EXPERIENCES WITH PROMPT SELF-POWERED DETECTORS IN NUCLEAR REACTORS OF WWER TYPE

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ABSTRACT

The total sensitivities of Co-SPND and Pt-SPGD have been experimentally determined to $(3.8 \pm 0.5) \cdot 10^{-23}$ A cm s and $(2.2 \pm 0.3) \cdot 10^{-23}$ A cm s, respectively. The γ-ray induced current components have been computed to be about -12 up to -20 % (Co) and 75 % (Pt). A direct proportionality between axial neutron flux density distribution and γ-ray distribution has been measured in the central channels of fuel assemblies.

First results of reactor-dynamic perturbation measurements by means of prompt responding SPD are discussed.

1. INTRODUCTION

In-core instrumentation is steadily gaining greater importance for the control of nuclear reactors and for providing information to operators on the actual state of the reactor.

The in-core instrumentation system for supervising the Greifswald WWER-440 units is based on 216 thermocouples and 60 installed rhodium self-powered neutron detectors (Rh-SPND) [1].

Essential knowledge of normal and abnormal operation of WWER units has been obtained by this system, such as time dependent spatial flux and power density distributions, parameters which can be used for supervision like differential rod worth, power coefficient of reactivity or space-time effects in the reactor core [2].

Besides well-known advantages (high current, low γ-ray sensitivity) Rh-SPND's possess a few shortcomings (relativily fast emitter burnup, delayed detector response).

In view of these facts prompt responding SPD will be favoured for solving special tasks, such as

- measurement of local neutron flux/γ-ray distribution
- investigation of space-dependent effects at reactor-dynamic perturbation measurements
- yield of experimental data during transients of neutron flux density
- study of space-dependent dynamic processes inside the core (including time behaviour of reactor γ-ray radiation)

- preparation of detector system usage in the reactor safety system
- development of detectors for measurement of high γ-ray field densities needed for investigations on reactor component life-times.

Thus investigations of the behaviour of prompt SPND's with Co-emitter and predominant prompt γ-ray sensitive self-powered detectors with Pt-emitter (Pt-SPGD) in WWER-reactors were started.

At first physical properties of SPND and SPGD, especially the analysis of detector current components and their dynamic time behaviour as well as the determination of spectral sensitivities were bound to examine under plant conditions on WWER-reactor. The compensational properties of mineral isolated cables have been tested too.

Measurements of local neutron flux/γ-ray distributions in the central channel of fuel assemblies have been carried out by means of SPND's and SPGD's.

First results have been gained by usage of prompt SPD's at reactor-dynamic perturbation measurements.

2. CHARACTERIZATION OF PROMPT SPD's IN WWER-440 REACTORS

In analogy to conventional in-core instrumentation with Rh-SPD's a special sensor lance was developed and prepared in the firm "VEB Walzwerk Hettstedt". This lance (Fig. 1) includes three Co-SPD's, two Pt-SPD's, one neutron sensitive delayed responding Rh-SPD for comparison measurements and a compensation detector. The compensation detector (CD), a sealed mineral insulated cable with two core wires, has been used to investigate the compensation properties of SPD signal cables. Materials and dimensions of the detectors and the cable are compiled in table I.

The current generation of prompt SPD's results from radiation interactions with different detector parts. The choice of the materials, especially the kind of emitter material, gives rise to two distinct classes of prompt SPD's. In the case of neutron sensitive prompt SPD's the main current portion is caused by interactions of emitter capture γ-rays with emitter material itself. On the contrary the principal signal component of γ-ray sensitive prompt SPD's is due to interactions of reactor γ-radiation with the emitter. Additional small current parts are produced by β^--decay of activation products of detector materials and electrons out of the detector environment too. The total detector current may be expressed as:

$$i_{tot} = i(n,\gamma,e^-) + i(\gamma,e^-) + i(n,\beta^-) + i_e + i_c$$

$i(n,\gamma,e^-)$: capture γ-ray induced current

$i(\gamma,e^-)$: reactor γ-radiation induced current

$i(n,\beta^-)$: activation portion

Table 1

Detector materials and dimensions

	Material	Diameter [mm] outer	Diameter [mm] inner	Length [mm]
<u>Detector</u>				
	Emitter Co	1.0	-	200
	Pt	1.0	-	200
	Rh	0.8	-	200
	Collector X8CrNiTi18.10	2.0	1.6	210
	Insulator Al_2O_3	1.6	1.0	205
<u>Cable</u>				
	Sheath X8CrNiTi18.10	1.0	0.7	
	Core wires NiSi(2.5 % Si)	0.3	-	-

