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EXPERIENCE IN SIMULATION OF STARTUP MEASUREMENTS IN THE VVER-440 REACTOR USING THE KIKO3D CODE

Gy. Hegyi, A. Keresztúri and Cs. Maráczy
KFKI Atomic Energy Research Institute
Reactor Analysis Laboratory
H-1525 Budapest 114, POB 49, Hungary
ghegyi@sunserv.kfki.hu

ABSTRACT

The purpose of this work carried out by MTA KFKI Atomic Energy Research Institute in Hungary, is to develop and validate a method for predicting the ex-core detector responses in the Russian pressurized water type VVER reactors. The time and space dependent neutron flux in the core during these measurements have been calculated by the KIKO3D nodal diffusion code. For calculating the ionization chamber signals the Green function technique has been applied. The Green functions of ionization chambers have been evaluated via solving the neutron transport equation in the reflector regions with MCNP Monte Carlo code. The detector signals have been calculated and compared with measured ones using the inverse point kinetics transformation. Large number of asymmetric rod drop measurements (with one rod stuck) and some differential rod worth measurements from the Zero Power Physics Tests were provided by the Paks NPP for validation. The initial state of experiments covers different fuels (without and with enrichment zoning) and loading patterns. The intermediate range ionization chambers have been used during the scram measurements. The newly developed method provides fairly sufficient match of measured and calculated results. The time behavior of the detector readings is well modeled. Their space dependent effects observed in the measurement are described by the code in a consistent manner. The uncertainty of scram rod worth is established by statistical analysis.

Key Words: Scram reactivity, differential control rod worth, reactor kinetic code, signal of the ex-core detector

1. INTRODUCTION

During the startup process of a VVER-440 nuclear power plant rod drop and differential control rod worth measurements are performed. Typically, the reading of a reactimeter connected to an ex-core ionization chamber (IC) does not correspond to the calculated change in the static reactivity of the core, based on calculated k_{eff} values and calculated point model parameters for the core. The static core calculations for VVER-440 plants are used to be performed by the KARATE code system, which was elaborated in the mid '90s in KFKI-AEKI [1]. In the framework of the program neutron-physical and thermohydraulic processes (the latter only for the feedback) at normal, startup, steady state, and slow transient conditions can be simulated. Having performed a wide verification and validation process it is extensively used for fuel cycle and reload design calculations [2]. Another important function of the code is to verify the fulfillment of reload limitations demanded by the safety analysis (e.g. reactivity coefficients and control rod worth). The scram rod worth is one of the limiting parameters in safety analysis. The uncertainty of its calculations helps in establishing safety (engineering) factors. In order to analyze these differences, calculations with a 3 dimensional kinetic code have been performed, which clearly showed that the local flux changes caused by dropped rods are responsible for the differences between calculated and measured rod worth. The time and space dependent neutron flux in the core during these measurements were calculated by the KIKO3D nodal diffusion code [3], developed by our institute, too [4]. For calculating the ionization chamber signals the Green function technique has been applied. The Green functions of ionization chambers were evaluated via solving the neutron transport equation in the reflector regions with MCNP Monte Carlo code. The detector signals during asymmetric scram measurements were calculated and compared with measured data using the inverse point kinetics (IPK) transformation. The sufficient agreement validates the KIKO3D code to determine the reactivity after scram.

Recently large number of asymmetric rod drop measurements (with one rod stuck) and some differential rod worth measurements were provided by the Paks NPP to validate the KIKO3D dynamic code and parallel with it to determine the uncertainty of scram rod worth of the KARATE-440 code system, which is used routinely in the engineering practice in our VVER type Nuclear Power Plants. The initial state of experiments covers different fuels (without and with enrichment zoning) and loading patterns. The calculated results were compared to measurements.

The differential control rod worth measurement was used also for validation. From the experiment the time dependent flux simulated by KIKO3D and the detector readings can be compared. The measured data were evaluated and compared to the results of the KARATE calculations, which use fine axial mesh size and detailed model for the control assembly. It provides fairly sufficient match of measured and calculated results. The validation against these real plant data includes the whole neutronic calculation system, i.e. nuclear data, burnup calculations and reactor kinetics.

In the following sections, a short overview of the measurements and the above mentioned development in KIKO3D code will be presented, the computational procedure will be described and the comparison of the calculated and measured figures will be discussed.

2. DESCRIPTION OF THE MEASUREMENTS

For safety reason in a VVER-440 reactor containing 349 assemblies there are 37 control assemblies (CA), from which 7 take part directly in the maneuvering of the core (**W**orking **G**roup). Details can be seen on Figure 1. In a case of emergency the other 30 CAs, which are fully withdrawn during normal operation, enter to the core their speed is 25 cm/s. Axially the CA consists of two main parts, the boron steel zone and that bellow the follower containing normal fuel. There is a short intermediate zone between fuel and boron steel. For a fully inserted CA this part concerns the bottom 30 cm of the absorber in the active core. In a reactor scram the boron steel is the most significant part of the CA and two-group albedos are introduced for it, in the KIKO3D and the KARATE code.

During physical start-up the initial power is about 1.E-5 of the nominal value, the moderator temperature is 260 ^{o}C. Currently, during the measurement of the reactor scram one of the most effective control assemblies is stuck at their upper positions. The intermediate range ionization chambers No. 5, 13 and 21 are used in the measurements (Fig. 1). The sector of stuck rod is selected to be close to one of the ionization chambers. The intermediate range ionization chambers were used during the scram measurements. To make the simulation more realistic the ionization chamber signal based on ^{3}He(n, p) reaction of thermal neutrons were calculated.

Results of 32 scram measurements (from 8 consecutive cycles of each unit) were selected by the Paks NPP which covers different fuels and loading patterns. The range of the initial control rod group position was 155-234 [cm]. The measured boric acid concentration was between 8.0 and 10.4 [g/kg]. In the simulations, the initial steady state of the core was described as well as possible, including the burnup state of the core and the other above mentioned data.

