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INTERNATIONAL STANDARD

Nuclear power plants – Instrumentation systems important to safety – In-core instrumentation: Characteristics and test methods of self-powered neutron detectors

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IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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NUCLEAR POWER PLANTS – INSTRUMENTATION SYSTEMS IMPORTANT TO SAFETY – IN-CORE INSTRUMENTATION: CHARACTERISTICS AND TEST METHODS OF SELF-POWERED NEUTRON DETECTORS

FOREWORD

International Standard IEC 61468 has been prepared by subcommittee 45A: Instrumentation, control and electrical power systems of nuclear facilities, of IEC technical committee 45: Nuclear instrumentation.

This second edition cancels and replaces the first edition, published in 2000, and its Amendment 1, published in 2003. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) Title modified.

b) Justify the requirements for SPND characteristics in terms of influencing factors.

c) Align the terminology with the current state of the regulatory framework.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
45A/1381/FDIS	45A/1383/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

a) Technical background, main issues and organisation of the Standard

This International Standard focuses on self-powered neutron detectors (SPNDs).

It is intended that this document be used by operators of NPPs (utilities), systems evaluators and by licensors.

b) Situation of the current Standard in the structure of the IEC SC 45A standard series

IEC 61468 is a third level IEC/SC 45A document.

IEC 61468 is to be read in conjunction with IEC 61513 which establishes general requirements for I&C systems and with IEC 60568 which establishes general requirements for in-core instrumentation for neutron fluence rate (flux) measurements in power reactors.

For more details on the structure of the IEC SC 45A standard series, see item d) of this introduction.

c) Recommendations and limitations regarding the application of the Standard

To ensure that the Standard will continue to be relevant in future years, the emphasis has been placed on issues of principle, rather than specific technologies.

d) Description of the structure of the IEC SC 45A standard series and relationships with other IEC documents and other bodies documents (IAEA, ISO)

The top-level documents of the IEC SC 45A standard series are IEC 61513 and IEC 63046. IEC 61513 provides general requirements for I&C systems and equipment that are used to perform functions important to safety in NPPs. IEC 63046 provides general requirements for electrical power systems of NPPs; it covers power supply systems including the supply systems of the I&C systems. IEC 61513 and IEC 63046 are to be considered in conjunction and at the same level. IEC 61513 and IEC 63046 structure the IEC SC 45A standard series and shape a complete framework establishing general requirements for instrumentation, control and electrical systems for nuclear power plants.

IEC 61513 and IEC 63046 refer directly to other IEC SC 45A standards for general topics related to categorization of functions and classification of systems, qualification, separation, defence against common cause failure, control room design, electromagnetic compatibility, cybersecurity, software and hardware aspects for programmable digital systems, coordination of safety and security requirements and management of ageing. The standards referenced directly at this second level should be considered together with IEC 61513 and IEC 63046 as a consistent document set.

At a third level, IEC SC 45A standards not directly referenced by IEC 61513 or by IEC 63046 are standards related to specific equipment, technical methods, or specific activities. Usually these documents, which make reference to second-level documents for general topics, can be used on their own.

A fourth level extending the IEC SC 45A standard series, corresponds to the Technical Reports which are not normative.

The IEC SC 45A standards series consistently implements and details the safety and security principles and basic aspects provided in the relevant IAEA safety standards and in the relevant documents of the IAEA nuclear security series (NSS). In particular this includes the IAEA requirements SSR-2/1, establishing safety requirements related to the design of nuclear power plants (NPPs), the IAEA safety guide SSG-30 dealing with the safety classification of structures, systems and components in NPPs, the IAEA safety guide SSG-39 dealing with the design of instrumentation and control systems for NPPs, the IAEA safety guide SSG-34 dealing with the design of electrical power systems for NPPs and the implementing guide NSS17 for computer security at nuclear facilities. The safety and security terminology and definitions used by SC 45A standards are consistent with those used by the IAEA.

IEC 61513 and IEC 63046 have adopted a presentation format similar to the basic safety publication IEC 61508 with an overall life-cycle framework and a system life-cycle framework. Regarding nuclear safety, IEC 61513 and IEC 63046 provide the interpretation of the general requirements of IEC 61508-1, IEC 61508-2 and IEC 61508-4, for the nuclear application sector. In this framework IEC 60880, IEC 62138 and IEC 62566 correspond to IEC 61508-3 for the nuclear application sector. IEC 61513 and IEC 63046 refer to ISO as well as to IAEA GS-R part 2 and IAEA GS-G-3.1 and IAEA GS-G-3.5 for topics related to quality assurance (QA). At level 2, regarding nuclear security, IEC 62645 is the entry document for the IEC/SC 45A security standards. It builds upon the valid high level principles and main concepts of the generic security standards, in particular ISO/IEC 27001 and ISO/IEC 27002; it adapts them and completes them to fit the nuclear context and coordinates with the IEC 62443 series. At level 2, IEC 60964 is the entry document for the IEC/SC 45A control rooms standards and IEC 62342 is the entry document for the ageing management standards.

NOTE It is assumed that for the design of I&C systems in NPPs that implement conventional safety functions (e.g. to address worker safety, asset protection, chemical hazards, process energy hazards) international or national standards would be applied.

NUCLEAR POWER PLANTS – INSTRUMENTATION SYSTEMS IMPORTANT TO SAFETY – IN-CORE INSTRUMENTATION: CHARACTERISTICS AND TEST METHODS OF SELF-POWERED NEUTRON DETECTORS

1 Scope

This document applies to in-core neutron detectors, viz. self-powered neutron detectors (SPNDs), which are intended for application in systems important for nuclear reactor safety: protection, instrumentation and control. This document contains SPND characteristics and test methods. In this document, the main sources of errors, and the possibilities for their minimization are also considered.

Self-powered neutron detectors can be used for measurement of neutron fluence rate and associated parameters in nuclear reactors. Most popular for the indicated applications are detectors with rhodium emitters.

In this document dynamic characteristics, emitter burn-up, identity and other factors influencing operational characteristics of detectors are considered.

Besides SPNDs with rhodium emitters, SPNDs with emitters from other materials and their main characteristics are also considered in this document.

This document contains requirements, recommendations and instructions concerning selection of SPND type and characteristics for various possible applications. This document about SPNDs uses the basic requirements of IEC 61513 and IEC 60568 and complements them with more specific provisions in compliance with IAEA Safety Guides.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60515:2007, *Nuclear power plants – Instrumentation important to safety – Radiation detectors – Characteristics and test methods*

IEC 60568:2006, *Nuclear power plants – Instrumentation important to safety – In-core instrumentation for neutron fluence rate (flux) measurements in power reactors*

IEC/IEEE 60780-323:2016, *Nuclear facilities – Electrical equipment important to safety – Qualification*

IEC 61226, *Nuclear power plants – Instrumentation, control and electrical power systems important to safety – Categorisation of functions and classification of systems*

IEC 61513, *Nuclear power plants – Instrumentation and control important to safety – General requirements for systems*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
background-compensation <of a self-powered neutron detector signal>
method employed for compensation of background contribution to the self-powered neutron detector current

Note 1 to entry: This is usually accomplished by placing an "emitterless" background detector in the in-core assembly, or by using detectors with an internal compensating lead wire.

Note 2 to entry: An equivalent term is “lead-compensation”.

