SPACE DEPENDENCE OF REACTIVITY PARAMETERS ON REACTOR DYNAMIC PERTURBATION MEASUREMENTS

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ABSTRACT

Practical application of reactor-dynamic perturbation measurements for on-power determination of differential reactivity weight of control rods and power coefficient of reactivity has shown a significant dependence of parameters on the position of outcore detectors.
The space dependence of neutron flux signal in the core of a VVER-440-type reactor was measured by means of 60 self-powered neutron detectors.
The greatest neutron flux alterations are located close to moved control rods and in height of the perturbation position.
By means of computations detector positions can be found in the core in which the one-point model is almost valid.

1. INTRODUCTION

Recently it has been manifold reported on the accomplishment of reactor-dynamic perturbation measurements (RDPM) on VVER-440-power reactors being in operation in the GDR [1-15].

By RDPM it is possible to estimate the differential weight of control rods or banks, the power coefficient of reactivity and its time constant at the actual reactor state.
The knowledge of these parameters is of interest for several reasons, for example for validation of reactor codes, for actual operator information and for estimation of reactor reactivity reserve.
Reactivity changes were carried out without any perturbation of energy production by small and time limited displacements of control rods.
The routinic application of RDPM has shown a significant dependence of reactivity parameters on detector position, which can be explained by deviations of the measured neutron flux behaviour from the behaviour according to the one-point model of neutron kinetics.
In [2,3,5,11] an improved model of RDPM was derived to minimize these deviations by a simple correction method based on adiabatic approximation.
It was shown, that space dependent effects can be corrected by the improved model only for the reactor without feedback.

Other investigations of space corrections have been started [13,16], but no significant results for routinic application have been obtained up to now.

The objective of investigations reported in this paper consists in finding out regions in the core or suitable measuring methods to determine reactivity parameters without systematic errors.

The model of RDPM is discussed in sect. 2 and the measuring arrangement using self-powered neutron detectors with Rh-emitters (Rh-SPND's) is presented in sect. 3.

The experimental results and the comparison with results of three-dimensional codes FLOS and FACSY are given in sect. 4. Incore positions on which the point model is valid can be found. One opportunity of realizing on-power RDPM without errors is to place detectors there.

On the other hand, in sect. 4 is demonstrated than an axial averaging of relative flux alterations of detectors of special lance positions yields flux values and reactivity parameters corresponding to the point model.

2. MODEL OF REACTOR-DYNAMIC PERTURBATION MEASUREMENTS

As mentioned an important condition for on-power reactivity measurements is the avoidence of distributions in the energy production of NPP. Therefore only small reactivity perturbations caused by time limited trapezoidal movements of a single or a bank of control rods are carried out. The time function of such a perturbation and the resulting power variation are shown in Fig. 1.

The reactivity model $\rho_{mod}(t)$ is the sum of the outer reactivity $\rho_o(t)$ and the inner reactivity $\rho_i(t)$.

$$\rho_{mod}(t) = \rho_o(t) + \rho_i(t)$$

For a small displacement $\delta z(t)$ of a control rod, the outer reactivity is

$$\rho_o(t) = c \cdot \delta z(t) \ ,$$

where $c = \left.\frac{d\rho_o}{dz}\right|_{z=z_o}$ is the differential weight of the moved control rod at the axial position $z = z_o$.

For inner or feedback reactivity a first order model has been chosen in result of attempts to identify a higher order system [2].

$$\tau \frac{d\rho_i}{dt} + \rho_i(t) = \Gamma_p(P_o) \, \Delta P(t)$$

$$\rho_i(t) = \frac{\Gamma_p(P_o)}{\tau} \int_0^t \Delta P(t') e^{-\frac{t-t'}{\tau}} dt'$$

$P(t)$ - power
P_o - initial power state
Γ_p - power coefficient of reactivity
τ - time constant of Γ_p
Δ - operator for the difference between time dependent and initial state.