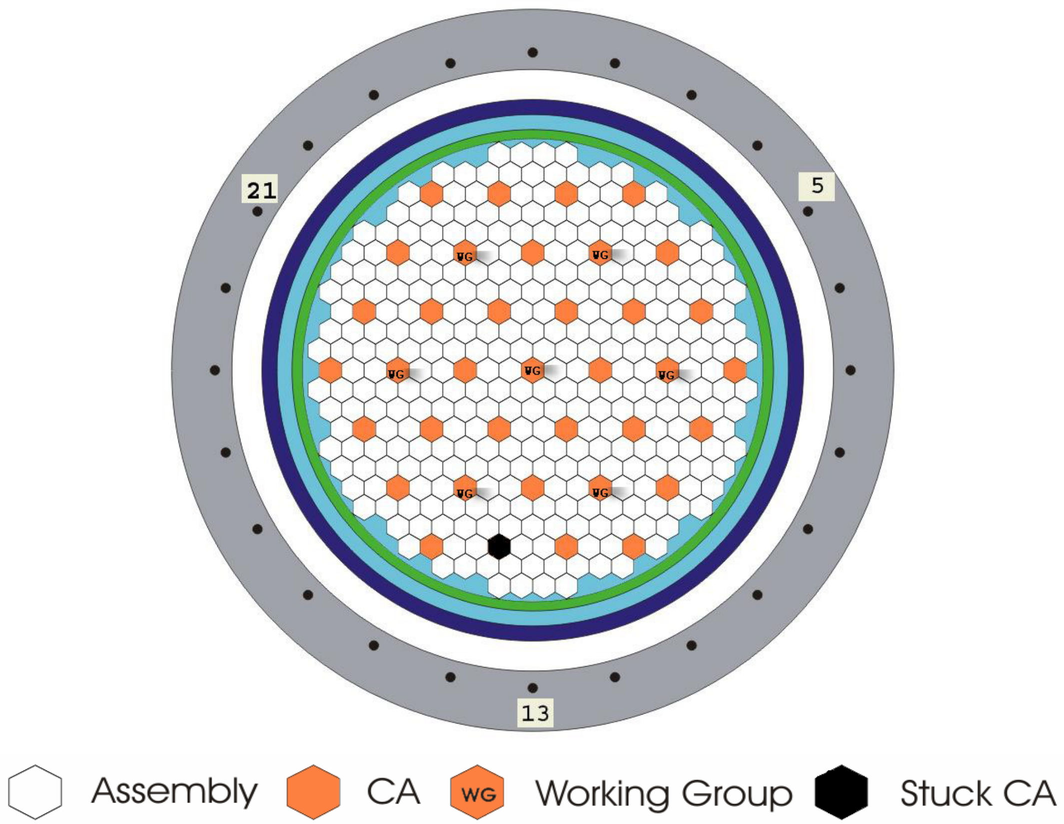

Figure 1. Location of the Control Assemblies and the position of the ionization chambers used at the start-up measurements in a VVER-440 NPP

The other results of the measurements were provided as primary ionization chamber (IC) signals with jumps at the lower end of measuring range. Three methods were used to join the signals: the first assumption implies that the IC reading jumps by a factor of ten after the change in the measuring range. The second and third methods demand the continuity of the reconstructed IC reading by supposing that the factor is not exactly ten and supposing nonlinearity in the measuring range. Figure 2 shows the comparison of the three methods to join the signals after the inverse point kinetic transformation (IPK). In the followings calculated predictions of ex-core detector signals in a given experiment are compared to the actual measured ones.

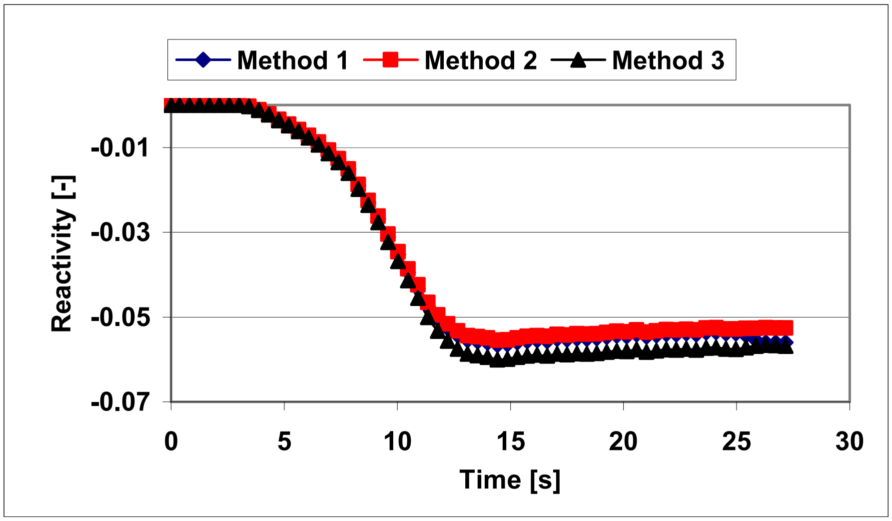

Figure 2. Comparison of the three methods to join the signals

In the last example, the process of measuring differential control rod worth in VVER-440 reactors was simulated. In that experiment the reactivity effect of the slowly diluted boric acid was compensated by the stepwise insertion of the working group (See Fig. 3). It was inserted from the initial 210 cm position to the 62 cm final one.