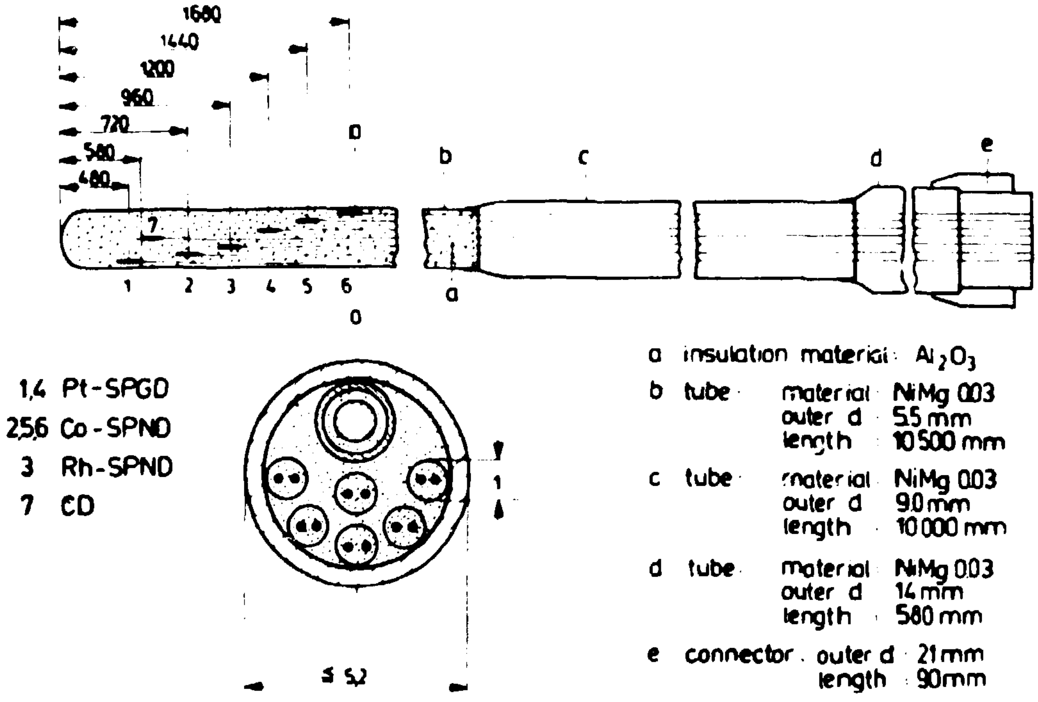

FIG. 1 Scheme of lance

i_c: cable current (only in the case of uncomplete compensation)

i_e: influence of environment

In consequence of changes of neutron flux a noninstantaneous current portion appears in the signal of prompt SPGD's connected with delayed γ-radiation component (about 30 % of total reactor γ-radiation).

The ratio total detector current/thermal neutron flux density is defined as the total detector sensitivity ε_{tot}. An experimental determination of sensitivities was carried out. The thermal neutron flux density was estimated by means of multicomponent wire activation detector system [3] and a Rh-SPND with known sensitivity. Following values were obtained:

$$\varepsilon_{tot}(\text{Co}) = (3.8 \pm 0.5) \cdot 10^{-23} \text{ A cm s}$$

$$\varepsilon_{tot}(\text{Pt}) = (2.2 \pm 0.3) \cdot 10^{-22} \text{ A cm s} .$$

A valuation of γ-ray induced signal part by the help of theoretical investigations of Goldstein [4] provided for Co-SPND's -12 % ÷ -20 % and for Pt-SPGD's 74 % ÷ 76 % of the total current under concrete working conditions of WWER reactors. The $i(\gamma,e^-)$-component of the Co-SPND's diminishes the wanted $i(n,\gamma,e^-)$-current.