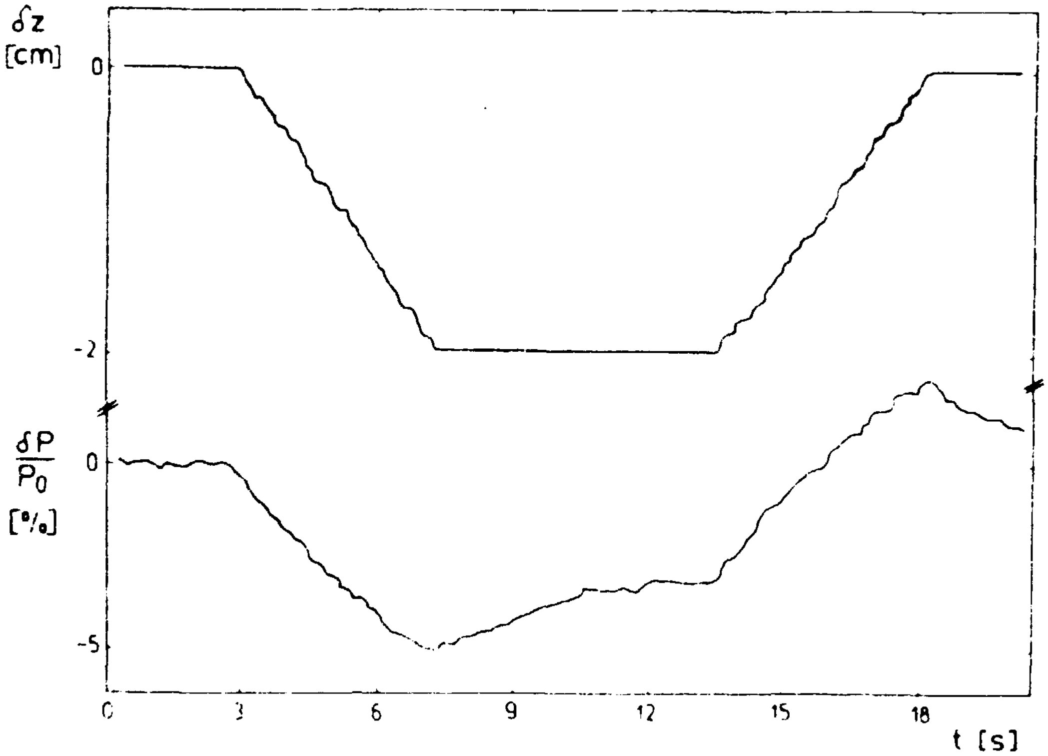

FIG. 1 Time functions of control rod movement and corresponding power variation

If there are no changes in the flux shape (validation of point model),

$$\frac{\Delta P(t)}{P_o} = \frac{\Delta \phi(t)}{\phi_o} \quad \text{holds,}$$

where ϕ_o, $\phi(t)$ is the neutron flux measured by means of a detector.
The reactivity $\rho_{exp}(t)$ is regarded as system output signal. It is expressed by the inverse point kinetic equation

$$\rho_{exp}(t) = \beta_{eff} + \frac{\beta_{eff}}{\phi(t)} \left[\frac{l}{\beta_{eff}} \frac{d\phi(t)}{dt} - \sum_j \frac{\beta_j}{\beta_{eff}} \left\{ e^{-\lambda_j t} + \lambda_j \int_0^t \phi(t') \, e^{-\lambda_j (t-t')} \, dt' \right\} \right]$$

β_{eff} - effective fraction of delayed neutrons
l - life time of prompt neutrons
β_j - fraction of delayed neutrons of group j
λ_j - decay constant of kernels of delayed neutrons of group j

$\rho_{exp}(t)$ is determined either digital or analogous (by means of so-called reactimeter) from the measured neutron flux $\phi(t)$.

Using a fit procedure and comparing the reactivity model $\rho_{mod}(t;\, c,\, \Gamma_p,\, \tau)$ with the measured reactivity $\rho_{exp}(t)$ in the time domain, the unknown parameters c, Γ_p and τ can be estimated:

$$V = \frac{1}{T} \int_0^T \left(\rho_{exp}(t) - \rho_{mod}(t;c,\Gamma_p,\tau)\right)^2 dt \overset{!}{=} \underset{c,\Gamma_p,\tau}{\mathrm{Min}}$$

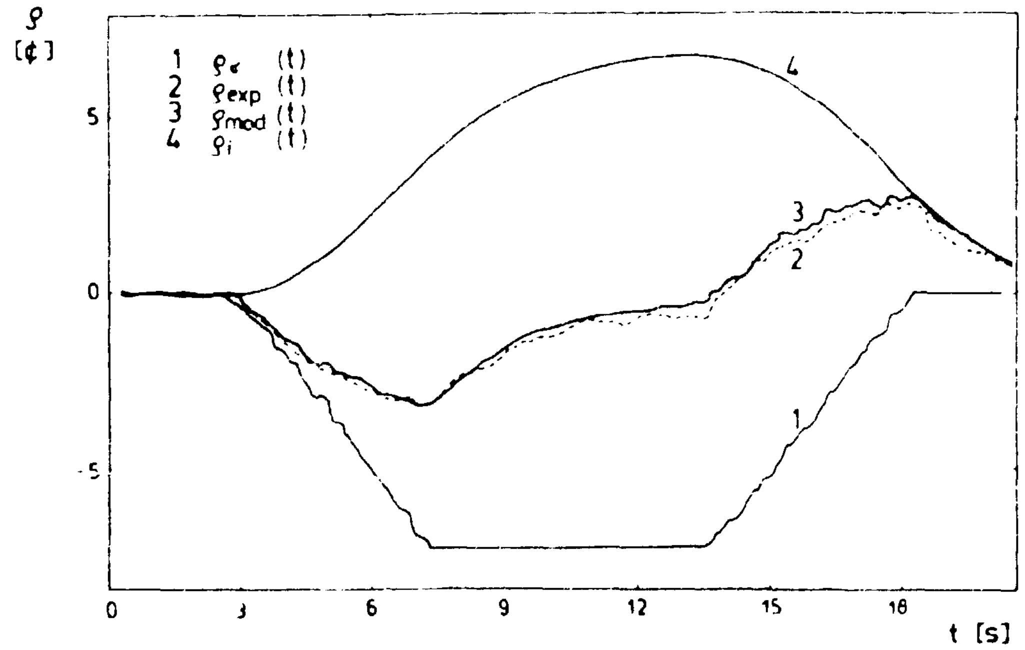

FIG. 2 Time behaviour of different reactivity components

Fig. 2 shows the time behaviour of $\varrho_0(t)$ (see Fig. 1) and the negative feedback reactivity $\varrho_i(t)$ and the comparison of measured (ϱ_{exp}) and fitted (ϱ_{mod}) reactivity.

3. MEASURING ARRANGEMENT

The space dependence of neutron flux signals $\phi(t)$ in the core of a VVER-440-type reactor was demonstrated by means of 60 Rh-SPND's, assembled into 12 lances. The positions of the lances can be seen in Fig. 11, 12 (Notice, that all positions are projected into a 30^0-sector by means of the existing symmetry relations.). Five Rh-detectors with a 20 cm emitter length are located at 40, 80, 120, 160 and 200 cm of the core height (250 cm). The current produced in the detector cable is compensated by an additional cable. After compensation the current-voltage conversion and amplification are carried out.
The power changes of about 5 % of RDPM yield changes in the Rh-SPND signals less than 1 %. Under NPP conditions an exact analysis of such small alterations can be done by noise analysis techniques, e.g. by high-pass filtering to separate direct and alternating voltage [6,11]. The noise component is separated with a time constant τ_f = 30 s and amplified by 40 dB (Fig. 3).