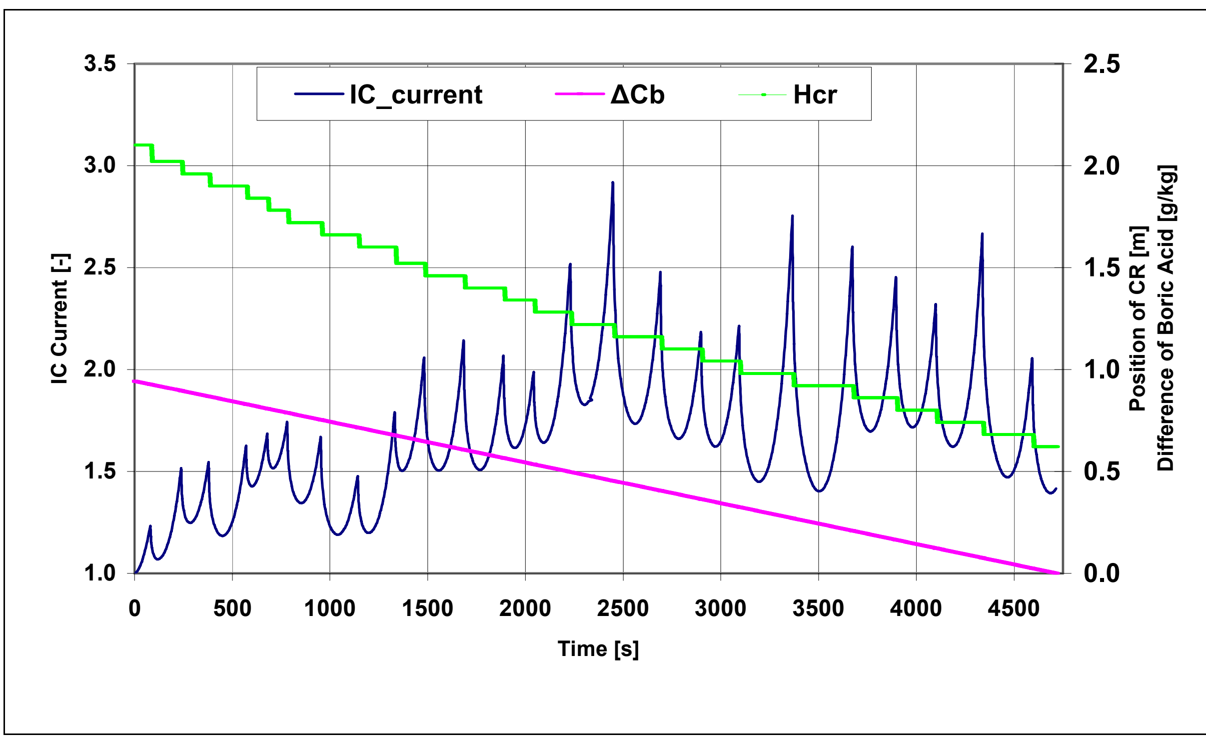

Figure 3. Change of boric acid concentration, position of working group and the currant of the ionization chamber during the ∂ρ/∂H measurement being simulated

The setting of working control group is symmetrical; same as the arrangement of ex-core detectors in this measurement (see Fig. 1). The seven control assemblies are moved together. Even in that case the fine control rod movement allows us to model fine reactivity changes, in a range of 4750 second, only one ex-core detector signal was available, so in this exercise the core amplitude function evaluated by KIKO3D code was used in the inter-comparison.

3. UPGRADINGS IN THE KIKO3D CODE

To elaborate a more accurate method which makes possible the evaluation of scram reactivity at physical start-up procedure using the time dependent IC signals, some modernization had to be performed.

3.1. New Development in the Calculation Procedures

As the power level is very low during this process, the signal of ionization chambers may be affected by the presence of the neutron source especially in case of fuel management strategy using high burnup assemblies at the core periphery consequently the inclusion of source term in the KIKO3D code was necessary. The neutron source originated from spontaneous fission and (α,n) reaction of oxygen was calculated with the ORIGEN2 code [5]. Up to 58000 MWd/tU burnup calculations were carried out at nominal power. The cooling time of the assemblies was taken into account, too. The neutron source library data was parameterized as a function of burnup and cooling time. The space dependent external neutron source term was built into the static and dynamic KIKO3D calculation.
The effective delayed neutron fraction of the point model is evaluated at every flux shape calculation of KIKO3D using node wise β data; however it is possible to fix it. Static β_{eff} KARATE calculations in the initial and final state of the asymmetric scram have shown 10% difference, so the analysis of the β_{eff} curve and the effect of using node-wise β on peripheral assembly flux curves seemed to be useful.
In a given case we have carried out 4 calculations to assess the effect of neutron source and using node wise β model. In the first case both the neutron source and the node wise β model was applied. In the second case there was no neutron source, but the node wise β model was applied. Then these two calculations were repeated using fixed β data from the initial steady state calculation. The dynamic reactivity can be seen in Figure 4. In case of no source the dynamic reactivity after scram changes slowly, with a tie constant of some hours. Using external source stabilizes the reactivity in some minutes.
During the dynamic calculations the shape function tends to approach the highly asymmetric flux distribution of the usual static calculation only very slowly. The neutron field partially preserves its previous shape via the delayed neutron precursor in case of high negative reactivities. The time constant is some hours, which far exceeds both the usual measuring time and the time at which the neutron field reaches the equilibrium sustained by the source from spontaneous fission.
In case of high negative reactivity the flux shape redistribution in extremely slow what can be easily enlightened by a simple qualitative model. Let us suppose that in case of asymmetric scram the two halves of the core are isolated. They have high negative reactivities which are

somewhat different (ρ and $\rho+\delta\rho$). Using one delayed neutron group approximation the fluxes behave as exp(ωt), where $\omega = \lambda\rho/(\beta-\rho)$, but the shape function for the whole core (the ratio of the halve-core fluxes) behaves as exp($\delta\omega$t), where: $\delta\omega= \lambda\beta\delta\rho/(\beta-\rho)^2$. This characteristic time of the flux shape redistribution is in the range of some hours.

