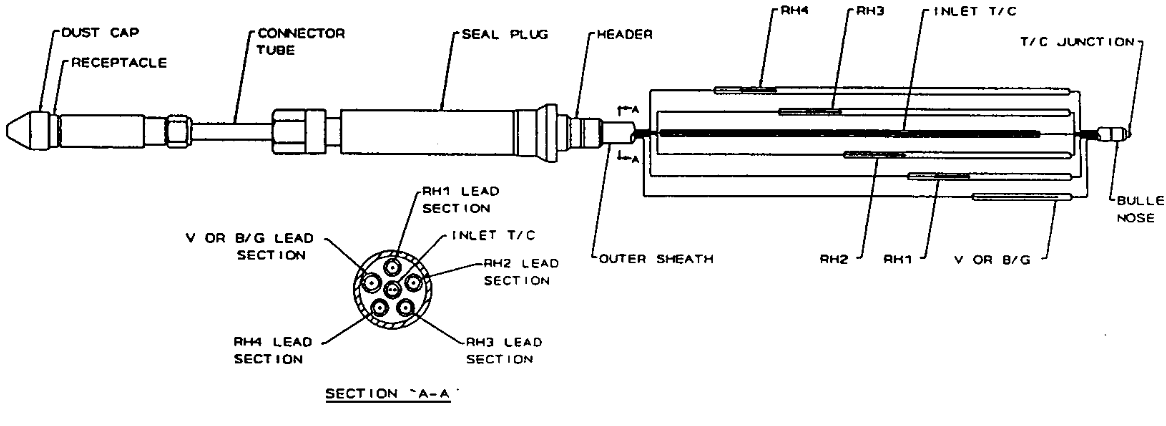
Figure 3. Bottom mounted rhodium self-powered detector assembly for pressurised water reactors



Typical top mounted rhodium self-powered detector assembly for pressurised water reactors

A typical top mounted Rhodium in-core self-powered detector assembly for pressurised water reactors is shown in Figure 4. The assembly consists of four rhodium self-powered detectors, one full core height vanadium detector, one full core height background detector and one core inlet thermocouple. All sensing elements are housed within an Inconel 600 outer sheath tube. A header, seal plug and multipin electrical receptacle complete the assembly which is approximately ten (10) meters long.

Figure 4. Top mounted rhodium self-powered detector assembly for pressurised water reactors



Typical heavy water reactor self-powered detector assembly

A typical heavy water reactor in-core self-powered detector assembly is shown in Figure 5. The assembly consists of a cluster of zircalloy dry detector well tubes, designed to accommodate various quantities and types of self-powered detector elements and one dry detector well tube which allows for installation of a travelling flux detector (TFD.). Well shield plugs are installed in all wells not occupied by detectors and all detector wells are contained within a protective zircalloy capsule.

Figure 5. Heavy water reactor self-powered detector assembly