3.2
beta decay
radioactive decay process in which mass number A remains unchanged, but the atomic number Z changes

Note 1 to entry: Processes include electron emission (b– decay), electron capture, and positron emission (b+ decay).

3.3
burn-up
depletion or reduction of target atoms when exposed to a thermal neutron flux density over time, due to conversion to other radioisotopes

3.4
burn-up life
time after which, at a given value of the neutron fluence rate of given energy distribution, the amount of emitter sensitive material will decrease to such an extent that the characteristics of the detector go beyond the tolerance established for their given application

3.5
Compton effect
effect which occurs when an incident high-energy photon is deflected from its original path by an interaction with an electron

Note 1 to entry: The electron is ejected from its orbital position and the x-ray photon loses energy because of the interaction but continues to travel through the material along an altered path. Energy and momentum are conserved in this process. The energy shift depends on the angle of scattering and not on the nature of the scattering medium. Since the scattered photon has less energy, it has a longer wavelength than the incident photon.

Note 2 to entry: An equivalent term is “Compton scattering”.

[SOURCE: IEC 60050-395:2014, 395-02-07]

3.6
cross-section
σ
measure of the probability of a nuclear reaction of a specific type, stated as the effective area which targets particles present to incident particles for that process

Note 1 to entry: The standard unit for measuring a nuclear cross-section is the barn, which is equal to 10−28 m^2 or 10−24 cm^2.

Note 2 to entry: A microscopic cross-section can be measured for each process of nuclear reaction (capture, fission, n-n′, n-2n, n-g,etc.).

Note 3 to entry: The macroscopic cross-section allows the calculation of the number of interactions for a given nuclear reaction in a given material; this value is the produce between the corresponding cross-section and the number of particles in volume of this material; it is expressed in m^{-1} or cm^{-1}.

[SOURCE: IEC 60050-395:2014, 395-01-23]

3.7
decay constant
λ
number of disintegrations per unit time dN/dt for an atomic nucleus divided by the number of nuclei N existing at the same time t

$$\lambda = -\frac{1}{N} \times \frac{dN}{dt}$$

Note 1 to entry: The decay constant is expressed in reciprocal seconds (s^{-1}).

Note 2 to entry: The decay constant may be considered the total probability of radioactive decay (disintegration and/or nuclear transition).

[SOURCE: IEC 60050-395:2014, 395-01-11]

3.8
fluence rate
φ
quotient of $d\Phi$ by dt where $d\Phi$ is the increment of particle fluence in the time interval dt:

$$\phi = \frac{d\Phi}{dt}$$

[SOURCE: IEC 60050-881:1983, 881-04-19]

3.9
in-core neutron detector
detector, fixed or movable, designed for the measurement of neutron fluence rate at a defined region of a reactor core

3.10
integral self-powered neutron detector
self-powered neutron detector in which the lead cable section is an extension of the detector section, i.e. the emitter is directly attached to the core/signal wire; both sections share common insulation, and the collector of the detector section is also the outer sheath of the lead cable section (see Figure 1)

Note 1 to entry: An equivalent term is "cable-type self-powered neutron detector".

3.11
modular self-powered neutron detector
self-powered neutron detector made by mechanically joining, welding or brazing a detector (emitter, insulator, collector) to a lead cable (core/signal wire, insulator, outer sheath) (see Figure 2)

Note 1 to entry: An equivalent term is "prefabricated self-powered neutron detector".

3.12
isotope
variants of a chemical element that differ by atomic mass, having the same number of protons and differing in the number of neutrons in the nucleus

EXAMPLE 13C refers to a carbon atom that has an atomic mass of 13.

Note 1 to entry: Radionuclides or nuclides with a non-natural isotopic ratio are shown in the structural representation with the nuclide number displayed. Natural abundance isotopes are represented by an elemental symbol without a nuclide number.

[SOURCE: ISO 11238: 2018, 3.37]

3.13
photoelectric effect
complete absorption of a photon by an atom with the emission of an orbital electron

[SOURCE: IEC 60050-395:2014, 395-02-08]

3.14
prompt response
signal generation from a self-powered neutron detector based on the (n, γ, e) reaction

3.15
radioactive half-life
time required for the activity of a radioisotope to decrease to half of its initial value

Note 1 to entry: The radioactive half-life is related to the decay constant λ by the expression: $T_{1/2} = \ln 2/\lambda \approx 0{,}693/\lambda$. This quantity is expressed in seconds (s).

[SOURCE: IEC 60050-395:2014, 395-01-12]

3.16
radioisotope
isotope of an element with the property of spontaneously emitting particles or gamma radiation or of emitting X-radiation

[SOURCE: ISO 5576:1997, 2.104]

3.17
self-powered neutron detector
neutron-sensitive radiation detector that requires no external power supply, consists of three basic elements: an emitter that interacts with neutrons to emit electrons; a collector that collects these electrons and an insulator that isolates the emitter from the collector and converts the neutron fluence rate into electrical signal

Note 1 to entry: See Figure 1 and Figure 2.

3.18
self-shielding
self-absorption which occurs in the emitter: as emitter diameter increases, the escape probability of an electron born in the interior of the emitter decreases, and current-producing efficiency drops

3.19
in-core detector assembly
mechanical arrangement for positioning different detectors inside the core of a nuclear reactor. In-core detector assembly may contain both single-type detectors as well as detectors for various purposes and designs, for example, SPND and thermoelectric converters

3.20
sensitivity <of a detector>
characteristic measure of the signal of a detector to radiation. If in a given range of radiation quantity, the response of the detector depends linearly on the applied radiation, then in this range the sensitivity is given by the ratio:

$$S = \frac{\Delta I}{\Delta \varphi}$$

where

ΔI is the variation of the output signal (detector response);

$\Delta \varphi$ is the variation of the quantity of applied radiation (neutron fluence rate or gamma dose rate)

3.21
sensitivity to conditional neutron fluence rate <of a detector>
sensitivity to the neutron fluence rate with the Maxwell energy density distribution of neutrons having the most probable velocity equal to 2 200 m/s corresponding to the energy of 0,0253 eV

Note 1 to entry: It is convenient to use the Westkott formalism[1] to determine the sensitivity of the detector to the neutron flux density with a soft spectrum other than the one indicated above.

3.22
thermal neutron
neutron with a kinetic energy close to that of neutrons in thermal equilibrium with the atomic nuclei of the surrounding medium

Note 1 to entry: In the case of a maxwellian nuclei distribution, the most probable energy is equal to 0,025 eV at 293 K, which corresponds to the neutron velocity equal to 2 200 m/s.

Note 2 to entry: In practice the upper limit is about 1 eV.

[SOURCE: IEC 60050-395:2014, 395-02-17]

3.23
useful life
operational life, under irradiation and environmental conditions restricted within specified limits, after which the detector characteristics exceed the specified tolerances

Note 1 to entry: The limitation of the useful life is associated, as a rule, with burn-up process and the capabilities of the measuring equipment.

Note 2 to entry: Useful life can be expressed in incident particle flux, time, etc.