A current-time analysis of the signal behaviour after a fast removal of the lance from radiation field of the reactor allows the separation of the $i(n,\beta^-)$-portion (Fig. 2). Two isotopes were identified:

$$\text{Insulator:} \quad {}^{27}_{13}\text{Al}(n,\gamma)^{28}_{13}\text{Al} \xrightarrow[2.24 \text{ min}]{\beta^-} {}^{28}_{14}\text{Si} ,$$

$$\text{Collector:} \quad {}^{55}_{24}\text{Mn}(n,\gamma)^{56}_{24}\text{Mn} \xrightarrow[2.57 \text{ h}]{\beta^-} {}^{56}_{25}\text{Fe} .$$

This fact was confirmed by a neutron activation analysis of collector and insulator material. The used stainless steel X8CrNiTi18.10 contains on an average 1.4 % manganese. The contribution of Mn induced current part to the total signal amount to 1 % only. For this reason no other material, such as Inconel, was chosen for the collector.

Properties of mineral insulated signal cable are determined by insulation resistance and also by geometrical arrangement of the sheath and the core wires. Cable sensitivity increases with the diameter of the cable. The following results were obtained in WWER reactor for core wire diameter between 0.2 mm and 0.35 mm:

Cable diameter [mm]	Sensitivity [A cm s]
1.0	$0.8 \cdot 10^{-23}$
1.5	$1.0 \cdot 10^{-23}$
2.0	$1.2 \cdot 10^{-23}$

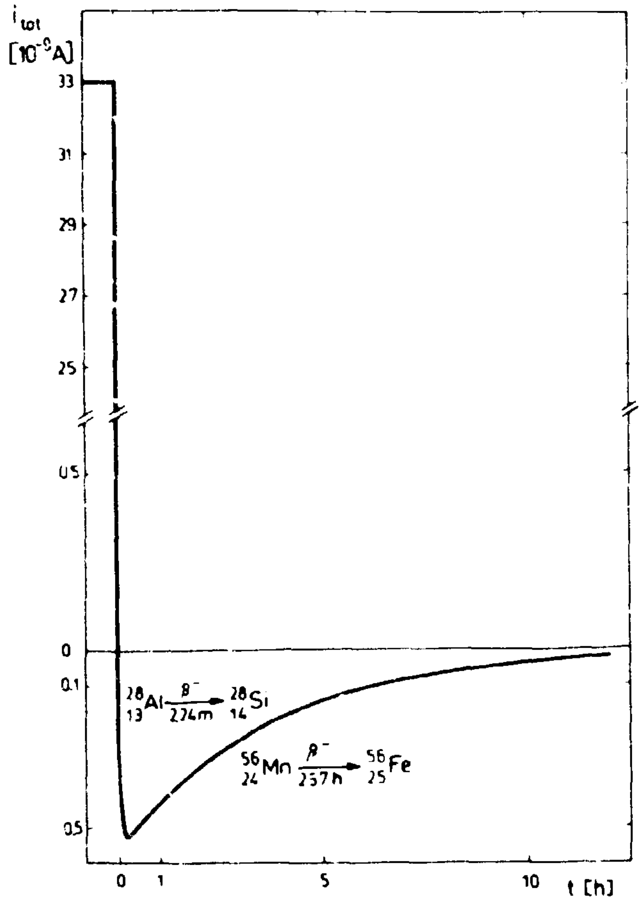

FIG. 2 Time behaviour of Co-SPND current after fast removal of detector out of core

Cables of 1 mm diameter were selected for a special lance to obtain a favourable ratio of detector current to cable current. Unfortunately cable currents between $20 \cdot 10^{-9}$ A and $50 \cdot 10^{-9}$ A appear for SPD in the lowest measuring position. In this case the detector current has the same magnitude. Cable current is directed from sheath to core wires and is composed of delayed and prompt parts. By the help of CD the difference between the two currents flowing from the sheath to the two core wires was estimated. The difference is in the range of $1 \cdot 10^{-9}$ A $\div$ $5 \cdot 10^{-9}$ A. Fig. 3 shows the time behaviour of a well compensated SPD after insertion of the lance into the reactor core,