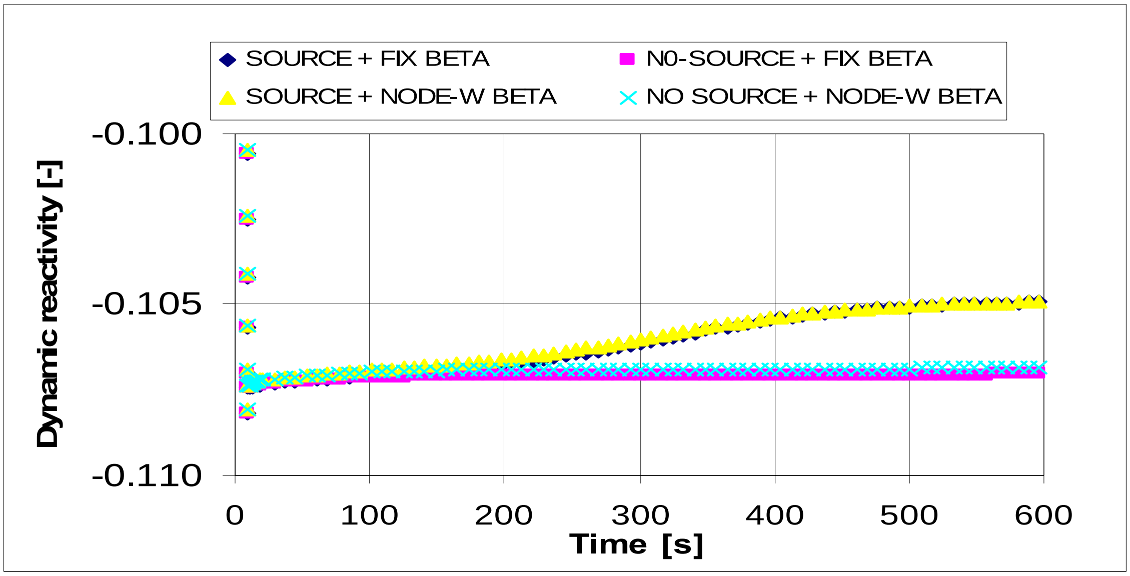

Figure 4. SCRAM with stuck CA. Effect of neutron source and node wise β on reactivity

3.2. Simulation of the Ex-core Detector Signal

To make our simulation realistic, in the last step, kernels for the ionization chambers, most frequently used in the Paks NPP, were built into our model (see Fig. 1). It is based on the Green function method. The KIKO3D code calculates the space and time dependent neutron flux on the core boundary faces, directly. The Green functions of IC responses on the core boundary face fluxes are evaluated via solving the neutron transport equation in the reflector regions with the MCNP4A Monte Carlo code [6-7]. Detailed geometrical model was elaborated for the MCNP calculations, which contains the details of the core boundary, the baffle plate, the core barrel, the thermal shield, the vessel, the concrete shield and the detectors. The neutron surface source spectrum on the core reflector faces for Monte Carlo calculation was calculated with the COLA transport solver of KARATE. The spectrum was calculated for assemblies with different enrichments, burnup and relative position to the core barrel. They hardly differed from each other. The preliminary MCNP calculations revealed that neutrons having energy below 55.7 keV on the core-reflector boundary practically do not reach the ionization chambers. Neutrons above this energy were started taking into account the linear flux anisotropy. Several fixed axial source distributions were used in the Monte Carlo simulations. The basic mode sin(Bz) gives by far the highest contributions to the detector signal, but the effect of some higher modes was also studied. The value of B is determined by the requirement: the function must vanish at the bottom and the top of reactor taking into account the extrapolation length. As in the MCNP calculations the surface source must be non negative, the higher sin(nBz) modes were admixed to the basic mode. Having prepared several scoping calculations, it could be seen that the flux shape could be expanded with good precision using the first 5 modes. The IC signals from the 138 outer node boundaries for the different axial distributions normalized for one source neutron have to be evaluated. The advantage of the method is that the transfer function calculation must be carried out only once.

The flux expansion by sin(nBz) modes for the core-reflector faces and the on-line calculation of IC signals using the amplitudes of the expansion and the transfer functions has been built into the KIKO3D code.

With the help of the upgraded kinetic code some reactor start-up scram measurements of the Paks NPP were simulated. The calculated IC signals were compared to the measured ones using the inverse point kinetic transformation (IPK). The source term in the IPK equations was set to 0, according to the current procedure. In Figure 5 the calculated and measured IPK "detector reactivities" can be seen in case of asymmetric rod drop measurement.

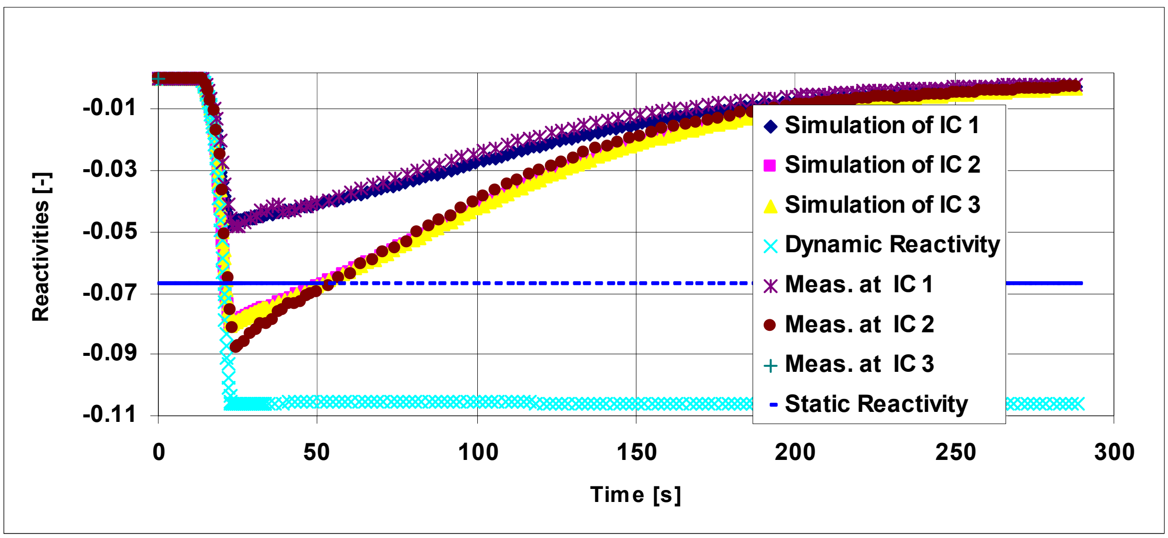

Figure 5. IPK reactivities based on measured and calculated IC signals and static and dynamic reactivities at a given measurement in Paks NPP