4 Abbreviated terms

BWR	boiling water reactor
CANDU	Canada, Deuterium, Uranium (Canadian reactor design featuring natural uranium fuel and heavy water moderator and coolant)
HWR	heavy water reactor (heavy water (D_2O) cooled and moderated reactor)
ICDA	in-core detector assembly
LWR	light water reactor (light water cooled and moderated reactor. Commercial types include the pressurized water reactor (PWR) and the boiling water reactor (BWR))
PWR	pressurized water reactor
RBMK	graphite moderated light water-cooled reactor

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1 See Westcott C.H., Walker W.H., Alexander I.K., "Cross-Sections and Cadmium Rations for the Neutron Spectra of Thermal Reactors", *Proceedings of the Second United Nations International Conference of the Peaceful Uses of Atomic Energy*, Geneva, 1958, V.16, United Nations, 1959.

SPND self-powered neutron detector

VVER abbreviation from the Russian name "water-water power reactor" – PWR reactor type

5 Self-powered neutron detectors general advantages and disadvantages

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. The principles and characteristics of SPND design and operation are given in Annex A.

When compared to other types of detectors, they have the following advantages:

– no need of power supply;
– simple and robust construction;
– relatively small mechanical "size" well-suited for in-core installation;
– good stability under temperature, pressure, radiation and other conditions.

The main disadvantages of SPNDs are the low signal level and the inertia of the neutron component of the signal.

6 Composition and construction

A typical SPND consists of an emitter, made of a material with a large neutron interaction cross-section, its surrounding insulator, collector and lead cable.

SPNDs are divided into two types according to their design and manufacturing technology:

– integral (or cable-type) SPND (see Figure 1), in which the signal wire of the lead cable mates directly to the emitter; isolation around the emitter is identical to the isolation of the signal line, and the collector is an extension of the signal line sheath;
– modular (or prefabricated) SPND (see Figure 2), which is made from separate detector and lead cable sections.

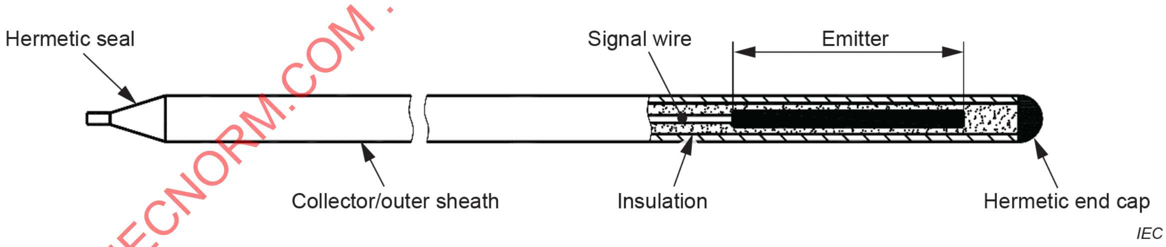


Figure 1 – Typical integral self-powered neutron detector

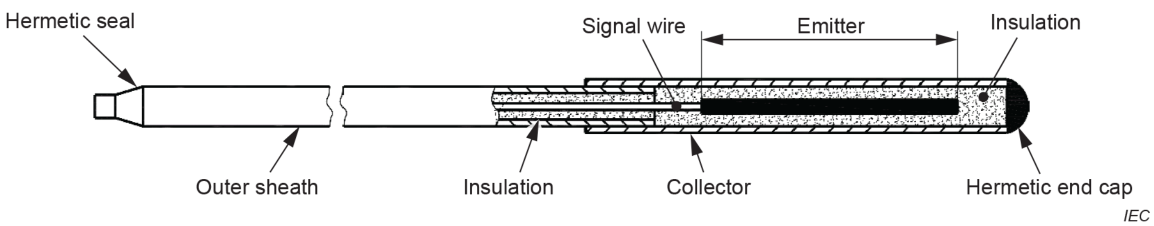


Figure 2 – Typical modular self-powered neutron detector

SPNDs are available in a variety of designs with sensitive lengths ranging from a few centimetres to full core height. The design of an SPND shall incorporate proper selection of emitter type and thickness, as well as sheath and insulation material types and dimensions, to optimize the mechanical design for a specific task.

SPND emitters shall be fabricated with materials resistant to operating conditions of detectors, with cross-sections of interaction with neutrons suitable for measured neutron energy range.

For power reactor applications, typical emitter materials used in SPNDs include vanadium, cobalt, rhodium, silver, platinum and hafnia. 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 for low temperature experimental reactors, 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 – Characteristics of SPND emitters

Emitter material	Stable isotope	Composition %	Cross-section σ	Resulting isotope	Half-life	Applications
Vanadium	$_{23}V^{50}$	0,24	100	$_{23}V^{51}$	Stable	HWR fluence rate mapping
	$_{23}V^{51}$	99,76	4,9	$_{23}V^{52}$	3,76 min	LWR fluence rate mapping
Cobalt	$_{27}Co^{59}$	100	37	$_{27}Co^{60}$	5,27 years	LWR fluence rate mapping LWR control LWR local core protection
Rhodium	$_{45}Rh^{103}$	100	11 (8 %)	$_{45}Rh^{104}$	4,4 min	LWR fluence rate mapping
			135 (92 %)	$_{45}Rh^{104}$	42 s	
Silver	$_{47}Ag^{107}$	51,82	35	$_{47}Ag^{108}$	2,42 min	Upgraded RBMK fluence rate mapping
	$_{47}Ag^{109}$	48,18	93	$_{47}Ag^{110}$	24,4 s	
Hafnia	$_{72}Hf^{174}$	0,18	390	$_{72}Hf^{175}$	70 d	LWR control
	$_{72}Hf^{176}$	5,20	15	$_{72}Hf^{177m}$	51,4 min	HWR control
	$_{72}Hf^{177}$	18,50	380	$_{72}Hf^{178m}$	31 years	
	$_{72}Hf^{178}$	27,14	75	$_{72}Hf^{179m}$	25,1 d	
	$_{72}Hf^{179}$	13,75	65	$_{72}Hf^{180m}$	5,5 h	
	$_{72}Hf^{180}$	35,23	14	$_{72}Hf^{181m}$	42,4 d	
Platinum	$_{78}Pt^{192}$	0,78	14	$_{78}Pt^{193m}$	4,3 d	RBMK fluence rate mapping
	$_{78}Pt^{194}$	32,90	2	$_{78}Pt^{195m}$	4,1 d	RBMK local control
	$_{78}Pt^{195}$	33,80	24	$_{78}Pt^{196}$	Stable	RBMK local protection
	$_{78}Pt^{196}$	25,30	1	$_{78}Pt^{197m}$	1,3 h	
	$_{78}Pt^{198}$	7,22	4	$_{78}Pt^{199}$	30,8 min	

The material of the collector and lead cable sheath shall be resistant to radiation and corrosion effects, the latter is especially important for detectors placed directly in the primary coolant. To eliminate the effects of corrosion and extend the lifetime, SPNDs may be installed in assemblies in which the SPND elements are not in contact with the primary coolant.

The collector may be fabricated from nickel-based alloys, characterized by excellent corrosion resistance. When choosing the material of the collector (as well as insulator), it shall be borne in mind that the presence of even a small amount of impurities with a large cross-section of interaction with neutrons can contribute to the detector reading.

The insulation should have an extremely low probability of interaction with neutrons or gamma rays. Under operating conditions, the insulation resistance of the detector should be substantially greater than the resistance of the signal line conductor and the input resistance of the measuring device in order to avoid leakage current through the insulation. Ceramic oxides are the preferred materials because they have a high resistivity and can withstand the hostile environment inside a nuclear reactor.