3. MEASUREMENT OF NEUTRON FLUX AND GAMMA-RAY DISTRIBUTION

Some of reactors of WWER type are equipped with in-core instrumentation systems based on Rh-SPND's to supervise online the reactor core [2]. The Rh-lances are installed in dry channels, which are located in the centre of the fuel assemblies. Measurements by means of prompt SPD's were carried out in these channels (after removal of Rh-lances) in order to determine the axial distribution of γ-ray and neutron flux density. The axial distribution at the beginning of campaign in a 3.6 % enriched fuel assembly is shown in Fig. 4. The lance was removed in steps of 12 cm out of the core. For comparison the result of a copper wire activation measurement is given in Fig. 4 too.

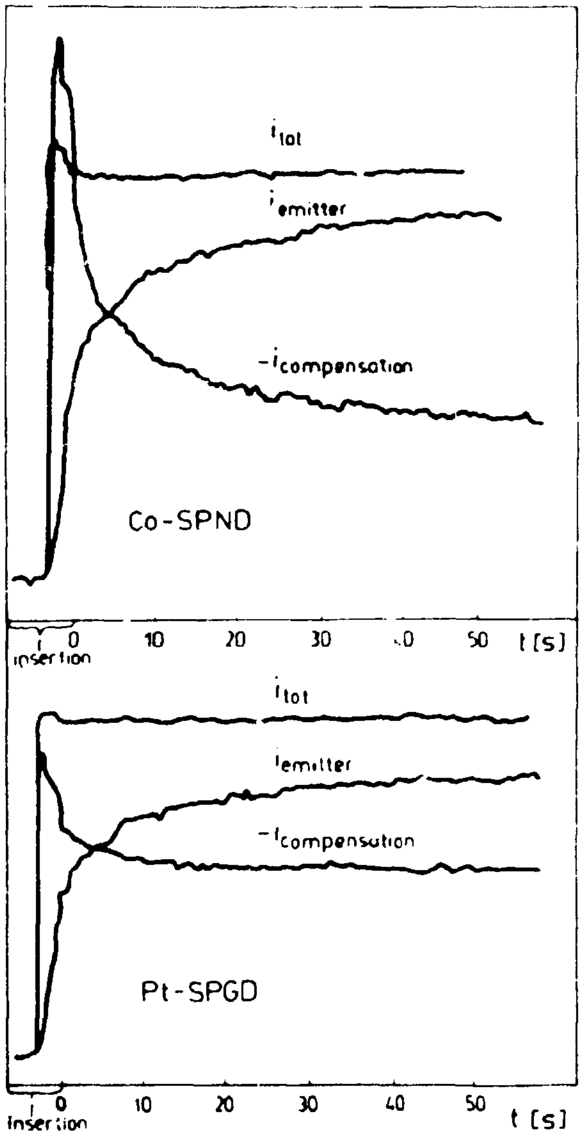

FIG. 3 Time behaviour of current components after fast insertion of detectors into the core

The influence of the distance grid is distinctly remarkable in the Co-signals, whereas the Pt-signals are not influenced in consequence of the greater photon range. The mean axial thermal neutron flux between 80 cm and 150 cm of the core height is 4.0 • $10^{13}/cm^2$ s [3]. The calculated value of the spectrum hardness (ratio of epithermal flux per lethargy unit to thermal flux) is 0.24. The influence of core reflector