The "detector reactivities" calculated from different IC signals are considerably different because of the change in the shape function. The detector reactivity curves in case of long measuring time, high burnup and low initial power tend to go upwards. This effect comes from the presence of external neutron source from spontaneous fission which results in the flattering of IC signals. With the help of raising the initial power level this effect can be eliminated during the usual measurements. Long times after the scram in case of asymmetric rod drop, the external source does not allow the initial flux distribution with low peaking factor to approach the distribution with high peaking calculated with standard static codes. The KIKO3D dynamic and static reactivities belonging to various rod positions during the scram are also presented in Figure 5.

4. SCRAM ROD WORTH UNCERTAINTY OF KARATE

According to our assumption, the differences between measured and calculated IC signal are originated from the uncertainty of the control rod albedo matrix and the uncertainty of the measurements. The latter could be determined from the differences between the IC signals in the symmetric positions taking into account the position of the stuck rod and the core loading. Both the calculated and measured signals were transformed into "reactivity" by using the IPK procedure and the uncertainty of the albedo matrix was determined.

4.1. Simulation of measurements

The rod drop measurements were used for the validation of the scram calculation method of KARATE code in the following way:

1. The static worth of scram was calculated by KARATE, using the all appropriate parameters of the measurement (the static reactivity calculation carried out by the KIKO3D code could give the same data as the albedos of CA are input parameters in this case).
2. The rod drop measurements were simulated by KIKO3D.
3. The calculated IC signals were compared to the measured ones by IPK transformation.
4. The identity of the measured and calculated IPK reactivities was achievable by a (further) albedo tuning.
5. Using this tuning in a second static calculation the transformation of the difference of calculated and measured IPK reactivities to static reactivity difference was obtained.
6. The statistical analysis of static reactivity differences was done for the three method of joining the signals.

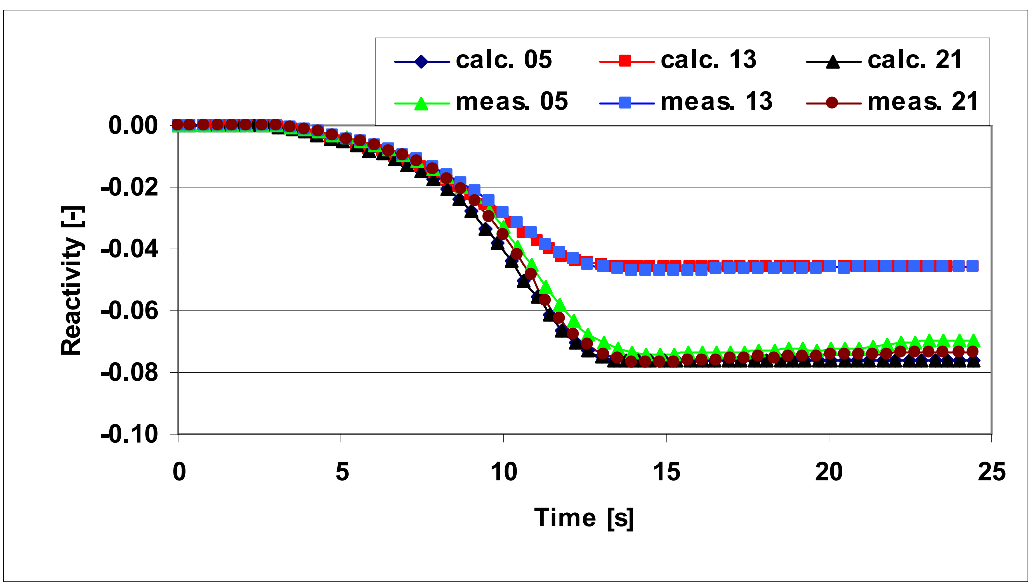

Figure 6. Calculated and Measured IPK Reactivities of IC signals, Paks NPP-3, Cycle 10

The procedure was applied for the all 32 cases. Figure 6 shows a good match of calculated and measured IPK reactivities for Unit 3 Cycle 10. In the data set delivered by the NPP, there were some cases, where according to our experience even though the calculated IPK reactivities of IC's far from the stuck rod are practically identical, the measured ones are different (see Fig. 7).

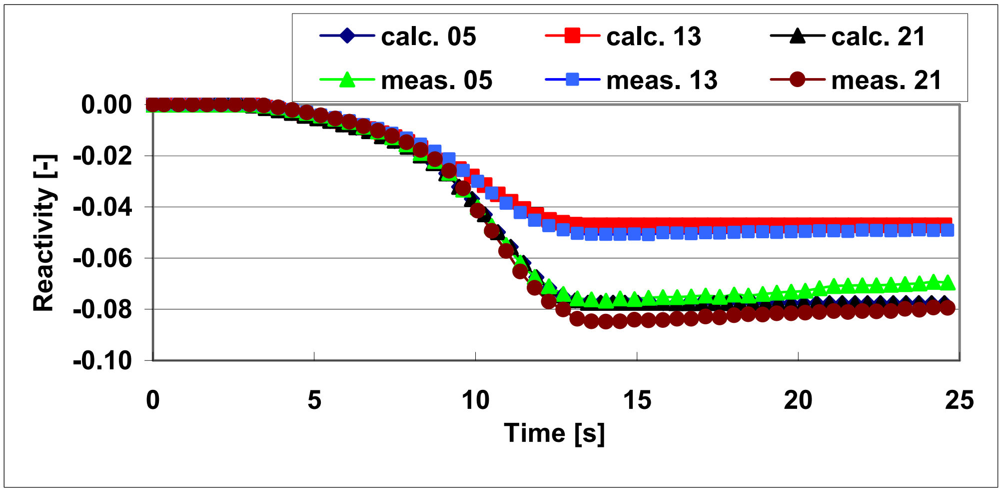

Figure 7. Calculated and Measured IPK Reactivities of IC signals, Paks NPP-1, Cycle 13

Even some detectors were excluded from the analysis, due to their unbelievable behavior enough data were left for the statistical analysis.