Typically, three materials are used for the insulation in SPNDs employed in power reactor applications, namely, Al_2O_3, MgO and SiO_2. Al_2O_3 has been chosen for most applications as it is readily available and, in powder form, is less sensitive than MgO to the effects of humidity. However, the currents of the signal line using Al_2O_3 insulation may be larger than the currents of the signal line with MgO insulation due to the formation of the beta-active isotope $_{13}Al^{28}$. MgO is hygroscopic and is therefore sensitive to cable swelling if moisture penetrates the cable sheath. SiO_2 may be used in some applications because its low density enhances emitter to collector electron transmission and thus maximizes sensitivity characteristics. However, SiO_2 has lower insulation resistance at high temperature than MgO or Al_2O_3.

The SPND connection cable should be a single-wire or two-wire cable with mineral insulation and a metal outer sheath. In order to minimise the contribution to the SPND signal from the interaction of neutrons and gamma radiation with the signal cable, appropriate materials should be selected in the cable design and construction, taking into account the relative geometric dimensions of the wires and cable sheath.

For SPNDs using a single core cable, the contribution to the SPND signal from the interaction of the signal cable with neutrons and gamma radiation may be minimised by using a background detector to provide a compensation signal. The background detector should be constructed without an emitter and using the same cable (see Figure 3).

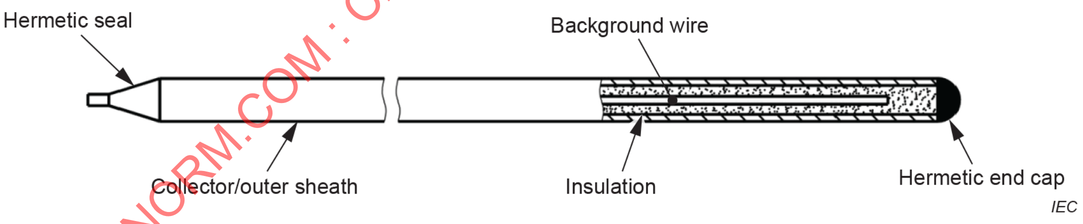


Figure 3 – Typical background detector

For SPNDs using a two-wire cable, one wire should be connected to the emitter of the SPND with the second wire being used as a background detector. In this case, the identity of the material and the geometry of the wires plays an important role. Special attention should be given to the selection of the materials and the geometry of the wires to minimise effects on the SPND signal. In order to compensate for possible differences in the irradiation conditions of the two wires, they should be arranged in a twisted pair arrangement (see Figure 4).

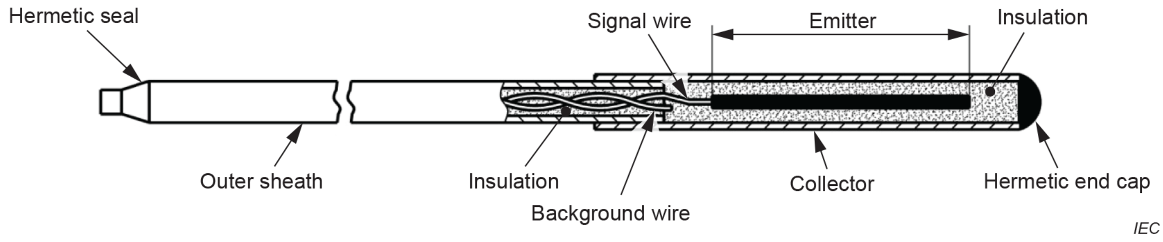


Figure 4 – Typical SPND with built-in background detector

7 Application recommendations

7.1 General

For each specific task, an SPND shall be selected with optimal characteristics for the solution of this problem. At the same time, for a solution of practically all problems, a small burn-up rate of the emitter is essential. High burn-up may be acceptable if a calibration system is available or burn-up is accounted for by the calculation method.

7.2 Fluence rate mapping – Core monitoring and surveillance

SPNDs may be used for fluence rate mapping and core monitoring and surveillance with or without an associated calibration system.

7.3 Power regulation – Feedback control

SPNDs may be used for feedback control purposes, however, acceptability of a signal delay will depend on the following limitations:

– axial power shape control may tolerate moderate delay;
– integral power control shall not permit signal delay.

7.4 Core protection

The characteristics required for SPNDs that are used for local core protection purposes shall be determined by consideration of the transient behaviour of the fluence rate levels.

Prompt signal response or adequate dynamic compensation to achieve prompt response is required.

Low sensitivity typical for prompt response SPND designs may be accepted by using amplifiers with low noise characteristics.

7.5 Reactor noise analysis

SPNDs with a large prompt signal response may also be used to analyse the reactor noise, this providing additional information about the reactor core and its elements.

7.6 Classification

SPNDs may be used as sensors in measurement channels that provide safety functions having different degrees of importance for safety. These safety functions should be categorised according to IEC 61226 and the SPNDs shall be designed to meet the appropriate safety class of the system.

8 Design recommendations

8.1 General

SPNDs shall withstand the effects of radiation, temperature, pressure, vibration, seismic and chemical corrosion caused by the environment present in the reactor core.

The design of the detector should, if necessary, provide for the possibility of fixing it in the core, and also provide the necessary resistance to bending and stretching during transportation and installation.

8.2 Reproducibility of SPND characteristics

The design of the SPND shall ensure the reproducibility of the SPND characteristics, which may be achieved due to the high accuracy of manufacturing of the SPND elements and taking into account the effect of changing the geometry of the SPND elements and the purity of the materials used for sensitivity.

A high degree of reproducibility of the sensitivity of the SPND makes it possible to provide high accuracy in relative measurements.

Confirmation of the identity of the geometric dimensions of the SPNDs and the materials used in their production can be used as an indirect calibration method.

8.3 Background signal

A background signal is generated primarily by neutron and gamma induced currents in the signal cable. Compensation may be achieved by using a separate background SPND (identical device without an emitter) and subtracting its signal from the SPND signal. Another technique involves the use of twin-wire cables (with twisted or not wires) in the SPND construction, with one wire connected to the emitter and the second wire used as the background wire.

8.4 Electrical interference noise

Electrical interference noise shall be minimized by adequate grounding and careful design of cables, electrical connectors, cable trays and cable routing.

8.5 Lifetime

The lifetime of an SPND may be expressed either as burn-up life or useful life. The detector burn-up life (see definitions in Clause 3) is dependent on the burn-up rate of the SPND emitter material, on the signal-to-noise ratio and the required value of the measurement error in a particular application.

The useful life of the SPND is dependent on the stability of the detector to operating conditions and on the burn-up rate of the emitter.

9 Test methods

9.1 General

Proposed test methods for SPNDs should follow the guidelines stated in IEC 60515, and IEC 60568. Qualification of SPNDs shall be done in accordance with the technical specification as defined by the user. In the absence of any specific instruction from the user, the qualification tests shall be performed in accordance with the methods and procedures provided in IEC/IEEE 60780-323.

9.2 Prototype testing

Prototype testing of SPNDs should take into account all the critical mechanical and electrical characteristics shown in Clause 6 and Clause 8. Emphasis should be given to performance characteristics relevant to long-term operation under in-core conditions, to demonstrate long-term stability of mechanical and electrical characteristics. Tests simulating in-core ambient conditions, including pressure and temperature cycling, shall be performed so that it is demonstrated that the SPND design can be expected to meet requirements with regard to the probabilities of failure in a power reactor application.