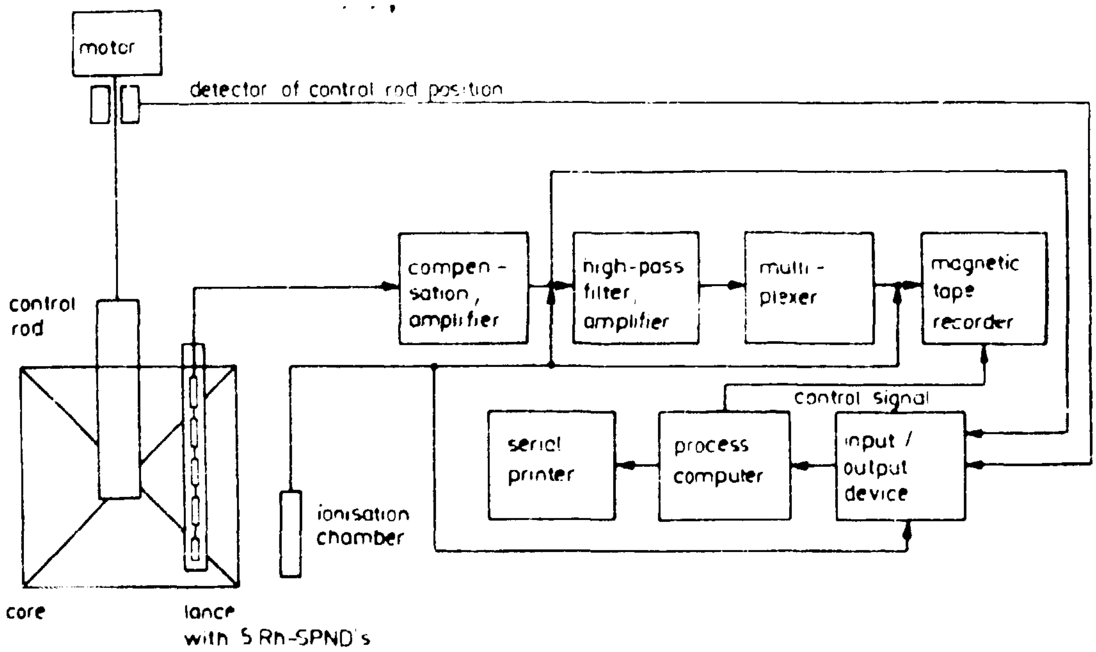

FIG. 3 **Incore noise system for dynamic reactivity measurements**

Using a multiplexer it is possible to store 32 different high-pass filtered signals of Rh-SPND's and ionization chambers in 4 channels of a magnetic tape recorder simultaneously. The cycling frequency of the multiplexer was 15.625 Hz for each signal.
The digital measuring point of control rod position, initial states of SPND's and the unfiltered signals of ionization chambers (to test the inverse high-pass filter procedure) are recorded by a special input/output device and a process computer with a tast frequency of 10 Hz. During the experiments the process computer has been put a control signal to the tape recorder to synchronize analogous and digital signals.
The signals of Rh-SPND's have to be corrected before they can be used to estimate the parameters c, Γ_p and τ .
The current of Rh-SPND's consists of a prompt and two delayed components. Therefore the high-pass filtered signals of Rh-detectors do not contain the complete dynamic parts of delayed components, especially in the cutted frequency domain 0...5.3 • 10^{-3} Hz.
It is necessary to carry out an inverse high-pass filter procedure:
The behaviour of high-pass filter with the time constant τ_f can be described by

$$i_m(t) = \int_0^t \left.\frac{d\bar{i}_m}{dt}\right|_{t=t'} e^{-\frac{t-t'}{\tau_f}} dt'$$

$\bar{i}_m(t)$ - detector response
$i_m(t)$ - high-pass filtered signal

Differentiation leads to

$$\frac{d\,\bar{i}_m(t)}{dt} = \frac{d\,i_m(t)}{dt} + \frac{1}{\tau_f}\, i_m(t) \quad .$$

The signal $\bar{i}_m(t)$ consists of all dynamic parts of prompt and delayed components (Fig. 4):

$$\bar{i}_m(t) = i_p(t) + i_d(t) \quad .$$

Using the well-known Rh-detector equations [11,17,18] it is possible to separate prompt and delayed components. $i_p(t)$ represents a signal proportional to the neutron flux alterations at the detector position.

Annotation:
Because it is known that the prompt fraction α can be different from detector to detector ($\tilde{\alpha}$ = 7.4 ± 1.2 % of the total signal [11]) and α represents an important value in the correction (separating) method, the exact knowledge of α is of great importance for reactivity parameter estimation, as has been shown in [11,18] (see Fig. 5).