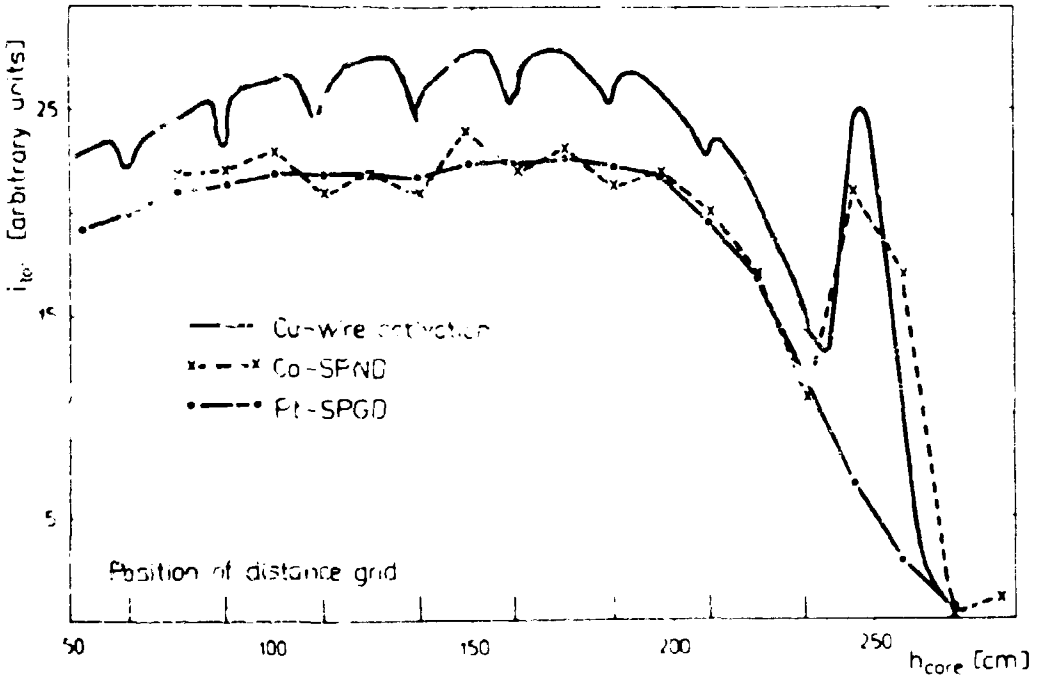

FIG. 4 The axial distribution of neutron flux and gamma-ray density at the beginning of the campaign in the in-core channel 11, unit 4, NPP Greifswald

results in a convexity of thermal neutron flux density distribution at core height of (245 ± 6) cm. The thermal neutron flux increases up to 4.7 · $10^{13}/cm^2$ s with simultaneous diminution of the spectrum hardness and epithermal neutron flux down to 0,03 and 0.14 · $10^{13}/cm^2$ s, respectively. Although the Pt-SPGD has a neutron induced current component of about 25 % the influence of the reflector can not be proved in the signal because the neutron sensitivity is mainly due to absorption of epithermal neutrons.

A direct proportionality was measured between neutron flux and γ-ray distribution over a large scope of core, excepting in the vicinity of neutron absorbents and core margins. In WWEP reactors the in-core ratio of thermal neutron flux and γ-ray field is nearly constant. So Pt-SPGD's seem to be useful for in-core safety systems. This type of detector could also be applied for in-core flux mapping and surveillance of power density distribution. But a more accurate knowledge of the relationship between the γ-ray field and the desired neutron flux is required.

4. REACTOR-DYNAMIC PERTURBATION MEASUREMENTS

In addition to determination of physical properties of promt responding SPD's in a power reactor these detectors have been used for detailed investigations of space dependent effects named in [5].

By means of the method of RDPM [5] control bank displacements have been accomplished for different axial control bank positions (z_I = 230 cm in Fig. 5, z_I = 197.5 cm in Fig. 6) for different axial positions of prompt SPD's and an outcore ionization chamber too.

Fig. 5 shows responses of different positioned detectors to a control bank displacement of Δz = 5.7 cm.

The dependence of measured relative neutron flux alterations $\Delta\phi/\phi_o$ on axial detector position can be seen:
The higher the detector was positioned the greater the alterations have been measured.

The axial position of control bank (perturbation position) was 230 cm near to the top of the core (250 cm).

In Fig. 5 it can be seen that the Pt-detector has recorded smaller signal alterations $\Delta i/i_0$: The time behaviour of the Pt-detector signal corresponds to the time behaviour of gamma flux which is following to neutron flux alterations prompt and delayed too.

Therefore if the Pt-detector is ment to measure neutron flux changes its signal has to be corrected by time constants of gamma flux (see Appendix).