It is recommended for prototype testing that a minimum of three SPNDs of a particular design should be prototype tested according to their mechanical and electrical specifications.

9.3 Production tests

SPNDs and assemblies shall undergo final testing to ensure that all established requirements have been met.

The following characteristics shall be measured on all production SPNDs:

– SPND sheath and detector envelope integrity under maximum hydrostatic pressure and temperature conditions (for wet assembly designs);
– insulation resistance at the temperature corresponding to the normal climatic conditions of the test: in the range from 15 °C to 35 °C (acceptable insulation resistance values should meet the requirements for this detector);
– in some cases, it is necessary to measure insulation resistance at the maximum operating temperature (typical maximum operating temperature is 350 °C);
– continuity of emitter-to-signal wire connection (by detecting a decrease in the insulation resistance of the SPND when the emitter location is heated, by capacitance measurement or other suitable method);
– the emitter's location within the SPND. This is typically performed using radiography techniques (in two or more planes).

In addition, the variability of SPND neutron sensitivity within a production lot should be established. This may be performed by calibrating a statistical sample of the production lot or by controlling in the production process the geometric dimensions of the detector elements that affect the sensitivity value and the subsequent calculation of the variability.

10 Detector calibration

10.1 Place of calibration

The calibration of self-powered neutron detectors may be performed at the installation site, or in a test reactor prior to final installation. When testing in a research reactor, it should be borne in mind that detectors after irradiation should be kept for some time before transport to the installation site and installation in the place of operation to reduce the induced activity.

Since the magnitude of the SPND signal depends on the neutron spectrum, either the calibration signal shall be done in an identical spectrum, or the differences shall be taken into account during the calibration procedure.

10.2 Absolute calibration

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

Sensitivity is readily calculated as measured output current divided by neutron fluence rate. The accuracy of absolute calibration of the SPND is usually in the range 5 % to 10 % due to the large number of factors affecting the measurement. These factors include the error in the measurement of the fluence rate, the error due to the location of the SPND in the neutron field and the error due to the natural variation in the neutron flux with time (See Annex A).

10.3 Comparison calibration

The absolute neutron sensitivity of an SPND may be determined through comparison with 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) under the same conditions 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 times the absolute neutron sensitivity of the standard SPND divided by the measured output current of the standard SPND.

In this case, the calibration error is greater than in the case of absolute calibration, since in addition to the absolute calibration error of the standard SPND, the errors in the placement of the SPND and errors due changes in the neutron field over time are added.

The comparison calibration can be performed indirectly by comparing the parameters of the detectors affecting the sensitivity: the geometric dimensions of the component parts of the detectors and the materials from which they are made. Comparison calibration eliminates the error associated with ensuring the identity of the conditions for irradiating the detectors.

10.4 In-core calibration

There are several well-proven in-core calibration systems that use fixed, or movable detectors, as well as activation techniques. These include:

- fixed in-core detectors characterized by no or low burn-up factors;
- 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 another gas which are irradiated in-core and later have their induced activity measured out-of-core;
- calibration by normalization to the final controlled parameter.

The most widely used method of calibration in operating conditions is normalization to the final controlled parameter (for example, power density). This procedure requires a special steady-state mode of operation of the reactor for precise measurement of thermal power.

10.5 Calibration procedure

The test reactor (activation) method may be used to obtain relative or absolute calibration results depending on the calibration of the reference detectors.

In-core calibration methods provide relative data which can be correlated to the integrated power of the core.

Several corrections may be necessary to obtain accurate results due to the nature of the calibration system, concerning for example:

– shielding correction due to the detector overlap or "shadowing";
– corrections due to lead cable sensitivity;
– spatial correlations (distances, locations);
– sensitivity with respect to the neutron spectrum;
– time dependencies of the measurement;
– allowable time limit for the entire core fluence rate map;
– radiation decay during the transport and measuring process;
– SPND sensitivity to gamma-radiation.

10.6 Recommended calibration periods

For in-core calibration systems, the calibration period should be chosen according to the burn-up rate of the specific SPND emitter material and the assignment of the signal to a particular function.

Annex A
(informative)

Self-powered detector principles and characteristics

A.1 SPND response mechanisms

All SPNDs react to neutron and gamma fluence rate to some degree. The main current-producing mechanisms are: beta decay (delayed response), neutron capture (prompt response), Compton effect (prompt response), and photoelectric effect (prompt response). Beta decay and neutron capture are caused by the neutron fluence rate, while the photoelectric and Compton effects are caused by the gamma fluence rate.

A.2 Beta decay (delayed response)

SPNDs which are based primarily on beta decay of products of n-gamma reaction, always have a delayed response. Beta decay occurs when an atom breaks down after absorbing a neutron. On breakdown, the atom releases an electron. A portion of the electrons leaving the emitter generates an output electric current. Of the four relevant processes, beta decay is, by far, the most efficient at producing current.

Delayed response SPNDs, such as those with rhodium or vanadium emitters, produce most of their current by this mechanism.

A.3 Neutron capture (prompt response)

SPNDs that generate current primarily from neutron capture (the n, γ, e reaction) give a prompt response. Compared to beta-decay SPNDs, neutron capture SPNDs have emitters with intermediate sized cross-sections and a relatively long half-life. The long half-life results in very little beta-decay current being generated. Instead, these SPNDs generate their current from the initial neutron capture. Because of the emitters intermediate sized cross-section, many neutrons are captured. Upon capture, these newly created radioisotopes emit a photon which in turn collides with an electron. A number of these electrons can travel to the collector. Compared to beta decay, this is a very inefficient process. Typically, only about 2 % of the neutrons captured contribute to the output current.

SPNDs with cobalt or hafnia emitters generate most of their current via neutron capture.

A.4 Photoelectric effect (prompt response)

The photoelectric effect takes place when atoms of large atomic number (i.e. high electron densities) are exposed to low energy photons. This interaction occurs in the emitter, the insulator and the collector. Electrons knocked out of the collector travel to the emitter and cancel some of the electrons leaving the emitter. Electrons ejected from the insulation can go in either direction. The total current that leaves the SPND is the difference between the outward current from the emitter and insulator and the inward current from the collector and insulator.

A.5 Compton effect (prompt response)

The Compton effect is much like the photoelectric effect except that it involves smaller atoms and photons of medium energy. Like the photoelectric effect, the Compton effect takes place in all three regions of the SPND: the collector, insulator, and emitter. The SPND's actual output is the difference between the inward and outward flow of electrons.

Detectors with platinum emitters generate current from both Compton and photoelectric effects as well as neutron capture.

A.6 Nature of SPND response

The nature of the response of an SPND to any neutron or gamma interaction, is determined primarily by the (capture) cross-section of its emitter. Generally, the larger the cross-section, the greater the probability of interaction and the greater the output current of the detector (also, for neutron interactions, the faster the emitter burns up). Elemental cross-sections are readily available from most standard isotope tables.

A.7 Thermal neutron interactions

For thermal neutron interactions, the effective capture cross-section, denoted σ_{eff} is dependent on the isotope cross-section, emitter shape and dimensions, and self-shielding. Emitter geometry is directly related to self-shielding. Generally, as emitter diameter increases, the beta escape probability, or chance that an electron freed from the interior of the emitter reaches the collector, decreases.