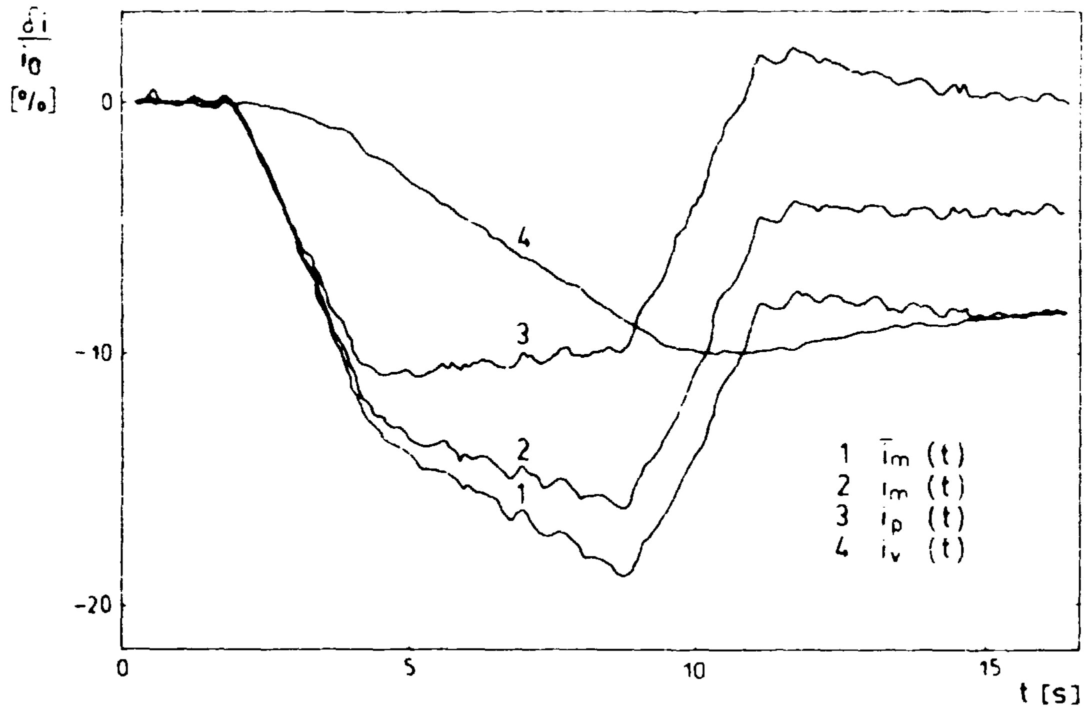

FIG. 4 Time functions of measured and corrected dynamic signal components of Rh-SPND

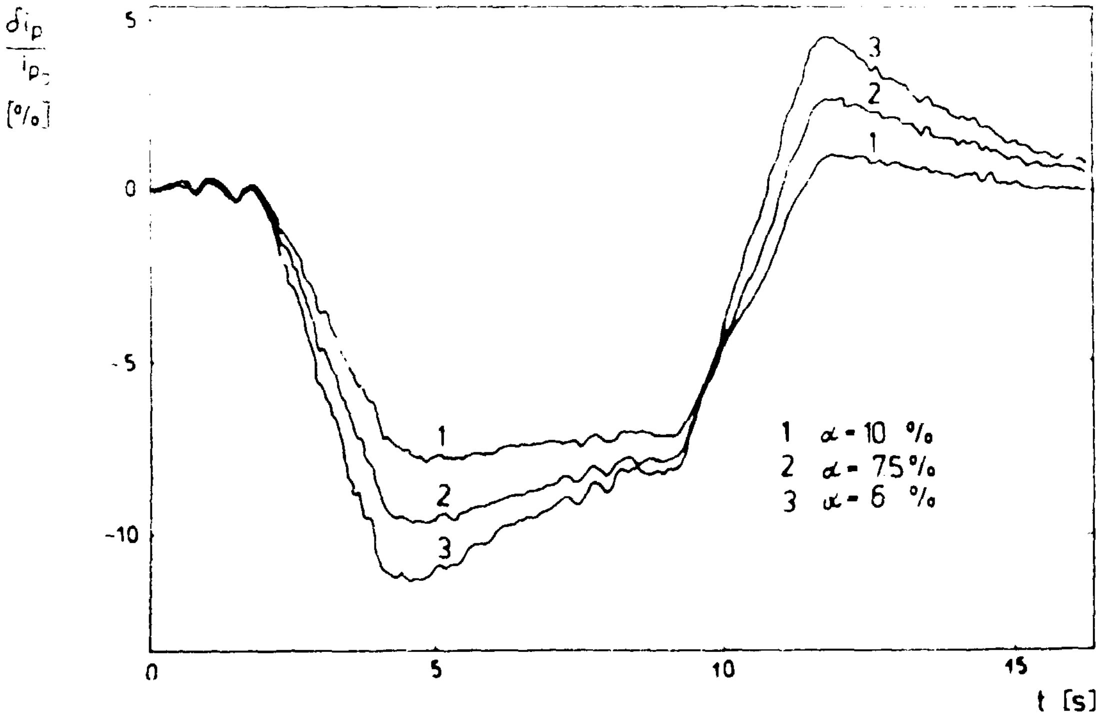

FIG. 5 Examples for the influence of prompt fraction α on the time function of corrected Rh-SPND signal $i_p(t)$

4. EXPERIMENTAL RESULTS AND COMPARISON WITH RESULTS OF THREE-DIMENSIONAL CODES

During the first reactor period of unit 4 of NPP Greifswald RDPM have been accomplished with control rod bank K6 positioned at 170 cm,
The maximal control bank displacement Δz of about 4 cm caused a power decrease of about 5 %. The corresponding neutron flux signals measured by Rh-SPND's change from 3 to 11 %.
The greatest alterations are located in the height of perturbation position (axial effect) and close to moved control rods (radial effect). Fig. 6 and 7 show examples for this axial and radial dependence of relative neutron flux alterations $\delta\phi/\phi_0$ for selected detector lances. By means of measured control bank position and neutron flux signals and computed reactivities (via inverse point kinetics) the differential weight of control bank (c), the power coefficient (Γ_p) and its time constant (τ) have been estimated.
In [6,11] it is reported on the results of all detectors. Some important remarks are:

- The axial and radial dependences of estimated control rod weights correspond to space effects of relative neutron flux alterations and are demonstrated in table 1.