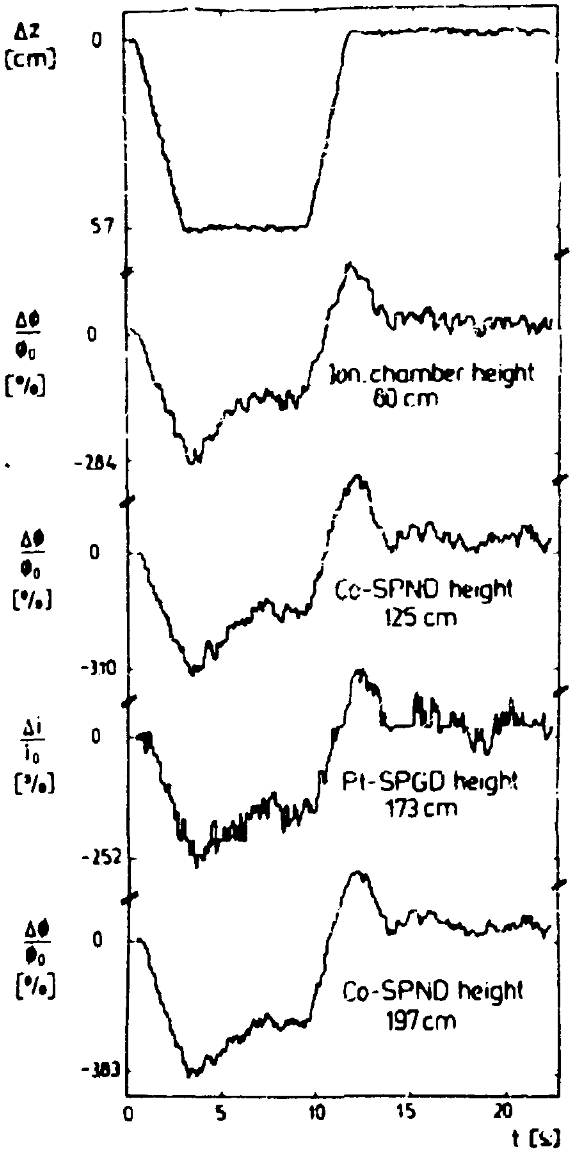

FIG. 5 Time functions of control rod movement and corresponding signal alterations of different types of detectors

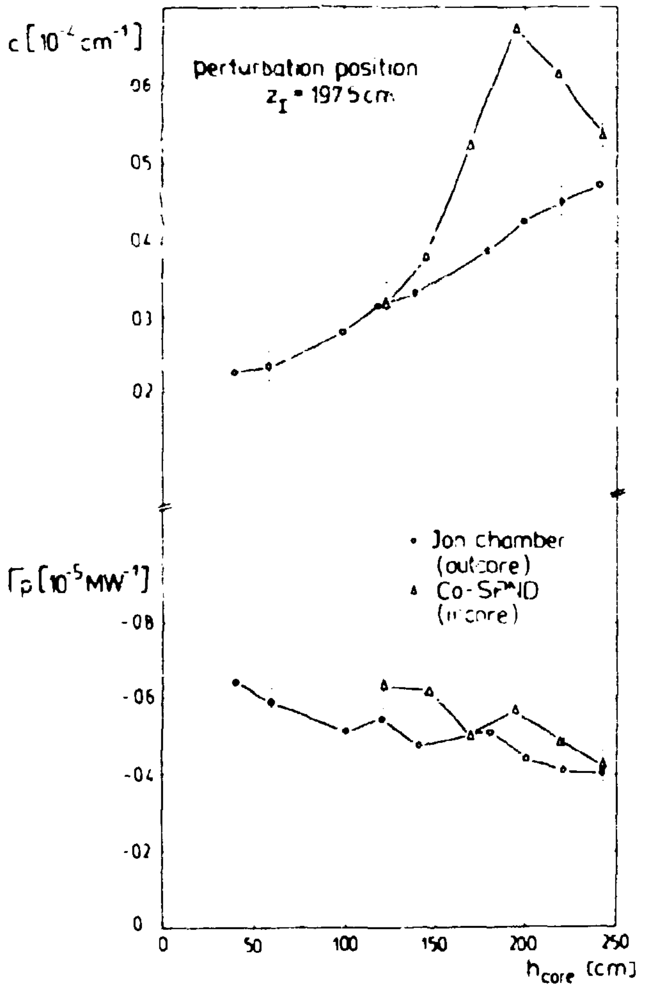

FIG. 6 Evidence of dependence of reactivity parameters on detector position by means of prompt SPD; comparison of in-core and out-core results

By means of measured control bank position and neutron flux signals and computed reactivities (via point kinetics) the differential reactivity weight of control bank (c) and the power coefficient of reactivity (Γ_p) can be estimated [5]. The results of differential weights (Fig. 6) show the known space dependent effects.