A.8 Gamma interactions

Gamma interactions depend on the gamma ray interaction cross-section, emitter geometry and self-shielding. For the Compton effect, the interaction cross-section increases with Z (the atomic number, i.e. the number of protons in the atom) and decreases with E (photon energy). For the photoelectric effect, the interaction cross-section increases as Z^5 and decreases with E^3, i.e.

$$\sigma_{pe} \sim Z^5 (h\nu)^{-3}$$

A.9 Dynamic characteristics of SPND

Detectors with emitters of different materials have different dynamic characteristics. Some detectors have a predominantly instantaneous signal (for example, a SPND with an emitter of platinum or hafnium), the other SPNDs have the prevailed activation component.

The activation component of the SPND signal can be formed both due to the decay of predominantly one isotope (for example, an SPND with an emitter of vanadium), or due to several isotopes (for example, an SPND with an emitter of rhodium).

For the inertial-free determination of the neutron fluence rate by SPND with prevailed activation component, it is necessary to solve the formula which, for SPND with emitter of rhodium, has the form:

$$i_n + \frac{\lambda_1 + \lambda_2}{\lambda_1 \times \lambda_2} \times \frac{di_n}{dt} + \frac{1}{\lambda_1 \times \lambda_2} \times \frac{d^2 i_n}{dt^2} = \eta_n \varphi + \left[\frac{\eta_{n\gamma}(\lambda_1 + \lambda_2)}{\lambda_1 \times \lambda_2} + \frac{\eta_{1a}}{\lambda_2} \right] \frac{d\varphi}{dt} + \frac{\eta_{n\gamma}}{\lambda_1 \times \lambda_2} \times \frac{d^2 \varphi}{dt^2}$$

where

i_n is the neutron induced current, A;

φ is the neutron fluence rate in the detector's emitter location place ($m^{-2} \cdot s^{-1}$);

η_n is the detector's neutron sensitivity ($A \cdot m^2 \cdot s$);

$\eta_{n\gamma}$ is the prompt component of neutron sensitivity ($A \cdot m^2 \cdot s$);

η_{1a} is the activation component of neutron sensitivity determined by Rh_{104} direct generation (A·m²·s);

λ_1 is the Rh^{104} isotope disintegration constant (s^{-1});

λ_2 is the $Rh^{104\ m}$ isotope disintegration constant (s^{-1});

$\lambda =$ $0{,}693/T_{1/2}$;

$T_{1/2}$ is the isotope's half-life;

t is the time.

The solution of this formula by analog or digital methods enables practically immediate determination of the neutron fluence rate.

A.10 Detector burn-up life

As the emitter absorbs neutrons it undergoes burn-up. Each emitter atom can absorb only one neutron and when this occurs, it then practically does not take part in the current generation process. All SPND emitters based on neutron capture undergo burn-up when exposed to neutrons. As burn-up occurs the SPND sensitivity decreases. To compensate for this, burn-up rates are carefully calculated for each emitter type and are then used to correctly interpret the changing emitter current. In addition to this, SPNDs may be periodically calibrated by a movable detector that is inserted into the in-core assembly calibration tube (if present).

The burn-up life of any SPND may be determined, to a first approximation, based on the formula, $N = N_0 \exp[-(\lambda + \sigma_{eff} \cdot \Phi_{th}) \cdot t]$, as follows:

$$t = \frac{-\ln\left(N/N_0\right)}{\lambda + \sigma_{eff} \cdot \Phi_{th}}$$

where

N_0 is the initial number of emitter atoms;

N is the number of emitter atoms remaining after the burn-out period t;

λ is the decay constant of the isotope formed as a result of the absorption of the neutron by the emitter atom, s^{-1};

σ_{eff} is the cross-section for the absorption reaction, b;

Φ_{th} is the neutron fluence rate, $m^{-2}\ s^{-1}$;

t is the lifetime, s.

A.11 Measurement errors

A.11.1 General

Different types of errors can occur.

A.11.2 Error for determination of SPND actual response

It is determined by the accuracy of entering corrections on the burn-up or error of the SPND in-service calibration. Error of determination of SPND actual response ($\delta\eta_t$) is determined as follows:

$$\delta\eta_t = \frac{\left(\delta_B + \delta_Q\right) \times B \times Q}{100 - B \times Q}$$

where

$Q = \int_0^t i_n \, dt$ is the sum of the electrical charges generated by an SPND;

B is the change of response due to burn-up in respect to a unit of electrical charge generated by an SPND due to interaction of the emitter's material with neutrons;

δ_B and δ_Q are the fractional errors of determining B and Q.

The value of δ_Q tends to grow with the increase of error of definition of SPND current induced by neutrons. The value of δ_B depends on the reproducibility of the SPND parameters determining the scattering of the initial response characteristics (emitter's diameter and length, thickness and density of insulation).

When manufacturing technology is used which does not ensure reproducibility of SPND geometrical dimensions, neutron calibration may be used following fabrication to determine the initial neutron response of a batch of SPNDs.

A.11.3 Error determined by gamma-component of SPND current

It depends on the ratio of the neutron and gamma response values of SPND detectors. During operation of the detector, it is all but impossible to measure the contribution of the current induced by gamma radiation in the SPND current. In the steady-state mode of reactor operation, the current generated due to gamma-quanta is proportionate to the SPND current determined by its neutron response.

A.11.4 Error determined by leakage currents

The leakage current (i_l) of SPND detectors, to a first approximation, is determined by the following formula (see Figure A.1, which shows a simplified equivalent circuit of the SPND)

$$i_l = (i_0 + i_{cl})[1 - r / (r + R_S + R_l)]$$

where

i_0 is the SPND signal current;

i_{cl} is the current of connecting line (background current);

r is the SPND insulation resistance;

R_s is the connecting line resistance;

R_1 is the input resistance of the measuring device.

To minimize the error associated with leakage currents, it is necessary to ensure the fulfilment of the relation $r » (R_S + R_l)$.

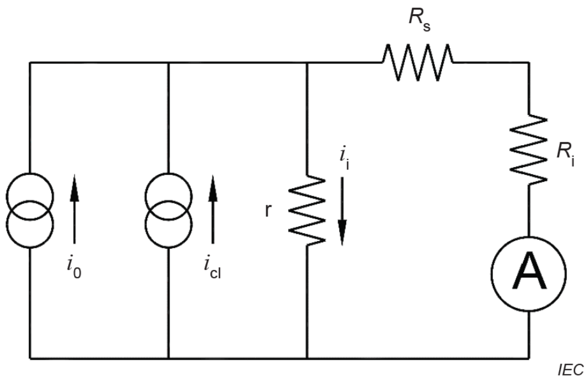


Figure A.1 – Simplified equivalent circuit of the SPND

A.11.5 Error determined by signal wire current

SPND electric current correction that takes into account the contribution to the detector signal of the current caused by radiation exposure to the communication line is achieved either by subtracting the current of the background wire included in the detector design, or by entering a correction determined using a special background detector.

The error in correcting the SPND current when using a background wire depends on the degree of identity of the signal and background wires of the detector and on the degree of identity of the irradiation conditions during the measurement process. Reducing the error value is achieved by using a two-wire cable with the same twisted wires as the SPND communication line.

The error in correcting the SPND current when using a background detector depends on the degree of identity of the SPND communication line and the background detector, as well as on the degree of identity of the irradiation conditions during the measurement process. As a rule, in this case, the correction error is greater than when using the background wire.