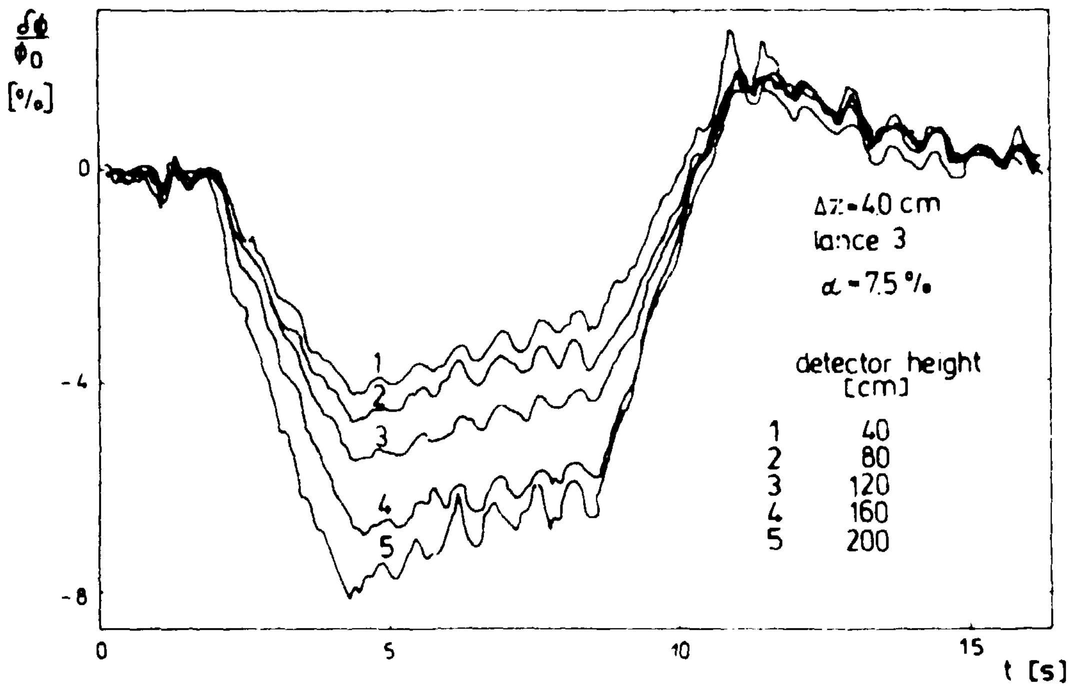

FIG. 6 Axial dependence of relative neutron flux alterations on detector position

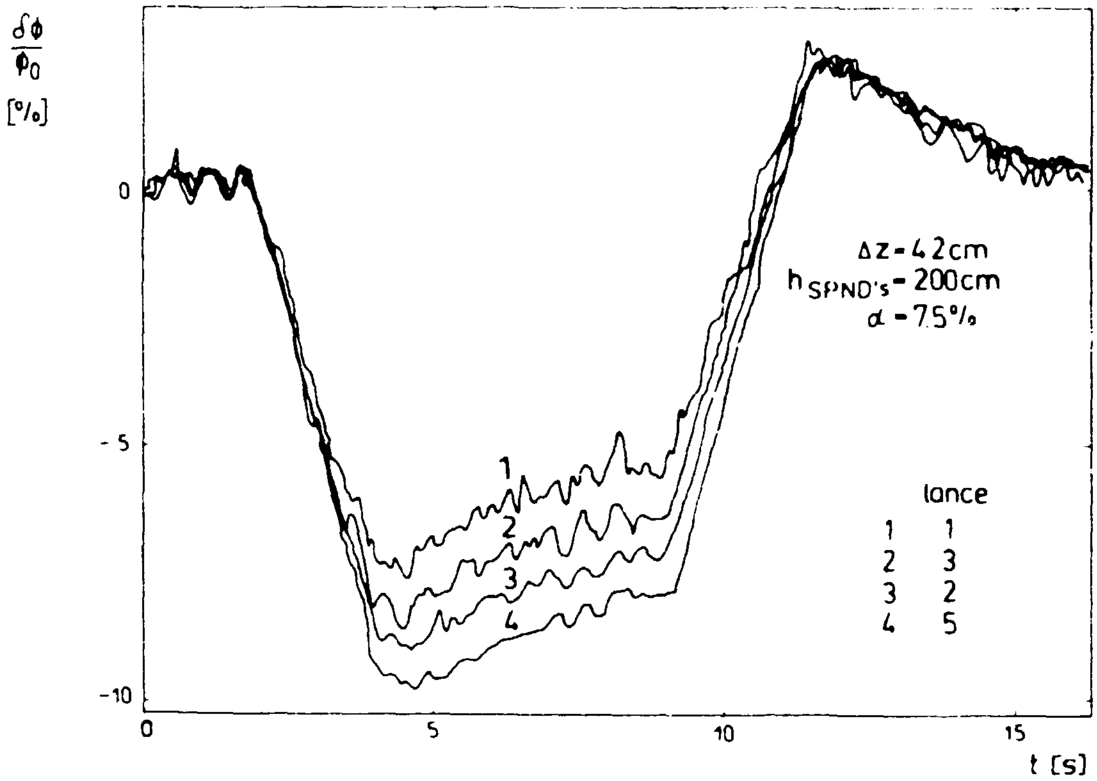

FIG. 7 Radial dependence of relative neutron flux alterations on detector position

Table 1 Dependence of control rod weights on axial and radial detector positions

detector position [cm]	mean value of differential weights estimated from detectors at the same height $[10^{-4} \cdot cm^{-1}]$	dispersion (see results of code FLOS) [%]
200	1.62 ± 0.15	18.6
160	1.65 ± 0.26	31.6
120	1.15 ± 0.11	19.2
80	0.88 ± 0.05	11.4
40	0.76 ± 0.06	15.8

- The distribution of power coefficients ($\overline{\Gamma_p} = -0.75 \pm 0.09 \cdot 10^{-5}\ MW^{-1}$) does not show a significant space dependence.
- The mean value of time constant is $\overline{\tau} = 5.5 \pm 1.3$ s.

It was not possible to compare directly the estimated reactivity parameters or the measured neutron flux alterations with results of reactor codes, because the available codes FLOS [7,9] and FACSY [7,8] are not able to consider feedback effects.
The code FLOS, based on perturbation theory, calculates the spatial distribution of a neutron flux disturbance caused by local periodic alterations. It is not possible to calculate the time dependent neutron flux behaviour $\delta\phi(t)$ corresponding to trapezoidal displacement of control rods $\delta z(t)$. FLOS calculates the so-called prompt jump of relative neutron flux alterations $\Delta\phi/\phi_0$.
Thus the finite velocity of control rod movements and the influence or delayed neutrons are neglected.
The code FACSY estimates the time dependent neutron flux behaviour corresponding to trapezoidal rod movement by means of flux separation and synthesis approximation. The results of differential control rod weights can be used to calculate the reactivity worthes occurring by control rod displacements of 4 cm, neglecting feedback effects.