4.2. Statistical Analysis

The difference of calculated and measured scram rod worths contains the error of measurements. According to the calculations the signals of the two detectors far from the stuck rod are practically identical. The error of measurements is assessed on the basis of the measured signals in the quasi-symmetric positions. Table 1 contains the expected value $\rho_{(c-m)}$ and standard deviation $\sigma_{(c-m)}$ of the difference of calculated (c) and measured (m) static reactivity differences. $\sigma_{(m)}$ and $\sigma_{(c)}$ denotes the standard deviation of measurement and calculation, respectively.

Table I. Expected values and standard deviations – scram rod worths of Paks NPP Unit 1-4

Method	1.	2.	3.
ρ(c-m)	0.00366	-0.00028	0.00840
σ(c-m)	0.00340	0.00378	0.00437
σ(m)	0.00211	0.00278	0.00266
Nodal	0.00267	0.00256	0.00346
relative 3σ(c) [%]	11.6	11.1	15.0

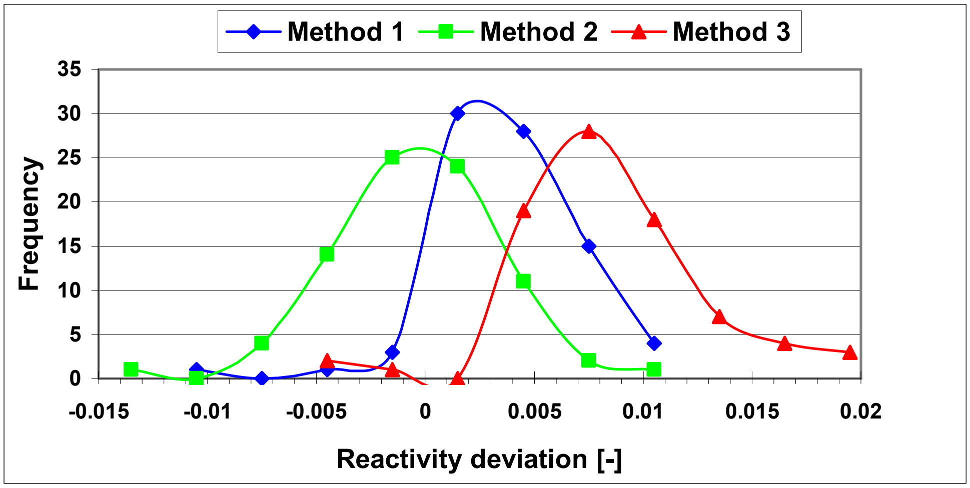

Figure 8. Difference of Calculated and Measured Scram Rod Worths Paks NPP Unit 1-4

On the basis of the expected value $\rho_{(c-m)}$ and standard deviation of calculation $\sigma_{(c)}$ method 2 was selected. The scram rod worth uncertainty of the KARATE system is 11.1%, which corresponds to the 3σ limit. The statistical analysis of static reactivity differences was done for the three methods of joining the signals (see Fig. 8).

The difference of calculated and measured SCRAM rod worths contains the error of measurements. Figure 9 shows the histogram of the calculated minus measured and the measured distributions for method 2. Normality tests confirmed the selection of method 2.

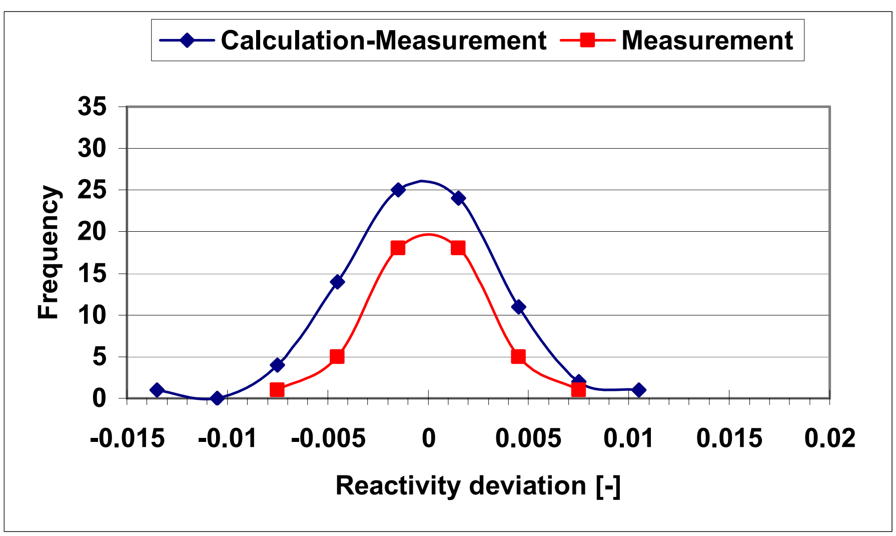

Figure 9. Difference of Calculated and Measured Scram Rod Worths Paks NPP Unit 1-4

5. SIMULATING THE DIFFERENTIAL ROD WORTH MEASUREMENTS

The experimental conditions mentioned in section 2 were used during the simulation of the measurements (see Fig. 1 and 3). Figure 10 shows the time dependent core amplitude calculated by the KIKO3D code and the IC signal during the simulated $\partial\rho/\partial H$ measurement. The core amplitude is used only for methodical purpose.