A.12 Self-powered detector operating characteristics

A.12.1 General

The following information presents the characteristics of self-powered detectors most commonly used in nuclear power plants. This information is intended to serve as reference for the user of this document in selecting the optimum SPND for specific uses for in-core instrumentation systems. Examples of characteristics for typical SPNDs used in power reactors are given in Table A.1.

Table A.1 – Examples of specifications for typical SPNDs used in power reactors

	Emitter material					
	Vanadium	**Cobalt**	**Rhodium**	**Silver**	**Hafnia (HfO_2)**	**Platinum**
Emitter diameter mm	2,0	2,0	0,46	0,65	1,24	0,51
Emitter length mm	100	210	400	7000	7000	3050
Insulator type	Al_2O_3	Al_2O_3	Al_2O_3	MgO	MgO	Al_2O_3
Collector material	Inconel	Inconel	Inconel	Stainless steel	Stainless steel	Inconel
Collector diameter mm	3,5	3,5	1,57	3,0	3,0	1,6
Thermal neutron sensitivity, reduced to 1 m emitter length, 10^{-24} A/(m^2·s)	4,8	2,6	9,0	6,0	1,1	0,008
^{60}Co gamma sensitivity, reduced to 1m emitter length, 10^{-20} A/(Gy×h)	4,0	2,7	1,8	1,9	0,4	1,1
Response time (0-63 %)	5,5 min	Prompt	1,1 min	0,5 min	Prompt	Prompt
Burn-up rate % per month at 10^{17} m^{-2}·s^{-1}	0,01	0,09	0,39	0,16	0,30	0,03

A.12.2 Vanadium emitter characteristics

^{51}V has an n-gamma interaction with a thermal neutron cross-section of 4,9 b featuring a 1/v characteristic without resonances in the energy range of thermal/epithermal neutrons.

The burn-up rate is 0,012 % per month in a thermal neutron fluence rate of 10^{17} m^{-2} s^{-1}.

99 % of the signal has a half-life of 3,76 min, 1 % of the signal is prompt.

There is a parallel beta emission of 2,6 MeV.

An SPND with a vanadium emitter has a relatively low sensitivity, low burn-up rate, a very long delayed signal and high sensitivity to gamma-radiation. Current generated due to gamma-radiation has polarity opposite to current generated due to neutrons.

A.12.3 Cobalt emitter characteristics

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

The burn-up rate is 0,094 % per month in a thermal neutron fluence rate of 10^{17} m^{-2} s^{-1}.

The signal is prompt, but requires long-term compensation due to build-up of radioactive isotopes ^{60}Co and ^{61}Co.

An SPND with a cobalt emitter has relatively low sensitivity, a moderate burn-up rate and a prompt signal.

A.12.4 Rhodium emitter characteristics

^{103}Rh has an n-gamma interaction with a 145 b cross-section for thermal neutrons and a resonance at 1,25 eV.

The burn-up rate is 0,39 % per month in a thermal neutron fluence rate of 10^{17} m^{-2} s^{-1}.

92 % of the signal has a half-life of 42 s.

8 % of the signal has a half-life of 4,4 min.

The beta emission has an energy of 2,44 MeV.

An SPND with a rhodium emitter has a relatively high sensitivity and high burn-up rate and has a (two-fold) delayed signal.

A.12.5 Silver emitter characteristics

Ag has a n-gamma interaction with a 64,8 b cross-section for thermal neutrons and a few resonances in the range 5 eV – 134 eV.

The burn-up rate is 0,16 % per month in a thermal neutron fluence rate of 10^{17} m^{-2} s^{-1}.

66 % of the initial signal has a half-life of 24,4 s.

25 % of the signal has a half-life of 2,42 min.

9 % of the signal is a prompt signal.

An SPND with a silver emitter has an average sensitivity, average burn-up rate and a (two-fold) delayed signal.

A.12.6 Platinum emitter characteristics

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

The burn-up rate is 0,03 % per month in a thermal neutron fluence rate of 10^{17} m^{-2} s^{-1}.

The signal is prompt and has both neutron and gamma components.

An SPND with a platinum emitter is sensitive to both gamma and neutron radiation with 93 % of the signal current due to gamma fluence rate response and 7 % due to neutron fluence rate response in a typical light water reactor core radiation environment.

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

A.12.7 Hafnia emitter characteristics

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

The average burn-up rate is 0,3 % per month in a thermal neutron fluence rate of 10^{17} m^{-2} s^{-1}.

96 % of the signal is prompt, 4 % of the signal is delayed as gamma-radiation from fission products.

An SPND with a hafnia emitter has relatively low sensitivity, a high burn-up rate and has a prompt signal.

A.13 Self-powered detector assemblies

A.13.1 General

SPNDs may be located in the reactor core as single elements, or more typically, in assemblies of several units located along the assembly axis or grouped around a central tube in which the sensor of a calibration system can be located. Examples are described in Figure A.2 to Figure A.6, showing typical assembly configurations used in light water and heavy water nuclear power plants.

The following description and figures show typical self-powered detector assembly configurations used in light water and heavy water nuclear power plants worldwide. 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.

A.13.2 Typical bottom-mounted rhodium self-powered detector assembly for pressurized light water reactors

A typical bottom-mounted in-core self-powered detector assembly for pressurized water reactors is shown in Figure A.2. 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.

A.13.3 Typical top-mounted rhodium self-powered detector assembly for VVER–type light water reactors

A typical top-mounted rhodium in-core self-powered detector assembly for VVER reactors is shown in Figure A.3. The assembly consists of seven rhodium self-powered detectors, one core inlet thermocouple, two thermocouples at the outlet from the fuel assemblies and one thermocouple under the reactor cover. All sensing elements are housed within a stainless steel outer sheath tube. A header, seal plug and multipin electrical receptacle complete the assembly.