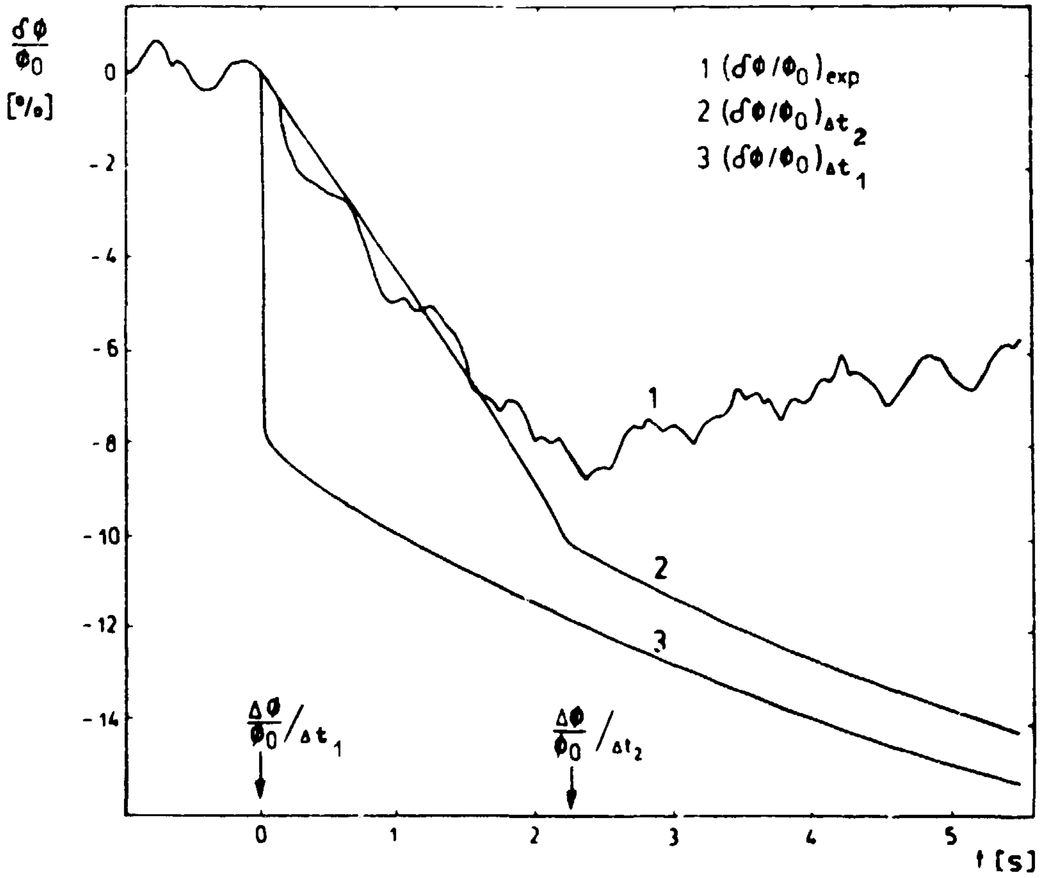

FIG. 8 Illustration of correction of measured relative neutron flux signal to different reactor states (prompt jump, no feedback)

If different rod moving times $\Delta t_1 = 0.001$ s (prompt jump) and $\Delta t_2 = 2.25$ s are selected, the values $(\Delta\phi/\phi_0)_{\Delta t_1}$ and $(\Delta\phi/\phi_0)_{\Delta t_2}$ can be calculated from measured relative neutron flux changes $(\delta\phi/\phi_0)_{exp}$ via point kinetic equations (Fig. 8).

$(\Delta\phi/\phi_0)_{\Delta t_1}$ and $(\Delta\phi/\phi_0)_{\Delta t_2}$ correspond to relative neutron flux alterations of codes FLOS ($\Delta t_1 = 0.001$ s) and FACSY ($\Delta t_2 = 2.25$ s).

The dependence of relative flux alterations or perturbation amplitudes $\Delta\phi/\phi_0$ calculated by FLOS on detector height is shown in Fig. 9 for three different positioned incore lances. It is important, that all curves (The curve representing an outcore detector corresponds to this behaviour too [15]) are coming together in the lower and, obviously in the upper part of the reactor,too. The greatest dispersion is located close to perturbation height (170 cm). If the theoretical results are multiplied by a constant factor [7], calculations show a good correspondence to experimental results (Fig. 10, table 1). For reactivity measurements such detectors have to be chosen which are positioned in that height in the lances, where point model is valid (curve "ρ" in Fig. 9). The height in each assembly, where the point model is valid, is displacing in dependence on axial position of control bank K6.

The mean value of all $\Delta\phi/\phi_0$ of one assembly i represents the so-called channel-reactivity ρ_i [7,11].

Calculated channel-reactivities of assemblies nearly absorbing regions (reactor ledge) are negative in comparison to reactivity ρ. Inner regions of the reactor are characterized by positive deviations (Fig. 11).

Those channel positioned on the boundary line between negative and positive deviations (lances 10, 11) are most suitable for reactivity measurements; Here reactivity can be measured from data of a single channel without knowing the height, where the point model is valid ($\rho = \rho_i$). The shape of this boundary line is nearly independent on different axial control bank positions (corresponding to fuel burn-up) in regions between single control rod positions.

Distributions of perturbation amplitudes $\Delta\phi/\phi_0$ calculated by code FACSY have shown a good correspondence to FLOS and measuring results too [7,11]. In accordance to results obtained by FLOS, the point of intersection between different curves of perturbation amplitudes and point kinetic straight line "ρ" is located by 120 cm (see Fig. 9).

The differential weight c estimated by FACSY using point kinetics is $c = 1.17 \cdot 10^{-4}\ \mathrm{cm}^{-1}$.