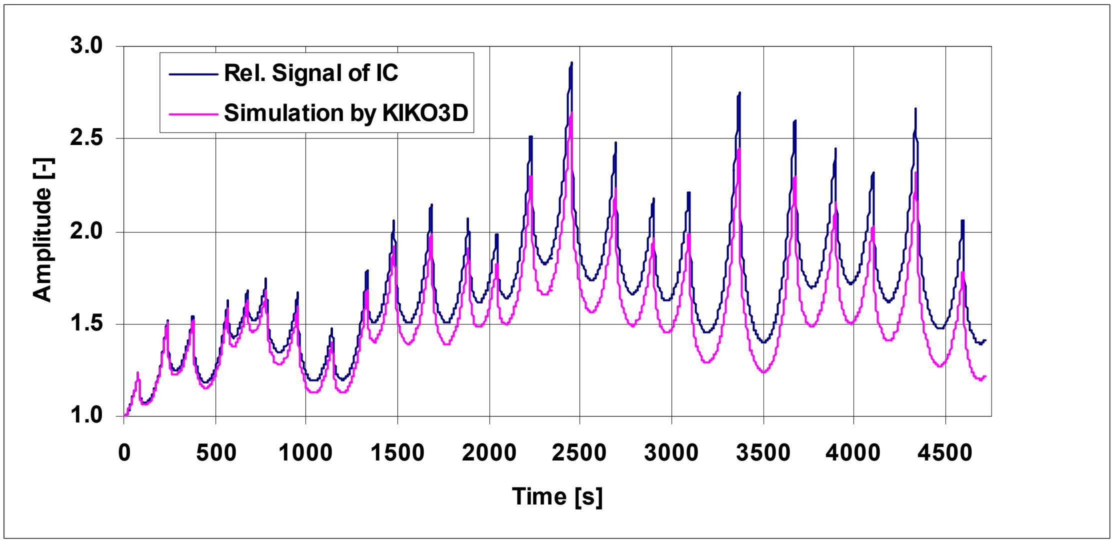

Figure 10. Core amplitude and IC signal (upper curve) during simulated $\partial\rho/\partial H$ measurement with KIKO3D Paks NPP Unit 3, Cycle 15

From the figure can be seen, that the calculated amplitude function is more sensitive to the change of the control rod position than the IC signal which depends only form the flux of the assemblies vicinity of the detector.

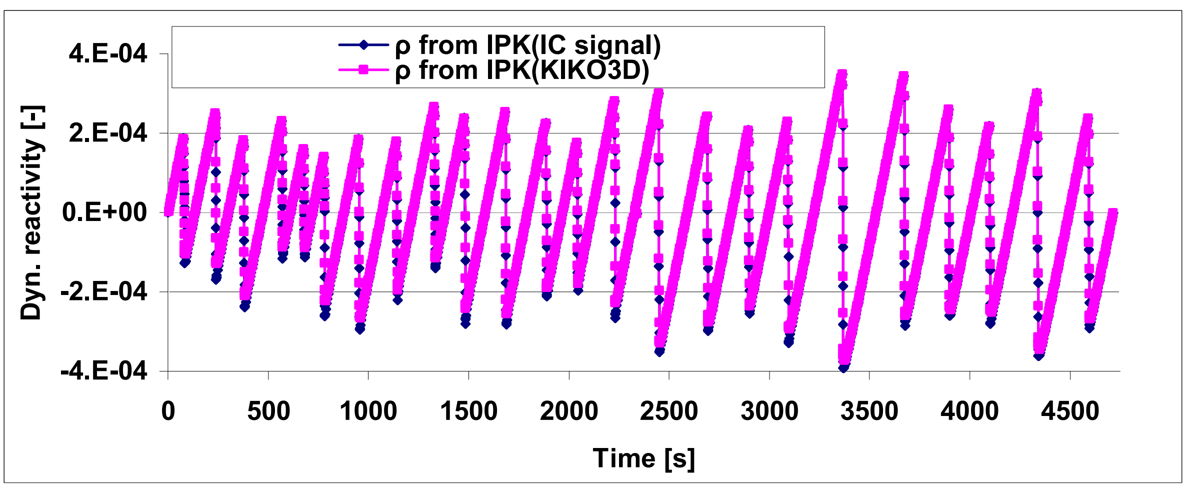

Figure 11. Inverse point kinetic reactivity derived from core amplitude and IC signal during simulated $\partial\rho/\partial H$ measurement with KIKO3D Paks NPP Unit 3, Cycle 15

The result of the IPK transformation using the core amplitude and the IC signal can be seen in Figure 11.

The inverse point kinetic reactivity curve using the amplitude is the dynamic reactivity with good approximation. The explanation of the difference is the fact that the point kinetics parameters are changing somewhat during the transient whilst we have used constant values in the inverse point kinetic transformation. An enlarged detail of Figure 11 can be seen in Figure 12.