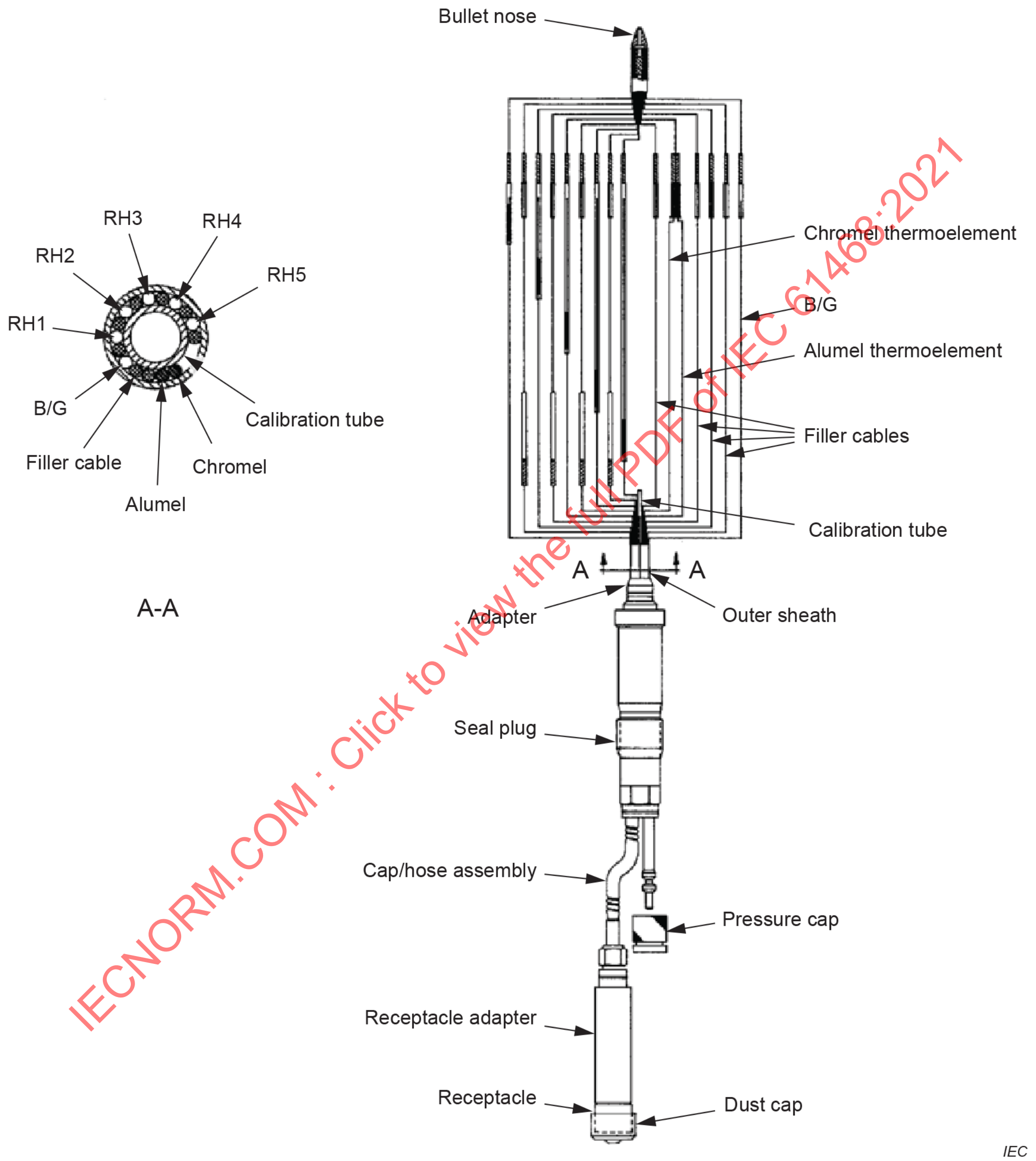
The small size of rhodium SPND allows the production of assemblies not only with several thermocouples, but also with the installation in the assembly of a heat level indicator that provides the ability to control the coolant level in the reactor, including in emergency modes. A typical assembly of an SPND with a level indicator having three control points is shown in Figure A.4.

A.13.4 Typical top-mounted cobalt self-powered detector assembly for pressurized light water reactors

A typical top-mounted instrumentation assembly with Aeroball probes and self-powered detectors for pressurized water reactors is shown in Figure A.5. There are eight lance assemblies per core, each consisting of five fingers: one finger containing six cobalt self-powered detectors, and four fingers for steel ball insertion thimbles of the Aeroball flux mapping system, which also serves as the calibration system for the self-powered neutron detectors. The self-powered detector assembly also incorporates three thermocouples for core exit temperature measurements located in the same fuel element head in different levels and different radial positions. The lance fingers are made of stainless steel while the self-powered detectors and cables are constructed of Inconel 600.

A.13.5 Typical heavy water reactor self-powered detector assembly

A typical CANDU pressurized heavy water reactor in-core self-powered detector assembly is shown in Figure A.6. 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. Well shield plugs are installed in all wells not occupied by detectors, and all detector wells are contained within a protective zircalloy capsule.

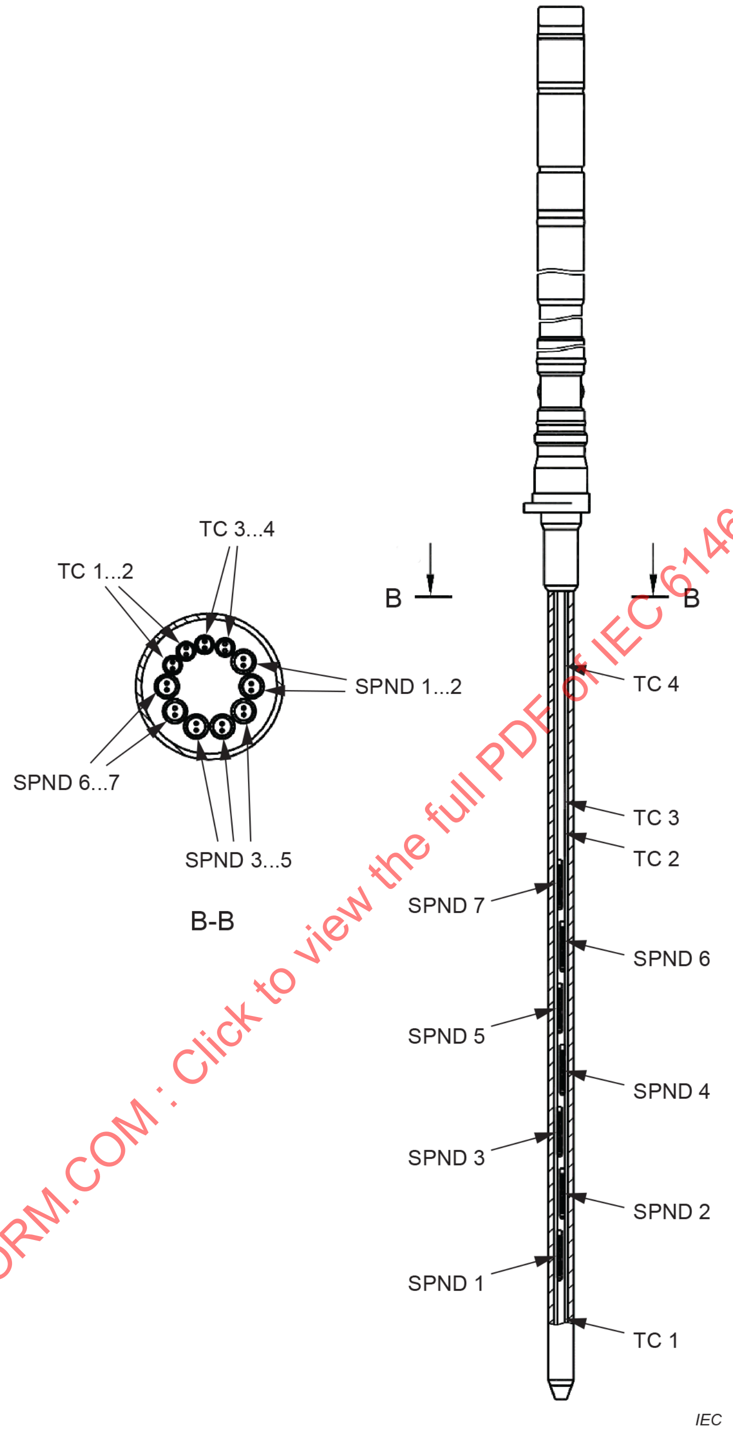


Key

RH rhodium SPD

B/G background cable

Figure A.2 – Bottom-mounted rhodium self-powered detector assembly for pressurized water reactors



Key

TC thermocouple

Figure A.3 – Top-mounted rhodium self-powered detector assembly for VVER reactors with four thermocouples