This result agrees with

- the mean value of all differential weights measured by Rh-SPND's

$$\bar{c}^{core} = 1.17 \cdot 10^{-4}\ \mathrm{cm}^{-1}$$

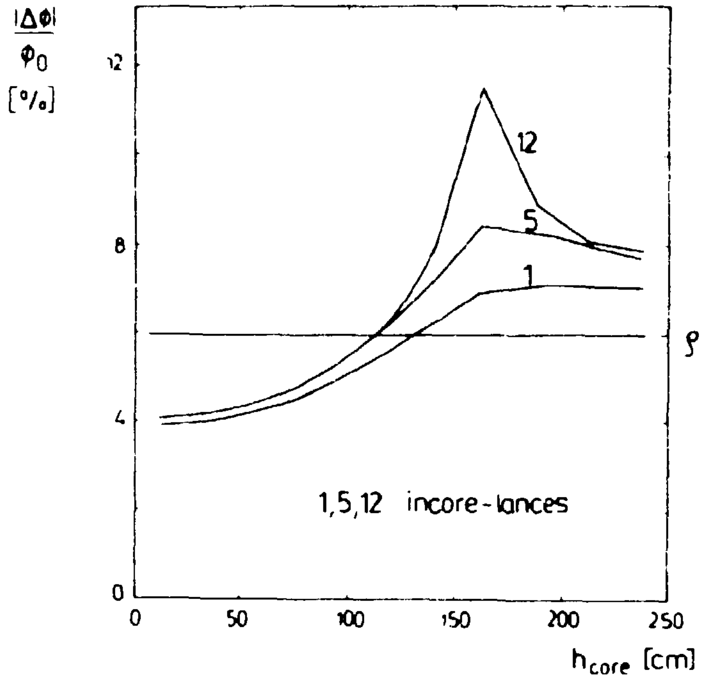

FIG. 9 Dependence of relative neutron flux alterations on detector position (results of code FLOS)

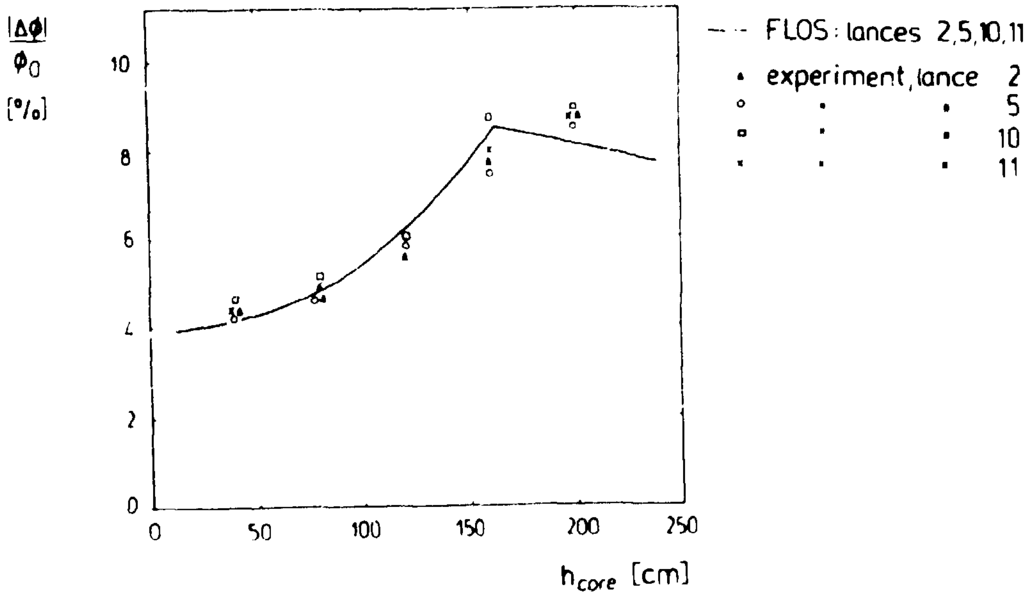

FIG. 10 Comparison of theoretical and measured relative neutron flux alterations

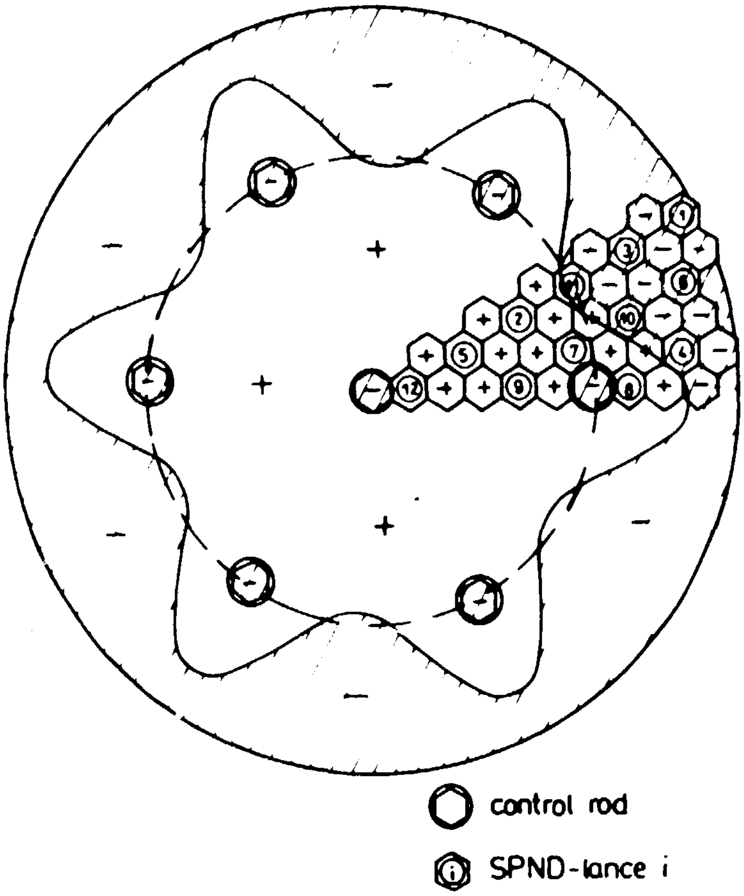

FIG. 11 Deviations of channel-reactivities from reactivity (results of code FLOS)

- and the mean value of differential weights of detectors in the height 120 cm

$$\bar{c}^{120} = 1.15 \cdot 10^{-4} \ \mathrm{cm}^{-1} .$$

Using the FACSY results $\Delta\phi/\phi_0$ the channel-reactivities have been calculated for each assembly too.
In accordance to FLOS results the outer assemblies show negative deviations in ρ_i from ρ. The control rod positions are centres of positive deviations (Fig. 12). (Notice, that lance positions 10 and 11 are located on the boundary line again.)