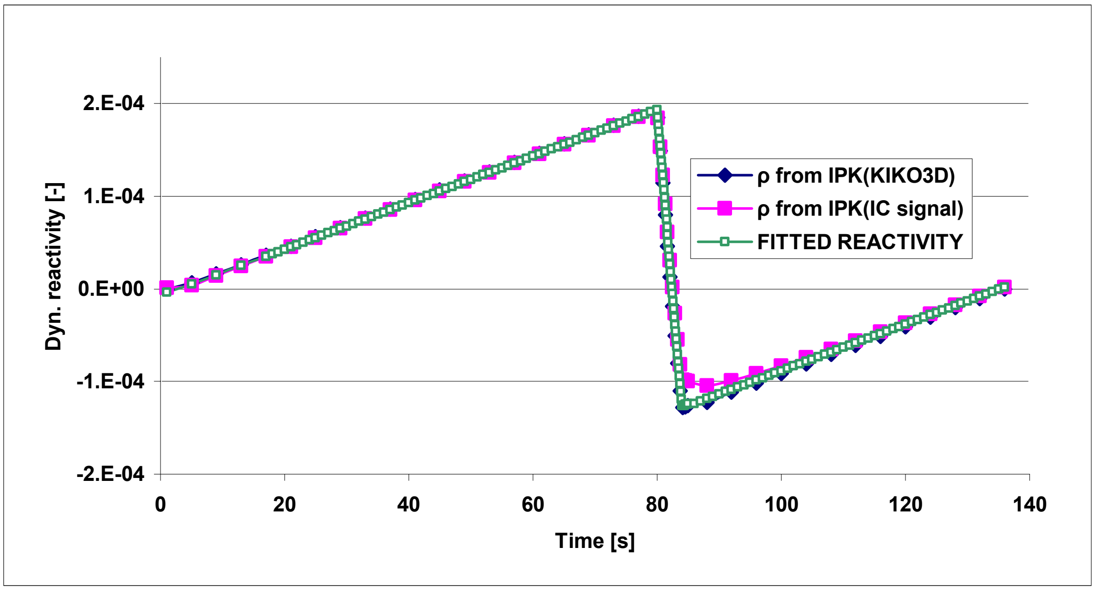

Figure 12. IPK reactivity derived from core amplitude and IC signal together with fitted reactivity curves during simulated ∂ρ/∂H measurement Paks NPP Unit 3, Cycle 15

The maximum difference between the amplitude and IC signal IPK reactivities is about 10%. The transient is slow; the reactivity insertion is low, so after some time the dynamic reactivity approaches well the static value. Using the IPK reactivity curves derived from the amplitude and the IC signals, knowing the rod positions and boric acid change the $\partial\rho/\partial H$ and $\partial\rho/\partial C_B$ reactivity coefficients can be determined by least squares fitting skipping the time values when the shape function did not reach closely the static value. To choose this time interval the convergence of IPK reactivities derived from amplitude and IC signal was used. Figure 12 contains the fitted reactivity curve from the IC signal, too.

For the given start-up measurements the differential control rod worth values were evaluated and compared to the results of the KARATE static calculations (See Figure 13.) which uses fine axial mesh size and detailed connecting part representation of the follower and the absorber. Figure 13 shows that the rod worth curve calculated from the IC signal are very close to the values of static calculations. Using this method the static reactivity coefficients are directly comparable to the results of the measurements evaluated by the above process.

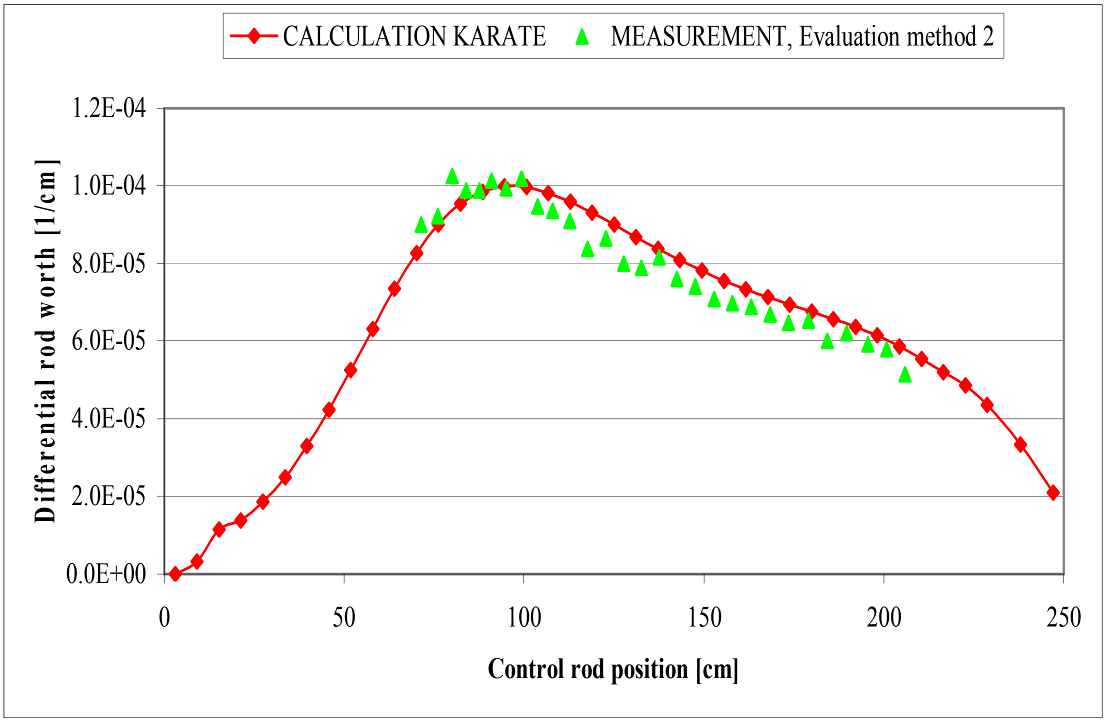

Figure 13. Differential worth of Working Group derived from KARATE calculations and from the chosen evaluation methods of the measured IC signals.

6. CONCLUSIONS

In strong non-homogeneous changes in the flux of the reactor core, such as in reactor scram with stuck CA, the reading of a reactivity meter connected to a particular ionization chamber does not directly represent the static or dynamic reactivity of the core. In order to use the measured signals (detector readings, current of ex-core detector) for code validation it is necessary to simulate the experiment, including the performance and to compare calculated predictions with actual measured values. Such simulations have been performed for a number of different cores of Paks NPP, using the upgraded KIKO3D kinetic code.

The uncertainty of scram rod worth of the KARATE code system was determined by static calculations and subsequent simulation of rod drop with the KIKO3D code. The calculations were comparison to measurements carried out at the Paks NPP. In the interpretation of the experiments the KIKO3D upgraded reactor dynamic code was used. To make the simulation more realistic the ionization chamber signal based on $^{3}He(n, p)$ reaction of thermal neutrons were calculated. The safety factor of scram rod worth was established by statistical analysis.

The presented experiment evaluation method and using the static KARATE code with fine axial mesh size provides fairly sufficient match of measured and calculated results.

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