The axial control bank position was 197.5 cm. In this height in-core detectors have measured the greatest relative neutron flux alterations.

In Fig. 6 the dependence of differential weights on the axial position of an outcore detector is shown too.

It can be seen that curves of measured relative neutron flux changes or differential weights are coming together in the lower and upper part of the core. These measurements point out a good correspondence to computations reported in [5]. The investigations carried out have demonstrated that prompt Co-SPND and Pt-SPGD are a qualified tool to measure the time dependent neutron flux behaviour.

Therefore it is planned to use these in-core detectors for reactor-dynamic measurements such as RDPM or reactor shutdown experiments to verify validation of reactor code results.

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APPENDIX

THE USE OF SELF-POWERED DETECTORS WITH Pt- OR Rh-EMITTER FOR MEASUREMENTS OF TRANSIENT NEUTRON FLUX

The current alterations of prompt responding Pt-detectors $\delta i_m(t)$ are proportional to gamma flux changes in the core. As mentioned in Sec. 2 the gamma flux includes delayed components in comparison to neutron flux.

If the measured signal of a Pt-SPGD is compared to neutron flux alterations however, the equation

$$\delta i_m(t) = \delta i_p(t) + \delta i_d(t)$$

holds.

For alterations of prompt (δi_p) and delayed (δi_d) components the following relationship

$$\delta i_d(t) = \sum_{i=1}^{k} \lambda_i a_i \int_0^t \delta i_p(t') \, e^{-\lambda_i (t-t')} dt' = F(\delta i_p(t))$$

is valid, where delayed components are characterized by

λ_i - decay constant of delayed component i of gamma flux

$$a_i = \frac{\text{fraction of delayed component i}}{\text{fraction of prompt component}}$$

During RDPM the prompt component $\delta i_p(t)$ represents the main component of measured signal alterations. Delayed components $\delta i_d(t)$ can be considered as a correction of measured signal $\delta i_m(t)$. Therefore an iteration cycle to separate $\delta i_p(t)$ and $\delta i_d(t)$ can be written:

$$\delta i_p^{(o)}(t) = \delta i_m(t)$$

$$\delta i_d^{(s)}(t) = F(\delta i_p^{(s-1)}(t))$$

$$\delta i_p^{(s)}(t) = \delta i_m(t) - \delta i_d^{(s)}(t)$$

$s=1,\dots,n$ (iteration index).

The condition of finishing the iteration is the alteration of delayed components at a fixed time T_o:

$$\left| \frac{\delta i_d^{(n)}(T_o) - \delta i_d^{(n-1)}(T_o)}{\delta i_d^{(n-1)}(T_o)} \right| \leqslant \varepsilon$$

The same method can be used to correct the delayed responding signal of Rh-SPND's.

The function $\delta i_d(t) = F(\delta i_p(t))$ for a Rh-SPND signal including a prompt and two delayed components is

$$\delta i_d(t) = \lambda_1 \int_0^t [b_1\, \delta i_p(t') + \lambda_2 b_2 \int_0^t \delta i_p(t'')\, e^{-\lambda_2(t'-t'')}\, dt''] \cdot e^{-\lambda_1(t-t')}\, dt'$$

where

λ_1, λ_2 - decay constants of activated Rh

$b_i = \dfrac{\text{fraction of delayed component } i}{\text{fraction of prompt component}}$

Investigations have shown that by RDPM the convergence is guaranteed in both cases (Pt- and Rh-SPD signal correction). For $\varepsilon \approx 0.001$, $T_0 \approx 20$ s about 7-11 iterations are needed to get $\delta i_p(t)$ which is proportional to neutron flux alterations.