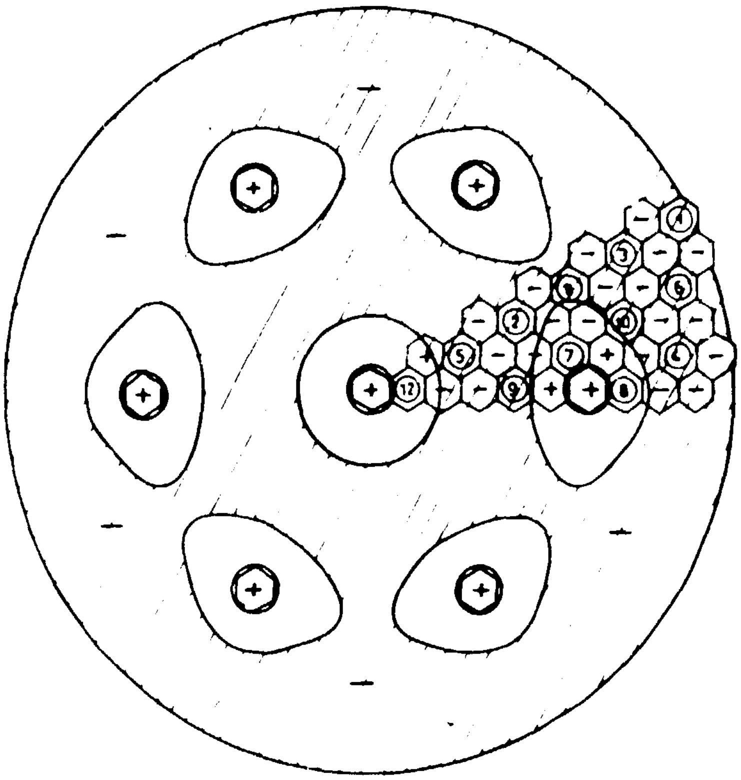

FIG. 12 Deviations of channel-reactivities from reactivity (results of code FACSY)

5. CONCLUSIONS

The following hints can be given for reactivity measurements using incore detectors:

- Such detector positions have to be selected where the point model of reactor kinetics is valid. For different reactor states it is necessary to calculate these positions by a reactor code.
- If measurements are carried out by different control bank heights and it is not possible to determine the detector position of point model validation, a so-called channel-reactivity measurement with detectors of selected lances is suggested.

There are core regions in which the boundary line of positive and negative deviations of channel reactivities from (global) reactivity does not vary its shape even by changed axial control bank positions.
Space dependence of reactivity parameters illustrated by RDPM with Rh-SPND's has been recently confirmed by means of prompt response incore detectors [11,15]. Outcore detectors have been used at these measurements, too. It has been shown that outcore detectors often yield smaller reactivity worthes in comparison to incore detectors [11].

This fact stresses the necessity of incore reactivity measurements.
In accordance to the given suggestions RDPM with incore detectors can be accomplished to determine important reactivity parameters without systematic errors.

REFERENCES

[1] ZIEGENBEIN, D., BALDEWEG, F., MALETTI, R. Nuclear Power Plant Control and Instrumentation (Proc. Symp. Cannes, 1978) Vol. 1, IAEA Vienna (1978) 251

[2] FUGE, R., ZIEGENBEIN, D., Nucl. Sci. Eng. 71 (1979) 309

[3] ZIEGENBEIN, D., GRUNDMANN, U., MALETTI, R., ROHDE, U., Kernenergie 23, 9 (1980) 318

[4] MALETTI, R., ZIEGENBEIN, D., KROEGER, J., Kernenergie 23, 11 (1980) 380

[5] ZIEGENBEIN, D., Atomkernenergie 36, 2 (1980) 140

[6] HESSEL, G., MALETTI, R., SCHUMANN, P., ZIEGENBEIN, D., Report ZfK-447 (1981)

[7] COLLATZ, S., GRUNDMANN, U., MALETTI, R., ROHDE, U.,ZIEGENBEIN,D., Kernenergie 24, 11 (1981) 415

[8] GRUNDMANN, U., ROHDE, U., Report ZfK-416 (1980)

[9] COLLATZ, S., Kernenergie 24, 1 (1981) 2

[10] JANKE, R., HAGEMANN, U., ZIEGENBEIN, D., Nuclear Power Plant Control and Instrumentation (Proc. Symp. Munich, 1982) IAEA-SM-265/86

[11] MALETTI, R., Thesis, Academy of Sciences of GDR, 1984

[12] HAGEMANN, U., SEIDENKRANZ, T., STEIN, H., ZIEGENBEIN,D., NEA Specialist Meeting, Halden, 10. - 13.10.1983

[13] REBUHM, H., International Temporary Collective of VVER-Physics, Moscow, 1983

[14] MOISEL, R., International Temporary Collective of VVER-Physics, Moscow, 1984

[15] SEIDENKRANZ, T.,BOEHME, K., HAGEMANN, U., MALETTI, R., STEIN, H., IAEA/NPPCI Specialist' Meeting Dresden, 23. - 25.4.1985

[16] KASTSCHIJEV, G.S. et al., 10th Symposium International Temporary Collective of VVER-Physics, Erevan, 1981

[17] BANDA, L.A., NAPPI, B.I., IEEE Trans.Nucl.Sci. Vol. NS-23, No. 1 (1976) 311

[18] BOUSCHIK, J. et al., Nukleonika 25, 9 (1980) 1143